STUDY OF NOR'WESTERS AND DEVELOPMENT OF PREDICTION TECHNIQUES IN BANGLADESH DURING THE PRE-MONSOON SEASON

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A thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Department of Physics

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By

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has been accepted as satisfactory in partial fulfillment for the degree of Doctor of Philosophy in Physics and certify that the student demonstrated a satisfactory knowledge on the field covered by this thesis in an oral examination held on 24 October, 2005.

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ABSTRACT

This dissertation is an attempt to study the nor'westers/thunderstorms over Bangladesh and their associated meteorological conditions with a view to finding the possible causes of formation together with the determination of the critical criteria of a number of meteorological parameters. The study includes the spatial and temporal distribution of mean monthly and seasonal nor'westers/thunderstorms and thunderstorm days over Bangladesh. This statistical analytic overview will be helpful to identify the climatological risk area for the nor'westers/thunderstorms and thunderstorm days over the country.

The inter-annual variability and trends of the frequency of thunderstorms have also been studied, which reveals that there exists 3-7 years cycles of variation in the monthly and seasonal frequency of thunderstorms over Bangladesh. The country-averaged monthly and seasonal frequency of thunderstorms during the pre-monsoon season has increasing trends. The rate of increase in the frequency of thunderstorms are 0.1912, 0.1059 and 0.2365/year in March, April and May respectively and 0.4566/year during the pre-monsoon season. The spatial distribution of the trends in the frequency of thunderstorms has been studied too.

The surface and upper air synoptic conditions, minimum temperature and surface humidity on the dates of occurrence of nor'westers in Bangladesh have been studied and the favourable conditions for the occurrence of nor'westers have been determined. Nor'westers have been found to occur over Bangladesh near the trough line at the surface. The causes of early nor'westers in Bangladesh have been found out. The study reveals that two air masses of different temperatures are found to be present over Bangladesh and adjoining West Bengal specially at 0000 UTC on the dates of occurrence of nor'westers and they form a discontinuous line. Sometimes more than one discontinuous line was present over the region. This indicates that 'pseudo-frontal' activity takes place over Bangladesh on the dates of occurrence of nor'westers. When this pseudo-frontal activity is found in the morning, severe thunderstorms/nor'westers occur in the evening or early night. Nor'westers have been found to occur near the point of intersection of axes of moist and dry areas.

The meteorological conditions associated with two tornadoes over Saturia and Tangail on 26 April 1989 and 13 May 1996 have been studied extensively. The tornadoes occurred near the point of intersection of the axes of moist and dry zones. The positive area

on Tephigram on the dates of occurrence was bigger than that on the previous day, indicating more instability of the troposphere on the dates of occurrence of the tornadoes. The available instability energy of the troposphere increased significantly on the dates of occurrence of tornadoes and these increases were 90.931003×10^6 Joule m^{-2} and 44.75421×10^5 Jm^{-2} in case of Saturia and Tangail tornadoes respectively as compared to that on the previous days. This tremendous quantity of instability energy was responsible for the occurrence of the tornadoes over Saturia and Kalihati on 26 April 1989 and 13 May 1996.

The rawinsonde observations at 0000 UTC over Dhaka, Chittagong and some stations of India have been utilized to compute different instability indices, water vapour and its fluxes, precipitable water content and different energy components of the atmosphere and their fluxes prior to the occurrence of nor'westers. The criteria of different instability for the occurrence of nor'westers have been determined. Some of the instability indices have been modified in order to have better criteria of these instability indices. For severe to very severe nor'westers, the critical values of MCT, MVT, MTT, MSWI, MKI and MEI at 0000 UTC over Dhaka are: MCT $\geq$ 22°C, MVT $\geq$ 28°C, MTT $\geq$ 54°C, MSWI $\geq$300, MKI $\geq$ 48°C and MEI< -9 Joule gm^{-1} respectively. For 5 cases of tornadoes, the critical values of the indices are: MCT $\geq$ 24°C, MVT > 30°C, MTT $\geq$ 55.0°C, MSWI $\geq$ 500, MEI $\leq$ -9 and MKI>58°C.

Satellite and radar cloud imageries have been used to study the movement of nor'westers over Bangladesh and to estimate vertical velocity associated with nor'westers from radar imageries.

The available instability of the troposphere gives a better indication for the occurrence of nor'westers. The higher the available instability energy of the troposphere, the greater is the possibility of occurrence of nor'westers, provided the other conditions especially the synoptic conditions are favourable. The vertical wind shear on the dates of occurrence of nor'westers has also been studied.

Simulated average surface wind fields and the rainfall fields for 24 hrs over the region bounded by Lat. 08-32° N and 70-110° E have been obtained by using the NCEP data. The wind fields indicate the surface circulation patterns favourable for the occurrence of nor'westers in Bangladesh and the rainfall fields for 24 hrs over Bangladesh and adjoining area give a good signature for the rainfall occurrence due to nor'westers in Bangladesh.

The forecasting techniques for the prediction of nor'westers and associated winds and rainfall have been developed. Four linear multiple regression equations for computation of maximum gusty wind speed associated with nor'westers have been developed. The R^2 values for the regressions are 0.2771, 0.3498, 0.3493 and 0.2433 which correspond to the correlation co-efficient of 0.52640, 0.59144, 0.59102 and 0.49325 respectively, which are not statistically significant. The computed values of maximum gusty wind speed have statistically significant correlation with the actual maximum gusty wind speed. The regression equations have been verified with data of current year (2005) and will be useful for the operational meteorologists for the computations of maximum gusty wind speed associated with nor'westers.

Simple linear regression equations and linear multiple regression equations have also been developed for the statistical prediction of 24 hrs rainfall over Dhaka, country-averaged 24 hrs rainfall over Bangladesh and 24 hrs maximum rainfall over Bangladesh due to nor'westers. The correlation co-efficients corresponding to these regression equations are statistically significant. These equations have also been verified with the data of current year.

The synoptic and statistical techniques developed for the forecasting of nor'westers and associated gusty wind and rainfall will be useful in operational purposes.

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CONTENTS

CHAPTER 1 INTRODUCTION

Page

1.1 General 1
1.2 Existing climatological aspects of nor'westers 4
1.3 Classification of local severe storms 7
1.4 Synoptic and other features 7
1.5 Conditions favourable for the occurrence of nor'westers 8
1.6 Tornadoes 9
1.6.1 Form, life cycle and damage 9
1.6.1.1 Form 9
1.6.1.2 Life Cycle 9
1.6.1.3 Damage 10
1.6.2 Favourable conditions for tornado genesis 11
1.6.3 Tornadoes detection 11
1.6.4 Measurement of wind speed 12
1.7 Objectives of the study 12
1.7.1 Analytical part 12
1.7.1.1 Distribution of nor'westers/thunderstorms and thunderstorm days over Bangladesh 12
1.7.1.2 Surface synoptic conditions and upper air circulation 13
1.7.1.4 Instability of the troposphere 13
1.7.1.5 Water vapour, precipitable water and water vapour fluxes associated nor'westers 13
1.7.1.6 Tropospheric energy and its fluxes 13
1.7.1.5 Dynamics of the troposphere 13
1.7.1.7 Tropospheric conditions associated with nor'westers in Bangladesh 14
1.7.2 Development part 14
1.7.2.1 Peak gusts and rainfall associated with nor'westers 14
1.7.2.2 Instability of the troposphere 14
1.8 Sequence of chapters 14

CHAPTER 2 CLIMATOLOGY OF THUNDERSTORMS AND THUNDERSTORM DAYS

2.1 Introduction 17
2.2 Data used 18
2.3 Methodology 19
2.4 Results and discussion 20
2.4.1 Thunderstorm frequency 20
2.4.1.1 Time of occurrence of nor'westers/thunderstorms in Bangladesh 20
2.4.1.2 Mean monthly thunderstorms 21
2.4.1.2.1 Temporal variation of mean monthly thunderstorms 21

2.4.1.2.2 Spatial distribution of mean monthly thunderstorms 22
2.4.1.3 Spatial distribution of mean seasonal thunderstorms 23
2.4.1.4 Co-efficient of variation of thunderstorms 23
2.4.1.4.1 Co-efficient of variation of monthly thunderstorms 23
2.4.1.4.2 Co-efficient of variation of seasonal thunderstorms 25
2.4.1.5 Interannual variability and trends of thunderstorm frequency 25
2.4.2 Frequency of thunderstorm days 29
2.4.2.1 Monthly mean frequency of thunderstorm days 29
2.4.2.1.1 Temporal variation of mean frequency of thunderstorm days 29
2.4.2.1.2 Spatial distribution of monthly mean thunderstorm days 30
2.4.2.2 Spatial distribution of seasonal mean thunderstorm days 32
2.4.2.3 Co-efficient of variation of thunderstorm days 33
2.4.2.3.1 Co-efficient of variation of monthly thunderstorm days 33
2.4.2.3.2 Co-efficient of variation of seasonal thunderstorm days 34

CHAPTER 3 SURFACE AND UPPER AIR SYNOPTIC CONDITIONS IN RELATION TO NOR'WESTERS AND TORNADOES

3.1 Introduction 36
3.2 Description of the tornadoes 37
3.2.1 Saturia tornado 37
3.2.2 Tangail tornado 38
3.3 Data used 39
3.4 Analyses 40
3.5 Results and discussion 41
3.5.1 Surface synoptic and upper air conditions associated with nor'westers 41
3.5.1.1 Mean sea level pressure distribution 41
3.5.1.2 Surface minimum temperature conditions 43
3.5.1.3 Surface humidity conditions 46
3.5.1.4 Upper air synoptic conditions 48
3.5.2 Synoptic and upper air conditions associated with tornadoes 50
3.5.2.1 Synoptic conditions on 26 April 1989 50
3.5.2.2 Synoptic conditions on 13 May 1996 51
3.5.2.3 Diurnal and spatial variation of 24-hr pressure change 52
3.5.2.3.1 Diurnal and spatial variation of 24-hr pressure change on 26 April 52
3.5.2.3.2 Diurnal and spatial variation of 24-hr pressure change on 13 May 1996 54
3.5.2.4 Spatial distribution of minimum temperature over Bangladesh 57
3.5.2.4.1 Spatial distribution of minimum temperature over Bangladesh on 26 April 1989 57
3.5.2.4.2 Spatial distribution of minimum temperature over Bangladesh on 13 May 1996 57
3.5.2.5 Spatial distribution of relative humidity over Bangladesh 58
3.5.2.5.1 Spatial distribution of relative humidity over Bangladesh on 26 April 1989 58

3.5.2.5.2 Spatial distribution of relative humidity over Bangladesh on 13 May 1996 60
3.5.2.6 Vertical profiles of specific humidity over Dhaka 60
3.5.2.7 Instability and available instability energy of the troposphere over Dhaka 61
3.5.2.7.1 Instability and available instability energy of the troposphere over Dhaka on 24-26 April 1989 61
3.5.2.7.2 Instability and available instability energy of the troposphere over Dhaka on 12-13 May 1996 62
3.5.2.8 Vertical distribution of wind over Dhaka 62
3.5.2.8.1 Vertical distribution of wind over Dhaka during the occurrence of tornado at Saturia 62
3.5.2.8.2 Vertical distribution of wind over Dhaka during the occurrence of tornado at Kalihati 63
3.5.2.9 Superposition of the axes of low-level maximum wind and the upper air jet stream of wind over Dhaka 64

CHAPTER 4 INSTABILITY OF THE TROPOSPHERE PRIOR TO THE OCCURRENCE OF NOR'WESTERS

4.1 Introduction 66
4.2 Data source 68
4.3 Methodology of stability analyses 70
4.3.1 Analysis of unmodified stability indices 70
4.3.1.1 Showalter Stability Index 70
4.3.1.2 Lifted Index 70
4.3.1.3 Dew-point Index 71
4.3.1.4 Dry Instability Index 71
4.3.1.5 Cross Total Index 71
4.3.1.6 Vertical total Index 72
4.3.1.7 Total Totals Index 72
4.3.1.8 Severe Weather Threat (SWEAT) Index 72
4.3.1.9 Energy Index 73
4.3.1.10 K-Index 73
4.3.2 Modified stability indices 73
4.3.2.1 Modified Cross Total Index 75
4.3.2.2 Modified Vertical Total Index 75
4.3.2.3 Modified Total Totals Index 75
4.3.2.4 Modified Severe Weather Threat Index 75
4.3.2.5 Modified Energy Index 76
4.3.2.6 Modified K-Index 77
4.4 Significance test of the coefficient of determination 77
4.5 Results and discussion 78
4.5.1 Stability indices at Dhaka in relation to the occurrence of nor'westers in Bangladesh 78

4.5.1.1 Showalter Stability Index and its frequency 78
4.5.1.2 Lifted Index and its frequency 79
4.5.1.3 Dew-point Index and its frequency 80
4.5.1.4 Dry Instability Index and its frequency 81
4.5.1.5 Cross Total Index and its frequency 81
4.5.1.6 Vertical Total Index and its frequency 83
4. 5.1.7 Total Totals Index and its frequency 84
4.5.1.8 Energy Index and its frequency 86
4.5.1.9 SWEAT Index and its frequency 87
4.5.1.10 K- Index and its frequency 89
4.5.2 Spatial distribution of different instability indices 91
4.5.3 Modified stability indices at Dhaka in relation to the occurrence of nor'westers in Bangladesh 94
4.5.3.1 Modified Cross Total Index and its frequency 95
4.5.3.2 Modified Vertical Total Index and its frequency 96
4.5.3.3 Modified Total Totals Index and its frequency 96
4.5.3.4 Modified SWEAT Index and its frequency 97
4.5.3.5 Modified Energy Index and its frequency 99
4.5.3.6 Modified K-Index and its frequency 100
4.5.4 Comparison of different stability indices with modified stability indices on the dates of occurrence of nor'westers in Bangladesh 101
4.5.5 Spatial distribution of different modified stability indices in relation to the occurrence of nor'westers in Bangladesh 104
4.5.6 Correlation among different modified and unmodified instability indices 108
4.5.7 Correlation of Showalter Stability Index with other instability indices 109
4.5.8 Correlation between Lifted Index and other instability indices 111
4.5.9 Correlation among unmodified and modified instability indices 113

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CHAPTER 5 TROPOSPHERIC MOISTURE, ITS FLUXES AND THE RELATION BETWEEN MOISTURE AND RAINFALL DUE TO NOR'WESTERS

5.1 Introduction 115
5.2 Data used 116
5.3 Methodology 117
5.3.1 Precipitable water content of the troposphere over Dhaka 117
5.3.2 Correlation of precipitable water content with different instability indices 118
5.3.3 Correlation of rainfall due to nor'westers with different instability indices and precipitable water content 118
5.3.4 Water vapour fluxes in the atmosphere 118
5.3.5 Vertically integrated fluxes of moisture 119
5.3.6 Significance test of the correlation co-efficients 119
5.4 Results and discussion 119
5.4.1 Precipitable water content of the troposphere and its relation with instability indices and rainfall due to nor'westers 119

5.4.1.1 Precipitable water content of the troposphere at 0000 UTC in relation to nor'westers 119
5.4.1.2 Correlation of precipitable water content of the troposphere with different instability indices 121
5.4.1.3 Specific humidity and weighted average specific humidity of the troposphere at 0000 UTC in relation to nor'westers 121
5.4.1.4 Statistical prediction of 24-hr rainfall due to nor'westers in Bangladesh 123
5.4.2 Fluxes of moisture 125
5.4.2.1 Zonal fluxes of moisture over Dhaka 125
5.4.2.2 Meridional fluxes of moisture over Dhaka 127
5.4.2.3 Vertically integrated zonal and meridional fluxes of moisture over Dhaka 129
5.4.2.4 Spatial distribution of the vertically integrated zonal and meridional fluxes of moisture 130

CHAPTER 6 ENERGETICS OF THE TROPOSPHERE AND THEIR FLUXES IN RELATION TO NOR'WESTERS

6.1 Introduction 132
6.2 Data used 134
6.3 Basic considerations 135
6.3.1 Energetics of the troposphere 135
6.3.2 Fluxes of energy components 136
6.3.3 Vertically integrated fluxes of energy components 137
6.4 Results and discussion 137
6.4.1 Sensible heat content (SH) of the troposphere 138
6.4.1.1 SH of the troposphere over Dhaka at 00 UTC during the pre-monsoon season 138
6.4.1.2 Comparison of the SH of the troposphere over Dhaka at 0000 UTC on the dates of occurrence and non-occurrence of nor'westers 139
6.4.1.3 Comparison of the SH of the troposphere over Dhaka at 0000 UTC on the dates of occurrence of nor'westers with the weekly normal 140
6. 4.1.4 Comparison of the SH of the troposphere over Dhaka at 0000 UTC on the dates of occurrence of nor'westers with the monthly normal 141
6.4.2 Latent heat (LH) content of the troposphere 142
6.4.2.1 LH of the troposphere over Dhaka at 0000 UTC during the pre-monsoon season 142
6.4.2.2 Comparison of the LH of the troposphere over Dhaka at 0000 UTC on the dates of occurrence and non-occurrence of nor'westers 143
6.4.2.3 Comparison of the LH of the troposphere over Dhaka at 0000 UTC on the dates of occurrence of nor'westers with the weekly normal latent heat 144
6.4.2.4 Comparison of the LH of the troposphere over Dhaka at 0000 UTC on the dates of occurrence of nor'westers with the monthly normal 145
6.4.3 Potential energy (PE) of a parcel in the troposphere 145
6.4.3.1 PE of a parcel of air in the troposphere over Dhaka at 0000 UTC during the pre-monsoon season 145

6.4.3.2 Comparison of the PE of a parcel of air in troposphere over Dhaka at 0000 UTC on the dates of occurrence and non-occurrence of nor'westers 146
6.4.3.3 Comparison of the PE of a parcel of air in troposphere over Dhaka at 0000 UTC on the dates of occurrence of nor'westers with the weekly normal PE 147
6.4.3.4 Comparison of the PE of a parcel of air in troposphere over Dhaka at 0000 UTC on the dates of occurrence of nor'westers with the monthly normal PE 149
6.4.4 Dry static energy (DSE) and moist static energy (MSE) contents of the troposphere 149
6.4.4.1 Vertical distribution of monthly normal DSE and MSE components over Dhaka during the pre-monsoon season 149
6.4.4.2 Comparison of the dry static energy and moist static energy components on the dates of occurrence of nor'westers with the normals 150
6.4.4.2 .1 Dry static energy 150
6.4.4.2.2 Moist static energy 152
6.4.4.3 Comparison of DSE and MSE components on the dates of occurrence of nor'westers at Dhaka with the previous weekly normal 154
6.4.4.3.1 Dry static energy 154
6.4.4.3.2 Moist static energy 155
6.4.5 Comparison of the DSE and MSE components of the troposphere over Dhaka between the dates of occurrence and non-occurrence of nor'westers 155
6.4.5.1 Dry static energy 157
6.4.5.2 Moist static energy 157
6.4.6 Comparison of the DSE and MSE components of the troposphere over Dhaka on the dates of occurrence of nor'westers in Bangladesh with the previous weekly normal 159
6.4.6.1 Dry Static Energy 159
6.4.6.2 Moist static energy 161
6.4.7 Maximum and minimum curves of DSE and MSE components of the troposphere over Dhaka on the dates of occurrence of nor'westers 164
6.4.8 Distribution of moist static energy at 850 and 500 hPa 166
6.4.9 Fluxes of energy components 166
6.4.9.1 Zonal fluxes of dry static energy over Dhaka 166
6.4.9.2 Meridional fluxes of dry static energy (MFDSE) over Dhaka 168
6.4.9.3 Vertically integrated zonal and meridional fluxes of DSE over Dhaka 170
6.4.9.4 Spatial distribution of the vertically integrated zonal and meridional fluxes of DSE 172
6.4.9.5 Zonal fluxes of moist static energy (ZFMSE) over Dhaka 173
6.4.9.6 Meridional fluxes of moist static energy (MFMSE) over Dhaka 174
6.4.9.7 Vertically integrated zonal and meridional fluxes of MSE over Dhaka 176
6.4.9.8 Spatial distribution of the vertically integrated zonal and meridional fluxes of MSE 178

CHAPTER 7 USE OF RADAR AND SATELLITE IMAGERIES IN THE STUDY OF NOR'WESTERS

7.1	Introduction	180
7.2	Data used	181
7.3	Methodology	182
7.3.1	Surface MSL charts, radar and satellite imageries	182
7.3.2	Vertical velocity at 300 hPa	182
7.4	Results and discussion	183
7.4.1	Pseudo-frontal activity	183
7.4.2	Study of satellite imagery	184
7.4.3	Study of radar imagery	186
7.4.4	Vertical velocity at 300 hPa	188

CHAPTER 8 AVAILABLE INSTABILITY ENERGY AND VERTICAL WIND SHEAR ASSOCIATED WITH NOR'WESTERS

8.1	Introduction	190
8.2	Data used	191
8.3	Basic computation	192
8.3.1	Available instability energy	192
8.3.2	Vertical wind shear	192
8.4	Results and discussion	192
8.4.1	Gusty wind speed	192
8.4.2	Available instability energy over Dhaka	194
8.4.3	Relation between available instability energy and maximum gusty wind over Dhaka	195
8.4.4	Vertical wind shear on the dates of occurrence of nor'westers	198

CHAPTER 9 SIMULATION OF SURFACE WIND AND RAINFALL FIELDS ASSOCIATED WITH NOR'WESTERS IN BAGLADESH

9.1	Introduction	201
9.2	Data used	202
9.3	Results and discussion	202
9.3.1	Simulated average wind fields	202
9.3.2	Simulated average rainfall fields	202

CHAPTER 10 PREDICTION TECHNIQUES FOR THE NOR'WESTERS AND ASS0CIATED MAXIMUM WIND SPEED AND RAINFALL

10.1 Introduction 210
10.2 Data used 212
10.3 Methodology 212
10.4 Significance test 214
10.5 Results and discussion 214
10.5.1 Frequency of maximum wind speed of nor'westers at Dhaka 214
10.5.2 Multiple regression of maximum wind speed with different parameters 215
10.5.2.1 Experiment-1: Multiple regression of maximum wind speed with different parameters 215
10.5.2.2 Experiment-2: Multiple regression of maximum wind speed with different parameters 216
10.5.2.3 Experiment-3: Multiple regression of maximum wind speed with different parameters 218
10.5.2.4 Experiment-4: Multiple regression of maximum wind speed with different parameters 218
10.5.3 Linear multiple regression equations for the rainfall due to nor'westers 218
10.5.3.1 Linear multiple regression equations for the country-averaged 24 hrs rainfall 219
10.5.3.2 Linear multiple regression equations for the 24 hrs maximum rainfall in Bangladesh 219
10.5.3.3 Linear multiple regression equations for the 24 hrs rainfall at Dhaka 219
10.5.4 Correlation between the actual maximum wind speed and the computed maximum wind speed 220
10.6 Validation of the linear multiple regression equations for maximum gusty wind speed associated with nor'westers 220
10.6.1 Experiment-1 &2 for the multiple regression of maximum gusty wind 220
10.6.2 Experiments-3 &4 for the multiple regression of maximum gusty wind 222
10.7 Validation of the regression equations for 24 hrs rainfall 223
10.7.1 Validation of the simple regression equations for the country-averaged rainfall in Bangladesh 223
10.7.2 Validation of the simple regression equations for the 24 hours rainfall at Dhaka and maximum rainfall in Bangladesh 225
10.7.3 Validation of the linear multiple regression equations for 24 hrs rainfall 227
10.7.3.1 Validation of the linear multiple regression equation for the country averaged 24 hrs rainfall in Bangladesh 227
10.7.3.2 Validation of the linear multiple regression equation for the maximum 24 hrs rainfall in Bangladesh 228
10.7.3.3 Validation of the linear multiple regression equation for the 24 hrs rainfall at Dhaka 229
10.8 Synoptic techniques for the prediction of nor'westers 230

10.8.1 Synoptic techniques for the prediction of nor'westers in Bangladesh 230
10.8.2. Key forecasting parameters and intensity of nor'westers in Bangladesh 232

CHAPTER 11 CONCLUSIONS 234

REFERENCES 246

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6. On the dry static and moist static energy of the troposphere over Dhaka before the occurrence of nor'westers in Bangladesh during the pre-monsoon season, (Submitted for publication in MAUSAM, India).
7. On the tropospheric zonal and meridional fluxes of moisture in relation to nor'wester/thunderstorms in Bangladesh during the pre-monsoon season, (Submitted for publication in MAUSAM, India).

LIST OF SYMBOLS/ABBREVIATIONS

Symbols/abbreviations	Meaning
σ	Standard deviation
Q	Specific humidity
E	Vapor pressure
P	Pressure
L	Latent heat of phase change
T	Dry-bulb air temperature in °K
T_d	Dew-point temperature in °K
°K	Degree Kelvin
W	Precipitable water content of the troposphere
Q_{λ_L}	Zonal water vapour transfer for a given level (gm $kg^{-1} \times ms^{-1}$)
Q_{ϕ_L}	Meridional water vapour transfer for a given level (gm $kg^{-1} \times ms^{-1}$)
g	Acceleration due to gravity
u	Zonal wind component
V	Meridional wind component
W	Vertical velocity in (x, y, z, t) co-ordinates
ω	Vertical velocity in (x, y, p, t) co-ordinates
V	Magnitude of the wind vector
Kts	Knots (unit of wind speed in nautical miles per hour)
α	Direction wind vector measured from the true north.
F	Coriolis parameter
ρ	Density of air
ϕ	Latitude in degree
Z	Geometric height
Z	Geopotential height in geopotential meter
Ω	The angular speed of rotation of the earth
C_p	Specific heat at constant pressure
DSE	Dry Static Energy
MSE	Moist Static Energy
KJ	Kilo Joule
SI	Showalter Index
LI	Lifted Index
DPI	Dew-point Index
DII	Dry Instability Index
CT	Cross Total Index
VT	Vertical Index
TT	Total Totals Index
SWI	SWEAT Index
EI	Energy Index
KI	K-Index
MCT	Modified Cross Total Index
MVT	Modified Vertical Total Index

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MTT	Modified Total Totals Index
MSWI	Modified SWEAT Index
MEI	Modified Energy Index
MKI	Modified K-Index
Surface Code 17	Thunderstorm but no precipitation at the time of observation
Surface Code 29	Thunderstorm (with or without precipitation) + hail, small hail, snow during the preceding hour but not at the time of observation
Surface Code 95	Thunderstorm, slight or moderate, without hail but with rain and/or snow at the time of observation
Surface Code 96	Thunderstorm, slight or moderate, with hail at the time of observation
Surface Code 97	Thunderstorm heavy, without hail, but with rain and/or snow at the time of observation
Surface Code 98	Thunderstorm combined with dust storm or sandstorm at the time of observation
Surface Code 99	Thunderstorm, heavy, with hail at the time of observation
CV	Co-efficient of variation
Waq	Weighted average specific humidity
ZFDSE	Zonal Flux of Dry Static Energy
WFDSE	Westerly Flux of Dry Static Energy
EFDSE	Easterly Flux of Dry Static Energy
MFDSE	Meridional Flux of Dry Static Energy
SFDSE	Southerly Flux of Dry Static Energy
NFDSE	Northerly Flux of Dry Static Energy
ZFMSE	Zonal Flux of Moist Static Energy
WFMSE	Westerly Flux of Moist Static Energy
EFMSE	Easterly Flux of Moist Static Energy
MFMSE	Meridional Flux of Moist Static Energy
SFMSE	Southerly Flux of Moist Static Energy
NFMSE	Northerly Flux of Moist Static Energy
VIZFDSE	Vertically Integrated Zonal Flux of Dry Static Energy
VIMFDSE	Vertically Integrated Meridional Flux of Dry Static Energy
VIZFMSE	Vertically Integrated Zonal Flux of Moist Static Energy
VIMFMSE	Vertically Integrated Meridional Flux of Moist Static Energy

CHAPTER 1

INTRODUCTION

1.1 General

Bangladesh is a small country of about 1,47,570 sq. km (DOE, 2002) having the Bay of Bengal to the south and the Himalayas to the north. Because of its peculiar geographical location, the country is affected by a number of disastrous weather events like thunderstorms/nor'westers, tornadoes, cyclones, floods etc. The scales of atmospheric motion for different weather events or circulation are different and are given in Table 1.1 (Holton, 1979):

Table 1.1 Scales of atmospheric motion

Type of motion	Horizontal scale (m)
Gusts	$10\text{-}10^2$
Tornadoes	10^2
Cumulonimbus	10^3
Fronts/Squalls	$10^4\text{-}10^5$
Hurricanes	10^5
Synoptic cyclones	10^6
Planetary cycles	10^7

Thunderstorm is defined as one or more sudden electrical discharges, manifested by a flash of light (lightning) and a sharp or rumbling sound (thunder). A typical thunderstorm is made up of a single cumulonimbus cloud (Figs. 1.1 and 1.2). Thunderstorms are associated with strong winds, which are created by the downdraft, This downdraft in turn is created by cold air rushing out of the thunderstorm as precipitation inside of it evaporates and cools the air. If the environment outside the thunderstorm is particularly dry, evaporation will be enhanced, and so will the threat for severe winds. A downburst is defined as an area of strong winds produced by a downdraft. Once it comes in contact with the earth, it spreads out laterally and causes damage at ground level. There are two types of downbursts, a macroburst and a microburst. The macroburst covers an area larger than 4 kilometers in diameter, and the microburst is smaller than 4 kilometers in diameter, as defined by the Ted Fujita (1985). Both are a serious threat to structures on the ground and to planes in the air. Damage caused by

downbursts is frequently mistaken for tornado damage. People who have experienced this phenomenon describe it as a loud (sometimes dark) cloud rushing toward them and when it reaches them, the wind becomes very violent.

There are four types of thunderstorms. These are the single cell (ordinary), multicell (squall line), multicell cluster and supercell.

The ordinary or single cell thunderstorm is nothing more than ephemeral bursts of convection. Each burst creates a towering cumulus or "cell" of convection. Once the cell gets large and tall enough, it is classified as a cumulonimbus, or thunderstorm. The updraft and of this small cloud interfere with each other, resulting in a fairy short-lived cell, but the downdraft from one single cell may give rise to a new cell nearby. This "parent-daughter" effect allows an ordinary thunderstorm to pulse with convection for up to one hour (MESO, March 2001).

The multicell or squall line thunderstorms form in long lines with a well-developed gust front at the leading edge of the line. The name multicell simply means that there are many cells that grow to form a group of cells that move together as one unit. Squall lines are prolific downburst producers. Occasionally an extreme strong downburst will accelerate a portion of the line forward causing it to form what is called ***bow***. On the leading edge of this bow formation is where the most damaging winds are found. Tornadoes will sometimes form just to the north of this bow, or on the line's southernmost cell, which is called the ***anchor cell***. Cells that form on the southern ends of squall lines tend to inherit supercell characteristics since there is nothing to the south of them to disrupt air flow being entrained into them.

The multicell cluster is the most common type of thunderstorm. A multicell cluster thunderstorm results from a vigorous parent-daughter effect. In this case, an ordinary thunderstorm creates neighbouring storms via the downdraft and a gust front. If the surrounding atmosphere is unstable and moist enough (and with adequate low-level vertical shear), new cells will be created around the old one, giving birth to cluster of active thunderstorms. Each cell will be in a different phase of the life cycle. Each individual cell will have its turn to be the dominant one. New cells tend to form on the western or southwestern edge of the cluster, while the more mature cells are usually found in the centre. The dissipating cells are often found on the eastern or northeastern edge of the cluster. The

multicell cluster storms last a bit longer than ordinary, or single cell storms and cover a larger area. Each cell in a multicell cluster storm usually lasts about 20 minutes, but the cluster of storms itself can persist for several hours.

. The supercell thunderstorm is the classic cumulonimbus tower with the anvil top and on occasion the overshooting updraft tower. These storms are notorious for producing damaging straight-line winds, frequent lightning, flash floods, large hail, and violent tornadoes. The base of the storm may be only 20-50 km across, but the anvil aloft can stretch for many hundreds of kilometers. The supercell is unique because the updraft actually rotates; this rotating updraft is called a mesocyclone. Organization within the storm is incredible. The updraft and downdraft regions do not interfere each other like the ordinary thunderstorm; instead, they collaborate to prolong the life of the storm. The inflow, outflow, updrafts, and downdrafts all work together like a living, breathing creature. A supercell can exist in a quasi-steady state for hours, advecting along the ground with the ambient wind. In order to form a supercell, three ingredients are necessary: high thermal instability, strong winds in the middle and upper troposphere, and veering of the wind with height in the lowest kilometer. As the precipitation is produced in the updraft, the strong upper-level winds blow the precipitation away from the updraft, allowing little or none of it fall back down through the updraft core. Keeping the precipitation away from the updraft is what allows the supercell to thrive for many hours, capable of producing violent weather throughout its lifetime. Light rain will begin as the supercell approaches. As the updraft area comes closer, the areas to the north and east will see an increase in rain and hail, and then near the updraft itself is where most severe weather (tornadoes) will occur.

The life cycle of a thunderstorm has three stages: (a) Cumulus stage, (b) Mature stage and (c) Dissipating stage. The three stages are shown in Fig. 1.3.

Nor'westers are meso-scale severe thunderstorms that occur in Bangladesh during the pre-monsoon season (March-May). These are local severe storms. Sometimes tornado cells are embedded in mother thunderstorm cloud. These severe weather events cause fairly widespread destruction of properties and loss of lives throughout Bangladesh. Economic losses are also enormous due to these weather events. Two transition periods between southwest and northeast monsoons over the India-Bangladesh-Pakistan subcontinent are characterized by local severe storms. In Bangladesh, these transition periods are known as pre-monsoon (March-May) and post-monsoon (October-November) seasons. Of these, it is

pre-monsoon (March-May) and post-monsoon (October-November) seasons. Of these, it is the pre-monsoon season when most of the local severe storms occur over different parts of Bangladesh with frequent intervals. These storms are popularly known as **Nor'westers** or

Fig. 1.1: Cumulonimbus cloud

Fig. 1.2: Lightning in a thunderstorm

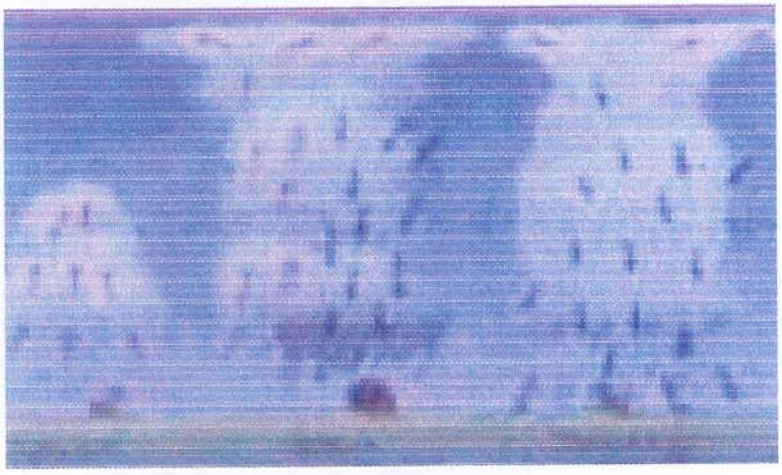

Fig. 1.3: Three stages of the life cycle of a thunderstorm

Kalbaishakhi in Bangladesh, West Bengal and Assam of India and Andhi (dust storms) in North India. Though they occur locally, their violence and destruction often become very significant. Because of this fact, nor'westers have always been of interest to the working meteorologists since long. Various aspects of these phenomena have been studied by different authors like Sen (1931), Chatterjee and Sur (1933), Malurkar (1949), Bose (1955),

Mukherjee and Bhattacharya (1972), Mukherjee *et al.* (1977), Chowdhury *et al.* (1991), Das *et al.* (1994), and Akram and Karmakar (1998). In all of these studies, a number of important results have been obtained as regards formation, structure, timing and devastation of nor'westers, etc. There has been, of course, some difference of opinions among the authors as well.

1.2 Existing climatological aspects of nor'westers

Nor'wester activities in these parts of the region are directly linked up with the apparent movement of the sun towards north causing steady rise in temperature over Southern India and gradually extending to the north. Such a situation becomes increasingly prominent from March and prolongs up to the end of May. Frequency of nor'westers in Bangladesh usually reaches its maximum in May, having maximum value over the Sylhet-Mymensingh-Dhaka region (Chowdhury and Karmakar, 1986) and is comparatively minimum over the northwestern and southwestern parts of Bangladesh. There are occasions when nor'westers have been observed to occur in late February and early June. The occurrences of nor'westers in late February can be attributed to the early withdrawal of winter from Bangladesh, Assam, Bihar, West Bengal and adjoining area as well as due to the penetration of the easterly lows through the southern tip of India and their subsequent movement towards north-east (Das *et al.*, 1994), while those in early June are due to delay in the onset of south-west monsoon over this region. The delay in the occurrence of nor'westers over Bangladesh is due to presence of intense subtropical high over the Bay of Bengal.

Nor'westers do not approach always from the same direction and their time sequence is not always the same. However, the majority of nor'westers usually start in West Bengal and Chota Nagpur of India in the early afternoon and proceeds in a NW-SE direction (Tech. Note No. 10 of IMD, 1944). There could be some variation with respect to the origin of nor'westers to a certain extent depending on the synoptic situations. The usual speed of travel of nor'westers varies between 48 km/hr (30 mph) and 64 km/hr (40 mph). In the early study made of India Meteorological Department (1944), nor'westers occurring in this region have been classified broadly into four types designated as A, B, C & D. Type-A nor'westers are most predominant and account for 45% of thunderstorms during April and May. This type of storms usually starts in West Bengal and Chota Nagpur region of India in the afternoon and proceed in the southeasterly direction with a speed of 48-64 km/hr. Squally winds in these thunderstorms generally have a velocity of 64-96 km/hr and they are associated with hail

either at the beginning or at the end of the storm. The other three types of nor'westers originate from the foot of the Hills flanking northern and eastern borders of West Bengal, Bangladesh and Assam. They are differentiated according to the place of their origin. Those starting from the sub-mountainous district of West Bengal and Northern Bangladesh are classified as type-B; nor'westers, those originating from the Eastern Hills as Type-C and those starting from the foot of the Khasi Hills as Type-D.

Type-B nor'westers start mostly in the night and early morning and move slowly with a speed of 16-32 km/hr to the Meghna estuary from the north. They are accompanied with copious rainfall but seldom with hail. The nor'westers of Type-C are very rare. The squally winds associated with this type of storm come mainly from a northeasterly direction. Storms of Type-D are very similar to those of Type-B and come from a northerly direction. The movement of different of nor'westers in Bangladesh is shown in Fig. 1.4.

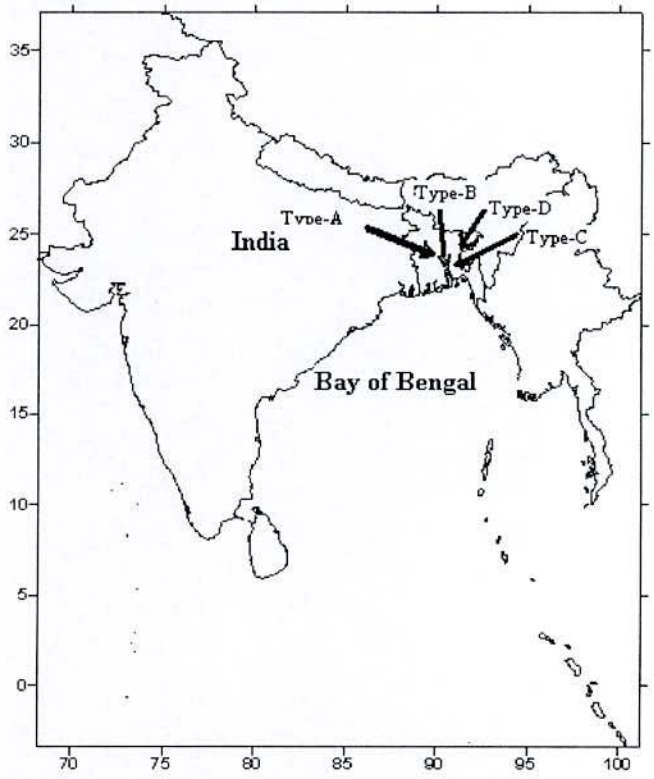

Fig. 1.4: Movement of different types of nor'westers

Severe nor'westers are sometimes associated with Mamatocumulus cloud (Fig. 1.5) especially near the anvils of the Cumulonimbus cloud.

Fig. 1.5: Mamatocumulus cloud

1.3 Classification of local severe storms

In the study, thunderstorms are the local severe storms, which have been classified as follows:

Local severe storms		Maximum gusty wind (km/hr)
(a) Thunderstorms with gusty winds	:	31-40
(b) Thunderstorms with squally winds/light nor'westers	:	41-60
(c) Moderate nor'westers	:	61-90
(d) Severe nor'westers	:	91-120
(d) Very severe nor'westers	:	121-150
(e) Tornado	:	≥ 151

1.4 Synoptic and other features

Suitable synoptic features are important to cause local severe storms. These features are required to exist both at the surface and the upper levels and can be easily identified in the weather charts, which are analyzed in a forecasting office.

Surface and lower troposphere: In the pressure distribution from surface to about 1 km over Northern India, Bangladesh and Pakistan during the months of local severe storms especially in March, April and May. The main feature is the existence of a trough of low pressure over Uttar Pradesh and Bihar with its axis extending west-east direction across the

plains. The orientation of the axis and its intensity are affected by the passage of western disturbances in the form of low-pressure area. In such a situation, the accentuated axis of the trough extends southeastwards up to Gangetic West Bengal and Bangladesh. Around the trough SW/S'ly wind normally blows from the Bay of Bengal up to a level of about 1 km or more incurring influx of moisture over the region covering Bangladesh, West Bengal and Assam. Quite often, through NE-Assam, ENE/NE'ly dry and cooler wind descends downwards to the west across the foot of the Himalayas. In such typical situation with the existence of ENE/E'ly wind over extreme North Assam and SW/S'ly wind from the south, east-west line of wind discontinuity takes place over Northern Bangladesh and upper Assam.

Upper troposphere: In the upper troposphere, westerlies or north-westerlies prevail over Pakistan, North Indian Plains, Bangladesh and Assam. The passage of upper troughs in the westerlies or the jet maxima across this region can often be detected at about 9.0 km to 12.0 km levels. The superposition of upper divergence having association with a perturbation like a jet, jet-cum-trough or trough on the convergence having association with a low-level low or even straight southerly flow up to 1 km is quite a significant feature on the days of nor'westers over this area (Koteswaram and Srinivasan, 1958).

It has been found that the place of occurrence of severe nor'westers and tornado lies very near to the point of intersection of the axes of low level maximum wind (850 hPa) and upper level jet stream at 250/200 hPa (Das *et al.* 1994, and Akram and Karmakar, 1998).

Prior to the occurrence of nor'westers, there occurs an increase in different energy components such as dry static energy, latent heat energy and moist static energy in the troposphere. The increase in latent heat energy is significant on the day of occurrence of nor'westers as compared to the other energy components (Chowdhury *et al.*, 1991). This is mainly due to the influx of moisture from the Bay of Bengal and its subsequent condensation from which tremendous latent heat is released.

1.5 Conditions favourable for the occurrence of nor'westers

Like any other severe weather, nor'westers are the severe thunderstorms and are mainly the products of a highly unstable atmosphere. This instability can result with the modification of a more stable atmosphere. Along with this instability, a number of other conditions are also necessary to cause local severe storms. Srinivasan (1962) summarized those conditions conducive to the occurrence of nor'westers:

a) a mechanism to cause low-level convergence, which will enable the lower layer of the atmosphere to ascend,

b) high-level positive vorticity advection causing divergence (or mass depletion), which will enable the lower ascending air to ascend further to higher levels,

c) sufficient inflow of moisture in the lower layers, and

d) a favourable lapse-rate in the lower and middle troposphere.

Koteswaram and Srinivasan (1958) have shown in their investigation that the nor'westers fail to occur in the Gangetic West Bengal and by inference over Bangladesh and Assam in the absence of southerly winds up to at least 1 km in spite of the other conditions being fulfilled. However, it is possible that the initial shallow layer of moist air can even become deep due to the stretching of the lower layer by convergence. It has also been observed by them that there is a definite need for the existence of a suitable lapse rate in the lower and middle troposphere. Without such suitable lapse rate, the conditions identified in section 1.4 (a, b & c) seem to produce only heavy rain without any severe storm. These findings amply demonstrate the inter-dependability of these favourable conditions and as such their combination can only determine the probability of occurrence of nor'westers.

1.6. Tornadoes

A tornado is an intense atmospheric vortex, violently rotating, tall, narrow column of air that occasionally extends to the ground from a cumuliform cloud. It is seen as a funnel-shaped cloud pendant from a cloud base (Fig. 1.6). The funnel does not always extend to the ground, and may be obscured by dust (Ghose, 1986). The tornadoes move in a zigzag path.

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Fig. 1.6: Funnel shaped tornado cloud

1.6.1 Form, life cycle and damage

1.6.1.1 Form

The funnels may assume various forms such as a thin rope, a cylindrical or conical shape, a thick mass of black cloud or multiple funnels. The funnel outline may be sharp-edged or very ragged, suggesting that the flows in tornadoes may be either smooth or highly turbulent. Almost all tornadoes rotate cyclonically but anticyclonic ones also exist.

1.6.1.2 Life Cycle

The tornado life cycle may broadly be divided into the following five stages (Davies Jones, 1982)

(i) **The dust whirl stage** – when the first signs of circulation are visible as dust swirling upwards from the surface.

(ii) **The organizing stage** – characterized by overall downward descent of the funnel.

(iii) **The mature stage** – when the funnel reaches its greatest width and is almost vertical and when damage is most intense.

(iv) **The shrinking stage** – marked by decreasing funnel width, increasing funnel tilt and a narrow damage sweep.

(v) **The decay stage** – when the vortex is stretched into a rope shape.

1.6.1.3 Damage

A tornado inflicts damage in various ways as in the following (Holford, 1977):

(a) By the direct impact of wind, whose force is proportional to the square of wind speed.

(b) By twist due to unequal wind speeds within the very narrow band of the circulation. Winds are often so much greater on one side of a tree than on the other that they screw off the tops of trees.

(c) By explosion when a tornado passes directly over a building which contains air at normal atmospheric pressure. Extremely high pressure gradients exist

across the narrow circulation, which would result in a momentary inequality of pressure between the outside and inside of a building. Roofs are sucked off and walls explode outwards. The advice given in tornado safety rules in the USA is to open doors and windows on the opposite side of the building from that of the approaching tornado, so as to facilitate the equalization of atmospheric pressure.

(d) By lift and drop in the vertical currents within the tornado. An up current of 240 km/h was indicated by a film taken in Dallas, USA, on 2 April 1957. Sheds, cattle and human beings are carried high into the air (Nandi and Mukherjee, 1966). Even vehicles such as buses with several persons inside are reported to have been lifted a few meters above the ground (Mukherjee and Bhattacharya, 1972; Gupta and Ghosh, 1980).

1.6.2 Favourable conditions for tornado genesis

The following conditions favourable for the formation of tornadoes:

(i) Abundant moisture in the surface layer to a depth of at least 1 km. The presence of a dry air mass at intermediate level (1 to 2.5 km), providing the potential for strong downdrafts through evaporative cooling, is also favourable.

(ii) Deep conditional and convective instability i.e., large lapse rate of temperature and moisture through a great depth.

(iii) The presence of a stable layer or inversion. This acts to prevent deep convection from occurring until the potential for explosive overturning is established.

(iv) A mechanism to remove the stable layer. The most common mechanism is dynamic lifting with surface heating and warm air advection below the inversion. Other possible mechanism includes lifting by terrain and by gravity waves. Dynamic lifting is strongest near thin zones of low-level convergence such as fronts or dry lines (dew-point fronts) and beneath regions of pronounced upper level divergence. Typically, these features occur in combinations to provide sustained lifting through deep layers.

(v) Moderate to strong winds that veer with height, with large values in a narrow horizontal band at altitudes above 6 km.

1.6.3 Tornadoes detection

Tornadoes are detected mostly on the basis of radar observations. Hook shaped echoes have been associated with tornadic storms but unfortunately the correlation is far from perfect. The most promising detection devise is Doppler radar. This radar can measure the speed of precipitation target toward or away from the radar antenna, as well as the reflectivity. The tornadic vertex signature (TVS) is a small scale, high shear region associated with the tornado itself. The TVS is first detected at mid-levels and it extends both upward and downward. It reaches cloud base co-incident with funnel cloud appearance. Attempts to detect tornado from geostationary satellite have met with little success. As already mentioned, tornadoes generally occur after the collapse of the storm's overshooting top but since this signature is not unique, it cannot be used for warning purposes.

1.6.4 Measurement of wind speed

There are many methods to estimate wind speed in tornadoes, which are of great interest to engineers to design vital structures. Some of the methods are described below:

(i) **Ground Marks:** Marks caused by suction on the ground often resemble cycloid. They consist of short pieces of stubble laid in cycloidal rows. They are indicative of suction vortices rotating around the axis of the tornado, because the combination of straight line and circular motion yields a cycloidal path. The path of a suction vortex depends on the translation velocity of the parent tornado, the radial distance between the suction vortex and tornado axis, and the speed at which the suction vortex is moving around the tornado axis. The first two can be estimated from radar data and the observed size of cyclonical loops. Analysis of suction marks reveals speed of 80 to 95 m/s (Fujita *et al.,* 1970). However there are many difficulties in the estimation of wind speed by this method because in many cases there are many suction vortices present simultaneously.

(ii) **Direct passage over instruments:** Anemometers are often blown away in tornadic conditions; in cases where they survive there is always the question of whether they received the storm's full force. The highest value ever recorded by an instrument was 67 m/s.

(iii) **Remote sensing**: The most important tool for measuring wind speed is the meteorological Doppler radar. This specialized radar measures the Doppler frequency shift caused by the component of radar target movement parallel to the radar beam.

1.7 Objectives of the study

1.7.1 Analytical part

1.7.1.1 Distribution of nor'westers/thunderstorms and thunderstorm days over Bangladesh

This includes the spatial and temporal distribution of mean monthly and seasonal nor'westers/thunderstorms and thunderstorm over Bangladesh. This statistical analytic overview will be helpful to identify the climatological risk area for nor'westers / thunderstorms and thunderstorm days over the country.

1.7.1.2 Surface synoptic conditions and upper air circulation

The surface synoptic conditions and upper air circulation prior to the occurrence of nor'westers and tornadoes have been studied. Charts containing synoptic conditions and distributions of some of the meteorological parameters have been prepared to evaluate the areas favourable for the occurrence of nor'westers in Bangladesh.

1.7.1.3 Instability of the troposphere

Different stability indices have been computed to determine the instability condition of the troposphere prior to the occurrence of nor'westers. The critical values of the indices will be determined in relation to the occurrence of nor'westers over the country. Their spatial distributions of the different instability indices over Bangladesh and adjoining Indian States have been studied for the delineation of the area of maximum instability prior to the occurrence of nor'westers in Bangladesh

1.7.1.4 Water vapour, precipitable water and water vapour fluxes associated nor'westers

The rawinsonde observations have been utilized to compute the water vapour, its fluxes and precipitable water content of the atmosphere prior to the occurrence of nor'westers. The spatial and temporal distribution of these parameters will be further studied and an attempt will be made to correlate the precipitable water with actual rainfall due to

nor'westers. Their spatial and vertical distributions of precipitable water, specific humidity and their fluxes over Bangladesh and adjoining Indian States have been studied for the delineation of the area of maximum moisture content and influx of moisture prior to the occurrence of nor'westers in Bangladesh

1.7.1.5 Tropospheric energy and its fluxes

The changes of the different energy components, total energy and their fluxes before the occurrence of nor'westers are studied extensively. This explains the physical processes which are responsible for the formation of severe thunderstorms / nor'westers.

1.7.1.6 Dynamics of the troposphere

The divergence / convergence, vertical wind shear, vertical velocity etc. have been computed by using radar imageries and rawinsonde data. The findings will cast in-depth look into the dynamic evolution of nor'westers and their movement. The low-level maximum wind and upper level jet stream data have been utilized to locate the probable area of occurrence of nor'westers in Bangladesh as well.

1.7.1.7 Tropospheric conditions associated with nor'westers in Bangladesh

Tropospheric conditions associated with nor'westers in Bangladesh have been studied extensively for some cases.

1.7.2 Development part

1.7.2.1 Peak gusts and rainfall associated with nor'westers

Some parameters obtained from the analysis of thermodynamic diagram and meteorological parameters obtained from the rawinsonde data are used to calculate the peak gusts associated with nor'westers. Multiple regression equations have been developed among the peak gusts associated with nor'westers and various instability indexes as well as other meteorological parameters. Similarly, simple and multiple regression equations have also been developed for the prediction of 24 hours rainfall associated with nor'westers.

1.7.2.2 Instability of the troposphere

Different stability indices, as obtained in section **1.7.1.4**, have been modified by taking into consideration of the 925 hPa in lieu of 850 hPa level. It is because of the fact that the low-level moisture plays an important role in making weather. The critical values of the indices have been determined in relation to the occurrence of nor'westers over the country.

The prediction of nor'westers does not depend on only one or two favourable meteorological parameters, but on a number of parameters and their temporal and spatial

distributions. The present study aims at the determination of the favourable conditions and criteria of different meteorological parameters for the prediction of nor'westers in Bangladesh.

1.8. Sequence of chapters

1.8.1 Chapter 2: Climatology of thunderstorms and thunderstorm days

In this chapter, the temporal and spatial variation and the variability of monthly and seasonal thunderstorm frequency and the frequency of thunderstorm days over Bangladesh have been studied during the pre-monsoon season. The inter-annual variability and the trends of thunderstorm frequency have also been studied. The optimum time of occurrence of nor'westers/thunderstorms has been determined.

1.8.2 Chapter 3: Surface and upper air synoptic conditions in relation to nor'westers

In this chapter surface and upper air synoptic data have been analyzed prior to the occurrence of nor'westers and tornadoes.

1.8.3 Chapter 4: Instability of the troposphere prior to the occurrence of nor'westers

In this chapter, the stability indices for a large number of nor'westers have been computed and analyzed in order to find out the critical values of different indices favourable for the occurrence of nor'westers in Bangladesh. Some of the existing instability indices have been modified and analyzed too. Attempts have been made to relate different instability indices, both unmodified and modified, among them statistically.

1.8.4 Chapter 5: Tropospheric moisture, its fluxes and the relation between moisture and rainfall due to nor'westers

In this chapter, the precipitable water content of the troposphere, weighted average water vapour have been computed and correlated these parameters with different instability indices and also with the next 24-hr rainfall, next 24-hr maximum rainfall and 24-hr country averaged rainfall in order to predicting rainfall due to nor'westers in Bangladesh. The linear regression equations corresponding to the significant correlation co-efficients have been developed with the help of scatter diagram accordingly. The fluxes of moisture have also been computed and analyzed prior to the occurrence of nor'westers.

1.8.5 Chapter 6: Energetics of the troposphere and their fluxes in relation to nor'westers

In this chapter different energy components and their fluxes before the occurrence of several nor'westers have been computed and analyzed with a view to find out some criteria for their occurrence. Attempts have also been made to integrate the energy components and their fluxes, which are also analyzed.

1.8.6 Chapter 7: Use of radar and satellite imageries in the study of nor'westers

In this chapter, the satellite and radar cloud imageries have been analyzed on the dates of occurrence of nor'westers and their subsequent movement over Bangladesh. Estimation of vertical velocity has also been made from the radar cloud imageries in this chapter.

1.8.7 Chapter 8: Available instability energy and vertical wind shear associated with nor'westers

In this chapter, attempts have been made to study available instability energy or instability energy of the troposphere, its relation with the gusty wind and vertical wind shear associated with nor'westers in Bangladesh during the pre-monsoon season.

1.8.8 Chapter 9: Simulation of surface wind and rainfall fields associated with nor'westers in Bangladesh

In this chapter, the surface winds at 10 m height and rainfall from 0000 UTC to next 0000 UTC have been simulated on the dates of nor'westers in Bangladesh.

1.8.9 Chapter 10: Techniques for the prediction of nor'westers and associated maximum wind speed and rainfall

In this chapter, correlations have been made between the maximum wind speed associated with nor'wester/thunderstorms, which occurred at Dhaka with a number of meteorological parameters in order to develop a multiple regression formula suitable for the forecasting of maximum gusty wind speed associated with nor'westers/thunderstorms. Linear multiple regression equations have also been developed for the forecasting of 24 hrs rainfall associated with nor'westers. Regression equations for the rainfall and the maximum gusty wind speed have also been verified.

1.8.10 Conclusions

In this chapter, conclusions have been drawn on the basis of the whole study.

CHAPTER 2

CLIMATOLOGY OF THUNDERSTORMS AND THUNDERSTORM DAYS

2.1 Introduction

Thunderstorms are the meso-scale phenomena, which develop from cumulonimbus clouds and are characterized by lightning discharges. They are often accompanied with strong gusts, hail, heavy rains and sometimes tornadoes. Because of the associated strong gusts and hails, these storms create hazards to aviation and river navigation in a country like Bangladesh, and cause enormous damage to standing crops, lives and properties every year. In Bangladesh and the adjoining states of India, thunderstorms of destructive nature, locally called "nor'wester" or "Kalbaishakhi", occur during the pre-monsoon season (March-May) when the temperature begins to rise over these areas and attains maximum in April or May. During this period, drought like weather sometimes prevails over some parts of Bangladesh and this has a significant negative impact on the agricultural products and so to the economy of the country. As a result, a thunderstorm with rain or shower has a beneficial effect on agricultural products though sometimes the destruction is also enormous. The distribution of nor'westers/thunderstorms along with thunderstorms days and their probabilistic frequency, both in time and space, over Bangladesh is important for aviation and agricultural purposes. Besides these, the climatology of thunderstorms, the inter-annual variability and trends of thunderstorm frequency are important for the operational meteorologists and the agriculturists of a country like Bangladesh.

In India and Bangladesh, some works have been done on the space and time variations of thunderstorms, the physical characteristics of the atmosphere for their formation and frequency distribution of days of thunder (Bhan 1955; Rao and Raman, 1961; Williams 1961; Gupta and Chorghade, 1962; Guha, 1986; Chowdhury and Karmakar, 1986; Chowdhury *et al.,* 1991). Kamble and Kanoujia (1990) made a critical analysis of the multiple squalls over central India (Vidarbha and Madhya Pradesh) for the 10-year period from 1969 to 1978. They also examined various characteristics of the multiple squalls and

their association with weather parameters. According to them, the frequency of occurrence of multiple squalls is maximum in the months of May and June at Nagpur and Bhopal whereas it is maximum in April and May at Jagdalpur. Three-hourly period between 0930-1230 UTC is the most favourable period for the development of multiple squalls over central India. But no study has so far been made on the frequency of thunderstorms and thunderstorm days in Bangladesh.

In the present chapter, an attempt has been made to study the temporal and spatial variation and the variability of monthly and seasonal thunderstorm frequency and the frequency of thunderstorm days over Bangladesh during the pre-monsoon season. The inter-annual variability and the trends of thunderstorm frequency have also been studied. The optimum time of occurrence of nor'westers/thunderstorms has also been identified.

2.2 Data used

(i) Source: Climate Division of Bangladesh Meteorological Department (BMD)

(ii) Period: (a) March through May, i.e. pre-monsoon season.
(b) 1972-1993 (i.e. 22 years).

(iii) Stations: 22 stations all over Bangladesh (as shown in Fig. 2.1)

(iv) Variable: Monthly nor'westers/thunderstorms and thunderstorm days, which include surface codes of 17, 29 and 95-99 [17(i.e. Thunderstorm but no precipitation at the time of observation), 29 {i.e. Thunderstorm (with or without precipitation) + hail, small hail, snow during the preceding hour but not at the time of observation}, and 95-99 [95: Thunderstorm, slight or moderate, without hail but with rain and/or snow at the time of observation; 96: Thunderstorm, slight or moderate, with hail at the time of observation; 97: Thunderstorm heavy, without hail, but with rain and/or snow at the time of observation; 98: Thunderstorm combined with dust storm or sandstorm at the time of observation; 99: Thunderstorm, heavy, with hail at the time of observation] (BMD, 1982)] and the dates and time of occurrence of nor'westers/thunderstorms.

It is important to note that some data are not available in some stations for a few years. These data have been considered as missing and have not been used in the statistical computations.

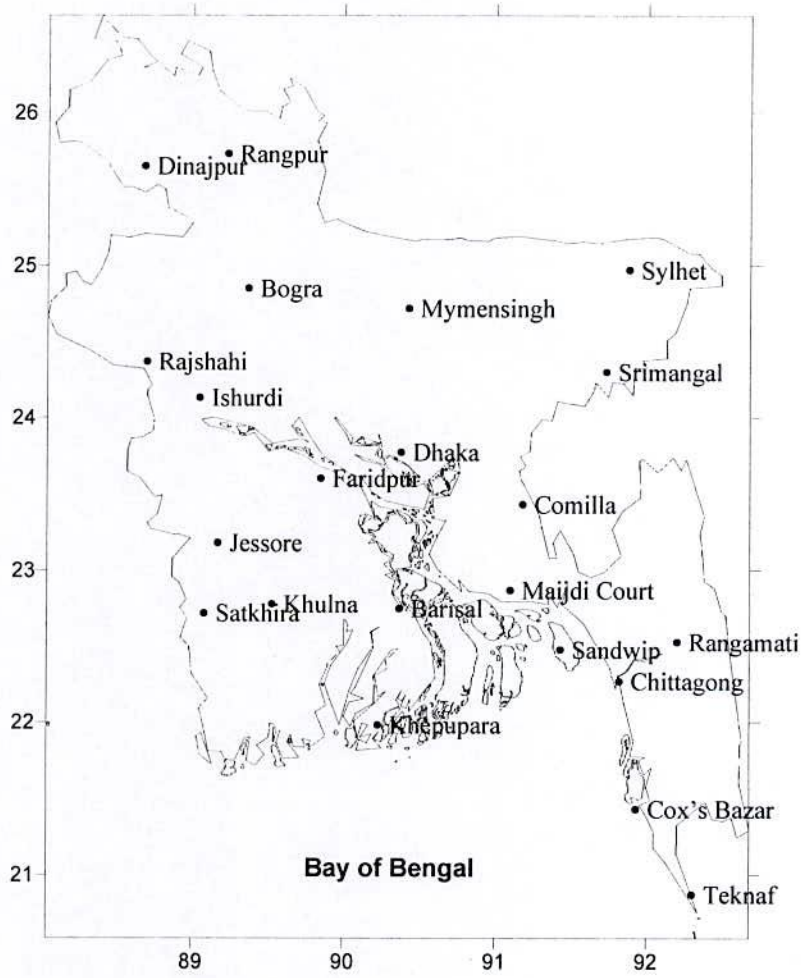


Fig. 2.1: Stations location map

2.3 Methodology

The dates and time of occurrence of nor'westers/thunderstorms have been used to identify the optimum time of occurrence of maximum thunderstorms/nor'westers in Bangladesh. Monthly frequency of nor'westers/thunderstorm and thunderstorm days is used to obtain the seasonal frequency of thunderstorms and thunderstorm days. These monthly and seasonal frequencies of nor'westers/thunderstorm and thunderstorms days are used to compute their mean, standard deviation and co-efficient of variation (CV). The CV of monthly and seasonal thunderstorms are computed by the relation:

$$CV(\%) = \frac{100 \times \sigma}{\bar{x}} \tag{1}$$

Where $\bar{x}$ is the mean frequency of nor'westers/thunderstorms or thunderstorm days and σ is the respective standard deviation. The spatial and temporal distributions of monthly mean frequency of thunderstorm and thunderstorm days with their CV and spatial distribution of seasonal thunderstorm frequency and its CV over Bangladesh have been analyzed.

The country-averaged frequency of thunderstorms has been obtained by averaging the frequency of 21 stations in each year.

2.4 Results and discussion

2.4.1 Thunderstorm frequency

2.4.1.1 Time of occurrence of nor'westers/thunderstorms in Bangladesh

The frequency of nor'westers at different time of occurrence in Bangladesh is shown in Fig. 2.2. The figure shows that the frequency of nor'westers increases sharply from noontime and becomes maximum in the evening/early night between 6 p.m. and 10 p.m. and then decreases again. This maximum frequency of occurrence of nor'westers may be related to the terrestrial radiation when convection process becomes prominent.

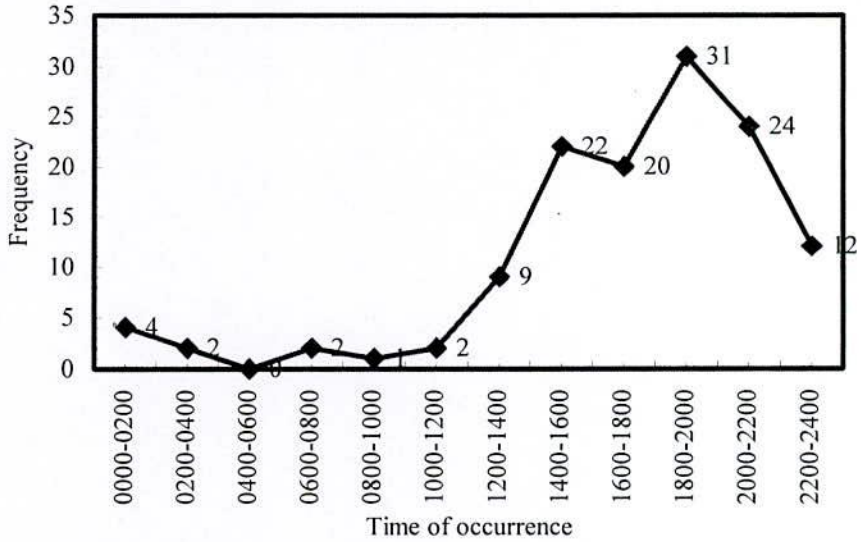


Fig. 2.2: Frequency of nor'westers at different time of occurrence over Bangladesh during the pre-monsoon season during 1990-1995

2.4.1.2 Mean monthly thunderstorms

Mean monthly thunderstorms over different stations of Bangladesh for the pre-monsoon season are given in Table 2.1. Their temporal and spatial variations are studied and discussed in the following subsections.

Table 2.1: Mean monthly thunderstorms over Bangladesh during the pre-monsoon season

Station	March			April			May		
	$\bar{x}$	n	σ	$\bar{x}$	n	σ	$\bar{x}$	n	σ
Dhaka	6.67	21	5.05	15.38	21	7.13	19.33	21	7.62
Faridpur	7.58	19	7.26	15.47	19	9.02	18.00	19	12.00
Mymensingh	4.74	19	4.97	11.21	19	8.13	22.11	19	14.38
Chittagong	4.96	22	6.30	14.73	22	9.86	17.64	22	8.91
Cox's Bazar	3.14	22	5.67	8.32	22	8.74	17.32	22	13.14
Rangamati	4.00	16	5.45	9.56	16	8.88	12.40	15	10.47
Comilla	5.19	21	5.44	8.52	21	7.43	11.52	21	9.28
Maijdi Court	4.00	16	7.23	5.31	16	5.49	7.56	16	6.55
Sylhet	29.81	21	20.56	78.91	21	32.51	95.76	21	44.60
Srimangal	6.33	21	12.39	15.29	22	22.83	51.64	11	43.51
Sandwip	2.76	21	3.92	6.19	21	6.43	6.10	21	5.23
Teknaf	0.82	17	1.98	4.24	17	4.72	7.00	17	7.00
Khulna	4.79	19	4.60	9.32	19	7.04	15.68	19	7.72
Satkhira	2.67	21	2.73	4.52	21	3.78	8.10	21	5.49
Barisal	5.50	22	5.20	10.50	22	7.18	13.50	22	8.27
Khepupara	4.40	20	6.61	6.80	20	6.01	11.00	20	7.13
Jessore	7.33	21	6.07	11.86	21	6.74	20.05	21	5.40
Rajshahi	4.91	22	3.45	8.96	22	5.09	14.32	22	6.53
Bogra	3.38	21	3.42	7.71	21	5.53	16.19	21	8.00
Ishurdi	4.96	22	4.22	10.68	22	6.21	14.36	22	6.80
Rangpur	2.91	21	3.45	7.48	21	6.46	19.62	21	12.59
Dinajpur	1.54	13	1.74	4.15	13	3.61	11.39	13	8.22

$\bar{x}$ = Mean value, n = No. of years, σ = Standard deviation.

2.4.1.2.1 Temporal variations of mean monthly thunderstorms

Table 2.1 shows that the mean thunderstorm frequency increases significantly as the season progresses from March to May over all the stations and are maximum in May. The temporal variation of mean monthly frequency of thunderstorms averaged over the country shows a linear relationship among the months March through May (Fig. 2.3).

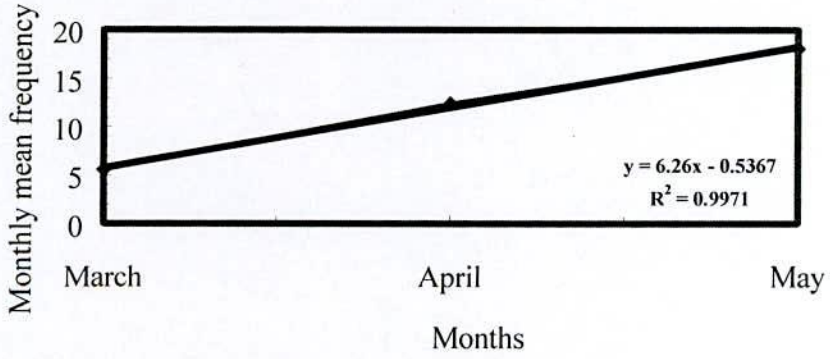


Fig. 2.3: Temporal variation of mean monthly thunderstorms over Bangladesh during the pre-monsoon season

2.4.1.2.2 Spatial distribution of mean monthly thunderstorms

The spatial distributions of mean monthly thunderstorm frequency have been analyzed for each month of the pre-monsoon season. The distribution patterns of mean thunderstorm frequency for March, April and May are similar to each other and the pattern is shown in Fig. 2.4 (a)..There are three areas of maximum thunderstorms. The area of primary maximum is over Sylhet region extending southwestward up to Dhaka region having an elongated area extended southward up to Barisal-Khepupara region. The areas of secondary and tertiary maximum thunderstorms are Jessore-Faridpur-Rajshahi and Chittagong-Cox's Bazar regions respectively. The distribution patterns also show that the mean thunderstorms are minimum over southern and extreme southeastern parts of Bangladesh, Rangamati-Maijdi Court-Comilla region and Dinajpur-northern Rajshahi region.

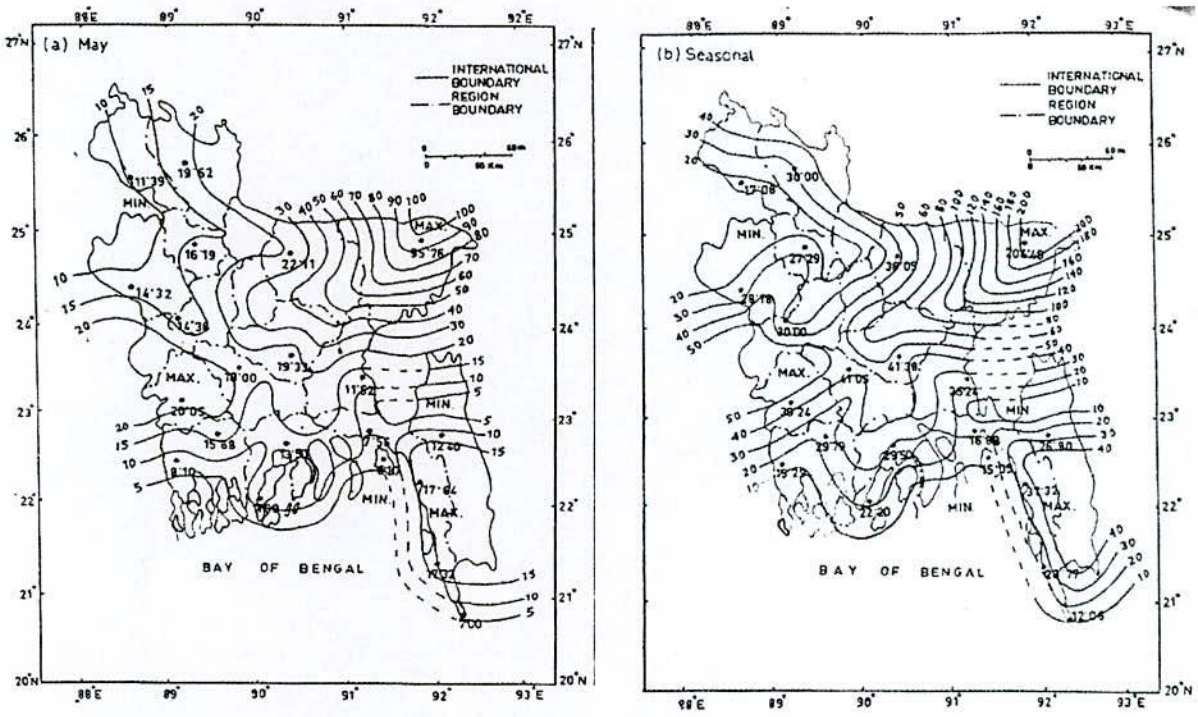


Fig. 2.4 (a-b): Spatial distribution of mean thunderstorm frequency over Bangladesh (a) in May and (b) seasonal

In March, the mean thunderstorm frequency varies from 1 to 30 having the maximum value over Sylhet and minimum over Teknaf (Table 2.1). The high values of mean thunderstorms are 30, 5-8 and 4-5 over Sylhet, Jessore-Faridpur-Rajshahi and Rangamati-Maijdi Court-Comilla region respectively. While the low values are 1-3 and 1-2 over southern and extreme southeastern parts of Bangladesh and Dinajpur-northern Rajshahi

region respectively. In April, the mean thunderstorm frequency over Bangladesh varies from 4 to 79 having the highest value at Sylhet and lowest at Dinajpur and Teknaf. The high values of mean thunderstorm frequency are 79, 9-15 and 8-15 over Sylhet, Jesssore-Fridpur-Rajshahi and Chittagong-Cox's Bazar regions respectively. The low values of mean thunderstorms are 4-7, 5-10 and 4-7 over southern and extreme southeastern parts of Bangladesh, Rangamati-Maijdi Court-Comilla region and Dinajpur-northern Rajshahi region respectively. In May, the mean thunderstorm frequency varies from 6 to 96 having the highest maximum at Sylhet and lowest minimum at Teknaf (Fig. 2.4a). The high values of mean thunderstorms are 96, 14-20 and 17-18 over Sylhet, Jessore-Faridpur-Rajshahi and Chittagong-Cox's Bazar regions respectively. The ranges of the low values of mean thunderstorms are 6-11, 8-12 and 10-11 over southern and extreme southeastern parts of Bangladesh, Rangamati-Maijdi Court-Comilla region and Dinajpur-northern Rajshahi region respectively.

2.4.1.3 Spatial distribution of mean seasonal thunderstorms

The spatial distribution of mean seasonal thunderstorm frequency is shown in Fig. 2.4 (b). The figure shows the same pattern of distribution as that of the mean monthly thunderstorms. The mean seasonal frequency of thunderstorms over Bangladesh varies from 12 to 204 having the highest frequency at Sylhet and lowest frequency at Teknaf. The high values of mean seasonal thunderstorms are 204, 28-41 and 29-37 over Sylhet, Jessore-Faridpur-Rajshahi and Chittagong-Cox's Bazar regions respectively. The southern and extreme southeastern parts of Bangladesh, Rangamati-Maijdi Court-Comilla region and Dinajpur-northern Rajshahi region have the ranges of mean seasonal thunderstorms of 12-22, 25-27 and 17-20 respectively.

2.4.1.4 Co-efficient of variation of thunderstorms

Co-efficient of variation (CV) of thunderstorms of monthly and seasonal thunderstorms has been computed for all the stations under consideration. The temporal variation of CV for monthly thunderstorms and the spatial distributions of both monthly and seasonal thunderstorms have been analyzed and studied.

2.4.1.4.1 Co-efficient of variation of monthly thunderstorms

The CV of monthly thunderstorms is given in Table 2.2. The table shows that the CV of thunderstorms is maximum in March and decreases significantly as the season progresses

at all the stations except in May when there is a slight increase in CV at Faridpur and Sylhet region.

The patterns of distribution of CV of monthly thunderstorms over Bangladesh for March through May are almost similar to each other and the pattern is shown in Fig. 2.5 (a). The CV of thunderstorms is maximum over extreme southern part of Bangladesh, Rangamati-Maijdi Court region and Dinajpur-Bogra-Rajshahi region whereas the CV of thunderstorms is maximum over western Sylhet-eastern Mymensingh-northeastern Dhaka region, Jessore-Rajshahi region and Chittagong-Cox's Bazar region. In March, the CV ranges from 68.97 to 239.93% having the highest value at Teknaf. The primary minimum CV of thunderstorms lies over western Sylhet-eastern Mymensingh-northern Dhaka region; the secondary minimum CV lies over Jessore-Rajshahi region and the tertiary minimum CV lies over Chittagong region with the minimum values of 68.97, 75.69, 70.28, 82.72 and 85.09% at Sylhet, Dhaka, Rajshahi, Jessore and Ishwardi respectively. In April, the CV of thunderstorms ranges from 41.22 to 111.50% having the highest value at Teknaf. The primary, secondary and tertiary minimum areas of the CV are the same as in March having the minimum values of 41.22, 46.34, 56.86, 56.88 and 58.15% at Sylhet, Dhaka, Jessore, Rajshahi and Ishurdi respectively.

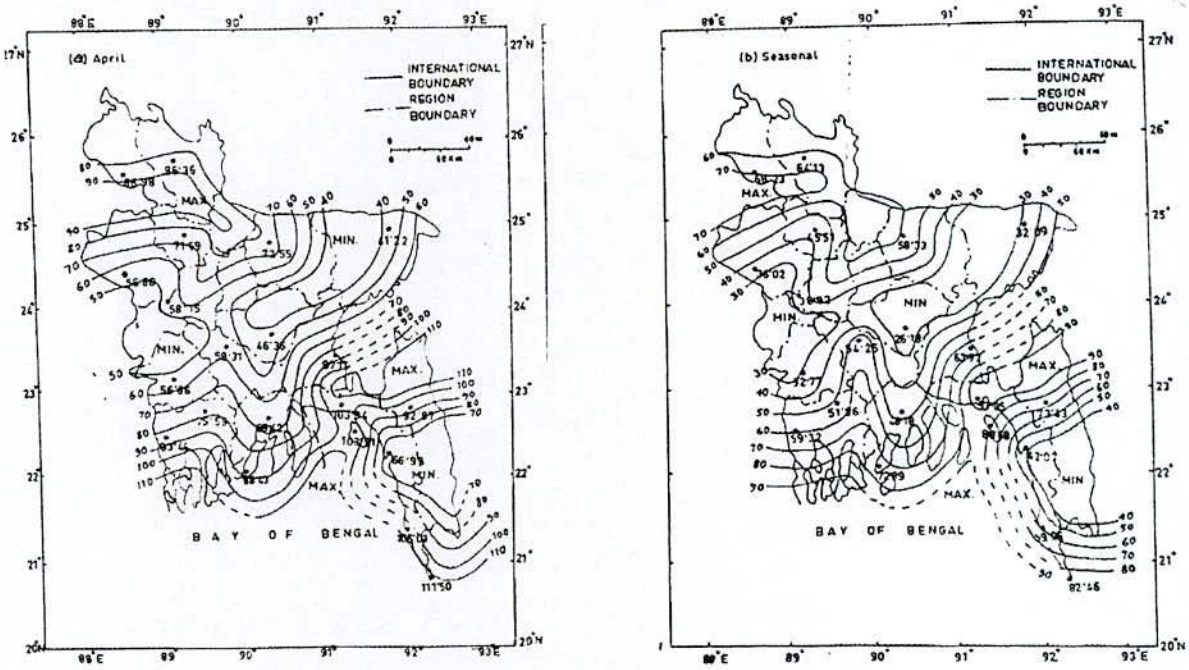


Fig. 2.5 (a-b): Spatial distribution of the CV (%) of thunderstorm frequency over Bangladesh (a) in April and (b) seasonal

In May, the CV of thunderstorms ranges form 26.95 to 99.94% having the highest value at Teknaf. In this month, the areas of minimum CV are different. The primary and secondary

minimum CV lies over Jessore-Rajshahi and western Sylhet-eastern Mymensingh-northeastern Dhaka regions respectively, the tertiary minimum CV being over the Chittagong region. The minimum values of CV are 26.95, 45.57, 39.40, 46.58 and 47.33% at Jessore, Rajshahi, Dhaka, Sylhet and Ishwardi respectively.

Table 2.2: CV (%) of monthly thunderstorms over Bangladesh during the pre-monsoon season

Stations	CV (%)		
	March	April	May
Dhaka	75.69	46.34	39.40
Faridpur	95.84	58.31	66.64
Mymensingh	104.96	72.55	65.04
Chittagong	127.12	66.98	50.50
Cox's Bazar	180.71	106.01	75.90
Rangamati	136.35	92.87	84.42
Comilla	104.80	87.17	80.50
Maijdi Court	180.70	103.24	86.58
Sylhet	68.97	41.22	46.58
Srimangal	195.65	149.33	84.26
Sandwip	141.75	103.81	85.76
Teknaf	239.93	111.50	99.94
Khulna	95.95	75.59	49.22
Satkhira	102.40	83.44	67.76
Barisal	94.60	68.42	61.27
Khepupara	150.14	88.43	64.79
Jessore	82.72	56.86	26.95
Rajshahi	70.28	56.88	45.57
Bogra	101.01	71.69	49.44
Ishurdi	85.09	58.15	47.33
Rangpur	118.73	86.36	64.18
Dinajpur	112.94	86.98	72.23

2.4.1.4.2 Co-efficient of variation of seasonal thunderstorms

The spatial distribution of the CV of seasonal thunderstorms is shown in Fig. 2.5(b). The figure shows the same pattern of distribution of the CV of seasonal thunderstorms as mentioned in case of monthly thunderstorms especially in March and April. The CV of the seasonal thunderstorms over Bangladesh varies from 26.18 to 82.46% having the highest value at Teknaf. The minimum values of the CV are 26.18, 32.09, 32.77, 36.02 and 42.07% at Dhaka, Sylhet, Jessore, Rajshahi and Chittagong respectively. The figure shows that the lowest value of the CV of seasonal thunderstorms is at Dhaka.

2.4.1.5 Interannual variability and trends of thunderstorm frequency

The country averaged monthly and seasonal frequencies of thunderstorms have been plotted against years to obtain the interannual variability of thunderstorms frequency. Figs. 2.6-2.9 show the interannual variability of country averaged monthly and seasonal frequencies of thunderstorms during the period 1972-1993. All the figures show that inter-annual variability in the monthly and seasonal frequency of thunderstorms exists over

Bangladesh. In March, the frequency of thunderstorms shows 3-4 years' short cycles of variation and 7 years' long cycle of variation. The frequency of thunderstorms also exhibits 4-5 years' cycles of variation and 3-6 years' cycles of variation in April and May respectively. Similarly, the seasonal frequency of thunderstorms shows 3-5 years' cycles of variation.

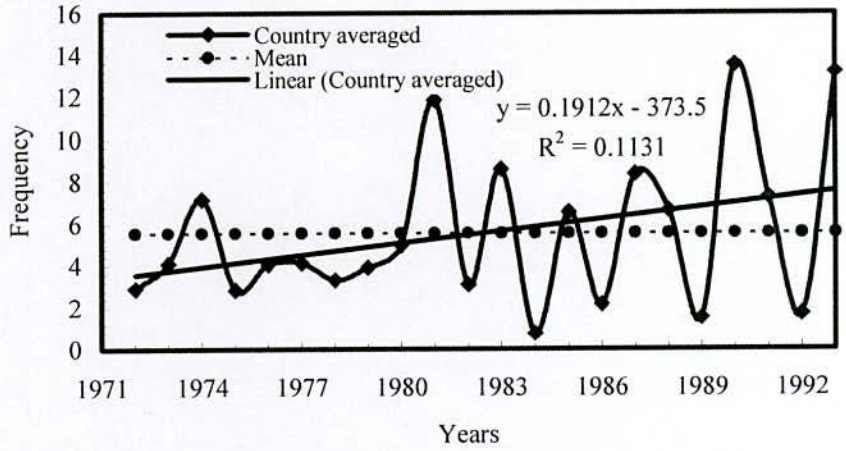


Fig. 2.6: Interannual variability of country averaged thunderstorm frequency in Bangladesh in March during 1972-1993

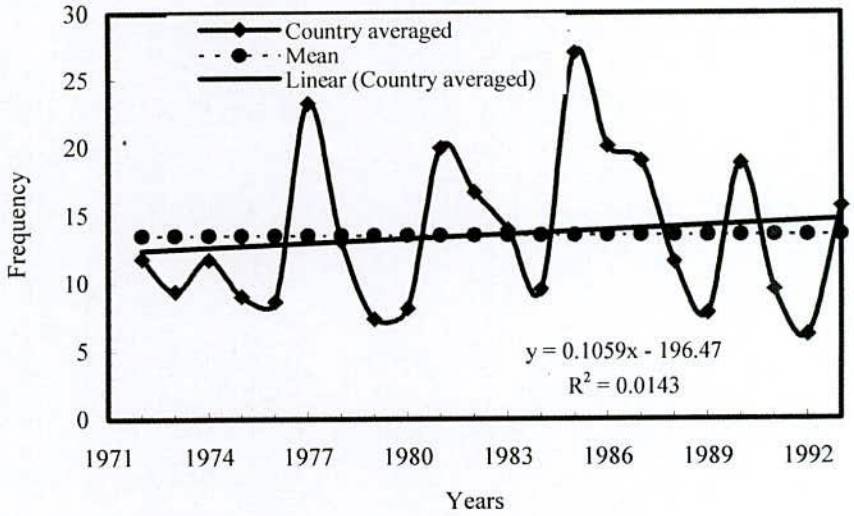


Fig. 2.7: Interannual variability of country averaged thunderstorm frequency in Bangladesh in April during 1972-1993

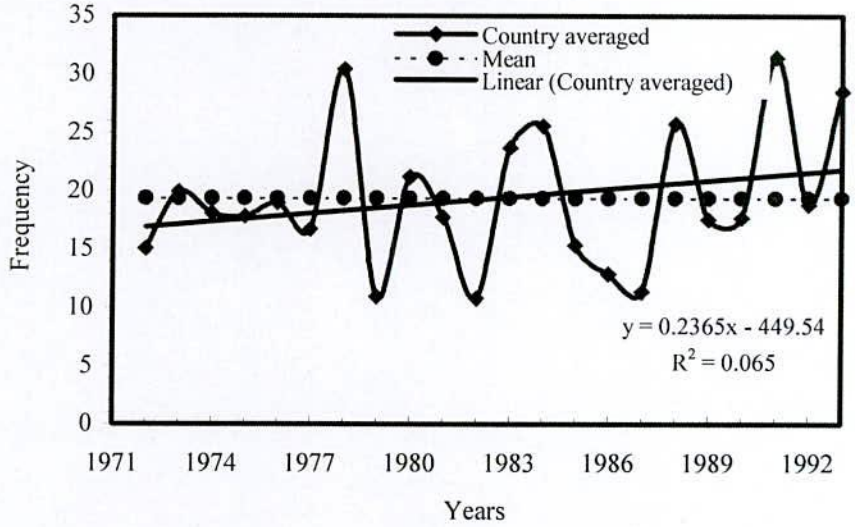


Fig. 2.8: Interannual variability of country averaged thunderstorm frequency in Bangladesh in May during 1972-1993

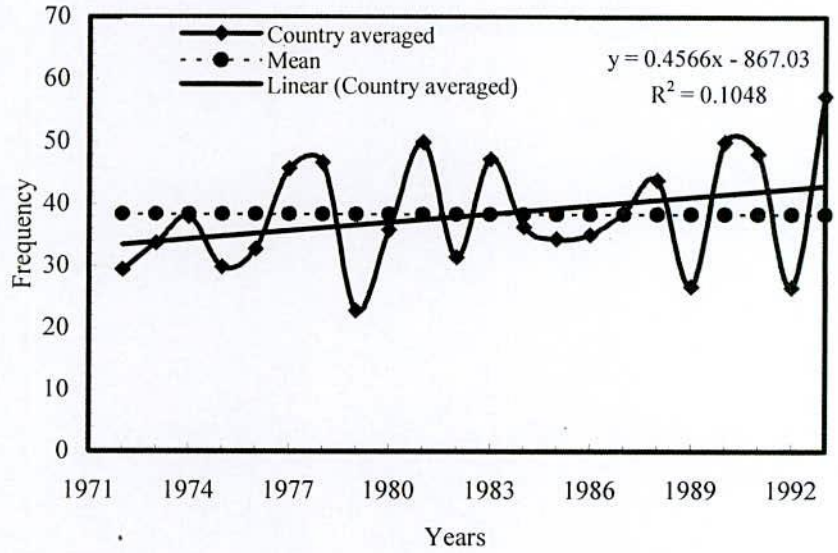


Fig. 2.9: Interannual variability of country averaged seasonal thunderstorm frequency in Bangladesh in March-May during 1972-1993

The country-averaged monthly and seasonal frequency of thunderstorms during the pre-monsoon season has increasing trends. The rates of increase are 0.1912, 0.1059, 0.2365/year in March, April and May respectively and 0.4566/year during the pre-monsoon season.

The trends in the monthly and seasonal frequency of thunderstorms during 1972-1993 have been computed for all the stations under study and the spatial distributions of the trends/decade over Bangladesh have been analyzed. The results are shown in Figs. 2.10-2.13.

It has been found that the frequency of thunderstorms has increasing trends all over Bangladesh in March except Sylhet where it has decreasing trend of –7/decade. The maximum increase in trends is 9/decade, which is found at Srimangal (Fig. 2.10).

In April, the thunderstorm frequency has decreasing trends at Sylhet region, Chittagong region and the southwestern part of Bangladesh, having maximum decreasing rate of –21/decade at Sylhet. Besides these regions, the frequency has increasing trends with maximum rate of 21/decade at Srimangal (Fig. 2.11). In May, the frequency of thunderstorms has increasing trends almost over the whole of Bangladesh except at five stations such as Sylhet, Chittagong, Cox's Bazar, Teknaf and Barisal where there are decreasing trends with maximum decreasing rate of –28/decade years at Sylhet and maximum increasing rate of 76/decade at Srimangal (Fig. 2.12). Similar is the case with seasonal frequency of thunderstorms, having maximum decreasing trend of –56/decade and maximum increasing rate of 65/decade at Sylhet and Srimangal respectively (Fig. 2.13). All these figures show a belt of increasing trends from northwestern part of Bangladesh towards southeast up to Rangamati across Bogra, Mymensingh, Srimangal, Comilla, Feni and Maijdi Court with the primary and secondary areas of increasing trends over Srimangal-Comilla and Dinajpur-Rangpur regions respectively.

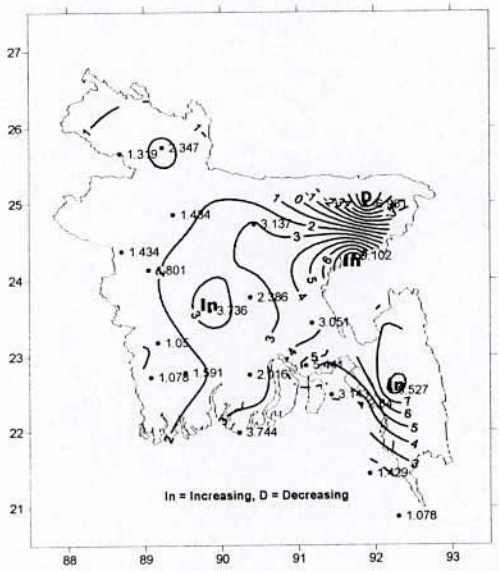


Fig. 2.10: Spatial distribution of the trends/decade of thunderstorm frequency over Bangladesh in March based on the data during 1972-1993

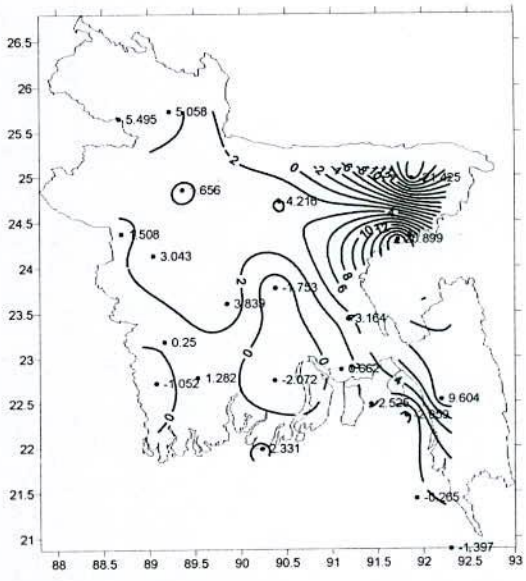


Fig. 2.11: Spatial distribution of the trends/decade of thunderstorm frequency over Bangladesh in April based on the data during 1972-1993

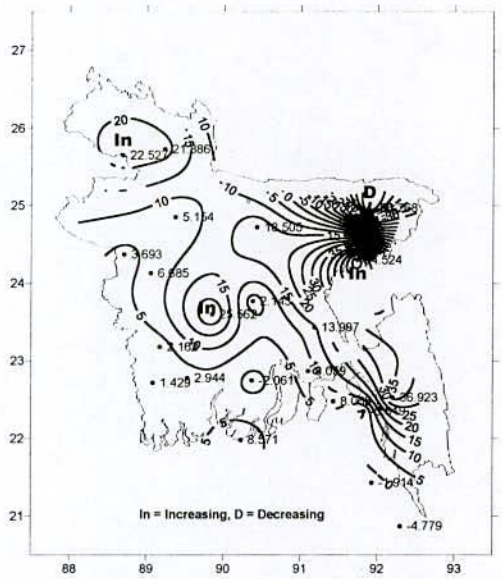


Fig. 2.12: Spatial distribution of the trends/decade of thunderstorm frequency over Bangladesh in May based on the data during 1972-1993

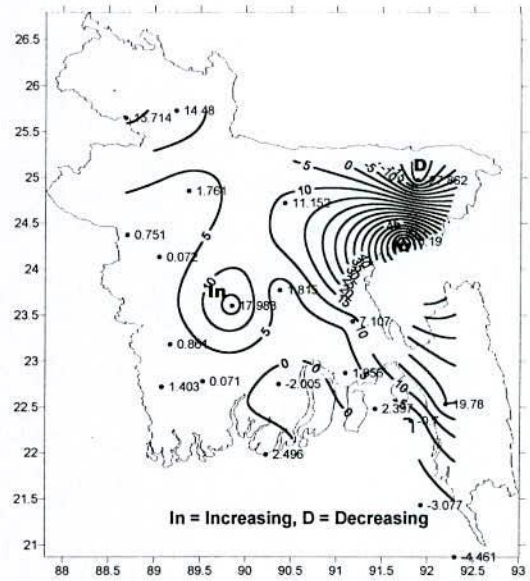


Fig. 2.13: Spatial distribution of the trends/decade of thunderstorm frequency over Bangladesh in pre-monsoon season based on the data during 1972-1993

2.4.2 Frequency of thunderstorm days

2.4.2.1 Monthly mean frequency of thunderstorm days

Mean monthly thunderstorms days over different stations of Bangladesh for the pre-monsoon season are given in Table 2.3. Their temporal and spatial variations are studied and discussed in the following sub-sections.

2.4.2.1.1 Temporal variation of mean frequency of thunderstorm days

The temporal variations of mean thunderstorm days over all the stations under consideration are studied graphically and the curves for all the stations under study are given in Fig. 2.14.

It has been found that the mean frequency of thunderstorm days increases significantly as the season progresses from March to May over all the stations and is maximum in May. The distribution patterns of thunderstorm days are almost the same at all stations during March through May and seems to have some correlation among the monthly mean thunderstorm days. The monthly mean thunderstorm days, when averaged over Bangladesh, have a linear relation among March, April and May as shown in Fig. 2.15. The co-efficient of determination of the fitted trend line is $R^2 = 0.9999$, which indicates that the data are best fitted and in this case the actual curve and the trend line has coincided with each

other. The monthly rate of increase of thunderstorm days, as seen from the trend equation (Fig. 2.15), is 3.1402.

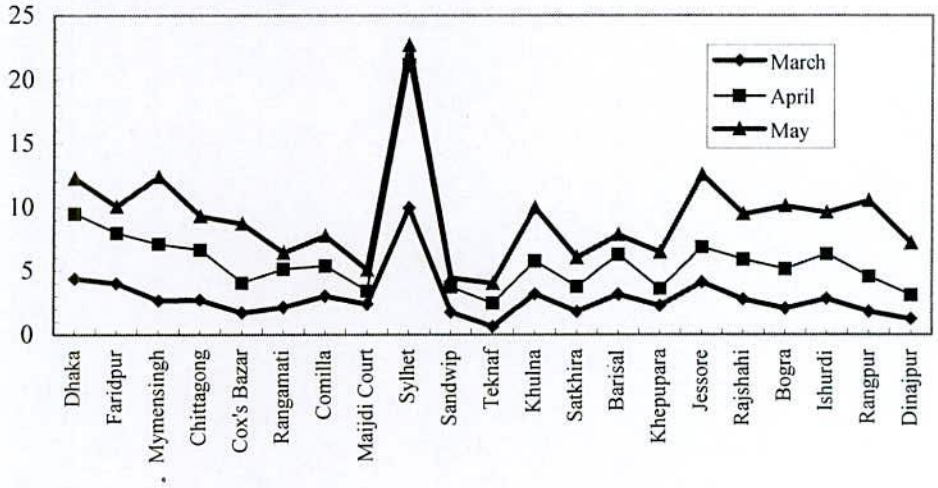


Fig. 2.14: Monthwise distribution of mean thunderstorm days at different stations of Bangladesh during the pre-monsoon season

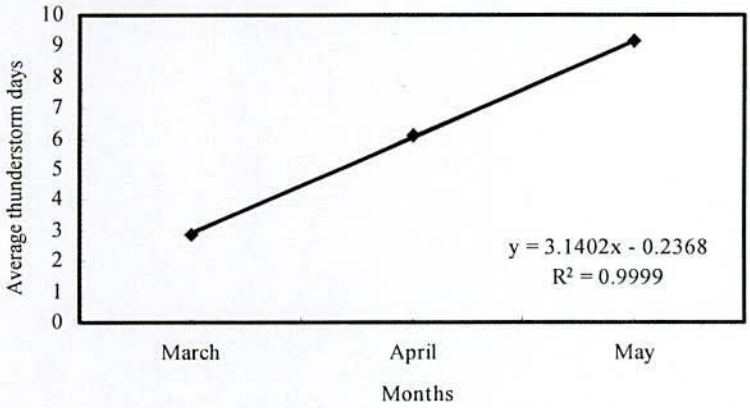


Fig. 2.15: Temporal variation of country averaged monthly thunderstorm days

2.4.2.1.2 Spatial distribution of monthly mean thunderstorm days

The spatial distribution of mean thunderstorm days have been analyzed and studied for each month of the pre-monsoon season. The distribution patterns of mean thunderstorm days for March, April and May are almost similar to each other and the pattern is shown in Fig. 2.16(a). There are three areas of maximum thunderstorm days over Bangladesh. These areas are Sylhet region, Jessore-Faridpur-Rajshahi region and Chittagong-Cox's Bazar region having the highest frequency at Sylhet. The thunderstorm days are minimum over southern and extreme southeastern parts of Bangladesh, Dinajpur-northern Rajshahi region and Rangamati-Maijdi Court-Comilla region. The area of highest thunderstorm days has been

found to extend southwestward from Sylhet region to Dhaka region having an elongated area extended southwards up to Barisal-Khepupara region.

Table 2.3. Mean frequency of monthly thunderstorm days over Bangladesh

Station	March			April			May		
	n	σ	$\bar{x}$	n	σ	$\bar{x}$	n	σ	$\bar{x}$
Dhaka	21	2.439	4.381	21	3.911	9.476	21	3.676	12.238
Faridpur	19	3.325	4.000	19	4.353	8.000	19	5.196	10.053
Mymensingh	19	2.341	2.684	19	3.878	7.105	19	5.940	12.368
Chittagong	22	2.799	2.727	22	3.879	6.636	22	3.756	9.273
Cox's Bazar	22	2.649	1.727	22	3.418	4.045	22	3.959	8.682
Rangamati	16	2.446	2.125	15	3.557	5.133	15	4.786	6.400
Comilla	21	2.795	3.000	21	3.769	5.381	21	4.968	7.714
Maijdi Court	16	2.421	2.375	16	3.181	3.438	16	3.508	5.063
Sylhet	21	4.776	9.952	21	4.167	21.143	21	4.804	22.667
Sandwip	21	2.348	1.762	21	3.666	3.714	21	3.017	4.429
Teknaf	17	1.678	0.647	17	2.090	2.471	17	3.290	4.000
Khulna	19	2.661	3.158	19	3.349	5.789	19	3.940	9.947
Satkhira	21	1.592	1.810	21	2.580	3.7620	21	3.450	6.000
Barisal	22	2.599	3.136	22	3.828	6.273	22	3.939	7.818
Khepupara	20	2.775	2.250	20	3.040	3.600	20	3.681	6.450
Jessore	21	2.991	4.095	21	3.060	6.857	21	3.304	12.524
Rajshahi	22	1.677	2.773	22	2.712	5.909	22	3.997	9.455
Bogra	21	1.731	2.048	21	3.012	5.143	21	4.174	10.095
Ishurdi	22	2.124	2.818	22	2.835	6.318	22	3.939	9.591
Rangpur	21	2.130	1.81	21	3.360	4.571	21	5.395	10.476
Dinajpur	13	1.310	1.231	13	2.168	3.077	13	4.785	7.154

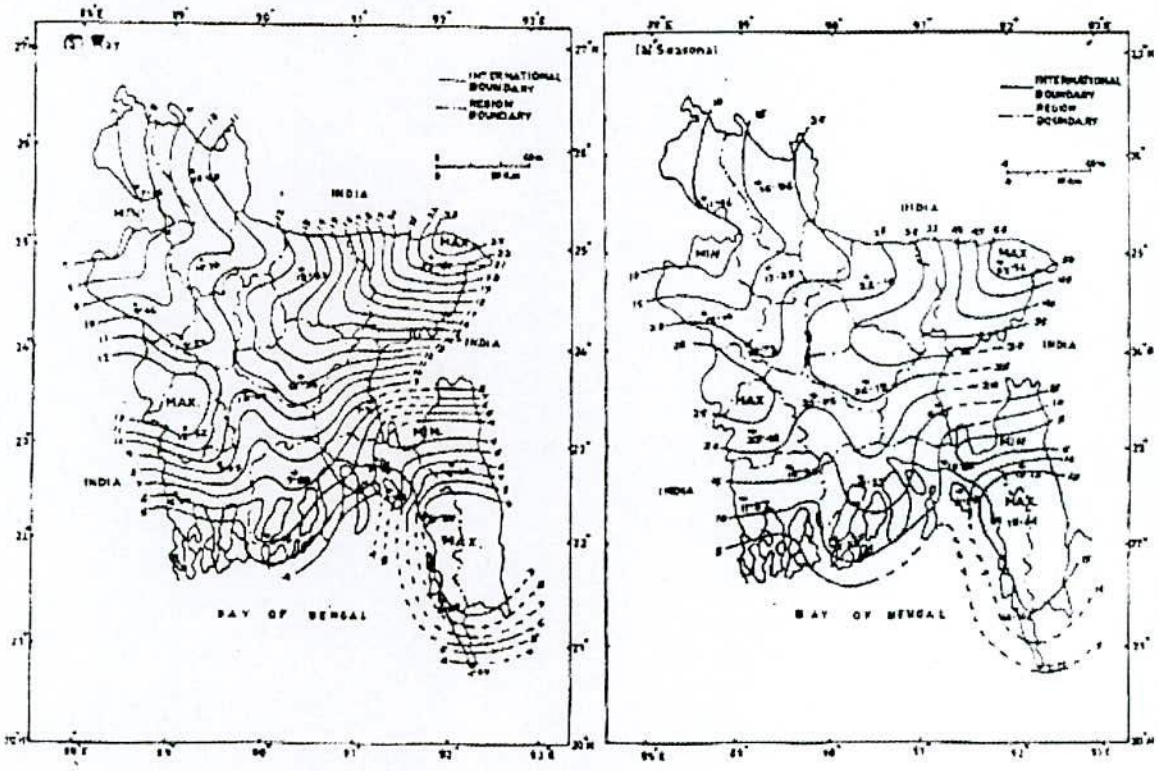
n = No. of years, σ = Standard deviation, $\bar{x}$ = Mean thunderstorm days.

In March, the mean thunderstorm days vary from 1 (Teknaf) to 10 (Sylhet) (Table 2.3). The high values of mean thunderstorm days are 10, 3-4 and 2-3 over Sylhet, Jessore-Faridpur-Rajshahi and Chittagong-Cox's Bazar regions respectively, whereas the minimum values of the thunderstorm days are over southern and extreme southeastern parts of the country, Rangamati-Maijdi Court-Comilla and Dinajpur-northern Rajshahi regions respectively. In April, the frequency of mean thunderstorm days varies from 2 to 21 having the high values of 21, 6-8 and 4-7 over Sylhet, Jessore-Faridpur-Rajshahi and Chittagong-Cox's Bazar regions respectively. The minimum values of mean thunderstorm days in this month are 2-4, 3-5 and 3-5 over southern and extreme southeastern parts of Bangladesh, Rangamati-Maijdi Court-Comilla region and Dinajpur-northern Rajshahi region respectively. In May, the mean thunderstorm days vary from 4 to 23 having the high values of 23, 9-13 and

9 over Sylhet, Jessore-Faridpur-Rajshahi and Chittagong-Cox's Bazar regions respectively. The minimum values of mean thunderstorm days are 4-6, 5-6 and 7-8 over southern and extreme southeastern Bangladesh, Rangamati-Maijdi Court-Comilla region and Dinajpur-northern Rajshahi region respectively [Fig. 2.16(a)].

2.4.2.2 Spatial distribution of seasonal mean thunderstorm days

The spatial distribution of mean thunderstorm days over Bangladesh is shown in Fig. 2.16(b). The figure shows the same pattern of distribution as that of the mean monthly thunderstorm days. There are three areas of maximum thunderstorm days over Bangladesh. These areas are Sylhet region, Jessore-Faridpur-Rajshahi region and Chittagong-Cox's Bazar region having the highest frequency of 54 days at Sylhet and lowest frequency of 12 at Teknaf. The thunderstorm days are minimum over southern and extreme southeastern parts of Bangladesh, Dinajpur-northern Rajshahi region and Rangamati-Maijdi Court-Comilla region. The area of highest thunderstorm days has been found to extend southwestward from Sylhet region to Dhaka region having an elongated area extended southwards up to Barisal-Khepupara region.



Figs. 2.16(a-b): Spatial distribution of mean thunderstorm days over Bangladesh (a) May and (b) seasonal

2.4.2.3 Co-efficient of variation of thunderstorm days

The CV of monthly and seasonal thunderstorm days has been computed for all the stations under consideration. The temporal variation of CV for monthly thunderstorm days and the spatial distributions of both monthly and seasonal thunderstorm days have been analyzed and studied.

2.4.2.3.1 Co-efficient of variation of monthly thunderstorm days

The CV of monthly thunderstorm days is given in Table 2.4. The table shows that the CV of thunderstorm days is maximum in March and decreases significantly as the season progresses in all the stations except in May when there is a slight increase in CV at Rangamati, Comilla and Sylhet.

Table 2.4: CV of monthly thunderstorm days over Bangladesh during pre-monsoon season

Stations	CV (%)		
	March	April	May
Dhaka	55.672	41.273	30.038
Faridpur	83.125	54.413	51.687
Mymensingh	87.221	54.581	48.027
Chittagong	102.640	58.454	40.505
Cox's Bazar	153.387	84.499	45.600
Rangamati	110.429	69.297	74.781
Comilla	93.167	58.892	64.402
Maijdi Court	101.937	92.525	69.287
Sylhet	48.020	19.709	21.194
Sandwip	133.258	98.708	68.119
Teknaf	259.351	84.581	82.250
Khulna	84.262	57.851	39.610
Satkhira	87.956	68.581	57.500
Barisal	82.876	61.023	50.384
Khepupara	123.333	84.444	57.070
Jessore	73.040	44.626	26.381
Rajshahi	60.476	45.896	42.274
Bogra	84.521	58.565	41.347
Ishurdi	75.373	44.872	41.070
Rangpur	117.680	73.507	51.499
Dinajpur	106.418	70.458	66.886

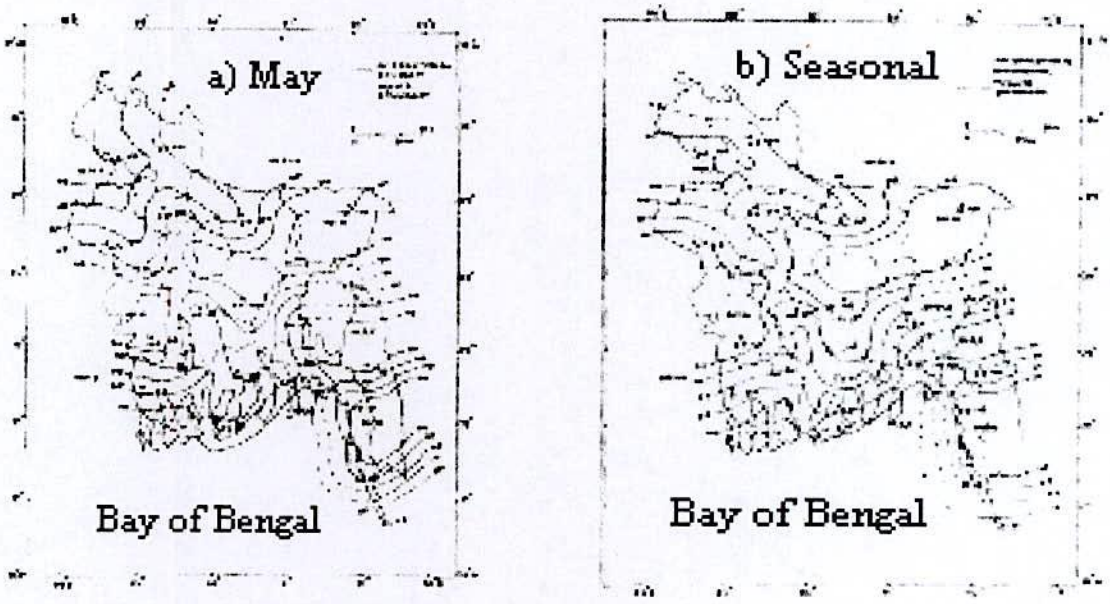
The study of the spatial distribution of the CV of monthly thunderstorm days reveals the same patterns of distribution in March through May and the pattern is given in Fig. 2.17(a). The CV of monthly thunderstorm days is minimum over Sylhet, Jessore-Faridpur-Rajshahi and Chittagong-Cox's Bazar regions, and maximum over southern and extreme

southeastern parts of Bangladesh, Rangamati-Maijdi Court-Comilla region and Dinajpur-northern Rajshahi region. The area of lowest minimum CV over Sylhet region extends southwestward up to Dhaka region with an elongated portion extended southward up to Barisal-Khepupara region.

In March, the CV of thunderstorm days varies from 48.02(Sylhet) to 259.35% (Teknaf). The minimum values of CV are 48.02, 60.48-83.13 and 102.64-153.39% over Sylhet, Jessore-Faridpur-Rajshahi and Chittagong-Cox's Bazar regions respectively. The range, though high, is relatively minimum with respect to nearby area. The maximum values of CV are 123.30-259.35, 93.17-110.43 and 106.42-117.68% over southern and extreme southeastern Bangladesh, Rangamati-Maijdi Court-Comilla region and Dinajpur-Rangpur-northern Rajshahi region respectively. In April, the CV of thunderstorm days over Bangladesh varies from 19.17 (Sylhet) to 98.71% (Sandwip). The minimum values of CV are 19.71, 44.63-54.41 and 58.45-84.50% over Sylhet, Jessore-Faridpur-Rajshahi and Chittagong - Cox's Bazar regions respectively. The maximum values of CV are 84.44-98.71, 58.89-92.53 and 70.46-73.51% over southern and extreme southeastern parts of the country, Rangamati-Maijdi Court-Comilla region and Dinajpur-Rangpur-northern Rajshahi region respectively. In May, the CV of thunderstorm days over the country varies from 21.19 (Sylhet) to 82.25% (Teknaf), having the minimum values of 21.19, 26.38-51.69 and 40.51-45.60% over Sylhet, Jessore-Faridpur-Rajshahi and Chittagong-Cox's Bazar regions respectively. The maximum values of CV are 57.07-82.25, 64.40-74.78 and 51.50-66.89% over southern and extreme southeastern Bangladesh, Rangamati-Maijdi Court-Comilla region and Dinajpur-Rangpur-northern Rajshahi region respectively.

2.4.2.3.2 Co-efficient of variation of seasonal thunderstorm days

The spatial distribution of the CV of seasonal thunderstorm days is shown in Fig. 2.17(b). Figure shows the same pattern of distribution of the CV of seasonal thunderstorm days as mentioned in case of monthly thunderstorm days. The CV of the seasonal thunderstorm days over Bangladesh varies from 15.01-73.21% having the minimum values 15.01, 25.31 and 35.73% at Sylhet, Jessore, and Chittagong respectively, and the maximum values 73.21, 70.81, 70.02, 64.99, 62.50 and 61.24% at Sandwip, Teknaf, Maijdi Court, Rangamati, Dinajpur and Khepupara respectively. The area of lowest minimum CV is also extended from Sylhet region to Dhaka region with an elongated portion extended southward up to Barisal-Khepupara region.



Figs. 2.17 (a-b): Spatial distribution of the CV (%) of thunderstorm days over Bangladesh (a) May and (b) seasonal

CHAPTER 3

SURFACE AND UPPER AIR SYNOPTIC CONDITIONS IN RELATION TO NOR'WESTERS AND TORNADOES

3.1 Introduction

Bangladesh is playground of a number of different natural calamities like nor'westers, tornadoes, tropical cyclones, floods, drought, etc because of its peculiar geographical location with the Himalayas in the north, the Bay of Bengal to the south and Myanmar hill in the east. During the pre-monsoon season most of the local severe storms occur over different parts of Bangladesh with frequent intervals. These storms are popularly known as Nor'westers or Kalbaishakhi in Bangladesh, West Bengal and Assam of India and Andhi (dust storms) in North India. Though they occur locally, their violence and destruction often become very significant. When sufficient instability and strong low-level convergence exist in the troposphere, a part of the thundercloud comes down as pendant from the base of the mother cloud and as a result tornado occurs. Because of the significant violence and destruction, nor'westers and tornadoes have always been of interest to the working meteorologists since long. Various aspects of these phenomena have been studied by different authors like Sen (1931), Chatterjee and Sur (1933), Malurkar (1949), Bose (1955), Koteswaram and Srinivasan (1958), Saha (1960), Sen and Basu (1961), Chowdhury (1961), Mukherjee and Bhattacharya (1972), and Mukherjee *et al.* (1977), Chowdhury and Karmakar (1986), Chowdhury *et al.* (1991), Das *et al.* (1994), and Akram and Karmakar (1998). In all these studies, a number of important results have been obtained as regards formation, structure, timing and devastation of nor'westers, etc. There has been, of course, some difference of opinions among the authors as well. Koteswaram and Srinivasan (1958) have shown in their investigation that the nor'westers fail to occur in the Gangetic West Bengal and by inference over Bangladesh and Assam in the absence of southerly winds up to at least 1 km in spite of the other conditions being fulfilled. However, it is possible that the initial shallow layer of moist air can even become

deep due to the stretching of the lower layer by convergence. Akram and Karmakar (1998) studied some meteorological aspects of the tornado at Saturia in Bangladesh on 26 April 1989. According to them, the point of intersection of the axes of the moist tongue and the dry zone at 0000 UTC was close to the place of occurrence of the tornado. There was a significant increase in moisture content of the troposphere from the surface up to 540 hPa level in the morning of the date of occurrence. The troposphere was sufficiently unstable on the occurrence date. The calculated available instability energy per unit area was greater by 90.93 $\times 10^5$ Jm^{-2} on the date of occurrence of the tornado (on 26 April as compared to that on 24 April). The place of occurrence of the tornado was very near to the point of intersection of the axes of low-level maximum wind and upper level jet stream.

In this chapter attempts have been made to study the surface and upper air synoptic conditions, minimum temperature and surface humidity for finding out the favourable conditions for the nor'westers prior to their occurrence. Attempts have also been made to locate the place of occurrence of nor'westers by superimposing the axes of the upper air jet stream and the lower level maximum winds. Synoptic conditions, and some surface and upper air meteorological parameters associated with two severe tornadoes at Saturia of Manikganj district on 26 April 1989 and at Kalihati of Tangail district on 13 May 1996 have also been studied.

3.2 Description of the tornadoes

3.2.1 Saturia tornado

This tornado occurred at 1150 UTC on 26 April 1989 over Saturia of Manikganj district and lashed three Upazilas of the district within only a few minutes. The type of damage, the length and breadth of the path of its travel indicated that the intensity of the tornado was of the order of F 3.5 in the Fujita scale and the corresponding wind was calculated around 338-418 km hr^{-1} (WMO/ESCAP, 1989). Total area affected by the tornado was about 10-12 km × 1-5 km. The place of occurrence and the path of the tornado are given in Fig. 14.1. The loss and damage due to the tornado is given below:

i)	Total number of Upazilas affected	: 3
ii)	Total affected area in square kilometer	:20
iii)	Loss of lives	:526
iv)	Total number affected people	:108,250

v)	Total crop damaged in acres	:9,200
vi)	Number of houses affected:	
	(a) destroyed	:39,201
	(b) damaged	: 3, 016
vii)	Poultry killed	: 27,500
viii)	Total number cattle killed	:402
ix)	Total number of educational institutions affected:	
	(a) destroyed	:43
	(b) damaged	:03
x)	Total number of religious institutions affected	:46
xi)	Total number Govt. buildings/houses affected	:17
xii)	Total number villages affected	:Many

The track of the tornado is given in Fig. 3.i.

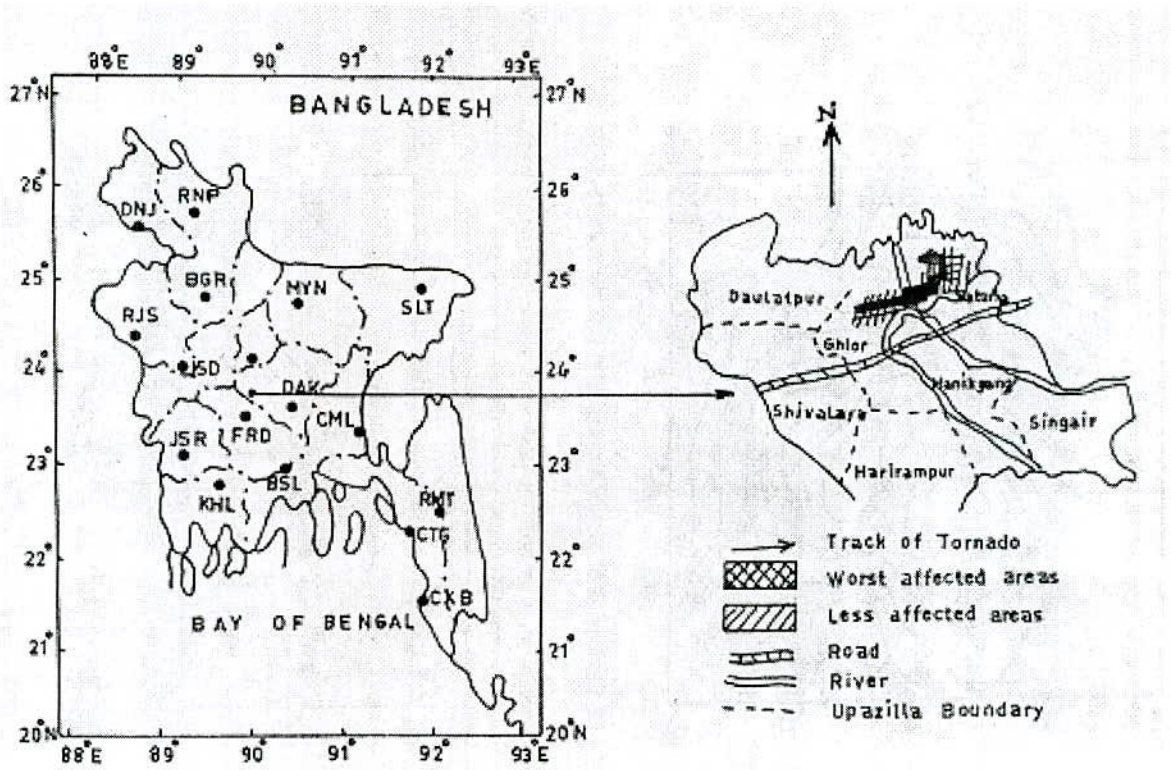


Fig. 3.i: Track of the tornado on 26 April at Saturia, Manikganj

3.2.2 Tangail tornado

A severe tornado in the afternoon on 13 May 1996 devastated 59 villages of six Upazilas under Tangail district located about 100 km north-northwest of Dhaka. The devastated area was about 50-60 km in length and 0.5-2.0 km in width. The extent of

damage, the length and width of the track of its movement indicated that the intensity of the tornado was of the order of F 3.5 in the Fujita Scale, the corresponding estimated wind speed of which was of the order of 320-400 $kmhr^{-1}$ and the whirl wind twisted itself about 20-30 times within 5-8 seconds. The pressure drop at the centre of the tornado was estimated to be more than 50-60 hPa as compared to its surrounding area. The loss and damage due to the tornado is given below:

i)	Loss of lives	: 570
ii)	Cattle heads lost	: 1,531
iii)	Seriously injured people	: 9,855
iv)	Destruction of homesteads:	
	(a) Fully	:16,225
	(b) Partially	:6,765
v)	Educational Institution damaged	: 31
vi)	Number of tube wells damaged	: 3000
vii.	Loss of crops (metric tons)	: 5,039

The track of the tornado is given in Fig. 3.ii.

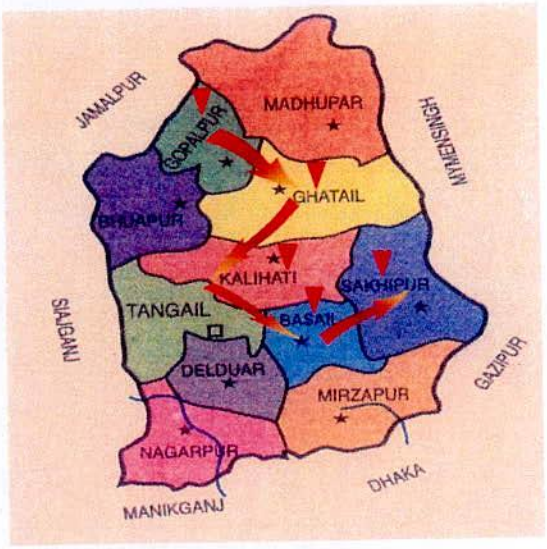


Fig. 3.ii: Track of the tornado on 13 May 1996 at Kalihati, Tangail

3.3 Data used

Surface synoptic charts, upper air pilot charts and constant pressure charts at different heights at different observation times during the pre-monsoon seasons of 1990-2004 have been collected from the Storm Warning Centre (SWC) of Bangladesh Meteorological Department. The dates of occurrence of nor'westers have been taken

from the Storm Warning Centre and different national dailies, and also from personal dairy.

For the study of two tornadoes, the following charts and data were used:

(i) Analyzed surface synoptic charts at 0000 and 1200 UTC on 26 April 1989 and 13 May 1996.

(ii) Analyzed pilot charts at 0000 and 1200 UTC on 26 April 1989 and 13 May 1996.

(iii) Analyzed constant pressure charts at 0000 and 1200 UTC 26 April 1989 and on 13 May 1996.

(iv) Mean sea level pressure at 0000, 0300, 0600, 0900, 1200, 1500, 1800 and 2100 UTC over 35 stations on 25-26 April 1989 and 12-13 May 1996.

(v) 5-day normal pressure during 1986-1995 at different stations.

(vi) Surface humidity at 0000 and 1200 UTC at 35 stations on 26 April 1989 and 13 May 1996.

(vii) Rawinsonde data over Dhaka at 0000 UTC on 24 & 26 April 1989 and 12-13 May 1996.

(viii) Surface minimum temperature at 35 stations of BMD on 25-26 April 1989 and 12-13 May 1996.

3.4 Analyses

The surface (MSL) and upper air meteorological charts were carefully analyzed, and the synoptic conditions at the surface and upper air and the distribution of different meteorological parameters were studied for both nor'westers and tornadoes. For the study of tornadoes, diurnal variation of 24-hr pressure change at Dhaka, Faridpur, Tangail and some other stations were analyzed and discussed critically. Spatial distributions of 24-hr pressure change, pressure departure from the 5-day normal, relative humidity and minimum temperature over Bangladesh were analyzed and studied.

Rawinsonde observations at Dhaka for the dates of occurrence and non-occurrence were plotted on Tephigrams and analyzed for the two tornadoes. The levels of free convection (LFC), the positive and negative areas on Tephigram were determined to study the instability of the troposphere associated with the tornadoes. From the positive areas,

the available instability energy (I) per unit area was determined (Sheet, 1969) by using the equation:

$$I = C_v g^{-1} \int_{P_0}^{P_h} (T_* - T_{env}) dp$$

Where $C_v = 7.201 \times 10^2$ Jkg^{-1} $°C^{-1}$,

T* = Temperature of the ascending parcel,

T_{env}=Environmental temperature.

3.5 Results and discussion

3.5.1 Surface synoptic and upper air conditions associated with nor'westers

3.5.1.1 Mean sea level pressure distribution

During the pre-monsoon season of 1990-2004, a number of severe thunderstorms/ nor'westers occurred over Bangladesh. The surface synoptic conditions for these nor'westers have been studied and their analyses have been discussed critically. During the study period, the main feature at the surface is the existence of a low pressure over eastern Uttar Pradesh, Bihar/West Bengal of India with its axis extending in the west-east direction across the plains. The orientation of the axis and its intensity are affected by the passage of western disturbance in the form of low-pressure area. In such a situation the accentuated axis of trough extends southeastwards into Gangetic West Bengal of India and Bangladesh. Around the trough south-southwesterly winds blow from the Bay of Bengal incurring moisture influx over the region covering Bangladesh, West Bengal and Assam. Quite often through northeast Assam, east-northeasterly dry and cooler wind descends downwards to the west across the foot of the Himalayas. In such typical situation with the existence of east-northeast/easterly wind over extreme north Assam and south/southwesterly wind from the south, an east-west line of wind discontinuity takes place over northern Bangladesh and upper Assam. Sometimes low pressure has been found to form over Orissa and adjoining West Bengal with its trough extending northeastwards to Bangladesh (Fig. 3.1). It has been found that at least 2-3 isobars pass over Bangladesh from the south across Bay of Bengal and these isobars show a converging tendency to the left on the dates of occurrence of nor'westers. During the pre-

monsoon season, sometimes more than 2-3 isobars pass over Bangladesh across the Bay of Bengal and are associated with strong prevailing winds at the surface but the isobars are seen to diverge to the right through the eastern side of the country. On these days, no nor'westers are observed to occur over Bangladesh.

Nor'westers are found to occur over Bangladesh in late February or early March in some years and sometimes nor'westers are found to occur late over Bangladesh. From the analysis of surface synoptic charts, it has been found that early nor'westers occurs over Bangladesh when the easterly low-pressure systems penetrate through the southern tip of India and subsequently move north/northeastwards through Madhya Pradesh, Orissa of India up to southwestern Bangladesh with their trough extending northeastwards over Bangladesh (Fig. 3.2). If the low-pressure systems persist for the whole season, the nor'wester activities have been found to increase over Bangladesh. In these cases the surface sub-tropical highs have been found to be weak over the Bay of Bengal and adjoining areas. For the late occurrence of nor'westers in Bangladesh, the easterly low-pressure systems have been found to move more westwards over the Arabian Sea and then move north/northeast over western India, which conjugates with the western disturbances to form cumulonimbus clouds over Bihar and adjoining West Bengal. These clouds move east-southeastwards over the northern part of Bangladesh and as a result nor'westers occur. In these cases the sub-tropical high-pressure system over Bay of Bengal has been found to be strong for which the easterly low-pressure systems move over the Arabian Sea. Nor'westers have been found to occur over Bangladesh near the trough line in the surface synoptic charts as can be seen from Fig. 3.2.

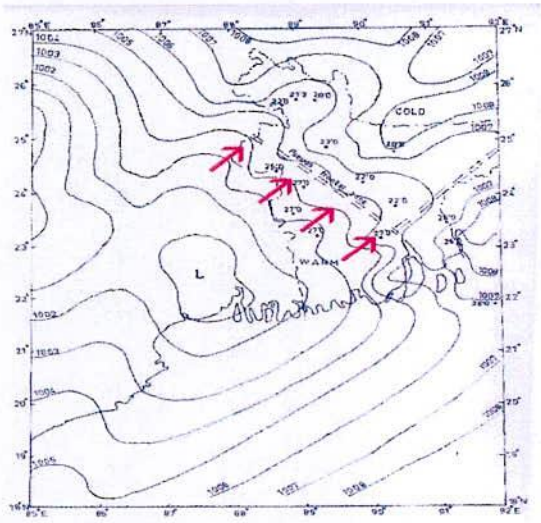


Fig. 3.1: Distribution of mean sea level pressure (hPa) and pseudo-frontal lines at 0000 UTC on 26 April 2002

During the pre-monsoon season, two air masses of different temperatures are found over Bangladesh and adjoining West Bengal especially at 0000 UTC on the dates of occurrence of nor'westers and they form a discontinuity line. Sometimes more than one discontinuity lines form over the region. This indicates that **'pseudo-frontal'** activity is found over Bangladesh and its surroundings as can be seen from Fig. 3.1. When this pseudo-frontal activity is found in the morning, severe thunderstorms/nor'westers occur in the evening or early night. It is interesting to note that the sky over Bangladesh and adjoining areas has been found to remain cloudless/clear from morning to afternoon in most of the days when the pseudo-frontal activity is present at the surface and on these days nor'westers have been found to occur over Bangladesh provided other conditions must be favourable. These nor'westers move from northwest to east-southeast up to Chittagong like a front causing a huge damage to crops and properties and loss to human lives.

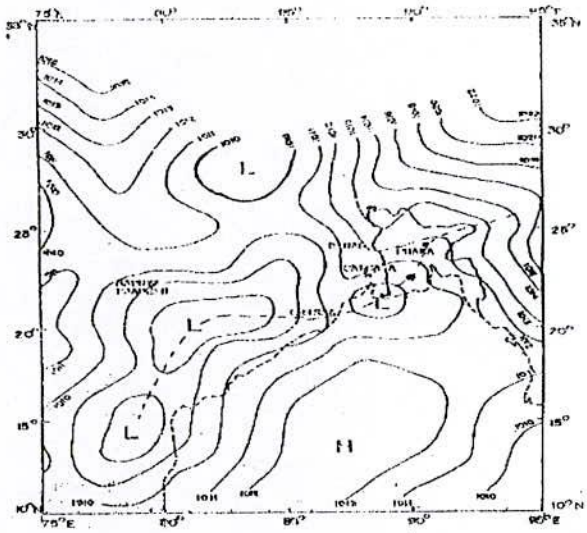


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Fig. 3.2: Distribution of mean sea level pressure (hPa) at 0000 UTC on 29 March 1990

(• place of occurrence of nor'westers)

3.5.1.2 Surface minimum temperature conditions

The spatial distribution of minimum temperature on the dates of occurrence has been studied for several cases and compared with the dates of non-occurrence (1 day before occurrence). It has been found that the minimum temperature is higher over the south and southwestern parts of the country and this higher minimum temperature extends northeastwards up to central Bangladesh or more northeastwards in most of the

cases on the dates of occurrence of nor'westers. Nor'westers have been found to occur near the point of intersection of the axes of warm and cold areas (Figs. 3.3-3.6). On the dates of occurrence of severe nor'westers or tornado, a very small warm area of minimum temperature has been found near the place of occurrence (Fig. 3.3 and 3.5) or there exists an interaction of relatively very cold air mass with warm air mass near the place of occurrence of tornado (Fig. 3.6).

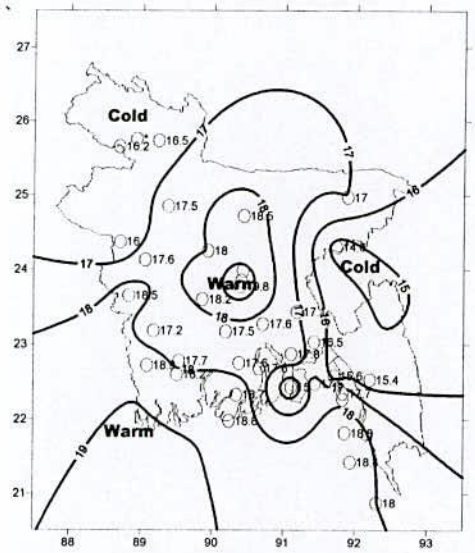

Fig. 3.3: Spatial distribution of minimum temperature (°C) over Bangladesh on 10 March 1990 (Nor'wester at Dhaka: wind = 74.19 kph at 4:50 PM)

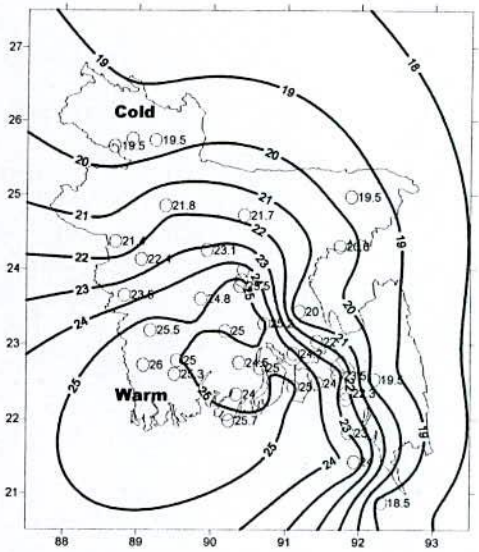

Fig. 3.4: Spatial distribution of minimum temperature (°C) over Bangladesh on 23 March 1990 (Nor'westers at Dhaka, Manikganj, Savar, Daudkandi, Khulna)

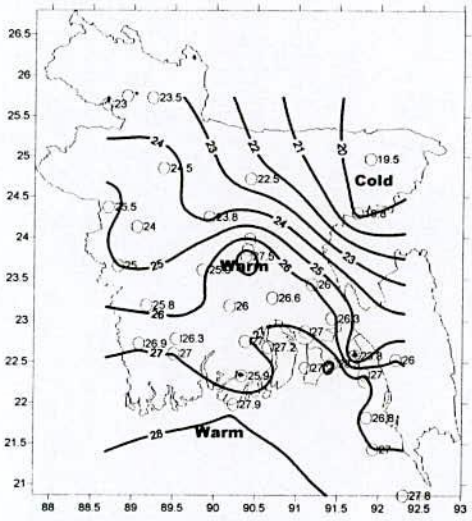

Fig. 3.5: Spatial distribution of minimum temperature (°C) over Bangladesh on 26 April 1989 (Tornado at Saturia)

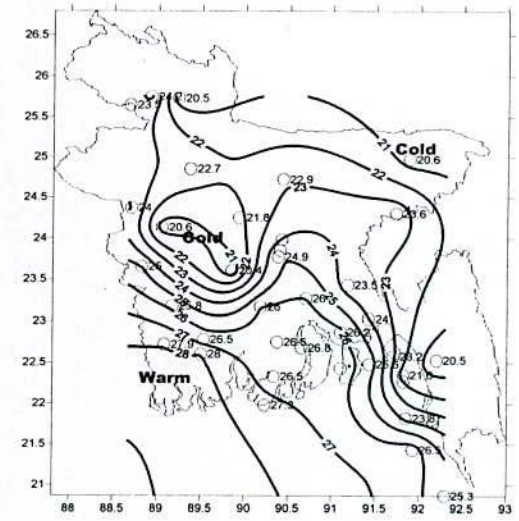

Fig. 3.6: Spatial distribution of minimum temperature (°C) over Bangladesh on 13 May 1996 (Tornado at Kalihati, Tangail)

On the dates of occurrence of nor'westers, the minimum temperatures have been found to rise as compared to minimum temperatures on the dates of non-occurrence of nor'westers (1 day before occurrence) over the northwestern and southwestern parts of the country as can be seen from Figs. 3.7-3.9. Strong gradient of fall in minimum temperature and its interaction with rise in minimum temperature exists near the place of severe nor'westers or tornado (Fig.3.8 and 3.9).

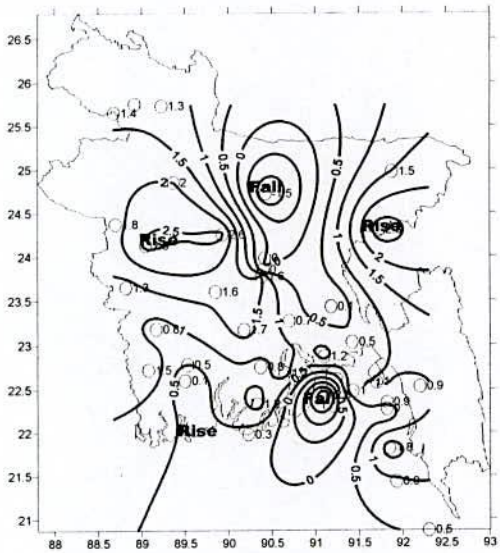

Fig. 3.7: Spatial distribution of the change in minimum temperatures (°C) over Bangladesh on 10 March (date of occurrence) 1990

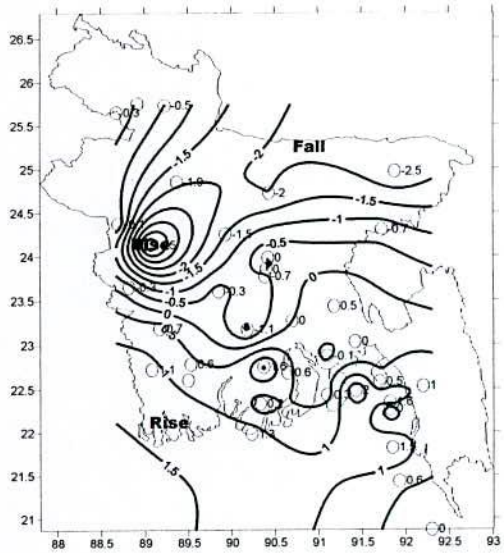

Fig. 3.8: Spatial distribution of the change in minimum temperatures (°C) over Bangladesh on 29 March (date of occurrence) 1990

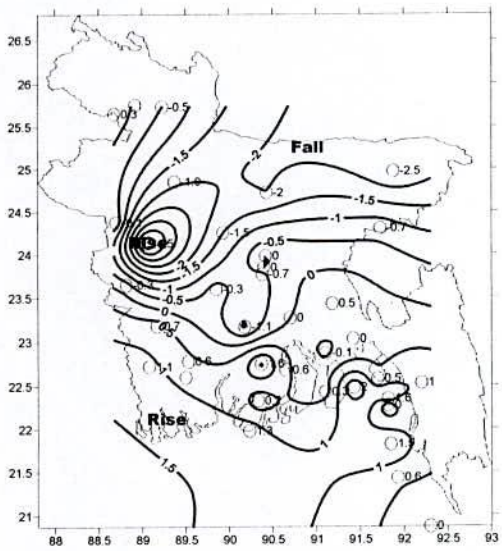

Fig. 3.9: Spatial distribution of the change in minimum temperatures (°C) over Bangladesh on 13 May (date of occurrence) 1996

3.5.1.3 Surface humidity conditions

The spatial distribution of surface humidity on the dates of occurrence has been studied for several cases and compared with the dates of non-occurrence (1 day before occurrence). Some examples are given in Figs. 3.10-3.16.

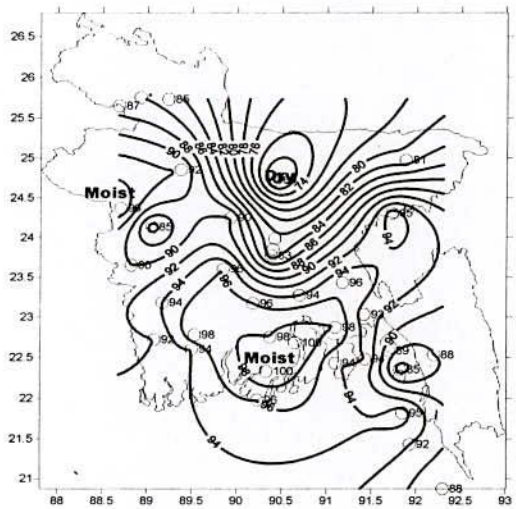

Fig. 3.10: Spatial distribution of surface humidity over Bangladesh at 0000 UTC on 10 March 1990 (Nor'wester at Dhaka: wind = 74.19 kph at 4:50 PM)

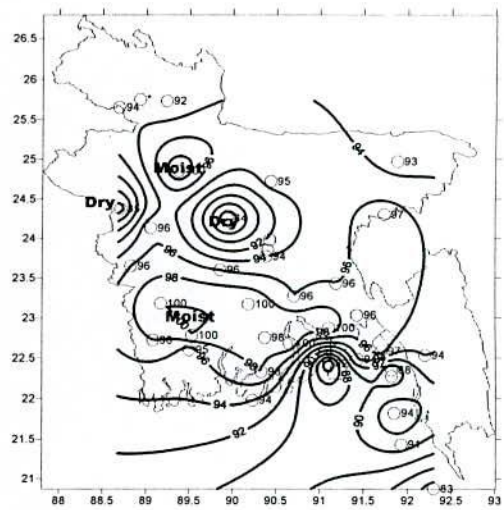

Fig. 3.11: Spatial distribution of surface humidity over Bangladesh at 0000 UTC on 29 March 1990 (tornado at Magura, thunderstorm at Sayedpur and Muradnagar, severe thunderstorm at Chuadanga, thunderstorm with hails at Kaliakoir)

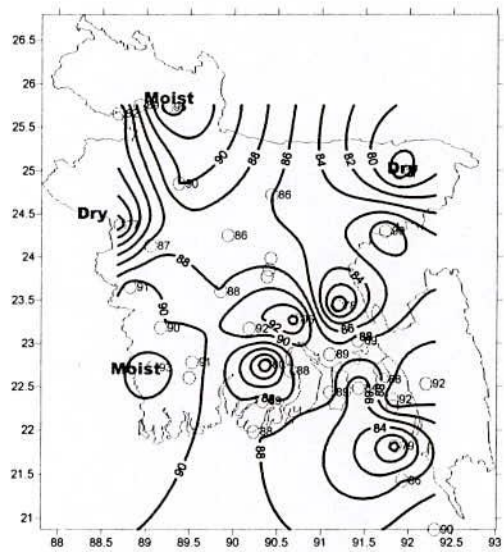

Fig. 3.12: Spatial distribution of surface humidity over Bangladesh at 0000 UTC on 26 April 1989 (Tornado at Saturia)

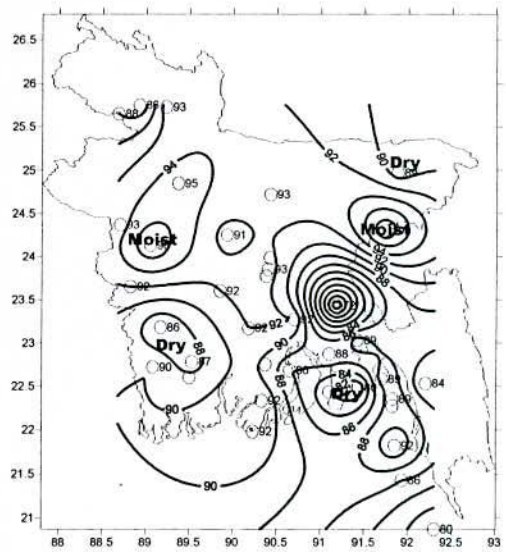

Fig. 3.13: Spatial distribution of surface humidity over Bangladesh at 0000 UTC on 13 May 1996 (Tornado at Kalihati, Tangail)

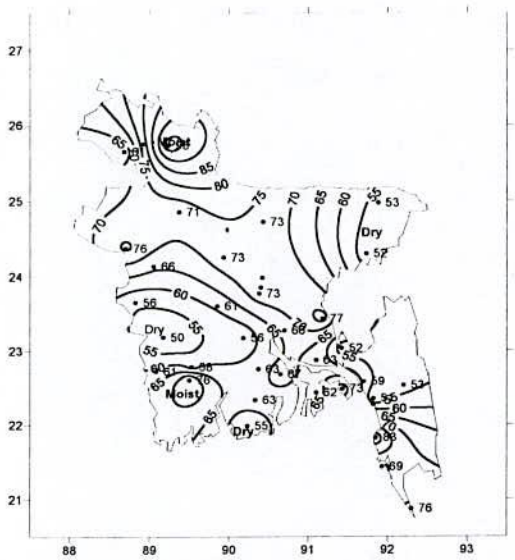

Fig. 3.14: Spatial distribution of surface humidity over Bangladesh at 1200 UTC on 10 March 1990 (Nor'wester at Dhaka: wind = 74.19 kph at 4:50 PM)

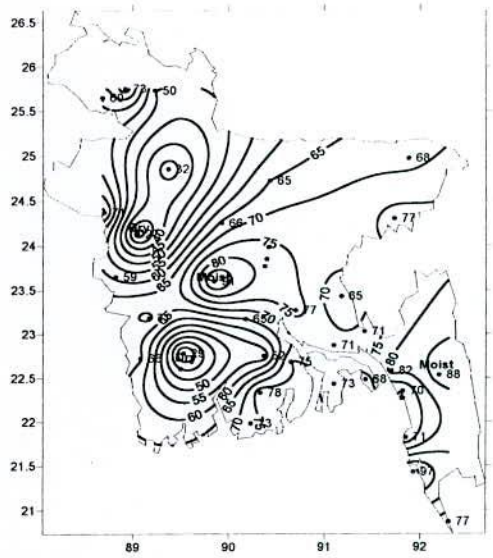

Fig. 3.15: Spatial distribution of surface humidity over Bangladesh at 1200 UTC on 26 April 1989 (Tornado at Saturia)

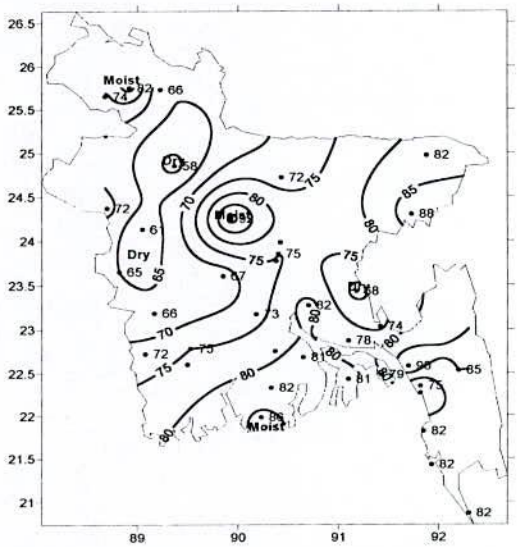

Fig. 3.16: Spatial distribution of surface humidity over Bangladesh at 1200 UTC on 13 May 1996 (Tornado at Kalihati, Tangail)

It has been found that the humidity is higher over the south and southwestern parts of the country and this humidity extends northeastwards up to central Bangladesh or more northeastwards in most of the cases on the dates of occurrence of nor'westers at 0000 UTC or 0300 UTC. Moist area has also been found near the place of occurrence of nor'westers. Nor'westers have been found to occur near the point of intersection of the axes of moist and dry areas (Figs. 3.10-3.13). On the dates of occurrence of severe nor'westers or tornado, a very small moist area has been found near the place of occurrence (Fig. 3.12). From the diurnal spatial distribution of humidity, it has been

found that the moist area shifts to the north in the afternoon in many cases as can be seen from the comparison in Figs. 3.10 and Figs. 3.14-3.15. On the dates of occurrence of severe nor'westers or tornado, severe drying of the atmosphere near the surface occurs in the afternoon and the gradient of humidity increases significantly (Figs.3.14-3.16).

3.5.1.4 Upper air synoptic conditions

A number of upper air synoptic charts (both constant pressure and pilot charts) on the dates of occurrence of nor'westers during 1990-2003 have been examined to find out the favourable synoptic as well as circulation patterns associated with nor'westers in Bangladesh. It has been found that cyclonic circulation or a strong trough must be present over the surface low at lower levels extending to about 1-1.5 km or more (Figs. 3.17-3.20, as for examples).

In many cases the cyclonic circulation has been found to strengthen and extend to greater heights in the afternoon. In the pilot chart, low-level circulation is more prominent as compared to that in the constant pressure chart. The cyclonic circulation is responsible for the influx of moisture from the Bay of Bengal. In some cases, it has been found the significant cyclonic circulation needs to be extended to greater heights at the beginning of the season or after some days without nor'westers. After the occurrence of one or two nor'westers, the moisture is present in the troposphere when low-level circulation up to 1 km is enough to cause thunderstorms/nor'westers. When trough in the upper air westerly jet stream is present over Bihar/West Bengal of India or over Bangladesh, severe nor'westers are found to occur in Bangladesh. The speed of the westerly jet stream has also been found to contribute to the severity of the nor'westers.

It has been difficult to find out the place of occurrence of nor'westers in Bangladesh. So, a several cases of nor'westers during the pre-monsoon season of 1990-2003 have been examined by studying the tropospheric synoptic charts. In these cases, the axis of the upper air maximum jet stream at 300 hPa or 200 hPa has been superimposed on the axis of the low-level maximum wind at 850 hPa at 0000 UTC. Severe nor'westers have been found to occur near the point of intersection of the axis of the maximum jet stream at 300/200 hPa and the axis of maximum wind at 850-hPa level [Fig. 3.21 (a-b)]. This method has been found to be effective in operational forecasting of nor'westers.

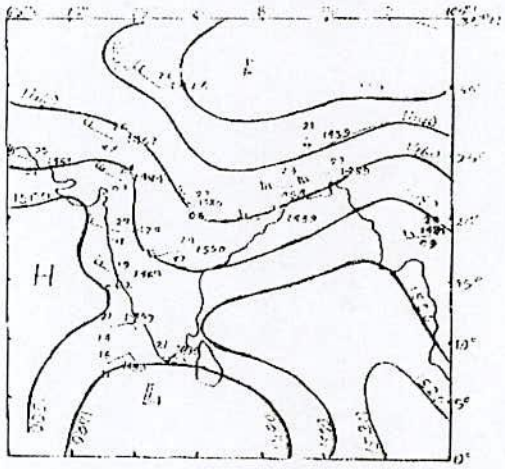

Fig. 3.17: Circulation pattern at 850 hPa at 00 UTC on 19 April 1990

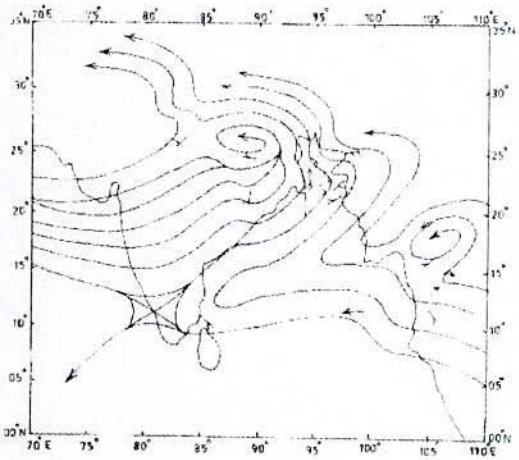

Fig. 3.18: Circulation pattern at 0.3 km (1000 ft) at 0000 UTC on 29 April 2002 (Tornado at Sylhet in the afternoon)

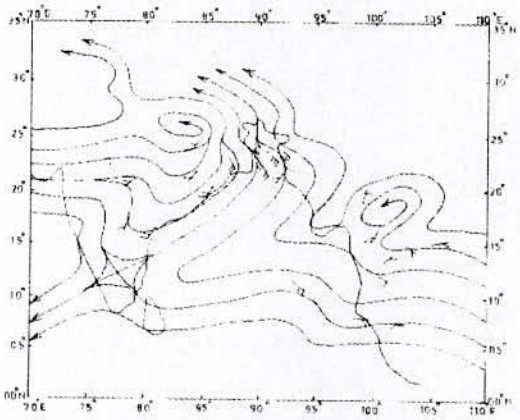

Fig. 3.19: Circulation pattern at 1.5 km (5000 ft) at 0000 UTC on 29 April 2002 (Tornado at Sylhet in the afternoon)

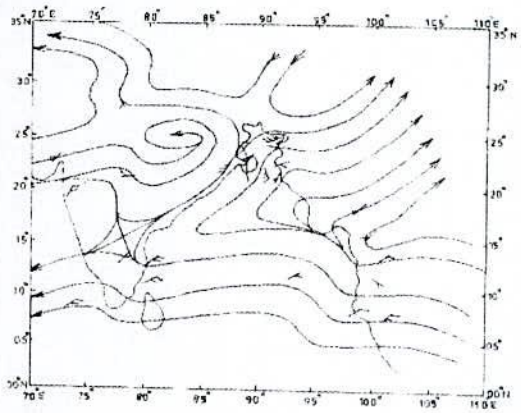

Fig. 3.20: Circulation pattern at 3 km (10,000 ft) at 0000 UTC on 29 April 2002 (Tornado at Sylhet in the afternoon)

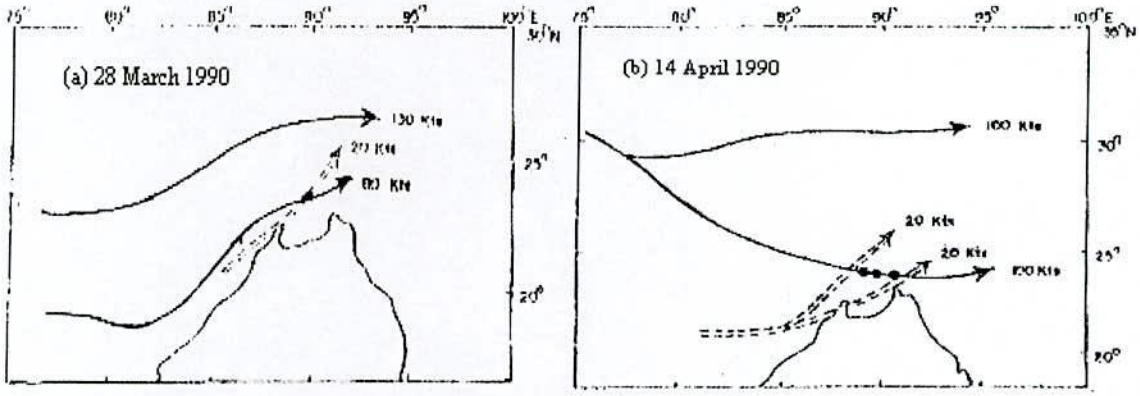

Fig. 3.21 (a-b): Superimposition of the axes of the upper air jet stream and the lower level maximum winds on the dates of occurrence of severe nor'westers

(Solid lines ⇒ 200 hPa and dashed lines ⇒ 850 hPa, •⇒ place of occurrence)

3.5.2 Synoptic and upper air conditions associated with tornadoes

3.5.2.1 Synoptic conditions on 26 April 1989

The surface synoptic condition at 0000 UTC of 26 April 1989 was characterized by the presence of a westerly low over western part of Bangladesh and adjoining West Bengal of India with a prominent trough extending to northeast. Moderately strong pressure gradients were found to exist over Bangladesh. The same synoptic conditions prevailed up to 1200 UTC with a little exception when there appeared a low over Madhya Pradesh and adjoining area and the pressure gradient became strong (Fig. 3.22 and 3.23).

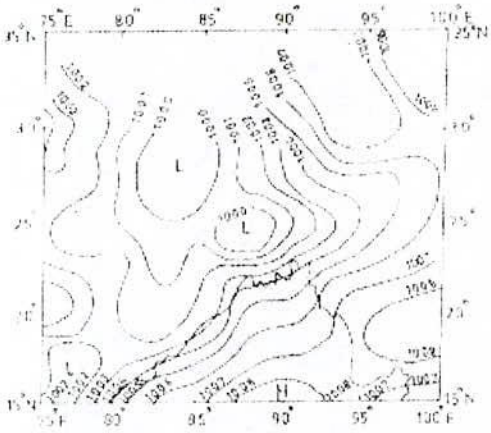

Fig. 3.22: Distribution of MSL pressure at 1200 UTC on 25 April 1989

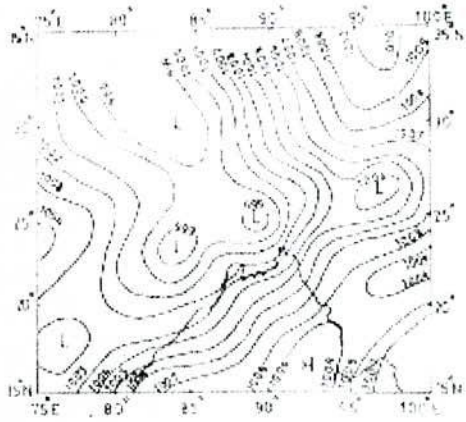

Fig. 3.23: Distribution of MSL pressure at 1200 UTC on 26 April 1989

At 0000 UTC on 25 April, strong cyclonic circulation was found to exist up to about 1.5 km (5000 ft). Westerly jet stream of speed 80 knots was found over northern India and Kolkata at about 12 km (40,000 ft). The same cyclonic circulation in the lower troposphere intensified further, extended up to 3.0 km (10,000 ft) and prevailed throughout the subsequent hours up to 0600 UTC on 26 April 1989. Westerly jet stream of speed about 130 knots was found over Dhaka at about 10.6 km (35,000 ft) at 0000 UTC on 26 April. A strong trough in the westerly jet appeared at 200 hPa (12 km) level over Bangladesh at 1200 UTC on 26 April (Fig. 3.24). The jet core of 100 knots was found to extend up to the place of occurrence as could be seen in the Fig. 3.24.

The above-mentioned synoptic conditions and the lower tropospheric circulation patterns together with upper tropospheric strong jet stream were favourable for the occurrence the severe tornado over Bangladesh.

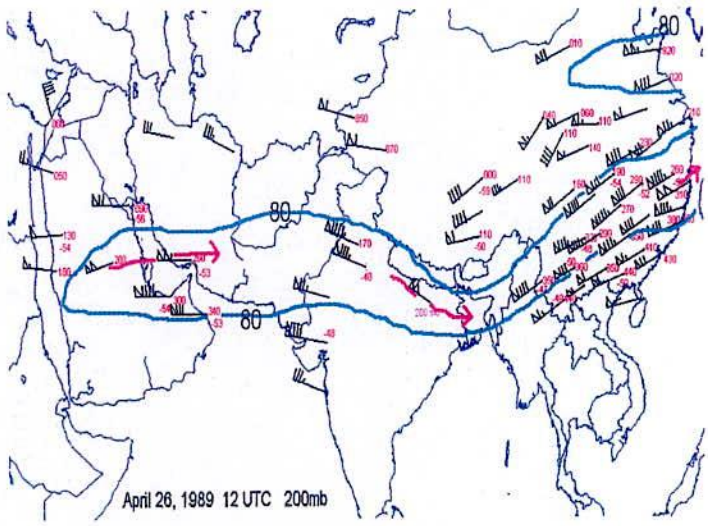

Fig. 3.24: 200 hPa circulation pattern at 1200 UTC on 26 April 1989 (Finch, J.D., 2004)

3.5.2.2 Synoptic conditions on 13 May 1996

The tornado originated under the influence of prominent westerly low at the surface over Bihar and adjoining West Bengal of India with its associated trough extended up to Assam across central Bangladesh having low level wind converging over the district of Tangail. Fig. 3.25 gives the spatial distribution of MSL pressure at 0000 UTC on 13 May 1996 showing the presence of prominent westerly low over Bihar and adjoining West Bengal of India with its trough extending towards northeast across northern Bangladesh.

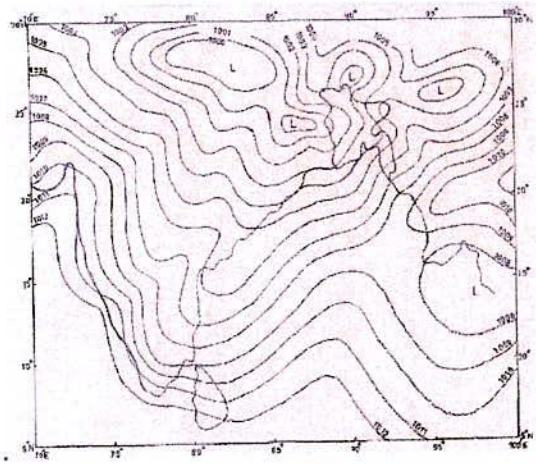

Fig. 3.25: Spatial distribution of MSL pressure at 0000 UTC on 13 May 1996

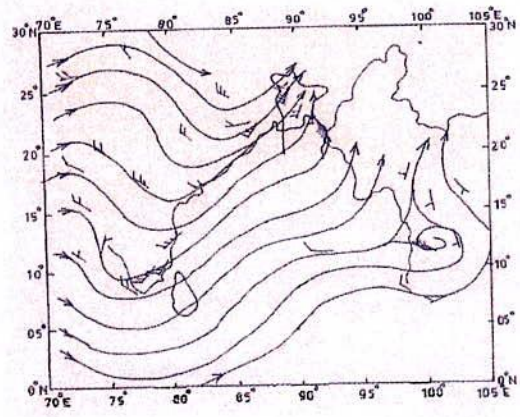

Fig. 3.26: Circulation pattern at 0.6 km (2000 ft) at 0000 UTC on 13 May 1996

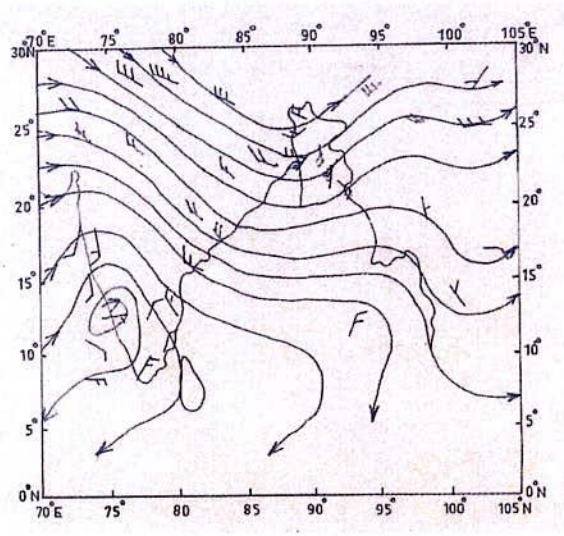

Fig. 3.27: Circulation pattern at 3.0 km (10,000 ft) at 0000 UTC on 13 May 1996

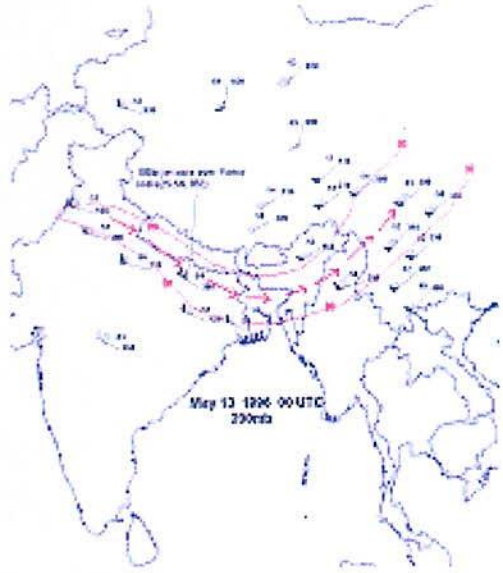

Fig. 3.28: 200 hPa circulation pattern at 0000 UTC on 13 May 1996 ((Finch, J.D., 2004)

The circulation patterns at 0.6 km (2000 ft) and 3.0 km (10,000 ft) show the presence of strong westerly trough over northwestern Bangladesh and adjoining area (Figs. 3.26-3.27). A strong trough in the westerly jet appeared at 200 hPa (12 km) level over northern Bangladesh at 0000 UTC on 13 May 1996 (Fig. 3.28). The jet core of 100 knots was found to extend up to the place of occurrence as could be seen in the Fig. 3.28.

The surface synoptic conditions and the low-level circulation together with strong trough in the westerly jet were favourable for the occurrence of the tornado over Bangladesh.

3.5.2.3 Diurnal and spatial variation of 24-hr pressure change

3.5.2.3.1 Diurnal and spatial variation of 24-hr pressure change on 26 April 1989

The diurnal variation of 24-hr MSL pressure change at some stations surrounding the place of occurrence of the tornado on 26 April is shown in Fig. 3.29. There was a fall in MSL pressure from morning to about 1200 UTC at Dhaka, Faridpur, Tangail Bogra and Ishurdi having maximum fall of -1.8 hPa at Dhaka at 1200 UTC.

The spatial distribution of 24-hr pressure change over Bangladesh has also been studied. The area of 24-hr negative pressure change extending from Bogra-Mymensingh

area to near Manikganj / Dhaka (Fig. 3.30). This pressure falling tendency continued up to about 1200 UTC over the same area.

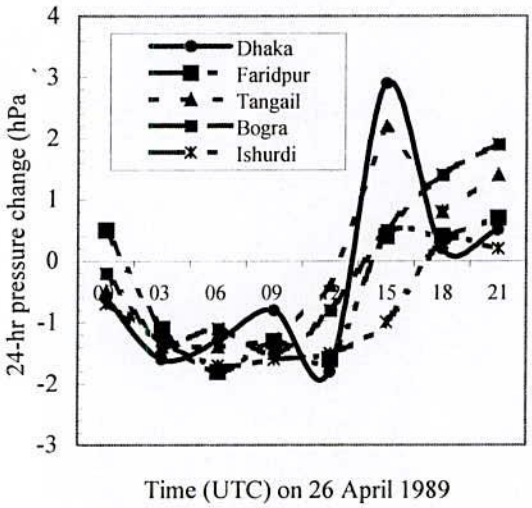

Fig. 3.29: Diurnal variation of 24-hr pressure change at some stations surrounding the place of occurrence of tornado on 26 April 1989

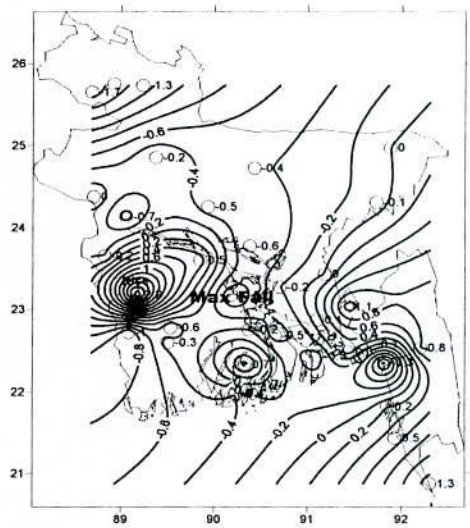

Fig. 3.30: Spatial distribution of 24-hr pressure change (hPa) at 0000 UTC on 26 April 1989

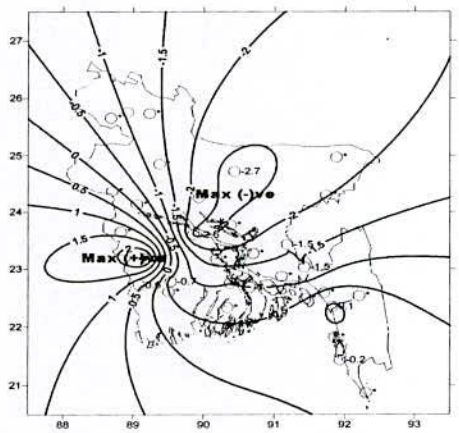

Fig. 3.31: Pressure departure from the 5-day normal at 1200 UTC on 26 April 1989

The departure of pressure from the 5-day normal at 0000 and 1200 UTC has been calculated and spatially distributed over Bangladesh. It has been found that the pressure was below normal by –2.7 hPa 1200 UTC over the area from Mymensingh region to Manikganj, having a cell extending from Mymensingh to Manikganj (Fig. 3.31). This pressure fall from the normal was favourable of the occurrence of tornado.

3.5.2.3.2 Diurnal and spatial variation of 24-hr pressure change on 13 May 1996

The diurnal variation of 24-hr pressure change at Tangail and some other stations are shown in Figs. 3.32 and 3.33 respectively. Fig. 3.32 shows that the MSL pressure on 13 May was less than that on 12 May at all observation times and had a sharp and significant decreasing trend at 0600 and 0900 UTC at Tangail and the maximum pressure fall was –4.5 hPa. After 0900 UTC the 24-hr pressure change, though negative, had a sharp increasing trend indicating that the tornado occurred at about 0900 UTC.

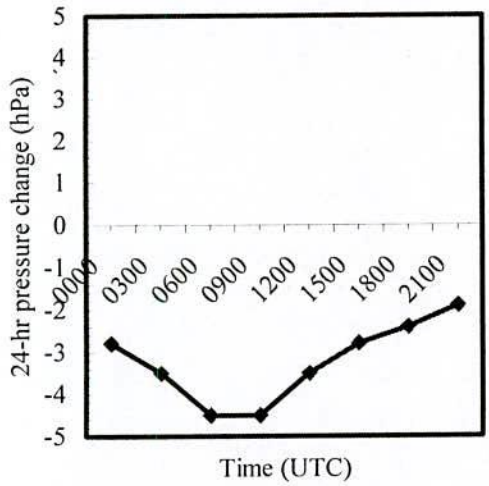

Fig. 3.32: Diurnal variation of 24-hr pressure (hPa) change at Tangail on 13 May 1996

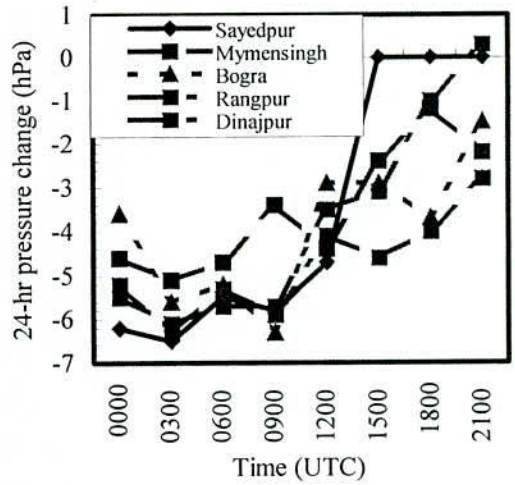

Fig. 3.33: Diurnal variation of 24-hr pressure change at different stations on 13 May 1996

At other stations such as Dinajpur, Rangpur, Sayedpur, Bogra (Fig. 3.33), the MSL pressure starts decreasing from 0000 UTC reaching a minimum at 0300 UTC, then increases slightly and again attains a secondary minimum value at 0900 UTC on 13 May 1996 as compared to that on 12 May 1996. After 0900 UTC the 24-hr pressure change, though negative, had a sharp increasing trend. This indicates that the tornado occurred at about 0900 UTC.

The spatial variation of 24-hr pressure change over Bangladesh on 13 May 1996 has been studied for different synoptic observations times. The spatial distributions of 24-hr pressure changes at 0000, 0300, 0600, 0900 and 1200 UTC are given in Figs. 3.34-3.38 respectively. It has been found from the distribution of pressure change that the pressure

on 13 May 1996 started falling as compared to previous 24-hr pressure since the morning especially over the northwestern part of Bangladesh, having the value of –6.0 hPa over Sayedpur-Rangpur-Dinajpur-Bogra region with its trough extending to Dhaka region at almost all the observation times. The area of pressure fall over northwestern part was in agreement with the track of the tornado. There was a significant rise in pressure on 13 May over the western part of the country starting from the morning to night. At 0300 UTC, two small bubbles of pressure fall were found over Tangail and adjoining area (Fig. 3.35) but these bubbles again merged with the main trough coming from the north-northwest (Fig. 3.36). The fall in pressure became more pronounced over the Sayedpur-Rangpur-Dinajpur-Bogra region and the extended trough became very narrow, which penetrated more southward even south of Dhaka at 0900 UTC (Fig. 3.37) and after that the main trough over the northwestern part began to be disorganized as can be seen from the spatial distribution of 24-hr pressure change at 1200 UTC on 13 May 1996 (Fig. 3.38). It indicates that the tornado occurred over Tangail at about 0900 UTC.

The departure of pressure from the 5-day normal at 0000 and 1200 UTC has been calculated and plotted all over Bangladesh. The distributions are shown in Figs. 3.39-3.40 respectively. These figures also show the pressure was below normal by –4.0 and –5.0 at 0000 UTC and 1200 UTC on 13 May 1996 respectively over the northwestern part of the country. This pressure fall from the normal was favourable for the occurrence of tornado.

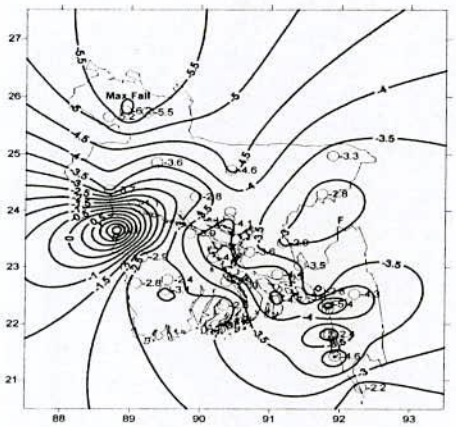

Fig. 3.34: Spatial distribution of 24-hr pressure change (hPa) over Bangladesh at 0000 UTC on 13 May 1996

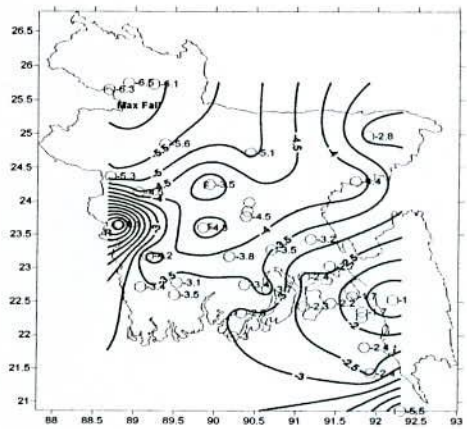

Fig. 3.35: Spatial distribution of 24-hr pressure change (hPa) over Bangladesh at 0300 UTC on 13 May 1996

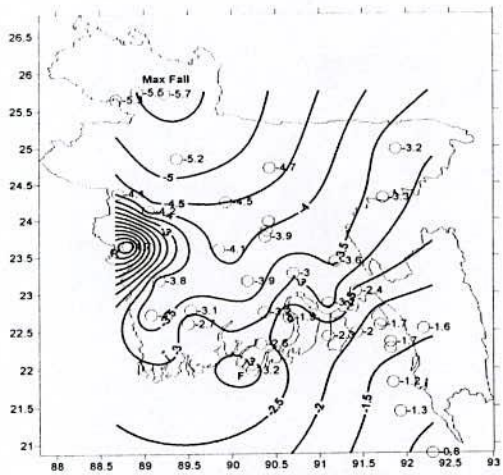

Fig. 3.36: Spatial distribution of 24-hr pressure change (hPa) over Bangladesh at 0600 UTC on 13 May 1996

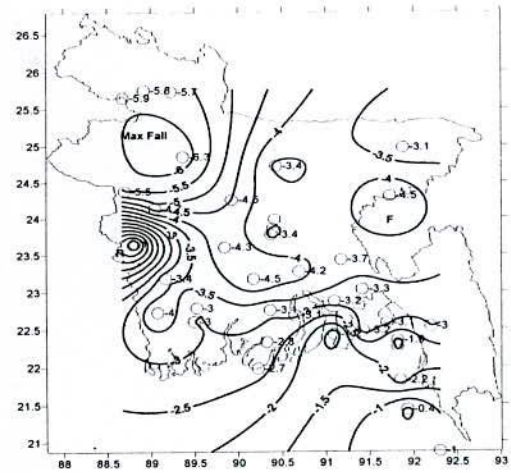

Fig. 3.37: Spatial distribution of 24-hr pressure change (hPa) over Bangladesh at 0900 UTC on 13 May 1996

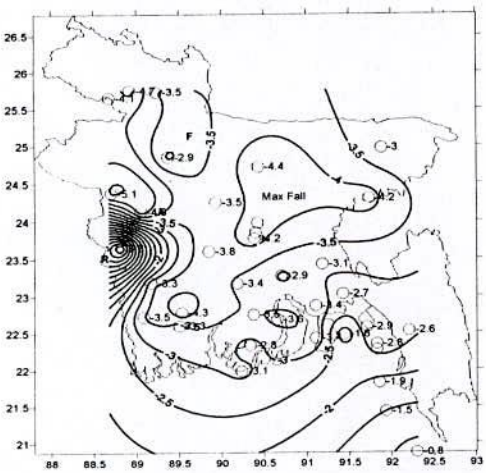

Fig. 3.38: Spatial distribution of 24-hr pressure change (hPa) over Bangladesh at 1200 UTC on 13 May 1996

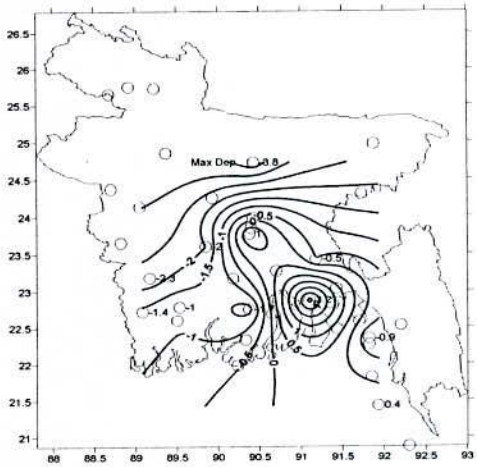

Fig. 3.39: Pressure departure from the 5-day normal at 0000 UTC on 13 May 1996

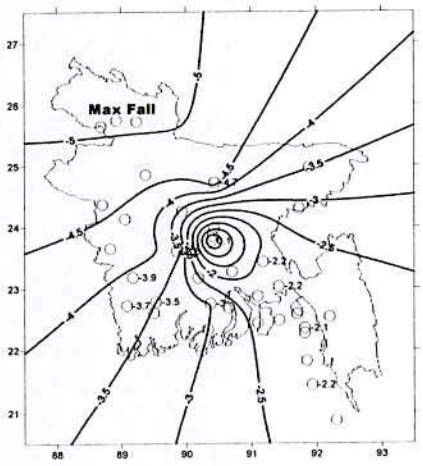

Fig. 3.40: Pressure departure from the 5-day normal at 1200 UTC on 13 May 1996

3.5.2.4 Spatial distribution of minimum temperature over Bangladesh

3.5.2.4.1 Spatial distribution of minimum temperature over Bangladesh on 26 April 1989

The spatial distribution of minimum temperature over Bangladesh on 26 April 1989 is shown in Fig. 3.41, which indicates intrusion of warm air through the southwestern part of the country up to Dhaka and presence of cold air just northeast of Dhaka over the Sylhet region. This condition was favourable for the formation of a convective cloud.

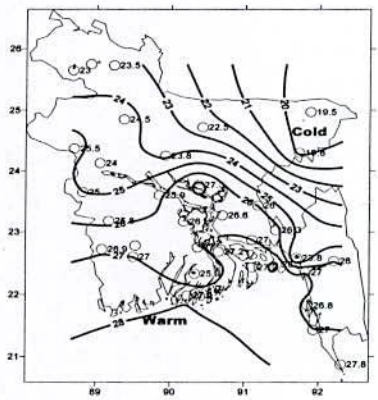

Fig. 3.41: Spatial distribution of minimum temperature over Bangladesh on the date of occurrence of tornado at Saturia on 26 April 1989

3.5.2.4.2 Spatial distribution of minimum temperature over Bangladesh on 13 May 1996

Fig. 3.42 shows the spatial distribution of minimum temperature over Bangladesh, which indicates intrusion of warm air through the southwestern part of the country up to Dhaka division and presence of cold air just northwest of Dhaka.

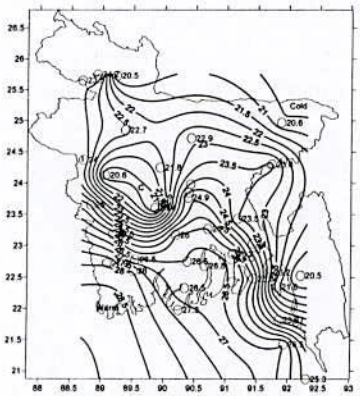

Fig. 3.42: Spatial distribution of minimum temperature (°C) over Bangladesh on 13 May 1996 (Tornado at Tangail)

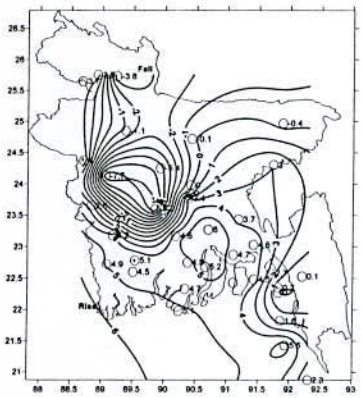

Fig. 3.43: Spatial distribution of the difference in minimum temperatures (°C) over Bangladesh between 13 May (date of occurrence) and 12 May (1 day before occurrence) 1996

Fig. 3.42 reveals that there was an interaction of cold and warm air over the Tangail and adjoining area. The difference in temperature on 13 May and 12 May shows a strong gradient of falling minimum temperature on 13 May over Tangail and adjoining area along with an adjacent area of rising minimum temperature over the Dhaka region just east of the fall in minimum temperature (Fig. 3.43). These conditions were favourable for the occurrence of tornado.

3.5.2.5 Spatial distribution of relative humidity over Bangladesh

3.5.2.5.1 Spatial distribution of relative humidity over Bangladesh on 26 April 1989

The spatial distribution of relative humidity at different synoptic hours has been made over Bangladesh. It seen that there was a moist area at 0000 UTC over Khulna-Faridpur region and over Bogra region with dry zone Jessore-Kushtia and Dhaka-Comilla region (Fig. 3.44).

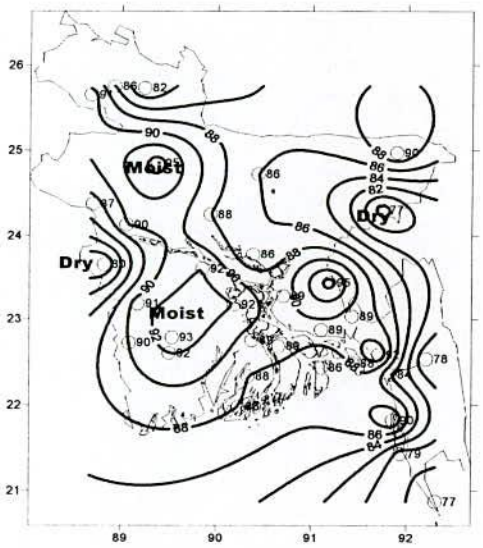

Fig. 3.44: Spatial distribution of relative humidity over Bangladesh on the date of occurrence of tornado at Saturia at 0000 UTC on 26 April 1989

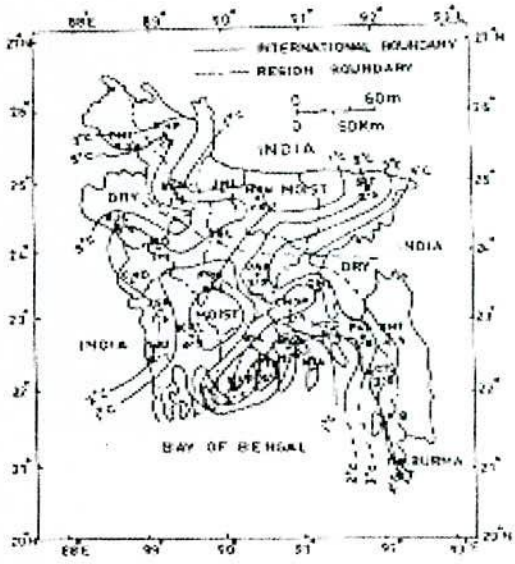

Fig. 3.45: Spatial distribution of dew-point depression over Bangladesh on the date of occurrence of tornado at Saturia at 0000 UTC on 26 April 1989

The distribution of dew-point depression also reveals that there was a dry zone along latitude belt of 23°-24° N at 0000 UTC on 25 April. This dry zone shifted a little northward in the western part of Bangladesh at 1200 UTC on the same day. The dry zone

became prominent in the western part of the country both at 0000 UTC and 1200 UTC on 26 April, having a very dry air over Rajshahi region at 1200 UTC.

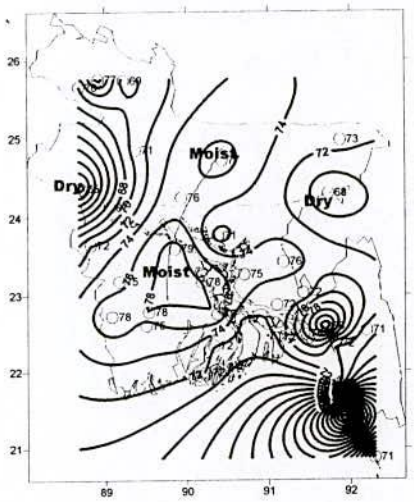

Fig. 3.46: Spatial distribution of relative humidity over Bangladesh on the date of occurrence of tornado at Saturia at 0300 UTC on 26 April 1989

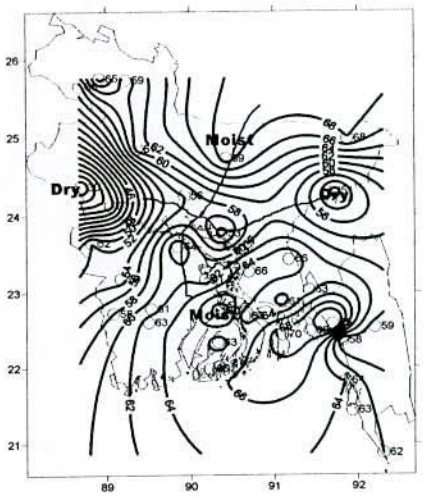

Fig. 3.47: Spatial distribution of relative humidity over Bangladesh on the date of occurrence of tornado at Saturia at 0600 UTC on 26 April 1989

At 0000 UTC on both 25 and 26 April, there was moist air over Khulna-Jessore-Barisal-Faridpur. This axis of moist tongue was found to extend northwards up to Mymensingh. The intersection of the axes of moist zone and dry zone is evident from the spatial distribution of dew-point depression at 0000 UTC on 26 April 1989 (Fig. 3.45). At 0300 and 0600 UTC, the moist area over Bogra was found to have shifted eastward over Mymensingh region (Figs. 3.46-3.47) and after 0600 UTC the moist area disappeared and overlain by dry air mass after the occurrence of the tornado (Fig. 3.48). The tornado occurred near the point of intersection of the axes of moist and dry zones.

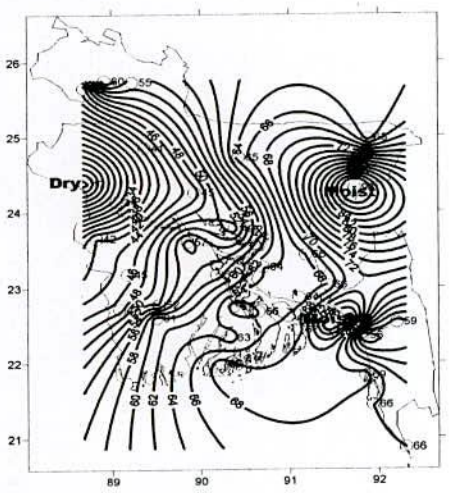

Fig. 3.48: Spatial distribution of relative humidity over Bangladesh on the date of occurrence of tornado at Saturia at 0900 UTC on 26 April 1989

3.5.2.5.2 Spatial distribution of relative humidity over Bangladesh on 13 May 1996

The spatial distributions of relative humidity at 0000UTC and 1200 UTC are shown in Figs. 3.49 and 3.50 respectively. It seen that there was a moist area at 0000 UTC on 13 May over central Bangladesh, having relatively more moist area near Tangail and adjoining area. At 1200 UTC, this moist area was removed and overlain by dry air mass after the occurrence of the tornado (Fig. 3.50).

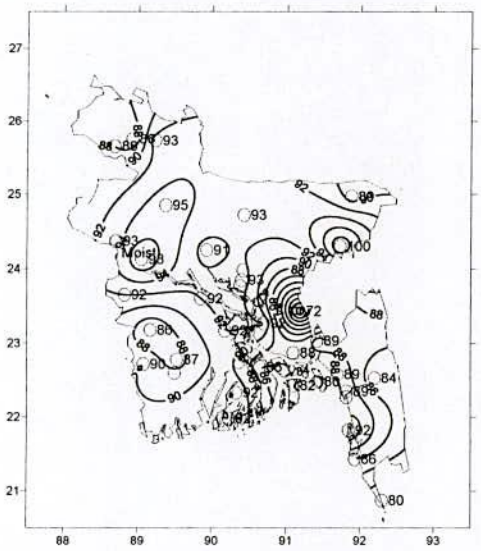

Fig. 3.49: Spatial distribution of surface humidity over Bangladesh at 0000 UTC on 13 May 1996 (Tornado at Kalihati, Tangail)

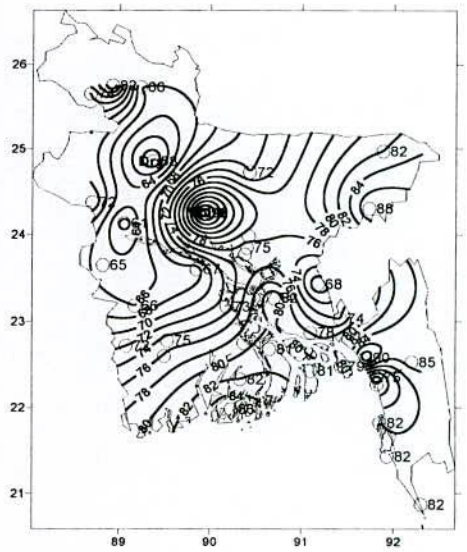

Fig. 3.50: Spatial distribution of surface humidity over Bangladesh at 1200 UTC on 13 May 1996 (Tornado at Kalihati, Tangail)

3.5.2.6 Vertical profiles of specific humidity over Dhaka

The vertical distributions of moisture in terms of specific humidity at 0000 UTC over Dhaka during the dates of occurrence of two tornadoes are shown in Figs. 3.51-3.52. Fig. 3.51 for Saturia tornado shows that there was a significant increase in moisture content from 1000 to 540 hPa level on 26 April 1989 as compared to that on 24 April, the maximum increase being 3.2-3.3 gm kgm^{-1} in the layer 850-700 hPa.

Fig. 3.52 for Kalihati tornado shows that there was a significant increase in moisture content from 1000 to 925 hPa level on 13 May as compared to that on 12 May 1996, the maximum increase being 2.01-6.27 gm kgm^{-1} in the layer. There was also a slight increase in moisture in the layer 700-500 hPa.

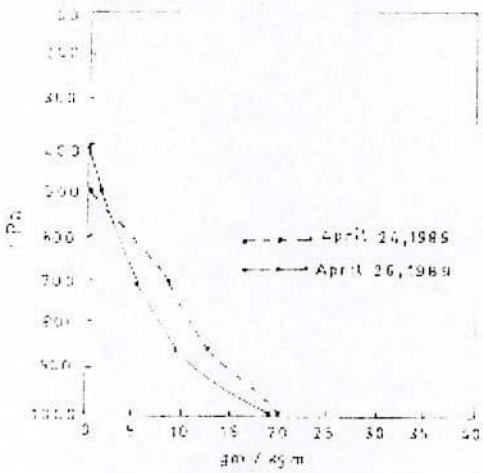

Fig. 3.51:Vertical profiles of specific humidity at 0000 UTC over Dhaka on 24-26 April 1989

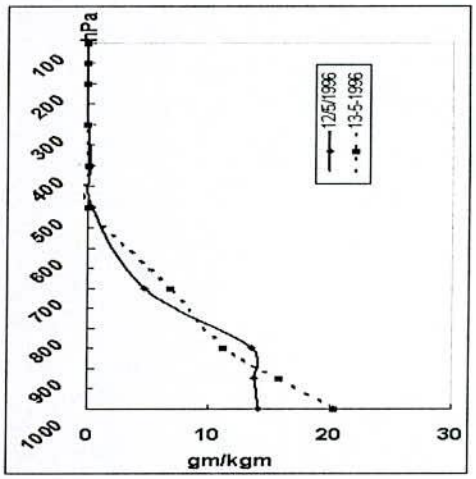

Fig. 3.52:Vertical profiles of specific humidity at 0000 UTC over Dhaka on 12-13 May 1996

3.5.2.7 Instability and available instability energy of the troposphere over Dhaka

Tephigrams on 24-26 April 1989 (data on 25 April was missing) and 12-13 May 1996 at 0000 UTC over Dhaka have been analyzed using the 925-hPa moisture and temperature and the positive and negative areas were evaluated. The levels of free convection (LFC) were determined during the two periods. The results are discussed below.

3.5.2.7.1 Instability and available instability energy of the troposphere over Dhaka on 24-26 April 1989

On 24 April 1989,the negative area on the Tephigram at 0000 UTC was greater than that on 26 April, indicating the stable troposphere. Whereas the positive area on 26 April 1989 was significantly greater than that on 24 April. The levels of free convection (LFC) at 0000 UTC over Dhaka were about 760 and 935 hPa on 24 and 26 April respectively. This shows that the LFC was much lower on the date of occurrence of the tornado at Saturia.

The available instability energy per unit area was 35.27020×10^6 Joule m^{-2} on 24 April and 36.17951×10^6 Joule m^{-2} on 26 April 1989. The difference of this energy was 0.90931×10^6 Joule m^{-2}. This higher amount of energy per unit area was responsible for the occurrence of tornado.

3.5.2.7.2 Instability and available instability energy of the troposphere over Dhaka on 12-13 May 1996

The analysis of Tephigram has shown that there were positive areas at 0000 UTC on 12 and 13 May 1996 but the positive area on 13 May was bigger than that on 12 May, indicating more instability of the troposphere on the date of occurrence of the tornado. The tops of the positive areas were 232 and 215 hPa on 12 and 13 May respectively. At 0000 UTC the LFC was 764 and 790 hPa on 12 and 13 May 1996 respectively and this descending of LFC was favourable indication for tornado formation.

From the Tephigram analysis, the available instability energy over Dhaka on 12 May (date of non-occurrence) and 13 May (date of occurrence) 1996 has been calculated by using the equation of Sheet (1969). The available instability energy over Dhaka on 12 and 13 May has been found to be 171.05976×10^6 Jm^{-2} and 175.53518×10^6 Jm^{-2} respectively, the difference in available instability energy being 44.75421×10^5 Jm^{-2}. This tremendous quantity of instability energy was responsible for the occurrence of the tornado on 13 May 1996.

3.5.2.8 Vertical distribution of wind over Dhaka

3.5.2.8.1 Vertical distribution of wind over Dhaka during the occurrence of tornado at Saturia

The vertical profiles of the zonal and meridional wind components at 0000 UTC on 24 and 26 April 1989 over Dhaka are shown in Fig. 3.53 (a-b). The zonal wind components on both the days were westerlies (positive) throughout the troposphere except at 1000 hPa level where the winds are easterlies (negative). In the lower troposphere up to 650 hPa level, there was not much difference in the westerlies between the dates of occurrence (26 April) and the non-occurrence (24 April), but the westerlies were very strong above on the date of occurrence. This means that the vertical wind shear was very large on that day, which were 66.48 and 107.24 knots (i.e. 36.43 and 55.20 ms^{-1}) on 24 and 26 April 1989 respectively.

The large vertical wind shear (U_{200}-U_{850}) provided strong ventilation effect, which was favourable for the occurrence of tornado. From the distribution of meridional wind components, it can be seen that there were southerly winds (positive) in the lower troposphere up to about 750 hPa or more, with an increase in the southerlies on 26 April as

compared to that on 24 April. Above 650 to about 250 hPa level the meridional wind components had a tendency to be more northerly (negative) on the date of occurrence of tornado. The presence of strong westerlies and northerlies in the middle troposphere supported the advection of cold and dry air into a region of warm and moist air in the lower troposphere. This helped to increase the lapse rate due to the differential advection of dry air above the moist air below.

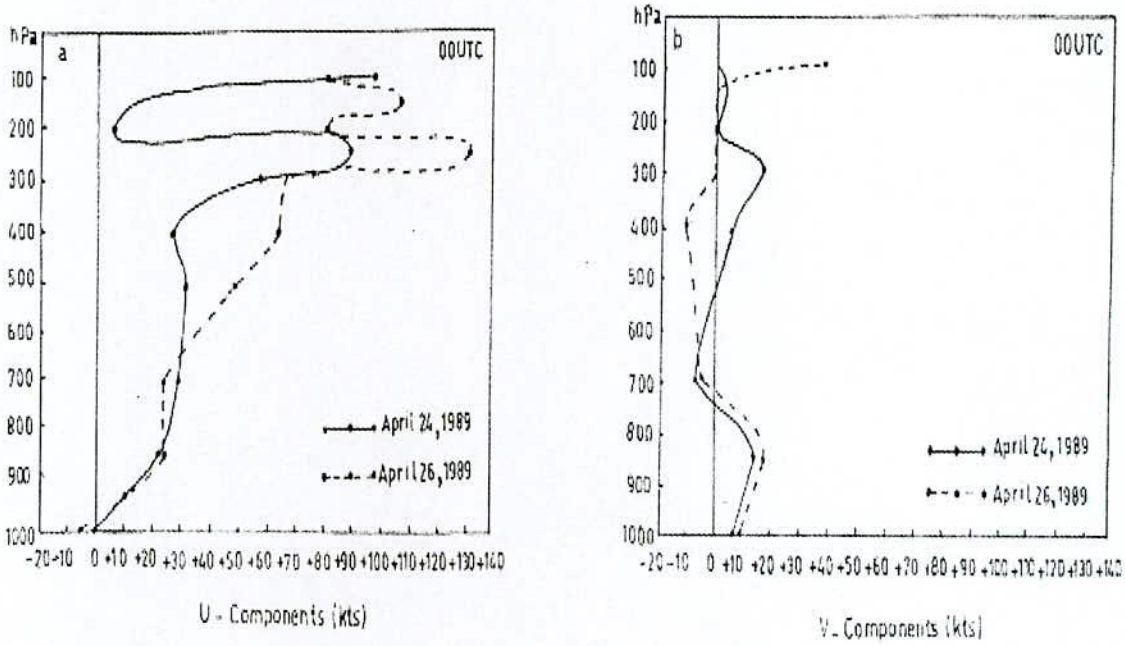

Fig. 3.53: Vertical profiles of (a) zonal and (b) meridional wind components at 0000 UTC over Dhaka on 24-26 April 1989

3.5.2.8.2 Vertical distribution of wind over Dhaka during the occurrence of tornado at Kalihati

Fig. 3.54 (a-b) shows the vertical distribution of zonal and meridional components of wind at 0000 UTC over Dhaka on the date of occurrence and one day before the occurrence of the tornado at Kalihati, Tangail.

The zonal wind was westerly (positive) throughout the troposphere on both the dates of occurrence and non-occurrence of tornado. The westerly wind was greater on the date of occurrence up to about 450 hPa as compared to that on the previous day. The

meridional wind component was southerly (positive) or more southerly from 925 to about 550 hPa on the date of occurrence of tornado and then it became significantly northerly (negative) in the upper troposphere. The southerly current was responsible for incurring moisture over Bangladesh and the northerly current in the middle and upper troposphere was responsible for the cold air advection, producing sufficiently instability in the troposphere and favouring the formation of tornado. The vertical wind shears over Dhaka at 0000 UTC on 12 and 13 May 1996 were 19.83 and 9.75 ms^{-1} respectively, indicating less wind shear on the date of occurrence of tornado.

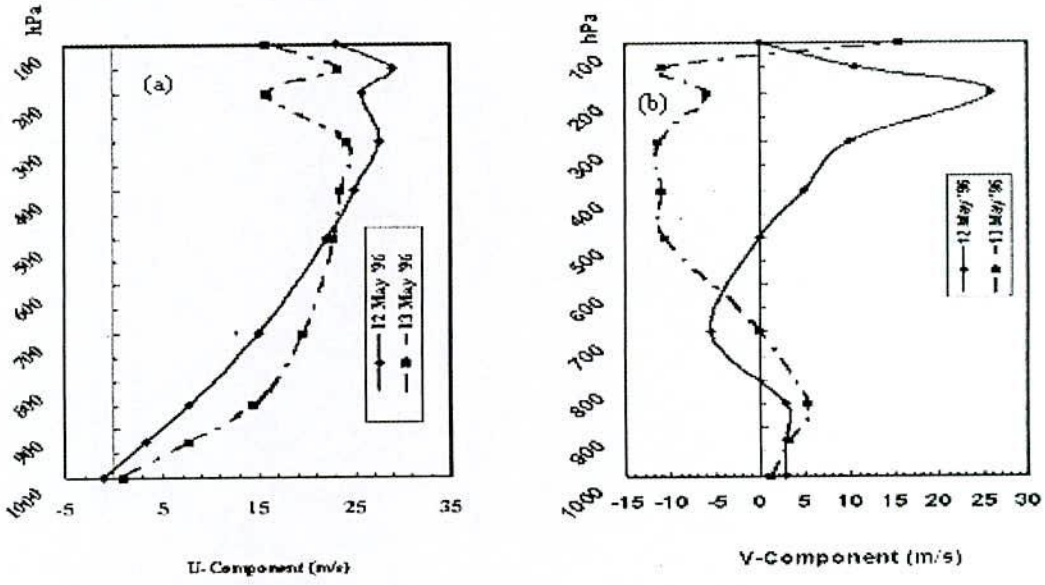

Fig. 3.54:Vertical profiles of (a) zonal and (b) meridional wind components at 0000 UTC over Dhaka on 12-13 May 1996

3.5.2.9 Superposition of the axes of low-level maximum wind and the upper air jet stream of wind over Dhaka

The superpositions of the axes of the low-level (850 hPa) maximum wind and upper level (250/200 hPa) jet stream on the dates of occurrence of the two tornadoes are given in Figs. 3.55-3.56 on 26 April 1989 and 13 May 1996 respectively. These figures clearly show that the tornadoes occurred near the point of intersection of the two axes.

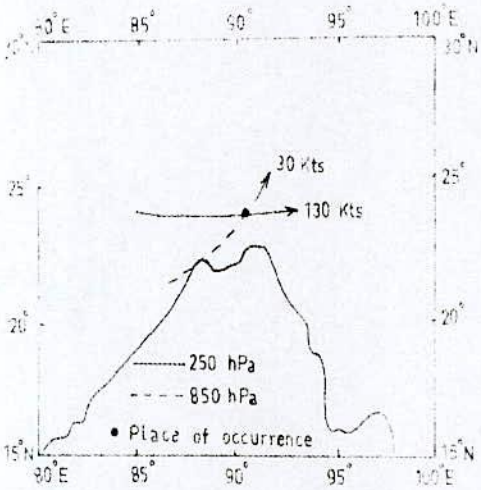

Fig. 3.55: Superimposition of the axes of low-level maximum wind and the upper level maximum jet stream on 26 April 1989

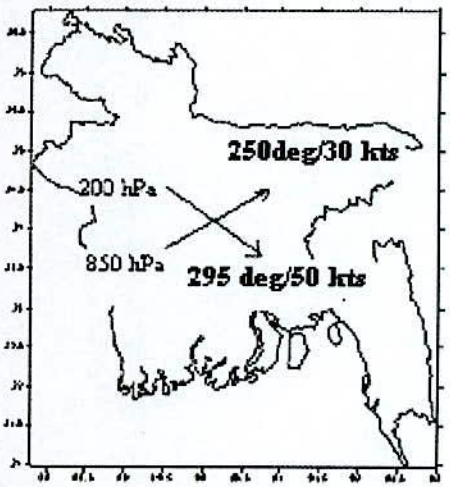

Fig. 3.56: Superposition of the axes of low-level maximum wind and the upper level maximum jet stream on 13 May 1996

CHAPTER 4

INSTABILITY OF THE TROPOSPHERE PRIOR TO THE OCCURRENCE OF NOR'WESTERS

4.1 Introduction

Pre-monsoon season over Bangladesh extending from March to May is characterized by very good convective activity all over the country. Convective activity progressively increases from March onwards as the season advances. The thunderstorms form from a cumulonimbus cloud, which incur substantial vertical development where the tops usually reach well into the upper levels of the troposphere. However, most cumulonimbus cloud tops are restricted in height by the tropopause, the boundary between the troposphere and stratosphere (Krishnamurti, 2003). Though the thunderstorm activity may continue over the country even during the southwest monsoon season, the severity of thunderstorms is marked only in the pre-monsoon season, when they, on a number of occasions, are accompanied by squalls and hails (Srinivasan, *et al.*, 1973).

A stability index is a measure of the potential instability of the atmosphere over a specified region. Since such an indicator can be calculated hours prior to the actual development of any convective activity, it acts as timely identifier of areas within an air mass, which are capable of supporting convective activity. Once these potential areas are identified, the severe weather forecaster can then take a closer and more precise examination of these areas, incorporating all available parameters, tools, and experience into making a final forecast (Thomson and Lin, 1985).

Over the years, studies of convective out-breaks have helped to isolate those altered during convective development. These careful isolations have led to the development of many stability indices that are in use by forecasters today. Since each storm outbreak may have its own varying environment, one index may prove to be more accurate over another within a particular storm setting.

Meso convective systems (MCS) are responsible for much of the beneficial precipitation and most of the severe weather (heavy rains, high winds, hail, tornadoes and lighting) that occur in Bangladesh during the pre-monsoon season (March-May). Thunderstorms occur during this season and these thunderstorms generally proceed from northwest in most cases and that's why they are known as "nor'westers" or "Kalbaishakhis". The accurate forecasting of severe thunderstorms and tornadoes during this season remain a challenging problems for operational meteorologists. Newton (1963) has identified (i) potential instability, (ii) low-level moisture, (iii) sheared and veered environmental winds and (iv) some triggering mechanism(s) as favourable conditions for severe storm development in addition to the favourable synoptic conditions. It is very important for forecasters to be able to distinguish between severe and non-severe thunderstorms. Extreme instability, strong vertical wind shear and atmospheric instability with SI or Li < -6 are considered as deciding factors (McNult, 1988: Johns and Doswell, 1992). Whereas Goliger *et al.* (1997) have considered the following meteorological features necessary for tornado formation (i) a deep layer of mid-tropospheric dry air above a moist surface, (ii) steep moisture and temperature gradients, (iii) high surface temperature, (iv) low level convergence and upper air divergence, (v) vertical wind shear and (vi) atmospheric instability. Stability indices, determined from environmental soundings, have been used by forecasting offices to locate the area in which the severe weather is likely to occur (Faubush *et al.,* 1951; Showalter, 1953; Galway, 1956; Miller, 1972). These stability indices provide necessary conditions (but not sufficient) conducive to storm occurrence.

In Bangladesh, the meteorologists use some of the stability indices to forecast nor'westers. But extensive studies have not so for been made on the stability indices to determine the stability criteria except a few studies (Chowdhury and Karmakar, 1986; Das *et al.*, 1994).

Meteorologists prepare charts of different stability indices to delineate the area of instability of the atmosphere conducive to the formation of thunderstorms. Some of the stability indices are SI, LI, DPI, DI I, SWI, EI, etc. [Showalter, 1953; Faubush *et al.*, 1951; Darkow, 1968; Miller, 1972; Galway, 1956; Chowdhury and Karmakar, 1986; Das *et al.*, 1994]. All the stability indices have been computed by using the 850-hPa levels as the low-level of which the data has been used before.

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Since the 850-hPa level sometimes remains relatively dryer and the low-level moisture plays a vital role in the formative stages of thunderstorm, 925-hPa level can be used as the low level. Not only that, the use of 850-hPa data gives some values in the morning showing the stability of the atmosphere and it becomes cumbersome to take any conclusive decision regarding the occurrence of nor'wester in Bangladesh specially in the afternoon or early night. From this point of view, the stability indices have been modified by considering the data at the boundary layer i.e. 925 hPa level.

In this chapter, the stability indices have been investigated for a large number of nor'westers in order to find out the critical values of different indices favourable for the occurrence of nor'westers in Bangladesh. The stability indices, which have been studied, are Showalter Stability Index (SI), Lifted Index (LI), Dew-point Index (DPI), Dry Instability Index (DII), Cross Total Index (CT) and Vertical Total Index (VT), Total Totals Index (TT), SWEAT Index (SWI), Energy Index (EI) and K-Index (KI). Low-level data at 850-hPa level has been considered to compute the stability indices such as SI, CT, VT, TT, EI, SWI and KI (Faubush *et al.*, 1951; Showalter, 1953; Darkow, 1968; Miller, 1972; Galway, 1956; Chowdhury and Karmakar, 1986; Das *et al.*, 1994).

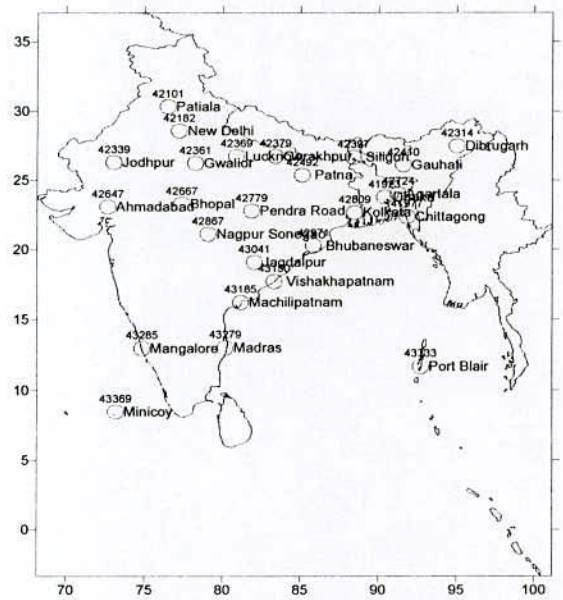
This chapter also deals with the computation and analysis of different modified stability indices with relation to the occurrence of nor'westers in Bangladesh. The modified stability indices, which have also been studied, are Showalter Stability Index (SI), Lifted Index (LI), Dew-point Index (DPI), Dry Instability Index (DII), Modified Cross Total Index (MCT), Modified Vertical Total Index (MVT), Modified Total Totals Index (MTT), Modified SWEAT Index (MSWI), Modified Energy Index (MEI) and Modified K-Index (MKI) by using the data at 925 hPa level. Attempts have been made to relate different instability indices, both unmodified and modified, among them statistically. Computations have also been made for the stations in and around Bangladesh for studying the spatial distribution of the stability indices.

4.2 Data source

Real time rawinsonde data of 0000 UTC at different isobaric heights from 1000 to 100 hPa at Dhaka, Chittagong and different Indian stations have been collected from the Storm Warning Centre (SWC) of Bangladesh Meteorological Department. SWC received these data on real time basis through GTS-Link. For frequency analysis of different unmodified and modified

instability indices, only the data at Dhaka has been considered and for spatial distribution all the available data of 26 stations have been considered. The stations are shown in Fig. 4.1(a). It may be mentioned that data of all the 26 stations were not available on the dates of occurrence of nor'westers.

For better understanding, a map of Bangladesh showing some greater districts is given in Fig. 4.1(b).



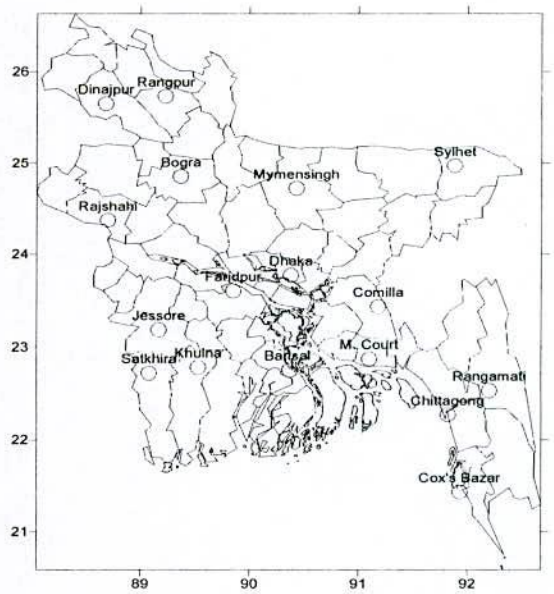


Fig. 4.1(a): Location of the Rawinsonde Stations under study

4.1(b): Map showing some districts in Bangladesh

In case of instability indices obtained from Tephigram analysis, 64 cases of nor'westers have been considered and in case of other instability indices 108 cases of nor'westers have been considered for the study. In some cases, rawinsonde data were not available at one/two levels. In those cases, number of data is less than 108 (say 105). These nor'westers occurred over different parts of Bangladesh.

In case of frequency analysis of modified instability indices, 108 cases of nor'westers have been considered and the rawinsonde data during this period especially over Dhaka has been considered.

For spatial distribution of the unmodified and modified instability indices, 26 cases of nor'westers have been considered for the study. It may be mentioned that

thunderstorms/nor'westers of maximum gusty wind speed ≥41 km hr^{-1} have been considered in the present study.

4.3 Methodology of stability analyses

4.3.1 Analysis of unmodified stability indices

The stability indices have been investigated for a large number of severe thunderstorms in order to find out the critical values of different indices favourable for the formation of thunderstorms in Bangladesh. The following stability indices are calculated by using the data at 0000 UTC (0600 BST i.e. 6 a.m.) for this purpose. It may be mentioned that most of the nor'westers occur in Bangladesh in the afternoon or at night.

4.3.1.1 Showalter Stability Index (SI)

This is the difference between the 500-hPa temperature and the wet-bulb temperature of the 850-hPa level raised along a pseudoadiabat to 500 hPa (T_{p500}). So

$$SI = T_{500} - T_{p500} \quad (1)$$

The criteria for Showalter index are:

(a) SI < +3°C means: showers are possible

(b) SI < 0°C means: thunderstorm may occur

(c) SI <-3°C means: severe thunderstorms are possible

(d) SI <-6°C means: tornadoes are suspected.

4.3.1.2 Lifted Index (LI)

The lifted Index can be used as a predictor of latent instability (Galway, 1956). This is a potential instability computed by lifting the mean moisture in the lower 0.9 km (3000ft) especially 925 hPa of the atmosphere moist adiabatically to 500 hPa and subtracting the temperature (T') at this point from the reported 500 hPa free-air temperature. So

$$LI = T_{500} - T'_{500} \quad (2)$$

The criteria for Lifted Index are:

L I	Weather
> +2	No convective activity
0 to +2	Showers are probable and isolated thunderstorms are possible
-2 to 0 -4	Thunderstorms are possible
≤ -4	Severe thunderstorms and/or tornadoes are possible

LI less than -6°C can be considered to be extreme with heavy to strong thunderstorm potential (McNulty, 1995) in the US.

4.3.1.3 Dew- point Index (DPI)

This is defined as the difference between the 500-hPa temperature (T) and mean dew point of the moist layer (mean T_d between 1000 hPa and 850 hPa or T_d at 925 hPa) raised along a pseudo-adiabat to 500 hPa (T'_d).

$$DPI = T_{500} - T'_{d500} \quad (3)$$

This index varies less with diurnal surface heating than Stability Index.

4.3.1.4 Dry Instability Index (DII)

This is the difference between the surface temperature raised along a pseudo-adiabat to 600 hPa (T') and the sounding temperature at 600 hPa (T). If an inversion exists below 600 hPa such that the temperature raised from its top would give a larger index, then this index value is used. So,

$$DII = T'_{600} - T_{600} \quad (4)$$

4.3.1.5 Cross Total Index (CT)

This is the 500-hPa Dry-bulb temperature subtracted from the 850-hPa dew point (T_d). Therefore,

$$CT = T_{d850} - T_{500} \quad (5)$$

The critical value of CT is 18 or more for the thunderstorms to occur.

4.3.1.6 Vertical total Index (VT)

This is defined as the 500-hPa dry-bulb temperature subtracted from the 850-hPa dry-bulb temperature. That is

$$VT = T_{850} - T_{500} \tag{6}$$

The critical Value of VT equal to 26 or more is favourable for the occurrence of a thunderstorm.

4.3.1.7 Total Totals Index (TT)

This is equal to the sum of the CT and VT.

$$TT = CT + VT$$

$$= T_{d850} - T_{500} + T_{850} - T_{500}$$

$$= (T_{850} + T_{850}) - 2T_{500} \tag{7}$$

The critical value of TT for thunderstorm is > 44, while TT>50 indicates potential for tornado formation.

4.3.1.8 Severe Weather Threat (SWEAT) Index (SWI)

The SWEAT Index as defined by Miller (1972) is given by

$$SWI = 12T_{d850} + 20\,(TT - 49) + 2f_8 + f_5 + 125\,(S + 0.2) \tag{8}$$

Where T_{d850} = 850 hPa dew–point temperature in °C

TT = Total Totals Index = $(T_{850} + T_{d850}) - 2T_{500}$

T_{500} = 500- hPa temperature in °C

f_8 = 850- hPa wind speed in knots

f_5 = 500- hPa wind speed in knots

S = Sin $(\alpha_5 - \alpha_8)$

α_5 = 500 hPa wind direction.

α_8 = 850 hPa wind direction.

None of the terms may be negative. Hence if $T_{d850} < 0$, the first term is set to zero; if TT < 49, the second term is set to zero; and the last term is set to zero if any of the following conditions are not met: α_8 between 130° and 250°, α_5 between 210° and 310°, $\alpha_5 - \alpha_8 > 0$, and

both f_8, $f_5 \geq 15$ knots. The critical value for severe thunderstorm is SWI = 300, while SWI $\geq$ 400 indicates potential for tornado formation. The nomenclatures of the different terms are as follows:

Term 1	= Low – level moisture part
Term 2	= Stability part
Term 3, 4	= Dynamic Part
Term 5	= Shear part.

4.3.1.9 Energy Index (EI)

The Energy Index is defined as the algebraic difference between the moist static energy (MSE) of the air at 500 and 850-hPa levels (Darkow, 1968), and may be expressed as

$$EI = MSE_{500} - MSE_{850} \tag{9}$$

Where $MSE = C_pT + gZ + Lq$.

The Energy Index is a measure of stability of the troposphere. The positive and negative values of the Energy Index indicate stability and instability of the troposphere, respectively. As per Darkow (1968), Energy Index has a slight but significant advantage over the Showalter Stability Index since it takes into account the possible contribution of potentially cold, mid tropospheric air to the moist static release of the severe convective storm.

4.3.1.10 K-Index (KI)

The K-Index can be computed by

$$\text{K-Index} = (T_{850} + T_{d850}) - (T_{d700} + T_{500}) \tag{10}$$

Where T_{850} = Temperature at 850 hPa in °C

T_{d850} =Dew-point temperature at 850 hPa in °C

T_{d700} = Dew-point temperature at 700 hPa in °C

T_{500} = Temperature at 500 hPa in °C

4.3.2 Modified stability indices

Some of the stability indices have been modified by taking into account of the mean low level moisture and temperature. The reason is that the low level moisture plays an important role in convective activity. Moreover, the standard isobaric surfaces were designated before as 1000,

850, 700 hPa and so on, but recently 925 hPa has been included as an standard isobaric surface and as such data at 925 hPa have been considered instead of 850 hPa to modify the stability indices. It has been found that 850 hPa level has less moisture at 0000 UTC in most of the dates of occurrence of nor'westers in Bangladesh and the stability indices do not show sufficient instability of the troposphere favourable for the occurrence of nor'westers. But in the afternoon/evening, nor'westers occur in Bangladesh. So, the existing instability indices are not enough to show the instability of the troposphere with which a forecaster cannot issue forecast for nor'westers and therefore, it has become imperative to modify the instability indices. The moisture conditions in terms of dew point temperature at 925 hPa and 850 hPa are shown in Fig. 4.2.

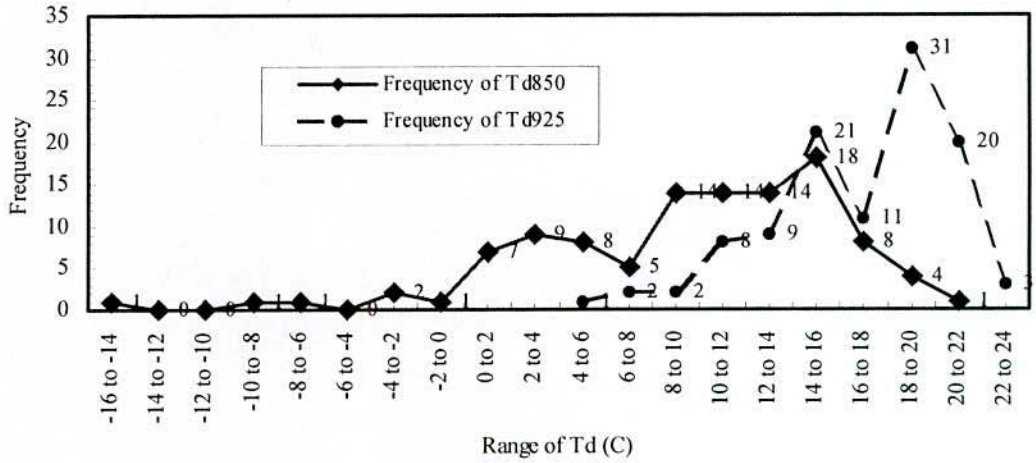


Fig. 4.2: Comparison of dew point temperatures (T_dT_d in °C) at 850 hPa and 925 hPa over Dhaka at 0000 UTC on the dates of occurrence of nor'westers in Bangladesh

It is seen that the dew-point temperature at 850 hPa level is ≤ 14 °C in most of the cases (in 77 out 108 i.e. 71.30% nor'westers) on the dates of occurrence and it is below 0°C to -16°C in 6 cases (5.56%). This indicates highly dry condition at 850 hPa. Whereas at 925 hPa level, the dew-point temperature is ≥ 14°C in 86 nor'westers (i.e. 79.63%) and is above 4°C. It is interesting to note that the two curves meet near 14°C and that is why 14°C may be taken as the threshold value above which the lower level may be considered as the moist level and below which the lower level may be considered as the dry level on the dates of occurrence of nor'westers. This is why 925 hPa has been considered instead of 850 hPa in the study.

In this study, 925 hPa has been considered as the low level, which is also the mean of 1000 and 850 hPa. The formulations of modified stability indices are given below:

4.3.2.1 Modified Cross Total Index (MCT)

Considering the dew-point temperature of 925 hPa instead of 850 hPa, the C T has modified. It is given by

$$MCT = T_{d925} - T_{500} \tag{11}$$

Where T_{d925} = 925-hPa dew-point temperature in °C.

4.3.2.2 Modified Vertical Total Index (MVT)

Considering the temperature of 925 hPa instead of 850 hPa, the VT has been modified as given below:

$$MVT = T_{925} - T_{500} \tag{12}$$

Where T_{925} = 925-hPa temperature in °C.

4.3.2.3 Modified Total Totals Index (MTT)

Considering the temperature and dew-point temperature of 925 hPa instead of 850 hPa, the TT has been modified. It is given by

$$MTT = MVT + MCT$$

$$= (T_{925} + T_{d925}) - 2\,T_{500} \tag{13}$$

Where T_{925} = 925-hPa temperature in °C

T_{d925} = 925-hPa dew-point temperature in °C.

4.3.2.4 Modified Severe Weather Threat Index (MSWI)

Considering the temperature and dew point temperature of 925 hPa instead of 850 hPa, the SWI been has modified. The MSWI Index is defined by:

$$MSWI = 12T_{d925} + 20(MTT - 49) + 2f_9 + f_5 + 125(S + 0.2) \tag{14}$$

Where T_{d925} = 925 hPa dew-point temperature in °C

MTT = Modified Total Totals Index = $(T_{925} + T_{d925}) - 2T_{500}$

T_{500} = 500–hPa temperature in °C

f_9 = 925–hPa wind speed in knots.

f_5 = 500–hPa wind speed in knots.

S = Sin (α_5 - α_9)

α_5 = 500 hPa wind direction measured from the true north.

α_9 = 850 hPa wind direction measured from the true north.

None of the terms may be negative. Hence if Td_{925} <0, the first term is set to zero; if MTT < 49, the second term is set to zero; and the last term is set to zero if any of the following conditions are not met:.α_9 between 130° and 250°, α_5 between 210° and 310°, α_5 - α_9 > 0, and both f_9, $f_5 \geq 15$ knots.

4.3.2.5 Modified Energy Index (MEI)

The modified EI has been calculated by considering moist static energy of 925-hPa level instead of moist energy of 850-hPa level. It is given by:

$$MEI = MSE_{500} - MSE_{925} \quad (15)$$

Where

MSE_{925} = Moist Static Energy at 925 hPa in Joule/gm, and

MSE_{500} = = Moist Static Energy at 850 hPa in Joule/gm.

$MSE = C_pT + gZ + Lq$.

C_p = Sensible heat content of the atmosphere

T = Temperature in °K

g = Acceleration due to gravity in ms^{-1},

Z = Geopotential height in geopotential meter, and

V = wind speed,

L = Latent heat of condensation and

q = Specific humidity.

4.3.2.6 Modified K-Index (MKI)

Considering the temperature and dew point temperature of 925 hPa instead of 850 hPa, the KI has been modified. The MKI can be computed by

$$MKI = (T_{925} + T_{d925}) - (T_{d700} + T_{500}) \quad (16)$$

Where T_{925} = Temperature at 925 hPa in °C.

T_{d925} =Dew-point temperature at 925 hPa in °C.

T_{d700} = Dew-point temperature at 700 hPa in °C.

T_{500} = Temperature at 500 hPa in °C.

Linear correlations between the unmodified instability indices such as SI, LI, DPI, DII, CT, VT, TT, KI, EI and the modified instability indices such as MCT, MVT, MTT, MKI, MEI computed on the days of occurrence of 108 nor'westers have been studied and the corresponding correlation co-efficients are computed. The regression equations and the co-efficient of determination (R^2) have been obtained through scatter diagrams by taking two indices at a time.

4.4 Significance test of the coefficient of determination

The significance test of the coefficient of determination (R^2) has been carried out by using F-Test (Makridakis, *et al.*, 1983; Alder and Roessler, 1964).

$$F = \frac{R^2(n-k)}{(1-R^2)(k-1)} \quad (17)$$

Where n is the number of observations (n-k) is the degree of freedom and k is the number of parameters. This coefficient of determination indicates how best the data are fitted to the regression line. If the calculated value of F is greater than the theoretical value at certain significance level (0.05 or 0.01 i.e. 95% or 99% significance level) then R^2 is taken as significant at that level i.e. the correlation co-efficient is also significant.

The Standard Error of Estimate (SEE) between the actual data and the forecasted values has been computed with the help of the equation:

$$SEE = \sqrt{\frac{(Y - Y_e)^2}{N}} \tag{18}$$

Where Y is the actual value, Y_e is the computed value and N is the number of data pairs.

4.5 Results and discussion

Different stability indices (at 0000 UTC i.e. 6 a.m.) of the atmosphere prior to the occurrence of nor'westers have been determined for the stations Dhaka, Chittagong and some Indian stations to study the degree of instability of the atmosphere for the formation of thunderstorms / nor'westers in Bangladesh. The different stability indices viz. SI, LI, DPI, DII, CT, VT, TT, EI, SWI and KI with their frequencies are tabulated in Tables 4.1-4.10 respectively. Attempts have been made to find out the critical values of the indices for the formation of thunderstorms and to study the spatial distribution of these indices for delineating the area of unstable atmosphere. The critical values have been considered from the relatively first increased frequency of instability indices. The results are described in the subsequent sub-sections.

4.5.1 Stability indices at Dhaka in relation to the occurrence of nor'westers in Bangladesh

4.5.1.1 Showalter Stability Index (SI) and its frequency

Table 4.1 shows that 11 out of 64 (i.e. 17.19%) nor'westers occur when the SI is above 3°C at 0000 UTC, which indicates highly stable atmosphere. This can be attributed to the fact that the atmosphere may sometimes remain highly stable in the morning, but as the day progresses, this stability may be thought of being destroyed and instability develops because of the incoming solar radiation as well as moisture influx from the Bay of Bengal extending to a greater height in the afternoon. The table also shows that 53 out of 64 (i.e. 82.81%) nor'westers occur when the SI is $\leq$ 3°C. It is interesting to note that that the atmosphere is treated as unstable when SI is below 0°C. As per the criteria of SI, tornadoes are suspected when SI ranges between -3 and -6°C or below. This criterion does not always hold good for Bangladesh.

Table 4.1: Frequency of SI at 0000 UTC over Dhaka

Range of SI (°C)	Frequency (f)	% of the total	
12 to 9	1	1.56	17.19
9 to 6	3	4.69	
6 to 3	7	10.94	
3 to 0	19	29.69	82.81
0 to -3	23	35.94	
-3 to -6	9	14.06	
-6 to -9	2	3.13	
Total	64	100	100

It is seen that that the frequency of nor'westers is considerably higher (19 i.e. 29.69%) when SI ranges between 3 and 0. So, SI $\leq$ 3°C may be taken as the critical value below which nor'westers are likely to occur in Bangladesh. It has been seen that 3 out of 5 (60%) severe nor'westers with marginal tornadic intensity occur when SI is < -3°C and 2 out of 5 (40%) severe nor'westers with marginal tornadic intensity occur when SI is 0 to -2°C. So, the critical value of SI for tornado may be taken as < -3°C.

4.5.1.2 Lifted Index (LI) and its frequency

Table 4.2 shows that 3 out of 64 (i.e. 4.69%) of thunderstorms / nor'westers occur when LI is above 3°C at 0000 UTC, which indicates the stable atmosphere.

Table 4.2: Frequency of LI at 0000 UTC over Dhaka

Range of LI (°C)	Frequency (f)	% of the total	
9 to 6	1	1.56	4.69
6 to 3	2	3.13	
3 to 0	10	15.63	95.31
0 to -3	22	34.38	
-3 to -6	25	39.06	
-6 to -9	4	6.25	
Total	64	100	100

It is seen from the table that first relatively higher frequency of 10 out of 64 (15.63%) nor'westers occur when LI is 0 to +3°C. The table also shows that 61 out of 64 (i.e. 95.31%) nor'westers occur when the LI is $\leq$3°C. The table also shows that maximum nor'westers occur

when the Lifted index is -3 to -6°C. Since the first higher frequency of LI lies between 3 and 0, the critical value of LI may be considered as $\leq$ 3°C for the occurrence of nor'westers in Bangladesh. It has been seen that 3 out of 5 (60%) severe nor'westers with marginal tornadic intensity occur when LI is < -3°C and 2 out of 5 (40%) severe nor'westers with marginal tornadic intensity when LI is between 1 and -3°C.

Therefore, from the above discussion, it may be concluded that nor'westers are likely to occur over Bangladesh when LI is $\leq$ 3°C and severe nor'westers with tornadic intensity are possible over Bangladesh when LI < -3°C.

4.5.1.3 Dew-point Index (DPI) and its frequency

Table 4.3 shows that 6 out of 64 (i.e. 9.38%) nor'westers occur when the DPI is above 0°C at 0000 UTC, which indicates the stable atmosphere. It is seen from the table that 62 out of 64 (96.88%) nor'westers occur when DPI is below 0 °C and 90.63% nor'westers occur when DPI is below -3°C. The table also shows that maximum nor'westers occur when DPI ranges between -6 and -9 (26 out of 64 i.e. 40.63%). First relatively higher frequency of nor'westers (16 out of 64) occurs in the DPI range of -3 to -6. Therefore, DPI $\leq$ -3°C may be taken as the critical value for the occurrence of nor'westers in Bangladesh. It has also been seen from the analysis of DPI that severe thunderstorms with tornadic intensity are likely to occur when DPI is < -4°C (4 out of 5 i.e. 80%) and 20% severe nor'westers occur when DPI is > -2°C at Dhaka in the morning. So, the critical value of DPI for severe nor'westers with tornadic intensity is < -4°C.

Table 4.3: Frequency of DPI at 0000 UTC over Dhaka

Range of DPI (°C)	Frequency (f)	% of the total	
6 to 3	1	1.56	9.38
3 to 0	1	1.56	
0 to –3	4	6.25	
-3 to –6	16	25.00	90.63
-6 to –9	26	40.63	
-9 to –12	11	17.19	
-12 to -15	4	6.25	
<15	1	1.56	
Total	64	100	100

4.5.1.4 Dry Instability Index (DII) and its frequency

From the frequency analysis of DII (Table 4.4), it seen that 7 out of 64 (i.e. 10.94%) nor'westers occur when the DII is above 0°C at 0000 UTC over Dhaka, which indicates the stable atmosphere. It is seen from the table that 57 out of 64 (89.06%) nor'westers occur when DII is below 0 °C (Table 4.4). The table also shows that maximum nor'westers occur when DII ranges between -3 and -6 (21 out of 64 i.e. 32.81%). Since the first higher frequency of nor'westers (18 out of 64) lies in the range of DII 0 to -3, DII $\leq$ 0°C may be taken as the critical value for the occurrence of nor'westers in Bangladesh. The lower the values of DII, the higher are the potential for nor'westers occurrence. It has also been seen from the analysis of DII that severe nor'westers with tornadic intensity are likely to occur when DII is < -4°C (3 out of 5 i.e. 60%) and 40% severe nor'westers occur when DII > -2°C at Dhaka in the morning. So, the critical value of DII for severe nor'westers with tornadic intensity is < -4°C.

Table 4.4: Frequency of DI I at 0000 UTC over Dhaka

Range (°C)	Frequency (f)	% of the total	
12 to 9	1	1.56	10.94
9 to 6	2	3.13	
6 to 3	1	1.56	
3 to 0	3	4.69	
0 to -3	18	28.13	89.06
-3 to -6	21	32.81	
-6 to -9	16	25.00	
-9 to -12	2	3.13	
Total	64	100	100

4.5.1.5 Cross Total Index (CT) and its frequency

The Table 4.5 shows that maximum nor'westers occur when CT is 20-22°C, which is 20.37% of the total number of nor'westers. The table also shows that 78.70% of nor'westers occur when CT >14°C. The Table also shows that 84.26% (91 out of 108) nor'westers occur when CT range is 10-26°C. Since the first relatively higher frequency of nor'westers occurs in the CT range of 14-16°C, the critical value of CT may be taken as CT $\geq$ 14°C.

The frequency of CT for 40 nor'westers of severe to very severe intensity is given in Table 4.5A. For severe to very severe nor'westers, the first relatively higher frequency is in the CT range of 16-18°C at Dhaka at 0000 UTC as can be seen from Table 4.5A. Therefore, the critical value of CT for severe to very nor'westers may be taken as $\geq$16°C. The higher the value of CT, the higher is the potential for occurrence of severe nor'westers.

Table 4.5: Frequency of CT at 0000 UTC over Dhaka

Range of CT (°C)	Frequency (f)	% of the total	
-10 to 0	1	0.93	21.30
0-10	13	12.04	
10-12	3	2.78	
12-14	6	5.56	
14-16	13	12.04	78.70
16-18	14	12.96	
18-20	10	9.26	
20-22	22	20.37	
22-24	15	13.89	
24-26	9	8.33	
26-28	2	1.85	
Total	108	100	100

Table 4.5A: Frequency of CT at 0000 UTC over Dhaka for nor'westers of severe to very severe intensity

Range of CT (°C)	Frequency	% of the total	
<10	7	17.5	40.0
10-12	3	7.5	
12-14	2	5.0	
14-16	4	10.0	
16-18	7	17.5	60.0
18-20	2	5.0	
20-22	6	15.0	
22-24	4	10.0	
24-26	2	5.0	
26-28	3	7.5	
Total	40	100	100

For severe nor'westers of tornadic intensity, 2 out of 5 (i.e. 40%) severe nor'westers of tornadic intensity occur when CT <13°C and 3 out of 5 (i.e. 60.0%) of severe nor'westers of tornadic intensity occur when CT ≥23.6°C. Therefore, CT ≥ 23.6°C may be taken as the critical value for the severe nor'westers of tornadic intensity to occur in Bangladesh.

4.5.1.6 Vertical Total Index (VT) and its frequency

The analysis of VT (Table 4.6) shows that maximum nor'westers occur when VT is 28-30°C, which is about 25.93% (28 out of 108) of the total number of nor'westers. The table also shows that 95.37% of nor'westers (103 out of 108) occur when VT > 24°C. Besides this, the first higher frequency of nor'westers lies in the range of VT of 24-26. Therefore, the critical value of VT may be taken as VT ≥ 24°C.

Table 4.6: Frequency of VT at 0000 UTC over Dhaka

Range of VT (°C)	Frequency (f)	% of the total	
<22	1	0.93	4.63
22-24	4	3.70	
24-26	17	15.74	95.37
26-28	23	21.30	
28-30	28	25.93	
30-32	18	16.67	
32-34	14	12.96	
34-36	3	2.78	
Total	108	100	100

To find out the critical value of VT for nor'westers of severe to very severe nor'westers, the frequency of nor'westers have been computed for different ranges of VT and is given in Table 4.6A.

Table 4.6A shows that the first relatively higher frequency of severe to very severe nor'westers fall in the range of VT = 26-28°C and 82.5% severe to very severe nor'westers occur when VT ≥ 26°C. So, VT ≥ 26°C may be taken as the critical value for severe to very severe nor'westers.

It has also been found that 40% (2 out of 5) severe nor'westers of tornadic intensity occur when VT <25°C, 60.0% (3 out of 5) occur when VT > 28°C. Therefore, VT ≥ 28°C may be taken as the critical value for the tornadoes to occur in Bangladesh.

Table 4.6A: Frequency of VT at 0000 UTC over Dhaka for nor'westers of severe to very severe intensity

Range of VT (°C)	Frequency (f)	% of the total	
<22	1	2.5	17.5
22-24	1	2.5	
24-26	5	12.5	
26-28	9	22.5	82.5
28-30	10	25	
30-32	6	15	
32-34	7	17.5	
34-36	1	2.5	
Total	40	100	100

4. 5.1.7 Total Totals Index (TT) and its frequency

TT of 0000 UTC at Dhaka has computed for 108 cases of nor'westers. The maximum nor'westers (21 out of 108) occur when TT range is 46-48°C, which is about 19.44% of the total number of nor'westers (Table 4.7). About 87.96% (95 out of 108) nor'westers occur when the TT range is 40-58°C. The table shows that first relatively higher frequency of 9 occurs in the range of 40-42°C of TT and so the critical value of TT may be taken as TT ≥ 40°C.

The TT for 40 nor'westers of severe to very severe intensity has been analyzed in order to find out the critical value of TT and the results are given in the Frequency Table 4.7A. It is found that the frequency of severe to very severe nor'westers is in the range of 46-48°C. Some nor'westers also occur when the value of TT remains lower in the morning, but the first relatively higher frequency of 9 is found in the range of 40-42°C of TT and 87.5 % of severe to very severe nor'westers are found to occur when TT ranges between 40°C and 60°C. So, the critical value of TT may be taken as ≥ 40°C at Dhaka for the severe to very nor'westers to occur in Bangladesh.

Table 4.7: Frequency of TT at 0000 UTC over Dhaka

Range of TT (°C)	Frequency (f)	% of total	
<32	2	1.85	12.04
32-34	4	3.70	
34-36	0	0	
36-38	3	2.78	
38-40	4	3.70	
40-42	9	8.33	87.96
42-44	10	9.26	
44-46	14	12.96	
46-48	21	19.44	
48-50	13	12.04	
50-52	11	10.19	
52-54	12	11.11	
54-56	2	1.85	
56-58	3	2.78	
Total	108	100	108

Table 4.7A: Frequency of TT at 0000 UTC over Dhaka for nor'westers of severe to very severe intensity

Range of TT (°C)	Frequency (f)	% of total	
<32	1	2.5	12.5
32-34	2	5.0	
34-36	0	0	
36-38	2	5.0	
38-40	0	0	
40-42	5	12.5	87.5
42-44	4	10.0	
44-46	5	12.5	
46-48	8	20.0	
48-50	3	7.5	
50-52	3	7.5	
52-54	3	7.5	
54-56	1	2.5	
56-58	2	5.0	
58-60	1	2.5	
Total	40	100	100

Analysis of TT in case of 5 tornadoes has revealed that only one tornado (i.e. 20%) occurred when TT is 37.8°C and 4 out of 5 cases (80%) occurred when TT > 49.50°C up to 56.6°C. Therefore, TT ≥ 49.5°C may be taken as the critical value for the tornado to occur in Bangladesh. It may be mentioned that data only for 5 tornadoes are available.

4.5.1.8 Energy Index (EI) and its frequency

The MSE has been determined by using the rawinsonde data over Dhaka at 0000 UTC and EI on the dates of occurrence of 105 nor'westers for the period 1990-1995 has been computed (Table 4.8). It is seen that 17 out of 105 (16.19%) nor'westers occur when EI is above 0 and 88 out 105 (83.81%) nor'westers occur when EI is below zero. Maximum number of (20 out of 105 i.e.19.05%) nor'westers occurs when EI ranges between -6 and -9. First relatively higher frequency of 13 out of 105 nor'westers (12.38%) occurs when EI ranges between 0 and -3. From the discussion, it may be concluded that EI ≤ 0 can be taken as the critical value of EI at Dhaka for the nor'westers to occur in Bangladesh. The lower the value of EI, the higher is the instability of the troposphere.

Table 4.8: Frequency of E at 0000 UTC over Dhaka

Range of EI (J/gm per 150 hPa)	Frequency (f)	% of the total	
12 to 9	1	0.95	16.19
9 to 6	2	1.90	
6 to 3	3	2.86	
3 to 0	11	10.48	
0 to-3	13	12.38	83.81
-3 to –6	16	15.24	
-6 to –9	20	19.05	
-9 to –12	17	16.19	
-12 to –15	7	6.67	
-15 to –18	10	9.52	
-18 to –21	3	2.86	
-21 to –24	1	0.95	
-24 to –27	0	0	
-27 to -30	1	0.95	
Total	105	100	100

The EI for 36 nor'westers of severe to very severe intensity has been computed using the data at 0000 UTC over Dhaka and the frequency in different ranges have been calculated. The results are given in Table 4.8A.

It is seen from Table 4.8A that severe to very severe nor'westers occur even though the atmosphere remains stable with EI of 0-12 in 8 cases out of 36 (i.e. 22.22%) at 0000 UTC.

Table 4.8A: Frequency of Energy Index (EI) at 0000 UTC over Dhaka for nor'westers of severe to very severe intensity

Range of EI (J/gm per 150 hPa)	Frequency (f)	% of the total	
12 to 9	1	2.78	36.11
9 to 6	0	0	
6 to 3	2	5.56	
3 to 0	5	13.89	
0 to-3	5	13.89	
-3 to -6	7	19.44	63.89
-6 to -9	6	16.67	
-9 to -12	2	5.56	
-12 to –15	3	8.33	
-15 to –18	3	8.33	
-18 to –21	1	2.78	
-21 to –24	0	0	
-24 to –27	0	0	
-27 to -30	1	2.78	
Total	36	100	100

Normally positive values of EI indicates stable atmosphere. This means that the stable atmosphere in the morning changes into unstable atmosphere in the afternoon due to incoming solar radiation, favourable surface and upper air synoptic conditions and moisture influx from the south. The frequency table also shows that 63.89% of severe to very severe nor'westers occur when EI range is -3 and -30. Therefore, EI ≤ -3 may be taken as the critical value of EI at Dhaka for the occurrence of severe to very severe nor'westers in Bangladesh. For cases of tornadoes it has been found that 2 tornadoes occurred when EI at Dhaka is 0.64 and –3.22, and 3 tornadoes when EI is between -10.87 and -28.99. Therefore, tornado may occur when EI ≤ -11.

4.5.1.9 SWEAT Index (SWI) and its frequency

It is seen from the Table 4.9 that 6 out of 108 (5.56%) nor'westers occur when SWI≤ 100 and 34 (31.48%) nor'westers occur when SWI≤200. But maximum (74 out of 108 i.e. 68.52%) nor'westers occur when SWI>200 and maximum frequency of 32(29.63%) falls in the

range of SWEAT Index 200-300. So, SWI > 200 may be taken as the critical value for the nor'westers to occur in Bangladesh

For 36 severe to very severe nor'westers, the ranges of the SWI with the frequency of nor'westers is given in Table 4.9A. In the morning on the dates of occurrence of nor'westers, 50% of severe to very severe nor'westers occur when SWI $\leq$ 250 and 50% occur when SWI > 250. The lower values of SWI indicates the stable atmosphere in the morning and it is difficult to specify the critical value of the index for the occurrence of severe to very severe nor'westers with the data at 0000 UTC.

Table 4.9: Frequency of SWI at 0000 UTC over Dhaka

Range of SWEAT Index	Frequency (f)	% of the total	
50-100	6	5.56	5.56
100-200	28	25.93	94.44
200-300	32	29.63	
300-400	28	25.93	
400-500	8	7.41	
500-600	4	3.70	
600-700	2	1.85	
Total	108	100	100

Table 4.9A: Frequency of SWI at 0000 UTC over Dhaka for severe to very severe nor'westers

Range of SWEAT Index	Frequency	% of the total	
100-150	8	22.22	50.0
150-200	7	19.44	
200-250	3	8.33	
250-300	7	19.44	50.0
300-350	1	2.78	
350-400	2	5.56	
400-450	2	5.56	
450-500	4	11.11	
500-550	0	0	
550-600	1	2.78	
600-650	0	0	
650-700	1	2.78	
	36	100	100

It is seen from Table 4.11 that the SWI values (> 400) at 0000 UTC are very favourable in case of 3 tornadoes; one (255.4) is favourable for moderately severe nor'westers and one value is not at all favourable for even thunderstorm. This indicates that the atmosphere may remain stable in the morning and this stability may be changed into instability with the progress of the day, increase of solar insolation and increase in the moisture influx on the date of occurrence. SWI> 400 may be taken as the critical value for the occurrence of tornadoes.

4.5.1.10 K-Index (KI) and its frequency

During the study period, KI on the dates of occurrence of 105 nor'westers has been computed by using the data at Dhaka. Table 4.10 containing the KI, reveals that most of the values of KI ranges between 34 and 58, when 89.52% nor'westers (94 out of 105) occur in Bangladesh. It can also be seen from the table that maximum nor'westers occur in the range of KI is 36-38°C, which is about 16.19% of the total number of nor'westers. 10.48% nor'westers occur when the KI range is 34-44°C in which the first relatively higher frequency of 11 lies. Therefore, the critical value of KI at Dhaka at 0000 UTC may be taken as KI ≥ 34°C for nor'westers to occur in Bangladesh.

Table 4.10: Frequency of KI at 0000 UTC over Dhaka

Range of KI	Frequency (f)	% of total	
20-22	1	0.95	10.48
28-30	2	1.90	
30-32	4	3.81	
32-34	4	3.81	
34-36	11	10.48	89.52
36-38	17	16.19	
38-40	13	12.38	
40-42	13	12.38	
42-44	16	15.24	
44-46	7	6.67	
46-48	5	4.76	
48-50	3	2.86	
50-52	2	1.90	
52-54	4	3.81	
54-56	1	0.95	
56-58	2	1.90	
Total	105	100	100

Table 4.10A: Frequency of KI at 0000 UTC over Dhaka for severe to very severe nor'westers

Range of KI (°C)	Frequency	% of the total	
30-32	2	5.88	11.76
32-34	2	5.88	
34-36	4	11.76	88.24
36-38	3	8.82	
38-40	4	11.76	
40-42	5	14.71	
42-44	8	23.53	
44-46	3	8.82	
46-48	0	0	
48-50	1	2.94	
50-52	1	2.94	
52-54	0	0	
54-56	0	0	
56-58	1	2.94	
Total	34	100	100

The ranges of the KI at Dhaka at 0000 UTC on the dates of occurrence of 34 severe to very severe nor'westers in Bangladesh is given in Table 4.10A. It is seen from Table 4.10A that the first relatively higher frequency of 4 occurs in the range of 34-36°C and above 34°C of KI, 88.24% of severe to very nor'westers occur. Hence, KI $\geq$ 34°C may be taken as the critical value of KI for the severe to very severe nor'wester in Bangladesh.

Table 4.11: SWI and KI at 0000 UTC over Dhaka for tornadoes in Bangladesh

Sl. No.	Date of occurrence of tornado	Place of occurrence of tornado	SWI at Dhaka	K-Index at Dhaka at 0000 UTC
1	20-04-1990	Sirajganj	446.7	56.2
2	03-05-1991	Rajshahi	563.5	42.8
3	07-05-1991	Gazipur	101.0	42.5
4	18-05-1991	Gournadi	470.8	-
5	08-04-1995	Munsiganj	255.4	44.9

From Table 4.11 it is seen that tornado may occur in Bangladesh when KI $\geq$ 42.5°C.

4.5.2 Spatial distribution of different instability indices

The different stability indices of the troposphere on the dates of occurrence of a number of nor'westers have been computed by using the rawinsonde data of Dhaka and Chittagong and a number of Indian stations at 0000 UTC and their spatial distributions have been studied critically.

The spatial distributions of SI and LI on the dates of occurrence of 26 nor'westers have been studied and examples of distribution are given in Figs. 4.3-4.4.

It has been seen from the analyses of these Stability Indices (SI and LI) that maximum negative values lay over the eastern Madhya Pradesh, Bihar, West Bengal and adjoining Bangladesh indicating the highly unstable area. The negative areas of the Indices in combination with the low-pressure area over Bihar, West Bengal and adjoining Orissa and Bangladesh as well as the cyclonic circulation in the upper air up to 3-4 km or above are favourable for the occurrence of nor'westers in Bangladesh. Normally, nor'westers have been found to occur at the northeastern or eastern part of the area of maximum instability, where the gradients of instability indices are steep.

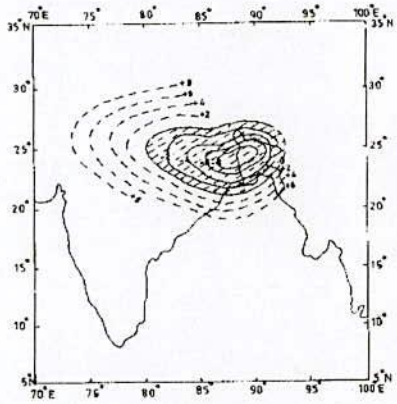


Fig. 4.3: Spatial distribution of SI on 14 April 1990, the date of occurrence of nor'wester in Bangladesh

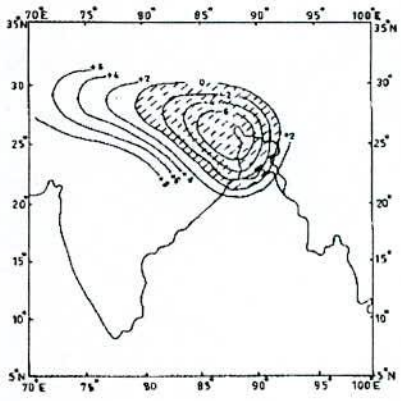


Fig. 4.4: Spatial distribution of LI on 14 April 1990, the date of occurrence of nor'wester in Bangladesh

The spatial distributions of CT, VT and TT for 26 cases of nor'westers have been examined. Examples of spatial distribution are given in Figs. 4.5-4.7. From the analysis of CT, it has been found that the area of maximum values exists over eastern Uttar Pradesh and adjoining eastern Madhya Pradesh, Bihar, Sub-Himalayan West Bengal extending towards north

Bangladesh in 9 out of 26 cases, over Bangladesh and adjoining area in 16 out of 26 cases and in 1 case over north Orissa and adjoining Gangetic West Bengal and Bangladesh. These areas indicate the highly unstable area. Nor'westers have been found to occur over the area of maximum CT or at the northeastern or eastern part of the area of maximum CT/unstable area.

In case of VT, the area of maximum value i.e. unstable area lies over Uttar Pradesh and adjoining Madhya Pradesh, Bihar, Sub-Himalayan West Bengal with its trough extended to Bangladesh in 18 out of 26, over north Orissa, Gangetic West Bengal and adjoining Bangladesh with its trough extended northeastwards in 6 out of 26 and in only 2 cases the area of maximum VT lies over Bangladesh. Considering the TT, it has been found that the area of maximum TT lies over Eastern Uttar Pradesh and adjoining Madhya Pradesh, Bihar, Sub-Himalayan West Bengal with its trough extended to Bangladesh in 13 out of 26 nor'westers, over Bangladesh in 6 cases and over north Orissa and adjoining Gangetic West Bengal with its trough extended northeastwards up to Bangladesh. The gradient of instability indices is maximum over Bangladesh. All these results substantiate that nor'westers occur at the eastern/northeastern part of the maximum unstable area or over the area of maximum instability in Bangladesh.

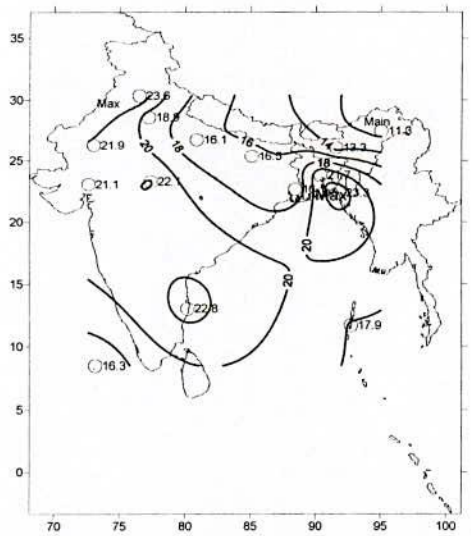


Fig. 4.5: Spatial distribution of CT on 26 March 1993

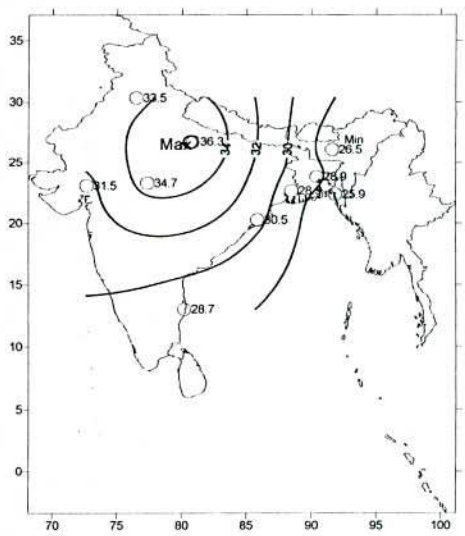


Fig. 4.6: Spatial distribution of VT on 17 May 1992

The spatial distribution of EI is shown in Fig. 4.8 as an example. It has been found from the analysis of EI that in 9 out of 26 nor'westers the area of minimum EI lies over Uttar Pradesh and adjoining eastern Madhya Pradesh or Bihar, West Bengal and adjoining Bangladesh, where the surface low and low-level circulation exist as has been observed from the analyses of surface

and pilot charts (not shown here). In these cases, the trough of minimum EI is found to extend east/southeastwards up to Bangladesh.

The area of minimum EI has been found to exist over Bangladesh in 12 out of 26 nor'westers and over Gangetic West Bengal and adjoining area in 5 out of 26 nor'westers. In this case, the trough of minimum EI has been found to extend northeastwards across Bangladesh. The nor'westers have been found to occur over the area of minimum EI or at the northeastern or eastern part of the area of minimum EI, where the injection of moisture takes place from the Bay of Bengal. This area of minimum EI indicates the area of unstable atmosphere, which is favourable for the occurrence of nor'westers in Bangladesh.

The spatial distributions of SWI and KI are shown in Fig. 4.9 and Fig. 4.10 respectively as examples. Form the analysis of SWI, maximum SWI has been found to exist over Uttar Pradesh and adjoining Madhya Pradesh or Bihar and sub-Himalayas in 6 out of 26 nor'westers with extended trough up to Bangladesh. In 12 out of 26 nor'westers, maximum SWI lies over Bangladesh, and over Orissa, Gangetic West Bengal and adjoining region in 7 out of 26 nor'westers with elongated area northeastwards over Bangladesh. In only one case, it is found over the area northeast of Bangladesh. In all the cases, Bangladesh has the area of instability on the dates of occurrence of nor'westers.

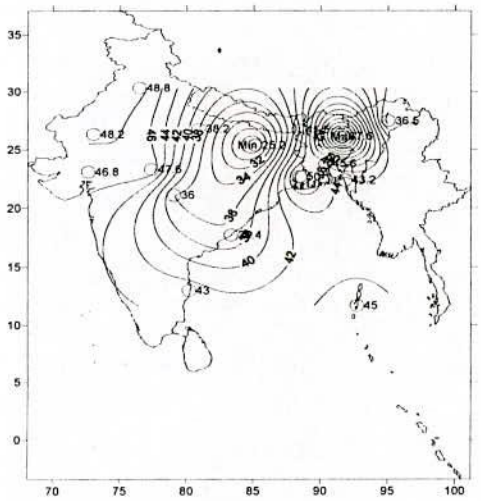


Fig. 4.7: Spatial distribution of TT on 10 April 1993

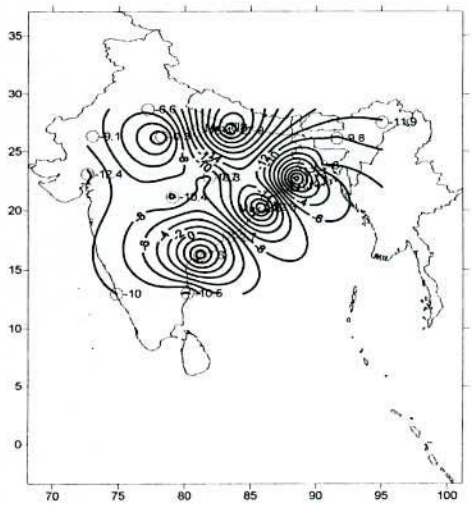


Fig. 4.8: Spatial distribution of EI on 14 May 1992, the date of occurrence of nor'wester

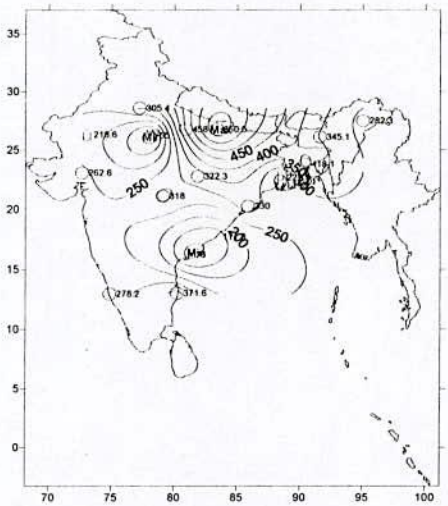


Fig. 4.9: Spatial distribution of SWI on 14 May 1992, the date of occurrence of nor'wester

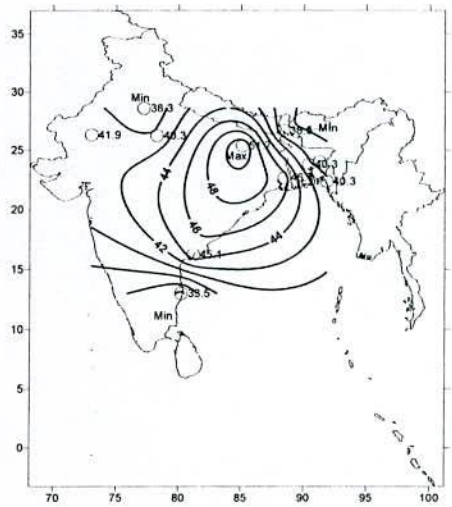


Fig. 4.10: Spatial distribution of KI on 21 April 1993, the date of occurrence of nor'wester

In case of KI, the maximum values have been found to exist over eastern Uttar Pradesh and adjoining Madhya Pradesh or Bihar, Sub-Himalayan West Bengal and adjoining area in 9 out of 26 nor'westers, and over Orissa and adjoining Gangetic West Bengal in 5 out of 26 nor'westers. Maximum values of KI have been found to lie over Bangladesh in 9 out of 26 nor'westers.

4.5.3 Modified stability indices at Dhaka in relation to the occurrence of nor'westers in Bangladesh

Different modified stability indices (at 0000 UTC i.e. 6 a.m.) of the atmosphere prior to the occurrence of nor'westers have been determined for the stations Dhaka, Chittagong and some Indian stations to study the degree of instability of the atmosphere favourable for the occurrence of nor'westers in Bangladesh. The different modified stability indices viz. MCT, MVT, MTT, MSWI, MEI and MKI with their frequencies are tabulated in Tables 4.12-4.17 respectively for nor'westers of all types and for severe to very severe nor'westers. Attempts have been made to find out the critical values of the indices for the occurrence of nor'westers and to study the spatial distribution of these indices for delineating the area of unstable atmosphere. The critical values have been considered from the relatively first increased frequency of instability indices. The results are described in the subsequent sub-sections.

4.5.3.1 Modified Cross Total Index (MCT) and its frequency

Table 4.12 shows that maximum nor'westers occur in the range of MCT = 24-26°C, which is about 24.37% of the total number of nor'westers. About 92.59% nor'westers occur when the MCT is greater than 20°C. The table also shows that 7.41% of nor'westers occur when MCT range is 10-20°C. Relatively first higher frequency of 11 is seen in the range 20-22°C. Therefore, the critical value of MCT may be taken as MCT ≥ 20°C.

For severe to very severe nor'westers, 34 out of 40 (85.00%) nor'westers are found to occur when MCT >22°C, and the first relatively higher frequency of 8 nor'westers occurs in the range of 22-24°C of MCT. Therefore, MCT ≥ 22°C may be taken as the critical value for the severe to very severe nor'westers to occur in Bangladesh.

For tornado, 5 out of 5 tornadoes (100%) occurred when MCT≥ 24.9° (e.g. MCT= 24.9, 27, 29.1, 29.8 and 29.8°C). Therefore, MCT ≥ 24°C may be taken as the critical value for the tornado to occur in Bangladesh

Table 4.12:Frequency of MCT at 0000 UTC over Dhaka on the dates of occurrence of nor'westers

Nor'westers of all types				Severe to very severe nor'westers			
Range of MCT (°C)	Frequency (f)	% of the total		Range of MCT (°C)	Frequency (f)	% of the total	
10-16	2	1.85	7.41				15.00
16-18	3	2.78					
18-20	3	2.78		<20	3	7.50	
20-22	11	10.19	92.59	20-22	3	7.50	
22-24	18	16.67		22-24	8	20.00	85.00
24-26	26	24.07		24-26	8	20.00	
26-28	22	20.37		26-28	5	12.50	
28-30	19	17.59		28-30	9	22.50	
30-32	4	3.7		30-32	4	10.00	
Total	108	100	100	Total	40	100	100

It is interesting to note that CT in the morning has been found to much lower than MCT in some cases and in those cases it is difficult to decide as to whether a nor'wester is going to occur in the afternoon or afterwards. For this reason MCT at 0000 UTC is better to be used in the forecasting of nor'westers in Bangladesh.

4.5.3.2 Modified Vertical Total Index (MVT) and its frequency

Analysis of MVT on the dates of occurrence of nor'westers reveals that maximum (41 out of 108 nor'westers i.e.37.96%) nor'westers occur when MVT ranges between 30 and 32°C. About 98.15% nor'westers occur when the MVT >26°C and the relatively first higher frequency (11 out of 108) of nor'westers is in the range of 26-28°C of MVT (Table 4.13). Therefore, the critical value of MVT may be taken as MVT ≥ 26°C for the nor'westers to occur in Bangladesh.

Table 4.13 shows the frequency distribution of MVT at 0000 UTC at Dhaka on the dates of occurrence of severe to very severe nor'westers in Bangladesh. 90.00% of severe to very severe nor'westers (36 out of 40) have been found to occur when MVT>28°C and relatively first higher frequency (8 out of 40) is found in the range of 28-30°C. So, MVT ≥28°C may be taken as the critical value of MVT for severe to very nor'westers. During the period 5 tornadoes have been reported to occur in Bangladesh. For 1 tornado, MVT is 28.1°C and for 4 out of 5 (80%) tornadoes MVT > 30°C (viz. 30.6, 30.7, 36.1 and 37.5). Therefore, MVT ≥ 30°C may be taken as the critical value for the severe nor'westers of tornadic intensity to occur in Bangladesh.

Table 4.13: Frequency of MVT at 0000 UTC over Dhaka on the dates of occurrence of nor'westers

Nor'westers of all types				Severe to very severe nor'westers			
Range of MVT (°C)	Frequency (f)	% of the total		Range of MVT (°C)	Frequency (f)	% of the total	
24-26	2	1.85	1.85	<26	1	2.50	10.00
26-28	11	10.19	98.15	26-28	3	7.50	
28-30	28	25.93		28-30	8	20.00	90.00
30-32	41	37.96		30-32	17	42.50	
32-34	13	12.04		32-34	7	17.50	
34-36	8	7.41		34-36	2	5.00	
36-38	3	2.78		36-38	2	5.00	
>38	2	1.85					
Total	108	100	100	Total	40	100	100

4.5.3.3 Modified Total Totals Index (MTT) and its frequency

Maximum frequency of nor'westers occurs in the range of MTT between 54 and 56°C, which is about 23.15% of the total number of nor'westers. 95.37% (105 out of 108) nor'westers

occur when the MTT range is 48-66°C. It can be seen from the Table 4.14 that relatively higher frequency of nor'westers is in the MTT range of 48-50°C. The critical value of MTT may be taken as MTT ≥ 48°C for the nor'westers to occur in Bangladesh.

Table 4.14: Frequency of MTT at 0000 UTC over Dhaka on the dates of occurrence of nor'westers

Nor'westers of all types				Severe to very severe nor'westers			
Range of MTT (°C)	Frequency (f)	% of total		Range of MTT (°C)	Frequency (f)	% of total	
42-44	1	0.93	4.63	<44	1	2.50	17.50
44-46	1	0.93		44-46	1	2.50	
46-48	3	2.78		46-48	0	0.00	
48-50	7	6.48	95.37	48-50	2	5.00	
50-52	9	8.33		50-52	2	5.00	
52-54	7	6.48		52-54	1	2.50	
54-56	25	23.15		54-56	14	35.00	82.50
56-58	19	17.59		56-58	4	10.00	
58-60	20	18.52		58-60	5	12.50	
60-62	11	10.19		60-62	7	17.50	
62-64	4	3.70		62-64	2	5.00	
64-66	1	0.93		64-66	1	2.50	
Total	108	100	100	Total	40	100	100

For severe very severe nor'westers, 90% (36 out of 40) occur when MTT > 50°C and 82.50% of severe nor'westers occur when MTT ≥ 54°C. It is also found from the table that relatively higher frequency of (14 out of 40) nor'westers occurs when MTT is 54-56°C (Table 4.14). Therefore, MTT ≥ 54°C may be taken as the critical value for the severe to very severe nor'westers to occur in Bangladesh.

In case of 5 tornadoes, the MTT values are 55.1, 59.7, 60.5, 61.0 and 61.7°C at 0000 UTC at Dhaka, which indicate that tornado is likely to occur when MTT ≥ 55.0°C.

4.5.3.4 Modified SWEAT Index (MSWI) and its frequency

It is seen from the Table 4.15 that 9 out of 108 (8.33%) nor'westers occur when MSWI is 100-300. But maximum nor'westers (32 out of 108 i.e. 29.63%) occur when MSWI is 400-500. Most of the nor'westers i.e. 99 out of 108 (91.67%) nor'westers occur when MSWI is > 300 and

the relatively first higher frequency of 20 occurs in MSWI range of 300-400. So, MSWI ≥ 300 may be taken as the critical value for the nor'westers to occur in Bangladesh.

Table 4.15: Frequency of MSWI at 0000 UTC over Dhaka on the dates of occurrence of nor'westers

Nor'westers of all types				Severe to very severe nor'westers			
Range of MSWI	Frequency (f)	% of the total		Range of MSWI	Frequency (f)	% of the total	
100-200	1	0.93	8.33				11.11
200-300	8	7.41		<200	1	2.78	
300-400	20	18.52	91.67	200-250	2	5.56	
400-500	32	29.63		250-300	1	2.78	
500-600	30	27.78		300-350	3	8.33	88.89
600-700	12	11.11		350-400	4	11.11	
700-800	4	3.70		400-450	5	13.89	
> 800	1	0.93		450-500	2	5.56	
				500-550	7	19.44	
				550-600	6	16.67	
				600-650	1	2.78	
				650-700	1	2.78	
				700-750	2	5.56	
				750-800	1	2.78	
Total	108	100	100	Total	36	100	

The frequency of severe to very severe nor'westers in different ranges of MSWI is also given in Table 4.15, which shows that 88.89% severe to very severe nor'westers occur when MSWI ≥ 300. The relatively first higher frequency, but not so prominent, falls in the range of MSWI = 300-350. So, MSWI ≥ 300 may be taken as the critical value for the occurrence of severe to very severe nor'westers.

In case of 5 tornadoes, MSWI values over Dhaka at 0000 UTC are 588.7, 733.9, 533.0, 552.0 and 549.8 on 20-4-90, 3-5-91, 7-5-91, 17-5-91 and 8-4-95 respectively. Therefore, MSWI ≥ 500 over Dhaka at 0000 UTC may be taken as the critical value for the occurrence of tornado occurrence in Bangladesh.

4.5.3.5 Modified Energy Index (MEI) and its frequency

The MSE has been determined using the rawinsonde data over Dhaka at 0000 UTC and MEI on the dates of occurrence of nor'westers for the period 1990-1995 has been computed and the frequency of MEI is given in Table 4.16.

Table 4.16 shows that 6 out of 105 (5.71%) nor'westers occur when MEI is above 0 Joule/gm and 94 out 105 nor'westers (89.52%) occur when MEI is less than -3 Joule/gm. Maximum frequency of 21 out of 105 (20%) nor'westers occur when MEI ranges between -9 and -12 Joule/gm. It has also been seen that the relatively first higher frequency of 16 lie in the range -3 to -6. From the discussion, it may be concluded that MEI < -3 can be taken as the critical value of MEI at 0000 UTC at Dhaka for the nor'westers to occur in Bangladesh.

Table 4.16: Frequency of MEI at 0000 UTC over Dhaka on the dates of occurrence of nor'westers

Nor'westers of all types				Severe to very severe nor'westers			
Range of MEI (J/gm)	Frequency (f)	% of the total		Range of MEI (J/gm)	Frequency (f)	% of the total	
+9 to +6	1	0.95	10.48				
+6 to +3	2	1.90		+6 to +3	1	2.86	
+3 to 0	3	2.86		+3 to 0	2	5.71	31.43
0 to –3	5	4.76		0 to –3	0	0	
-3 to –6	16	15.24	89.52	-3 to –6	5	14.29	
-6 to -9	10	9.52		-6 to –9	3	8.57	68.57
-9 to -12	21	20.00		-9 to –12	7	20.00	
-12 to –15	16	15.24		-12 to –15	6	17.14	
-15 to –18	16	15.24		-15 to –18	6	17.14	
-18 to –21	9	8.57		-18 to –21	3	8.57	
-21 to –24	4	3.81		-21 to –24	2	5.71	
-24 to -27	2	1.9		-24 to –27	0	0.00	
Total	105	100	100	Total	35	100	100

It has also been observed that maximum number of severe to very severe nor'westers (24 out of 35 i.e. 68.57%) occur when MEI $\leq$-9 at 0000 UTC over Dhaka (Table 4.16). The relatively first higher frequency of severe to very severe nor'westers occur in the MEI range of -9 to -12. Therefore, MEI $\leq$ -9 may be taken as the critical value of MEI at Dhaka for the occurrence of severe to very severe nor'westers in Bangladesh. For 5 tornadoes, MEI values are -

13.39, -11.62, -15.71, -23.67 and -8.94 and these values also indicate that tornado has the possibility to occur (80%cases) in Bangladesh when MEI $\leq$ -11 at 0000 UTC at Dhaka.

4.5.3.6 Modified K-Index (MKI) and its frequency

Table 4.17 for the frequency of MKI reveals that maximum nor'westers (67 out of 105 i.e.63.81%) have been found to occur when the values of MKI between 44 and 54, and 92.38% (97 out of 105) nor'westers occur in Bangladesh when MKI>42°C. It can also be seen from the table that the relatively first higher frequency of 6 is in the MKI range of 42-44 °C. Therefore, the critical value of MKI may be taken as MKI $\geq$ 42°C for the nor'westers to occur in Bangladesh.

Table 4.17: Frequency of MKI at 0000 UTC over Dhaka on the dates of occurrence of nor'westers

Nor'westers of all types				Severe to very severe nor'westers			
Range of MKI (°C)	Frequency (f)	% of the total		Range of MKI (°C)	Frequency (f)	% of the total	
34-36	1	0.95	7.62				
36-38	0	0					
38-40	3	2.86					
40-42	4	3.81					
42-44	6	5.71	92.38	<44	1	2.94	26.47
44-46	13	12.38		44-46	5	14.71	
46-48	14	13.33		46-48	3	8.82	
48-50	15	14.29		48-50	7	20.59	73.53
50-52	14	13.33		50-52	7	20.59	
52-54	11	10.48		52-54	2	5.88	
54-56	7	6.67		54-56	1	2.94	
56-58	3	2.86		56-58	2	5.88	
58-60	4	3.81		58-60	2	5.88	
60-62	2	1.90		60-62	1	2.94	
62-64	6	5.71		62-64	2	5.88	
64-66	1	0.95		64-66	1	2.94	
66-68	1	0.95		66-68	0	0.00	
Total	105	100	100	Total	34	100	100

For severe to very severe nor'westers, the first relatively higher frequency lies in the MKI range of 48-50°C, and it can be found from the table that 73.53% of severe to very severe nor'westers occur when MKI > 48°C. Therefore, MKI ≥ 48°C may be taken as the critical value for the severe to very severe nor'westers to occur in Bangladesh

In case of tornadoes at different places in Bangladesh, data are available for 4 out of 5 tornadoes and the MKI values are 61.8, 63.3, 65.7 and 58.9°C at 0000 UTC at Dhaka on the dates 20-4-90, 3-5-91, 7-5-91 and 8-4-95 respectively. So, MKI>58°C may be taken as the critical value for tornado occurrence in Bangladesh.

4.5.4 Comparison of different stability indices with modified stability indices on the dates of occurrence of nor'westers in Bangladesh

Different stability indices on the dates of occurrence of nor'westers have been compared with the corresponding modified stability indices and are discussed in the following.

The CT and the MCT have been computed using the relevant data on the dates of occurrence of nor'westers (108 cases) in Bangladesh during the period March-May of 1990-1995 with the data at 0000 UTC over Dhaka and their comparison is shown in Fig. 4.11.

Fig. 4.11 shows that the MCT is always greater than CT. It can be seen that CT values are less than 15^0C in many cases and even less than 10^0C. But MCT is almost greater than 15^0C except one or two cases. This indicates that CT shows relatively stable atmosphere in the morning, which leads the forecaster to be confused with the morning data for forecasting of nor'westers in the afternoon/evening. In that respect, MCT gives much greater values indicating unstable atmosphere, which is favourable for the occurrence of nor'westers in Bangladesh.

MVT and MTT as shown in Fig. 4.12 and Fig. 4.13 respectively show the similar results as in the case of MCT. The reason for the increased values of the MCT, MVT and MTT is due to the use of 925 hPa level data, where the temperature and dew-point temperature are greater than those of 850 hPa level. Therefore, it may be concluded that the modified indices are better to be used to determine the instability of the troposphere for the occurrence of nor'westers in Bangladesh.

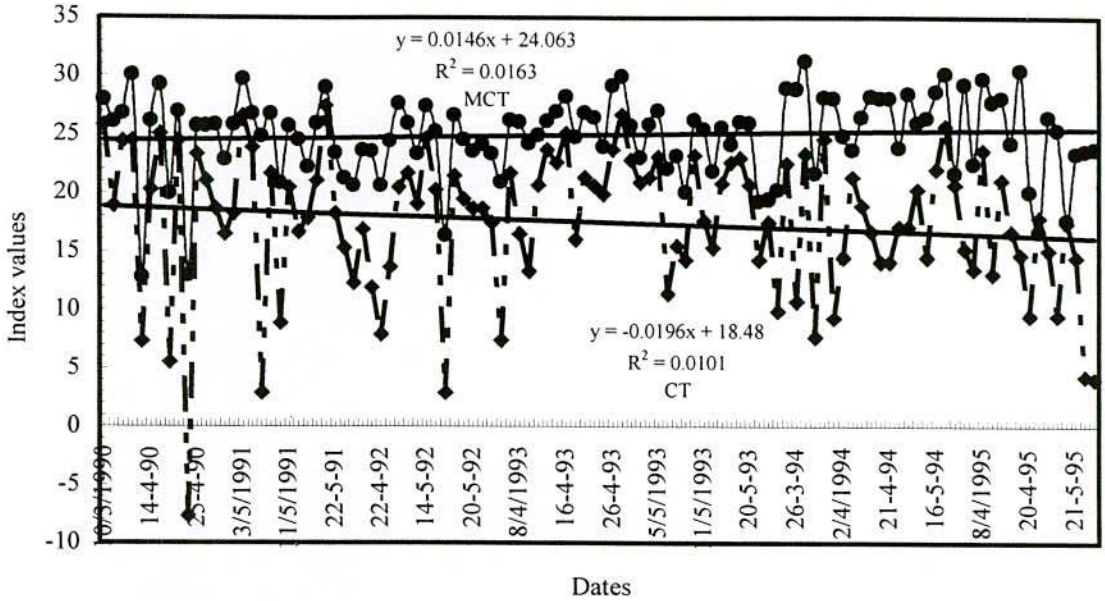


Fig. 4.11: Comparison of CT and MCT at Dhaka at 0000 UTC on the dates of occurrence of nor'westers in Bangladesh

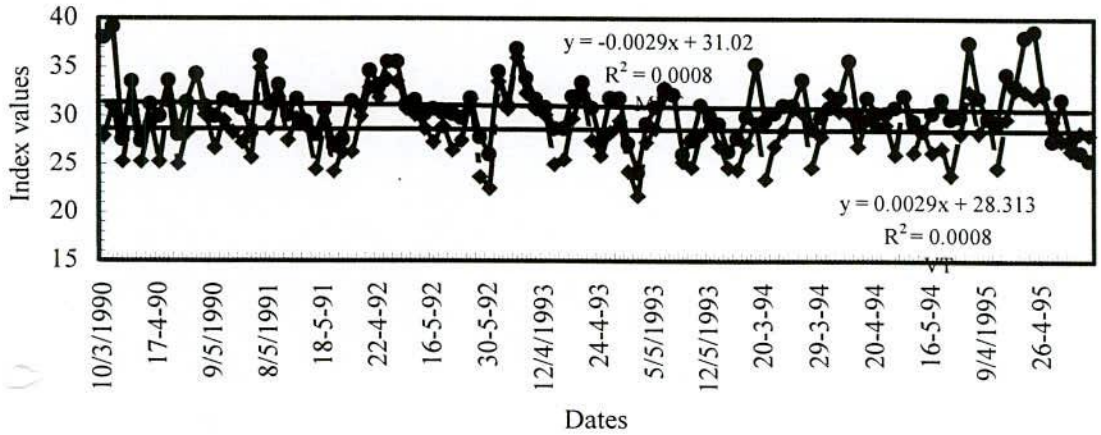


Fig. 4.12: Comparison of VT and MVT at Dhaka at 0000 UTC on the dates of occurrence of nor'westers in Bangladesh

The KI and EI have also been compared with the MKI and MEI and are shown in Fig. 4.14 and Fig. 4.15 respectively. Fig. 4.14 shows that the MKI is greater than the KI indicating relatively greater instability of the atmosphere. The pattern of variation is the same in both the

cases. The variation of MEI and EI are also the same as shown in Fig. 4.15. The figure reveals that the MEI s much lower than the EI, showing relatively greater instability of the troposphere.

The reason is that the moist static energy at 925 hPa generally remains greater than that of 850 hPa. Therefore, MKI and MEI at 0000 UTC are better to be used for the forecasting of nor'westers in Bangladesh.

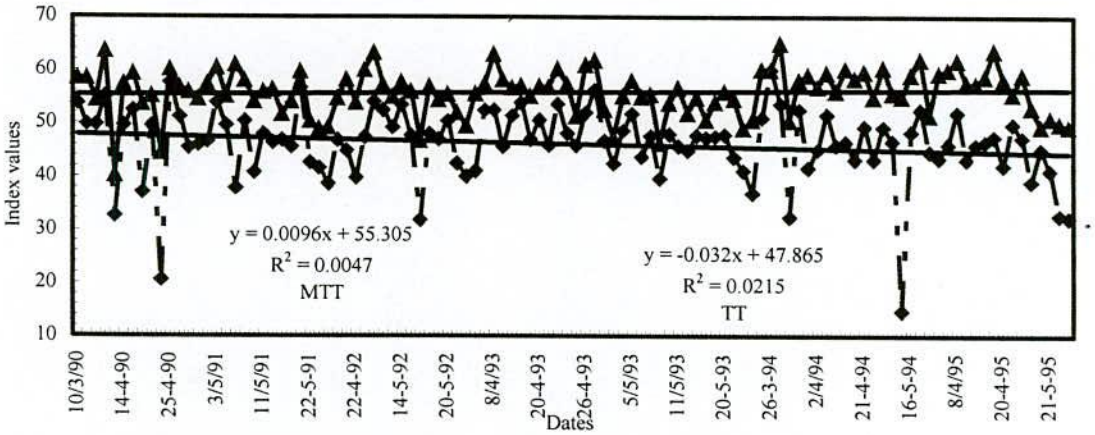


Fig. 4.13: Comparison between TT and MTT at 0000 UTC at Dhaka on the dates of occurrence of nor'westers in Bangladesh

In the same way, the MSWI is higher than the SWI at 0000 UTC on the dates of occurrence of nor'westers (Fig. 4.16).

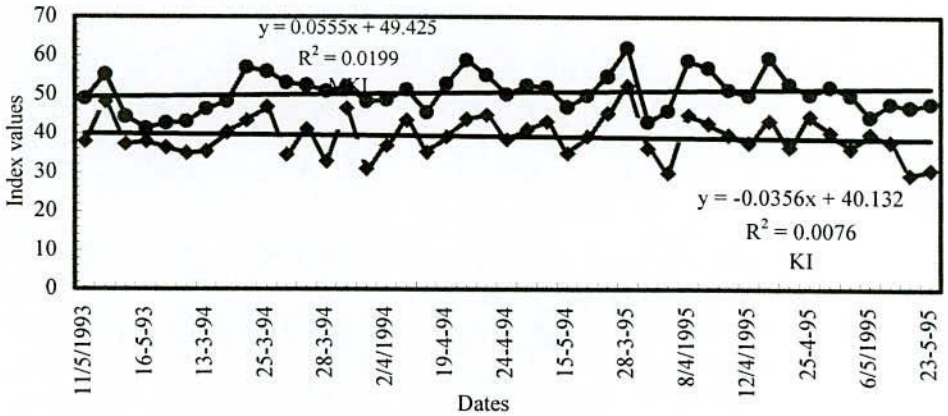


Fig. 4.14: Comparison of KI and M KI at Dhaka at 0000 UTC on the dates of occurrence of nor'westers in Bangladesh

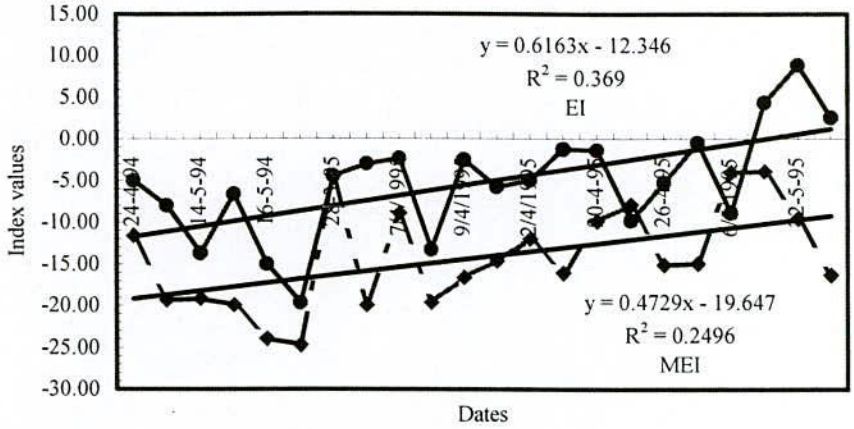


Fig. 4.15: Comparison between E I and MEI at 0000 UTC at Dhaka on the dates of occurrence of nor'westers in Bangladesh during 1990-1995

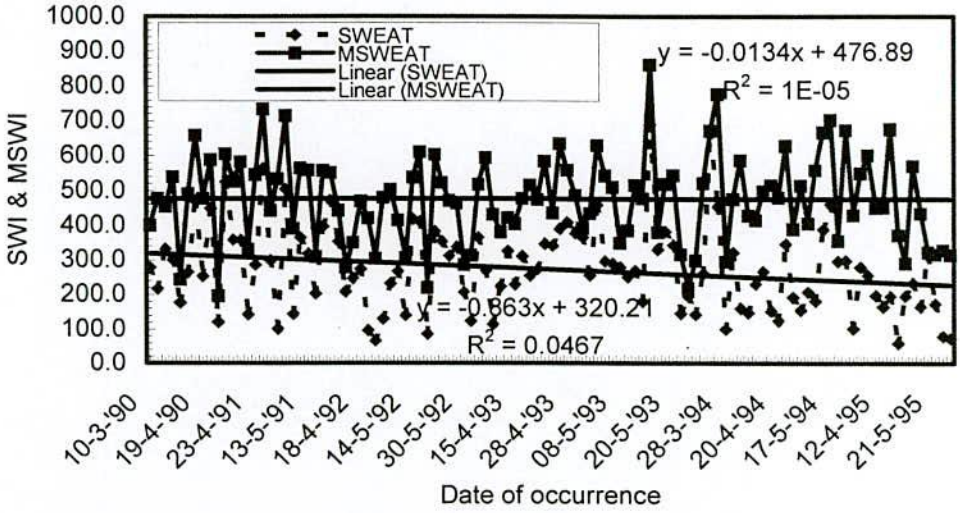


Fig. 4.16: Comparison between SWI and MSWI at 0000 UTC at Dhaka on the dates of occurrence of nor'westers in Bangladesh during 1990-1995

4.5.5 Spatial distribution of different modified stability indices in relation to the occurrence of nor'westers in Bangladesh

The different modified stability indices of the troposphere on the dates of occurrence of a number of nor'westers have been computed by using the rawinsonde data at different stations under study at 0000 UTC and their spatial distributions have been studied critically.

The spatial distributions of MCT, MVT, MTT, MKI, MSWI and MEI on the dates of occurrence of nor'westers are given in Figs. 4.17 - 4.22 respectively as examples.

The distribution patterns of MCT, MVT and MTT are shown in Figs. 4.17-4.19 for examples. It has been found that MCT is maximum over Bangladesh in 13 out of 26 (50% cases), over eastern Madhya Pradesh, Bihar, Sub-Himalayan West Bengal with its elongated area up to Bangladesh in 5 out of 26 (19.23% cases), and over Orissa and Gangetic West Bengal with northeastward extension up to Bangladesh in 8 out of 26 (30.77% cases). These maximum areas of MCT indicate the highly unstable area. Nor'westers have been found to occur over the area of maximum MCT or at the northeastern or eastern part of the area of unstable area.

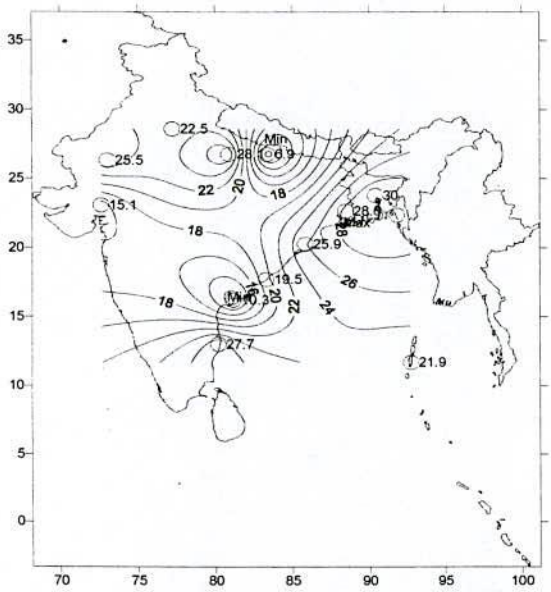


Fig. 4.17: Spatial distribution of MCT (°C) on 28 April 1993, the date of occurrence of nor'wester in Bangladesh

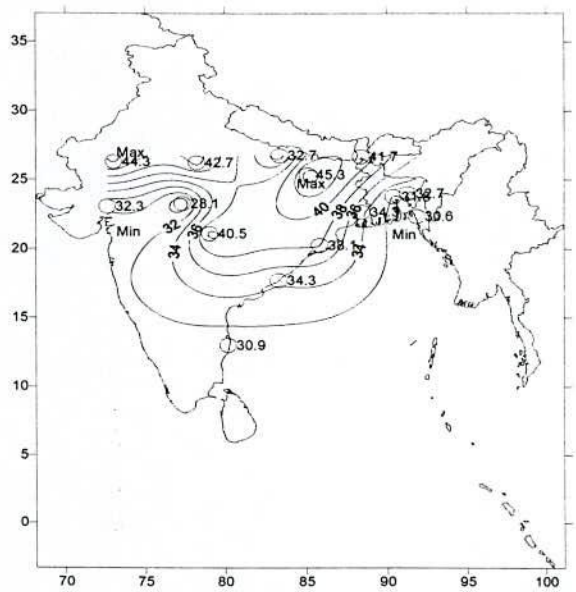


Fig. 4.18: Spatial distribution of MVT (°C) on 20 May 1992, the date of occurrence of nor'wester in Bangladesh

In case of MVT, maximum values lie over eastern Uttar Pradesh and adjoining eastern Madhya Pradesh, Bihar and Sub-Himalayan West Bengal in 19 out of 26 (73.08%) nor'westers with extension up to Bangladesh in most of the cases. In 5 out of 26 (19.23%) nor'westers, the maximum MVT lies over Orissa and Gangetic West Bengal with an extension up to southwestern Bangladesh, and in 2 cases (7.69%), the maximum MVT lies over Bangladesh and adjoining area. Orissa and Gangetic West Bengal have the maximum MTT with an elongated

portion northeastwards across Bangladesh in 30.86% cases of nor'westers (10 out of 26), Bangladesh has maximum MTT in 30.77% cases (8 out of 26) and eastern Uttar Pradesh, eastern Madhya Pradesh, Bihar and Sub-Himalayan West Bengal of India has also maximum MTT in 30.77% cases (8 out of 26) with an elongated area extended eastwards up to Bangladesh. The maximum areas of MCT, MVT and MTT in combination with the low pressure area over Bihar, West Bengal and adjoining Orissa and Bangladesh as well as the cyclonic circulation extending to 3-4 km or above (not discussed here) are favourable for the occurrence of nor'westers in Bangladesh.

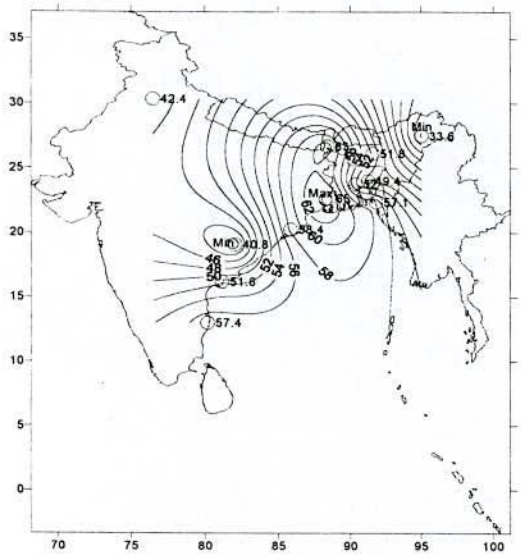


Fig. 4.19: Spatial distribution of MTT (°C) on 25 May 1992, the date of occurrence of nor'wester in Bangladesh

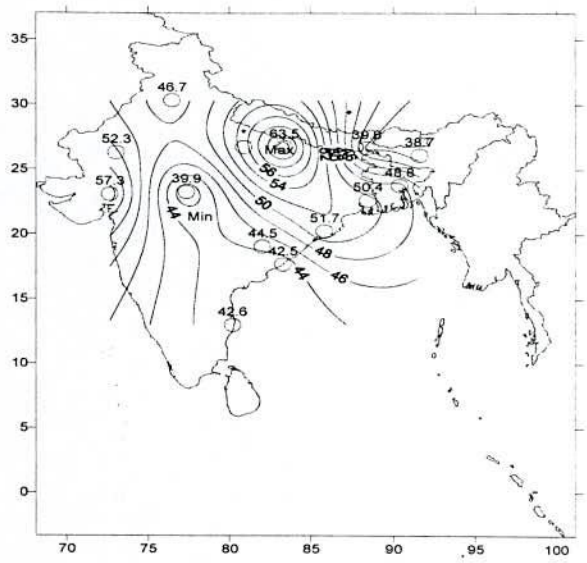


Fig. 4.20: Spatial distribution of MKI (°C) on 30 May 1992, the date of occurrence of nor'wester in Bangladesh

The spatial distribution patterns of MKI and MSWI are shown in Fig. 4.20 and Fig. 4.21, respectively as examples. It has been found that the highly unstable area with maximum MKI exists over Bangladesh (in 9 out of 26 i.e. 34.62 %) and adjoining area, and also over eastern Uttar Pradesh, Bihar and sub-Himalayan West Bengal of India (34.62 %) with an elongated area eastwards/southeastwards up to Bangladesh. Another area of maximum MKI exists over Orissa and Gangetic West Bengal (30.77%) with an elongated portion extended northeastwards over Bangladesh. MSWI has also maximum values over Bangladesh and adjoining area in 12 out of 26 (46.15%). In 34.62% cases, MSWI is maximum over Orissa and Gangetic West Bengal with

an elongated portion extended towards Bangladesh, and only in 19.23% cases the MSWI has maximum value over eastern Uttar Pradesh, and adjoining Madhya Pradesh, Bihar and Sub-Himalayan West Bengal with its extended area up to Bangladesh. The maximum areas of MKI and MSWI, indicating the maximum instability, are almost over the surface low-pressure area over Bihar, West Bengal and adjoining Bangladesh and nor'westers have been found to occur at the eastern end of the area of maximum instability.

The spatial distribution of the MEI for different nor'westers has also been studied. An example of the distribution is shown in Fig. 4.22. It has been found from the analysis of the spatial distribution of MEI that the maximum negative area (indicating greater instability) exists over Bangladesh and adjoining West Bengal in 50% cases of nor'westers, in 34.62% cases maximum negative MEI exists over Orissa and Gangetic West Bengal having a trough extended up to Bangladesh, and the area over eastern Uttar Pradesh and adjoining Madhya Pradesh, Bihar and Sub-West Bengal has maximum negative MEI in 15.38% cases with a trough extended eastwards up to Bangladesh. In general, the maximum negative area has been found over the surface low-pressure area. It may be noted that sometimes more than one unstable area are found to exist over India.

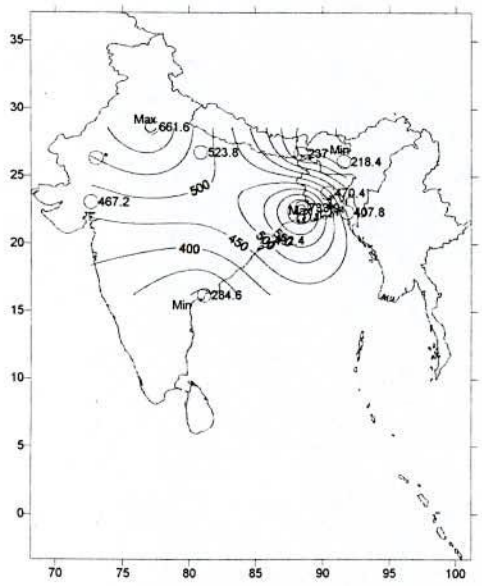


Fig. 4.21: Spatial distribution of MSWI on 16 April 1993, the date of occurrence of nor'wester in Bangladesh

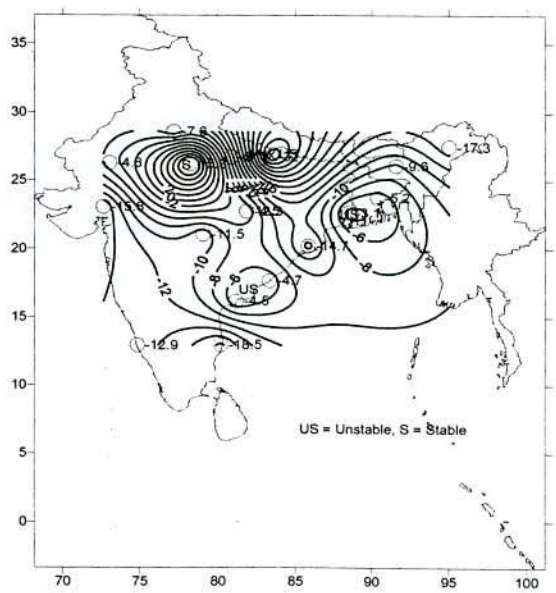


Fig. 4.22: Spatial distribution of MEI (Joule gm^{-1}) on 14 May 1992, the date of occurrence of nor'wester in Bangladesh

4.5.6 Correlation among different modified and unmodified instability indices

The linear correlations among different instability indices have been studied in order to find out the interdependent empirical regression equations for different instability indices with the help of scattered diagrams. Some of the scatter diagrams are given in Figs. 4.23-4.28.

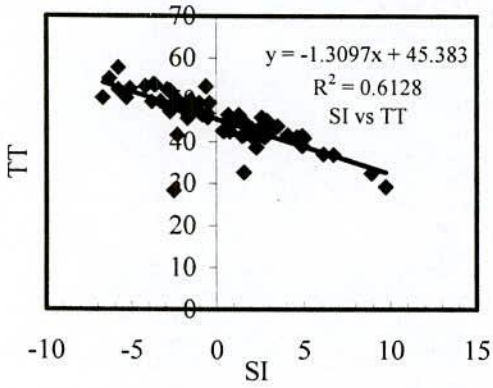


Fig. 4.23: Scattered diagram of SI and TT over Dhaka on the dates of occurrence of nor'westers in Bangladesh during the pre-monsoon season of 1990-1995

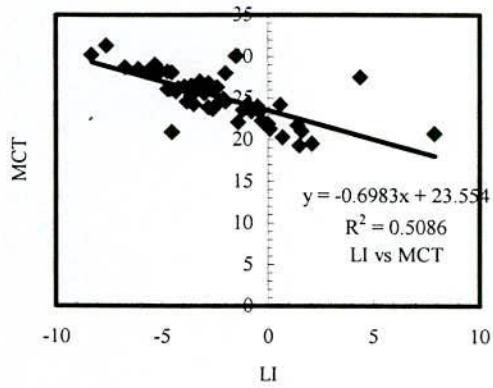


Fig. 4.24: Scattered diagram of LI vs MCT over Dhaka on the dates of occurrence of nor'westers in Bangladesh during the pre-monsoon season of 1990-1995

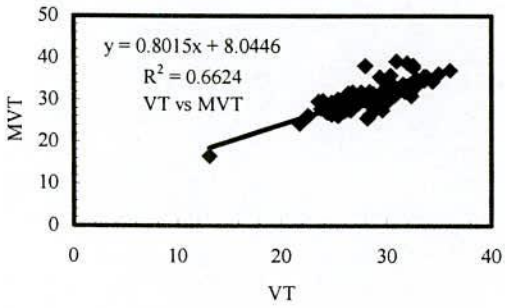


Fig. 4.25: Scattered diagram of VT vs MVT of the troposphere over Dhaka on the dates of occurrence of nor'westers in Bangladesh during the pre-monsoon season of 1990-1995

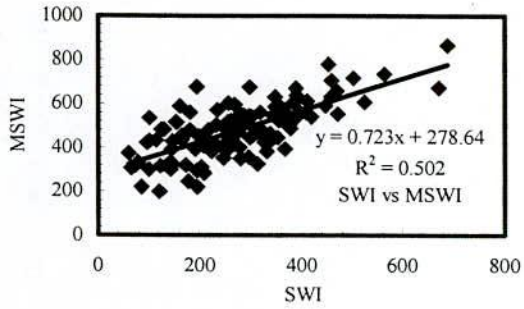


Fig. 4.26: Scatter diagram of SWI vs MSWI over Dhaka on the dates of occurrence of nor'westers in Bangladesh during the pre-monsoon season of 1990-1995

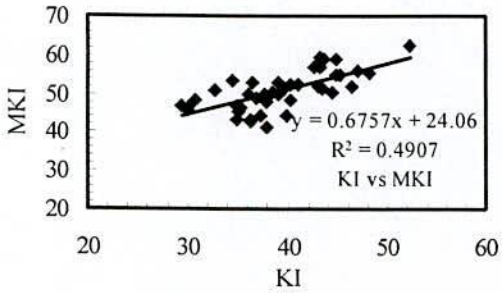


Fig. 4.27: Scatter diagram of KI vs MKI over Dhaka on the dates of occurrence of nor'westers in Bangladesh during the pre-monsoon season of 1990-1995

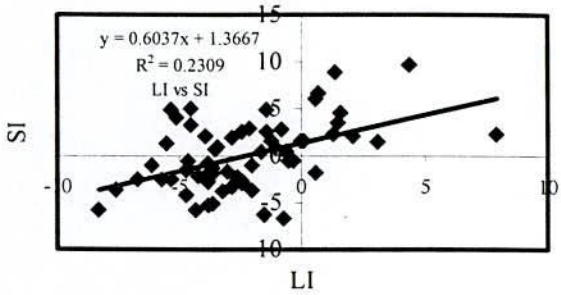


Fig. 4.28: Scatter diagram of LI with SI over Dhaka on the dates of occurrence of nor'westers in Bangladesh during the pre-monsoon season of 1990-1995

4.5.7 Correlation of Showalter Stability Index with other instability indices

The correlation of SI with other different instability indices has been studied and the correlation co-efficients (CC) have been computed. The correlation co-efficients (r), co-efficient of determination (R^2), standard error of estimates (SEE) and level of significance of r are given in Table 4.18.

Table 4.18 shows that SI has moderate to good correlation with different instability indices except DPI, VT, MVT and MKI. Most of the CC is significant up to 99% level of significance except DII, which has correlation with SI up to 95% level of significance. SEE are small in almost all the cases except the correlation of SI with SWI and MSWI in which cases the standard errors of estimate are ±120.095 and ±121.2301 respectively.

Table 4.18 also substantiates that SI has positive correlation with LI, DPI, DII, VT, EI, MEI and MKI. This means that the lower the values of LI, DPI, DII, VT, EI and MEI, the lower is the value of SI and greater is the instability of the troposphere. Since higher values of MKI and VT imply the higher instability, they have no correlation with SI, although the CC is positive. The negative correlation of SI with other indices indicates that the higher that values of CT, TT, KI, SWI, MCT, MVT, MSWI the lower is the value of SI and greater is the instability of the troposphere.

Table 4.18: Correlation of SI with other instability indices over Dhaka on the dates of occurrence of nor'westers in Bangladesh during the pre-monsoon season of 1990-1995

Correlation between	r	R^2	n	Significance	SEE
SI and LI	0.48053	0.2309	64	99%	±2.51338
SI and DPI	0.02611	0.0007	64	Insignificant	±3.61443
SI and DII	0.05409	0.0029	64	95%	±4.01215
SI and CT	-0.78356	0.614	64	99%	±3.74455
SI and VT	0.00224	5E-06	64	Insignificant	±3.05005
SI and TT	-0.78282	0.6128	64	99%	±3.74827
SI and KI	-0.43299	0.2771	56	99%	±5.10871
SI and EI	0.749034	0.5611	56	99%	±4.11850
SI and SWI	-0.43261	0.1872	56	99%	±120.095
SI and MCT	-0.51512	0.2654	57	99%	±2.45615
SI and MVT	-0.07342	0.0054	57	Insignificant	±2.74055
SI and MTT	-0.40469	0.1638	57	99%	±3.46557
SI and MKI	0.00162	8E-05	56	Insignificant	±5.08077
SI and MEI	0.32401	0.105	56	99%	±6.02954
SI and MSWI	-0.39383	0.1551	57	99%	±121.2301

n = Number of data, SEE = Standard Error of Estimate, r = Correlation co-efficient

The regression equations between Showalter Stability Index (SI) and other instability indices are given below for the significant correlation:

$$LI = 0.3825 \times SI - 2.252 \quad (19)$$

$$DII = 0.0604 \times SI - 3.4631 \quad (20)$$

$$CT = -1.3116 \times SI + 17.231 \quad (21)$$

$$VT = 0.0019 \times SI + 28.152 \quad (22)$$

$$TT = -1.3097 \times SI + 45.383 \quad (23)$$

$$KI = -0.7375 \times SI + 40.089 \quad (24)$$

$$EI = 1.2625 \times SI - 6.8538 \quad (25)$$

$$SWI = -15.738 \times SI + 281.3 \quad (26)$$

$$MCT = -0.4032 \times SI + 25.155 \quad (27)$$

$$MVT = -0.0551 \times SI + 31.109 \quad (28)$$

$$MTT = -0.4189 \times SI + 56.011 \quad (29)$$

$$MEI = 0.599 \times SI - 10.793 \quad (30)$$

$$MKI = -0.0102 \times SI + 50.844 \quad (31)$$

$$MSWI = -14.185 \times SI + 484.2 \quad (32)$$

The above regression equations will be useful in the computations of different instability indices, which will be used for the prediction of pre-monsoon nor'wester's in Bangladesh.

4.5.8 Correlation between Lifted Index (LI) and other instability indices

The correlation of LI with other different instability indices has been studied and the CC has been computed. The CC (r), co-efficient of determination (R^2), SEE and level of significance of R are given in Table 4.19.

Table 4.19 shows that LI has moderate to good correlation with different instability indices except DII, KI and MVT. Most of the CC is significant up to 99% level of significance except VT, SWI and MKI, which have correlations with LI up to 95% level of significance. Standard errors of estimate are small in almost all the cases except the correlation of LI with SWI and MSWI in which cases the standard errors of estimate are ±128.2326 and ±101.57365 respectively.

The regression equations between LI and other indices corresponding to the significant correlations are given below:

$$SI = 0.6037 \times LI + 1.3667 \quad (33)$$

$$DPI = 0.3549 \times LI - 6.249 \quad (34)$$

$$CT = -0.709 \times LI + 15.625 \quad (35)$$

$$VT = 0.2802 \times LI + 27.522 \quad (36)$$

$$TT = 0.9892 \times LI + 43.146 \quad (37)$$

$$EI = 1.0281 \times LI - 4.1618 \quad (38)$$

$$SWI = -12.833*LI + 252.16 \quad (39)$$

$$MCT = -0.6983 \times LI + 23.55 \quad (40)$$

$$MTT = -0.9233 \times LI + 53.66 \quad (41)$$

$$MKI = -0.4348 \times LI + 49.087 \quad (42)$$

$$MEI = 1.639 \times LI - 6.858 \quad (43)$$

$$MSWI = -28.5268 \times LI + 419.79 \quad (44)$$

It is interesting to note that the CC of LI with SI and R^2 are the same as the CC and R^2 of SI with LI, but the regression equation is different as can be seen from equations (19) and (32). The regressions (33) – (44) will be useful in the computation of several indices if the other indices are known.

Table 4.19 also indicates that LI has positive correlation with SI, DPI, DII, EI and MEI. This means that the lower the values of SI, DPI, DII, EI and MEI the lower is value of LI, which is related to the greater instability of the troposphere.

Table 4.19: Correlation of LI with other instability indices over Dhaka on the dates of occurrence of nor'westers in Bangladesh during the pre-monsoon season of 1990-1995

Correlation between	r	R^2	n	Sig.	SEE
LI and SI	0.480525	0.2309	64	99%	±3.15743
LI and DPI	0.28128	0.0791	64	99%	±3.46968
LI and DII	0.10054	0.0101	64	Insignificant	±3.99768
LI and CT	-0.33716	0.1137	64	99%	±6.97915
LI and VT	-0.26330	0.0693	64	95%	±2.94243
LI and TT	-0.47065	0.2215	64	99%	±5.31486
LI and KI	-0.16221	0.0263	57	Insignificant	±5.74972
LI and EI	0.45630	0.2082	57	99%	±5.78781

Table 4.19 (Cont'd)

Correlation between	r	R^2	n	Sig.	SEE
LI and SWI	-0.28014	0.0785	56	95%	±128.2326
LI and MCT	-0.71316	0.5086	55	99%	±1.99390
LI and MVT	-0.13310	0.0177	56	Insignificant	±2.70726
LI and MTT	-0.66955	0.4483	56	99%	±2.95689
LI and MKI	-0.24910	0.062	55	95%	±4.95630
LI and MEI	0.75746	0.5737	55	99%	±4.14147
LI and MSWI	-0.63559	0.404	55	99%	±101.57365

n = Number of data, SEE = Standard Error of Estimate, r = Correlation co-efficient

4.5.9 Correlation among unmodified and modified instability indices

The correlation among different unmodified and modified instability indices has been studied and the CC has been computed. The CC (r), co-efficient of determination (R^2), standard errors of estimate (SEE) and level of significance of R are given in Table 4.20. Table 4.20 shows that unmodified instability indices have moderate to strong correlation with the corresponding modified instability indices, having 99% level of significance. The correlation co-efficient of VT and MVT, SWI and MSWI, and KI and MKI are comparatively large. Standard errors of estimate are small except in the case of SWI and MSWI, which is ± 90.07745.

Some of the stability indices such as CT, VT, TT, SWI, EI and KI are defined in terms of 850-hPa level's parameters as the lower level. But the 850-hPa level sometimes remains relatively dryer in the morning, giving stability of the troposphere and the low-level moisture plays a vital role in the formative stages of thunderstorm, so 925-hPa level, which is the average of 850 hPa and the surface, can be used as the low level. Thus the above-mentioned indices are modified in terms of 925-hPa level's parameters. Table 4.20 shows that the modified indices have a good relation with the unmodified indices. It is clear that the higher the values of modified indices, the higher are the values of unmodified indices, indicating the instability of the troposphere.

The regression equations corresponding to the significant correlations are given below:

$$MCT = 0.3647 \times CT + 18.507 \quad (45)$$

$$MVT = 0.8015 \times VT + 8.0446 \quad (46)$$

$$MTT = 0.4197 \times TT + 36.469 \quad (47)$$

$$MSWI = 0.723 \times SWI + 278.64 \quad (48)$$

$$MEI = = 0.4923 \times EI - 11.62 \quad (49)$$

$$MKI = = 0.6757 \times KI + 24.06 \quad (50)$$

The regression equations obtained so far will be useful for the computations of different instability indices.

Table 4.20: Correlation among unmodified and modified instability indices over Dhaka

Correlation between	r	R^2	n	Significance	SEE
CT and MCT	0.62670	0.3927	108	99%	±2.78258
VT and MVT	0.81386	0.6624	108	99%	±1.877454
TT and MTT	0.65801	0.433	108	99%	±3.280246
SWI and MSWI	0.708553	0.502	108	99%	±90.07745
EI and MEI	0.64573	0.2785	106	99%	±5.06526
KI and MKI	0.77990	0.4907	105	99%	±3.88489

n = Number of data, SEE = Standard Error of Estimate, r = Correlation co-efficient

CHAPTER 5

TROPOSPHERIC MOISTURE, ITS FLUXES AND THE RELATION BETWEEN MIOSURE AND RAINFALL DUE TO NOR'WESTERS

5.1 Introduction

Two transition periods between southwest and northeast monsoons over the India-Bangladesh-Pakistan subcontinent are characterized by local severe storms. In Bangladesh, these transition periods are known as pre-monsoon (March-May) and post-monsoon (October-November) seasons. Of these, it is the pre-monsoon season when most of the local severe storms occur over different parts of Bangladesh with frequent intervals. These storms are popularly known as **Nor'westers** or **Kalbaishakhi** in Bangladesh, West Bengal and Assam of India and Andhi (dust storms) in North India. Nor'wester activities in these parts of the region are directly linked up with the apparent movement of the sun towards north causing steady rise in temperature over Southern India and Bangladesh, and gradually extending to the north. Such a situation becomes increasingly prominent from March and prolongs up to the end of May. Frequency of nor'westers in Bangladesh usually reaches its maximum in May, having maximum value over the Sylhet-Mymensingh-Dhaka region (Karmakar, 1998) and is comparatively minimum over the extreme northwestern and southwestern parts of Bangladesh. There are occasions when nor'westers have been observed to occur in late February and early June. The occurrences of nor'wester in late February can be attributed to the early withdrawal of winter from Bangladesh, Assam, Bihar, West Bengal and adjoining area as well as due to the penetration of the easterly lows through the southern tip of India and their subsequent movement towards northeast (Das *et al.*, 1994), while those in early June are due to delay in the onset of southwest monsoon over this region. The delay in the occurrence of nor'westers over Bangladesh is due to presence of intense subtropical high over the Bay of Bengal. Tropospheric moisture plays an important role in the formation of nor'westers and rainfall over Bangladesh during the pre-monsoon season. The higher the depth of moisture in the troposphere, the higher is the potential for the formation of nor'westers.

Nor'westers/thunderstorms bring the first rain after a long dry and hot weather during the pre-monsoon season. This rain is very important for agriculture. The knowledge of rainfall in any region is very helpful in sound cropping. In India a number scientists made efforts to correlate summer monsoon rainfall with different meteorological parameters (Venkataraman, 1955; Kulkarni and Pant, 1969; Banerjee *et al.*, 1978; Mooley and Shukla, 1989; Upadhyay *et al.*, 1990). But no works have been done to predict the pre-monsoon rainfall associated with nor'westers in a country like Bangladesh.

In this chapter, attempts have been made to compute the precipitable water content of the troposphere, weighted average water vapour and to correlate these parameters with different instability indices and also with the next 24-hr rainfall, next 24-hr maximum rainfall and 24-hr country averaged rainfall in order to predicting rainfall due to nor'westers in Bangladesh. The linear regression equations corresponding to the significant correlation co-efficients have been developed with the help of scatter diagram accordingly. The fluxes of moisture have also been computed prior to the occurrence of nor'westers.

5.2 Data used

Twenty-four hours rainfall on the dates of occurrence of 108 nor'westers in the months of March, April and May during 1990-1995 for 34 stations [as shown in Fig.5.1 (a)] of Bangladesh Meteorological Department (BMD) have been collected and utilized in the present study. Rawinsonde data of 0000 UTC at Dhaka, Chittagong and the available GTS real time data at some Indian stations on the dates of occurrence of the mentioned nor'westers have been collected from the Storm Warning Centre of BMD for the computation of specific humidity and the precipitable water of the troposphere.

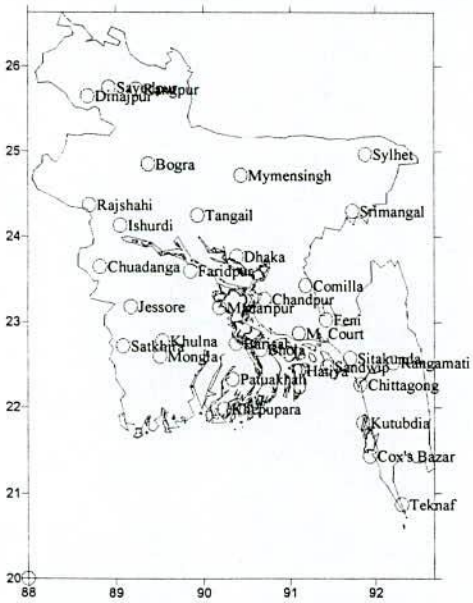


Fig. 5.1(a): Station location map of BMD

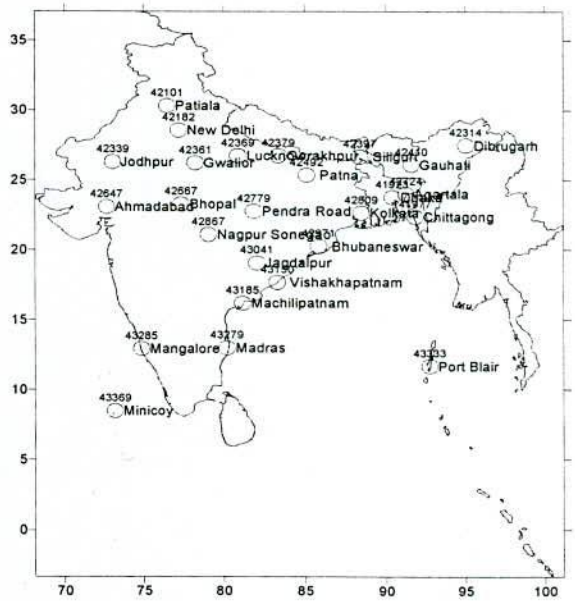


Fig. 5.1(b): Location of the Rawinsonde Stations

For the correlation study, rawinsonde data at 0000 UTC at Dhaka for 108 nor'westers have been considered. For spatial distribution, 26 rawinsonde stations of India and Bangladesh have been considered and the stations are shown in Fig. 5.1(b).

5.3 Methodology

5.3.1 Precipitable water content of the troposphere over Dhaka

The precipitable water in the atmospheric layer, bounded by p_1 and p_2 pressure surfaces, can be expressed by (Ananthakrishnan *et al.*, 1965):

$$W = \frac{1}{g}\int_{p_1}^{p_2} q\,dp \tag{1}$$

Where g is the acceleration due to gravity and q is the specific humidity at pressure level p. Generally, the water vapour is mainly concentrated in the lower atmosphere up to about 500 hPa above which it has negligible contribution. For this reason, the vertically integrated magnitude of the precipitable water vapour is approximated by

$$W = -\frac{1}{g}\int_{1000}^{500} q\,dp \tag{2}$$

To obtain W, one can utilize the trapezoidal rule (Haydu and Krishnamurty, 1981), which can be preformed in the following manner:

$$W = \frac{1}{g}\left[q_{1000}\int_{925}^{1000} dp + q_{850}\int_{775}^{925} dp + q_{700}\int_{600}^{775} dp + q_{500}\int_{500}^{600} dp \right]$$

$$\Rightarrow W = \frac{75}{g}q_{1000} + \frac{150}{g}q_{850} + \frac{175}{g}q_{700} + \frac{100}{g}q_{500} \tag{3}$$

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The units used here are gm kg^{-1}, cm sec^{-2}, and gm cm^{-2} for q, g and W, respectively. The value of W can be converted into mm by using 1 kg m^{-2} = 1 mm. (Mclntosh and Thom, 1973).

The vertical distribution of water vapour (q), and the spatial distribution and time cross-section of the precipitable water over Bangladesh has been studied to find out the critical values for the occurrence of nor'westers. The correlation between precipitable water and the actual rainfall due to nor'westers has also been studied, which is likely to be very useful for the quantitative prediction of rainfall due to nor'westers in Bangladesh.

The weighted average specific humidity (WAq) for the layer 1000-500 hPa considering the standard isobaric surfaces 1000, 925, 850, 700 and 500 hPa has been computed according to:

$$WAq = \frac{q_1 \times p_1 + q_2 \times p_2 + q_3 \times p_3 + q_4 \times p_4 + q_5 \times p_5}{p_1 + p_2 + p_3 + p_4 + p_5} \quad (4)$$

Where the symbols have their usual meanings. If the surface pressure is less than 1000 hPa, surface pressure is taken as p_1.

5.3.2 Correlation of precipitable water content with different instability indices

Linear regression method has been used to correlate the precipitable water and weighted average specific humidity (here in after called water vapour) with different instability indices.

5.3.3 Correlation of rainfall due to nor'westers with different instability indices and precipitable water content

Using the linear regression method attempts have been made to correlate the next 24-hr rainfall, next 24-hr maximum rainfall and 24-hr country averaged rainfall in Bangladesh with precipitable water content and different instability of the troposphere over Dhaka at 0000 UTC. The correlation coefficients are also computed.

5.3.4 Water vapour fluxes in the atmosphere

For a given level in the atmosphere, the magnitude of the instantaneous zonal and meridional fluxes of water vapour are given by:

$$Q_{\lambda_L} = qu \quad (5)$$

$$Q_{\phi_L} = qv \quad (6)$$

Where

Q_{λ_L} = Zonal water vapour flux for a given level (gm $kg^{-1} \times ms^{-1}$)

Q_{ϕ_L} = Meridional water vapour flux for a given level (gm $kg^{-1} \times ms^{-1}$)

q = Specific humidity (gm kg^{-1})

u, v = Zonal and meridional wind components (ms^{-1})

5.3.5 Vertically integrated fluxes of moisture

The vertically integrated zonal and meridional components of the moisture flux are given by

$$Q_{\lambda_L} = g^{-1} \int_{1000}^{400} qudp$$

$$Q_{\phi_L} = g^{-1} \int_{1000}^{400} qvdp$$

The integration has been done by taking the layer mean values of the fluxes of moisture from 1000 to 400 hPa level over Dhaka The integration has been done by taking the layer mean values of the fluxes of moisture from 1000 to 400 hPa level over Dhaka and for spatial distribution from 925 to 400 hPa level. Here 925 hPa has been taken because the surface pressure becomes less than 1000 hPa level in most of the stations during the pre-monsoon season. The unit of $Q_{\lambda L}$ or Q_{ϕ_L} is kg m^{-1} s^{-1}.

5.3.6 Significance test of the correlation co-efficients

The significant test for the correlation coefficient has been made with the help of Student's t-distribution (Alder and Roessler, 1964) and is given by

$$t = \frac{r\sqrt{(n-2)}}{\sqrt{(1-r^2)}}$$

Where r is the correlation coefficient, (n-2) is the degree of freedom and n is the sample size. At 5% level (i.e., 95% level of significance), if $t_{cal} > t_{0.05}$, the correlation coefficients are said to be significant.

5.4 Results and discussion

5.4.1 Precipitable water content of the troposphere and its relation with instability indices and rainfall due to nor'westers

5.4.1.1 Precipitable water content of the troposphere at 0000 UTC in relation to nor'westers

Frequency of precipitable water content of the troposphere over Dhaka on the dates of occurrence of nor'westers in Bangladesh has been computed and the diagrams are prepared accordingly. One example is given in Fig. 5.2.

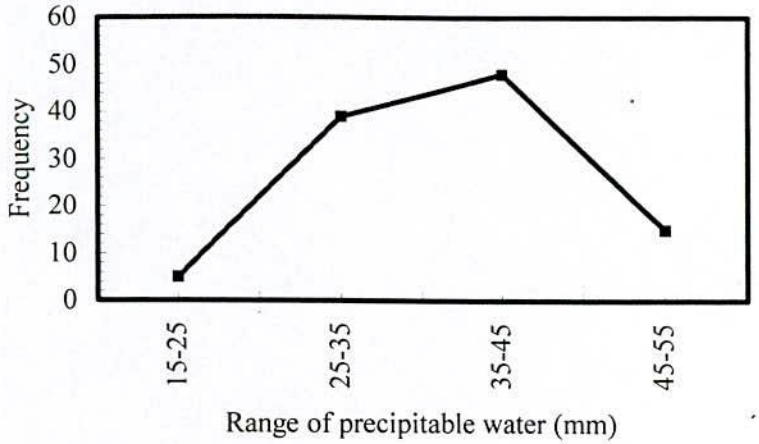

Fig. 5.2: Frequency of precipitable water content of the troposphere over Dhaka at 0000 UTC on the dates of occurrence of nor'westers in Bangladesh during 1990-1995

The frequency of precipitable water also indicates the frequency of nor'westers. It has been found that the maximum number of nor'westers occur when the precipitable water is 25-45 mm hr^{-1} up to 500 hPa, the maximum frequency being 48 in the range of 35-45 mm hr^{-1}.

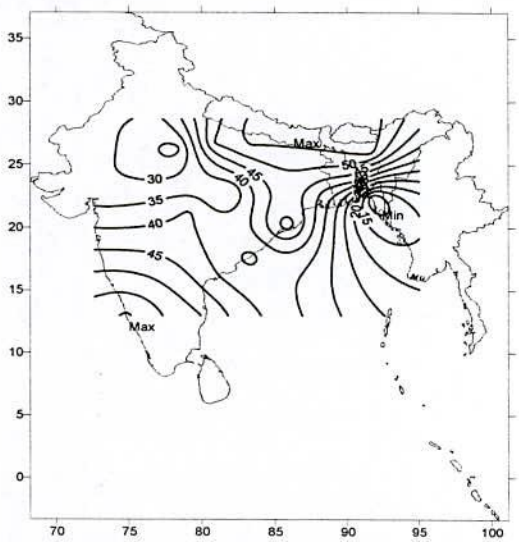

Fig. 5.3: Spatial distribution of precipitable water content of the troposphere at 0000 UTC on 14 May 1992

The spatial distribution of precipitable water on the dates of nor'westers has also been studied. The distribution pattern is given in Fig. 5.3 as an example. It has been found that the maximum precipitable water is concentrated over the area near the places of nor'westers or over Bihar, Sub-Himalayan West Bengal of India and adjoining Bangladesh. In some cases, maximum precipitable water has been found to concentrate over Orissa, Gangetic West Bengal and adjoining southwestern Bangladesh.

5.4.1.2 Correlation of precipitable water content of the troposphere with different instability indices

Since water vapour goes up into the troposphere due to the presence of convergence and instability of the troposphere, it may have some relation with the instability indices. Keeping this fact in mind, attempts have been taken to correlate the precipitable water content of the troposphere with different instability indices. The results are given in Table 5.1.

Table 5.1: CC of precipitable water with different instability indices at 0000 UTC over Dhaka

Correlation of precipitable water with	CC	SEE	Regression Equations
TT	0.35574**	± 6.63	W = 0.3692*TT+19.299
SWI	0.58237**	± 5.76	W = 0.033*SWI+27.314
SWI/TT	0.561696**	± 5.86	W= 1.6937*SWI/TT+26.431
MSWI	0.36005**	± 6.61	W= 0.02*MSWI+26.808
EI	-0.67304**	± 7.09	W = -0.6864*EI+31.709
MEI	-0.41686**	± 6.44	W = 0.4449*MEI+31.432

** Significant at 99% level of significance

The table shows that the precipitable water content of the troposphere at 0000 UTC over Dhaka has significant correlations with different instability indices namely TT, SWI, SWI/TT, MSWI, EI and MEI of the troposphere at 0000 UTC over Dhaka. The CC is significant at 99% level. SEE is significantly smaller ranging between 5.76 and 7.09. The regression equations corresponding to the significant correlations are developed with the help of scatter diagrams. The equations will be useful in the computation of precipitable water content of the troposphere.

5.4.1.3 Specific humidity and weighted average specific humidity (WAq) of the troposphere at 0000 UTC in relation to nor'westers

The specific humidity is maximum near the surface and generally decreases with height for obvious reason as can be seen from Fig. 5.4. It has been found that the specific humidity may be of the order of 15-20 g kg^{-1} near the surface on the dates of occurrence of nor'westers. The specific humidity has been found to increase on the dates of occurrence of nor'westers in Bangladesh as can be seen from Fig 5.4.

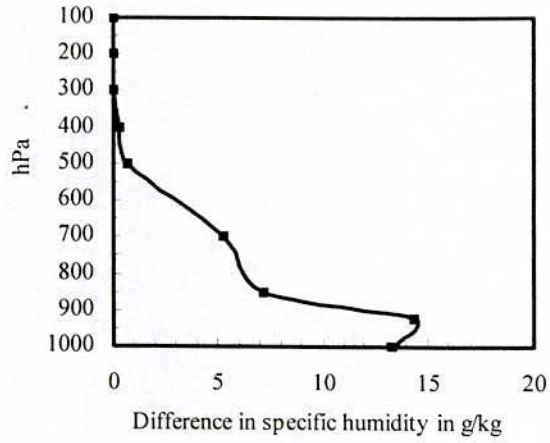

Fig. 5.4:Vertical cross-section of the difference in specific humidity on 8 May (date of occurrence of nor'westers) and 5 May (date of non-occurrence of nor'westers) 1994 over Dhaka at 0000 UTC

Frequency of WAq of the troposphere over Dhaka on the dates of occurrence of nor'westers in Bangladesh has been computed and the diagrams are prepared accordingly. One example is given in Fig. 5.5.

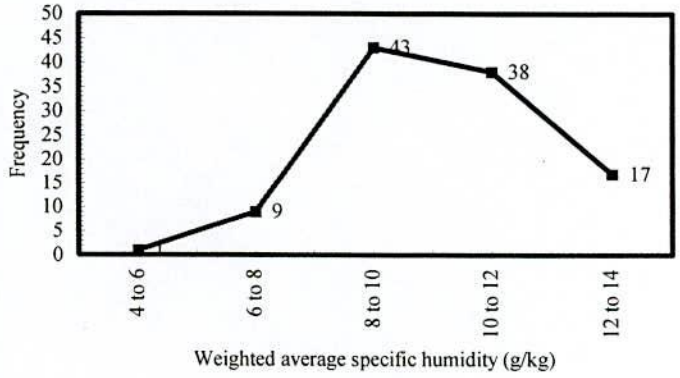

Fig. 5.5: Frequency of WAq of the troposphere between 1000-500 hPa over Dhaka at 0000 UTC on the dates of occurrence of nor'westers in Bangladesh during 1990-1995

The frequency of WAq also indicates the frequency of nor'westers. It has been found that the maximum number of nor'westers occur when the WAq between the surface and 500 hPa is 8-12 g kg^{-1}, the maximum frequency being 43 out of 108 (i.e. 39.18%) in the range of 8-10 g kg^{-1}.

The spatial distribution of WAq between the surface and 500 hPa on the dates of nor'westers has also been studied. The distribution pattern is given in Fig. 5.6 as an example. It has been found that nor'westers occur near or at the eastern/northeastern end of maximum

WAq, the maximum WAq being 14 -16 g kg^{-1} in most of the cases. Nor'westers have been found to occur near the point of inter-section of the axes of moist and dry zones.

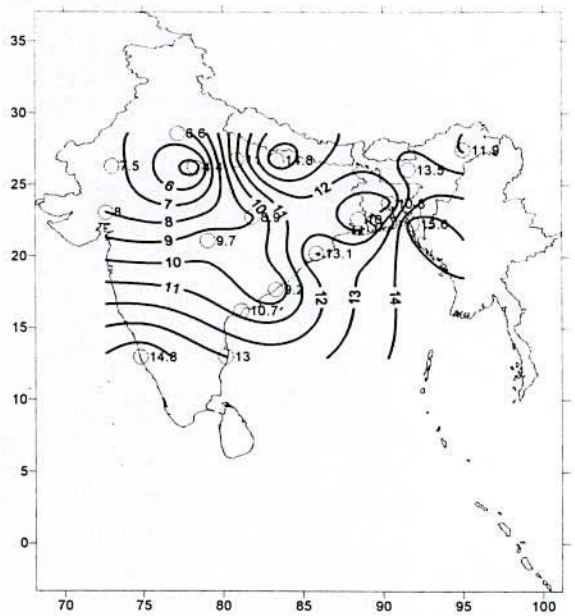

Fig. 5.6: Spatial distribution of WAq at 00 UTC on 14 May 1992

5.4.1.4 Statistical prediction of 24-hr rainfall due to nor'westers in Bangladesh

With a view to predicting 24-hour rainfall due to nor'westers, attempts have been made to correlate a number of parameters of the troposphere over Dhaka at 0000 UTC on the dates of occurrence of nor'westers such as precipitable water (mm/hr), MSWI, SWI, SWI/TT, difference in specific humidity at 1000 and 850 hPa (q_{1000}-q_{850}), WAq with next 24-hour rainfall at Dhaka, next 24-hour maximum rainfall in Bangladesh and country averaged 24-hour rainfall.

The correlation co-efficient, regression equations corresponding to the significant CC and the SEE has been computed. The results are given in Table 5.2.

The table shows that the CC are relatively small but are statistically significant and SEE are higher. The small CC are significant because of the large number of data (usually 106 or 108). Since the SEE are large, the regression equations cannot be used to predict the 24-hour rainfall due to nor'westers. Therefore, it is very difficult to predict rainfall due to nor'westers statistically.

Table 5.2: CC of 24-hr rainfall with different parameters on the dates of occurrence of nor'westers

Correlation of	CC	SEE	Regression Equations
W (mm/hr) at 0000 UTC vs next 24-hr CArain	0.24915**	± 8.43064	y = 0.306x - 1.3696 x=W, y = CArain
MSWI at 0000 UTC vs next 24-hr CArain in Bangladesh	0.30425**	± 8.52495	y = 0.0207x - 0.1335 x=MSWI, y = CArain
W (mm/hr) at 0000 UTC vs next 24-hr rainfall at Dhaka	0.24660*	± 20.22573	y = 0.7261x - 11.136 x=W, y=next 24-hr at Dhaka
W (mm/hr) at 0000 UTC vs next 24-hr maximum rainfall in Bangladesh	0.23215*	± 35.41168	y = 1.1923x + 13.296, x = W, y = next 24-hr maximum rainfall in Bangladesh
LnW at 000 UTC vs 24-hr rain at Dhaka	0.24941**	± 20.23195	y = 20.977x – 59.876 x=lnW, y=next 24-hr rain at Dhaka
LnW at 0000 UTC vs next 24-hr maximum rainfall in Bangladesh	0.227099*	± 35.46158	y = 37.199x – 76.594, x = ln W, y=next 24-hr maximum rain in Bangladesh
LnW at 0000 UTC vs 24-hr Carain in Bangladesh	0.245557**	± 8.43861	y = 10.484x – 27.796, x = ln W, y=next 24-hr CArain in Bangladesh
SWI at 0000 UTC vs next 24-hr rainfall at Dhaka	0.22718*	± 20.32454	y = 0.0379x + 4.8865, x = SWI, y=next 24-hr rain at Dhaka
SWI at 0000 UTC vs next 24-hr maximum rainfall in Bangladesh	0.29504**	± 34.78567	y = 0.0859x + 33.154, x = SWI, y=next 24-hr rain in Bangladesh
MSWI at 0000 UTC vs next 24-hr maximum rainfall in Bangladesh	0.19853*	± 35.68164	y = 0.0566x + 29.651 x=MSWI, y=next 24-hr maximum rain in Bangladesh
SWI/TT at 0000 UTC vs next 24-hr maximum rainfall in Bangladesh	0.25588**	± 35.19424	y = 3.9628x + 33.453 x=SWI/TT, y=next 24-hr maximum rain in Bangladesh
q_{1000}-q_{850} at 0000 UTC vs next 24-hr rainfall at Dhaka	-0.212758*	± 20.39245	y = -1.0167x + 22.956, x=q_{1000}-q_{850}, y=next 24-hr rain at Dhaka
q_{1000}-q_{850} at 0000 UTC vs next 24-hr CArain in Bangladesh	-0.32268**	± 8.239486	y = -0.6432x + 14.627, x=q_{1000}-q_{850}, y= next 24-hr Carain in Bangladesh
WAq at 0000 UTC vs next 24-hr rainfall at Dhaka	0.24844**	± 20.2159	y = 3.1863x - 17.265, x=WAq, y=next 24-hr rain at Dhaka
WAq at 0000 UTC vs next 24-hr maximum rainfall in Bangladesh	0.22882*	± 35.44041	y = 5.1191x + 4.3875 x=WAq, y=next 24-hr maximum rain in Bangladesh
WAq at 0000 UTC vs next 24-hr CArain in Bangladesh	0.20912*	± 8.51268	y = 1.1187x - 1.6665 x=WAq, y=CArain in Bangladesh

CArain = Country Averaged rain, W = Precipitable water, * Significant at 95% level of significance, ** Significant at 99% level of significance.

5.4.2 Fluxes of moisture

5.4.2.1 Zonal fluxes of moisture (ZFM) over Dhaka

The ZFM over Dhaka at 0000 UTC have been computed at different isobaric levels on the dates of occurrence of about 107 nor'westers over Bangladesh during pre-monsoon season of 1990-1995. The fluxes over Dhaka have also been computed for the dates of non-occurrence of nor'westers. A comparative study of the frequency of westerly (positive) of moisture (WFM) and easterly (negative) fluxes of moisture (EFM) has been made and is given in Table 5.3.

Table 5.3 shows that the EFM dominates at 1000 hPa in many cases over Dhaka on the dates of occurrence of nor'westers over Bangladesh and the EFM decrease with height. The WFM dominate in the troposphere from 925 to 300 hPa level having maximum frequency of WFM from 61.68 to 97.20% in the layer from 925 to about 300 hPa level. In the upper troposphere the ZFM become nil in most of the cases.

Table 5.3: %Frequency of positive and negative ZFM over Dhaka at 0000 UTC on the dates of occurrence of nor'westers in Bangladesh

hPa	Frequency of positive fluxes	Frequency of negative fluxes	Frequency of zero fluxes	Total frequency	%Frequency of positive fluxes	%Frequency of negative fluxes	%Frequency of zero fluxes
1000	44	52	11	107	41.12	48.60	10.28
925	91	14	2	107	85.05	13.08	1.87
850	101	3	3	107	94.39	2.80	2.80
700	104	0	3	107	97.20	0.00	2.80
500	75	0	32	107	70.09	0.00	29.91
400	70	1	36	107	65.42	0.93	33.64
300	66	1	40	107	61.68	0.93	37.38
200	11	0	96	107	10.28	0.00	89.72
100	0	0	107	107	0.00	0.00	100.00

The maximum WFM over Dhaka at 0000 UTC on the dates of occurrence of nor'westers may be 223.6, 203.8, 315.6, 174.1, 88.2, 38.7 and 19.1 gm $kg^{-1} \times ms^{-1}$ at 1000, 925, 850, 700, 500, 400 and 300 hPa levels respectively and then the fluxes become unimportant above. The maximum EFM over Dhaka at 0000 UTC may be -128.3, -59.7 and -12.6 gm $kg^{-1} \times ms^{-1}$ at 1000, 925 and 850 hPa levels respectively and then the fluxes become unimportant above. Fig. 5.7 as an example shows the variation of maximum and minimum ZFM with height. The maximum ZFM are always westerly on the dates of occurrence of nor'westers.

The vertical profiles of the ZFM over Dhaka at 0000 UTC on the dates of occurrence and non-occurrence of nor'westers in Bangladesh are studied and the variation is shown in Fig. 5.8 as an example. It has been found that the fluxes are mainly westerly and more westerly in the lower and middle troposphere on the dates of occurrence of nor'westers as compared to the fluxes on the dates of non-occurrence. The fluxes become nil in the upper troposphere.

From the above discussion it may be inferred that the WFM dominate in the troposphere from 925 to 200 hPa level having maximum frequency of WFM from 61.68 to 96.26% in the layer from 925 to about 300 hPa level. In the upper troposphere the ZFM becomes nil in most of the cases. The maximum WFM over Dhaka at 0000 UTC on the dates of occurrence of nor'westers may be more than 200 gm $kg^{-1} \times ms^{-1}$ in the lower troposphere and the maximum EFM over Dhaka at 0000 UTC may be -128.3 gm $kg^{-1} \times ms^{-1}$ at 1000 hPa. The fluxes are mainly westerly and more westerly in the lower and middle troposphere on the dates of occurrence of nor'westers as compared to the fluxes on the dates of non-occurrence.

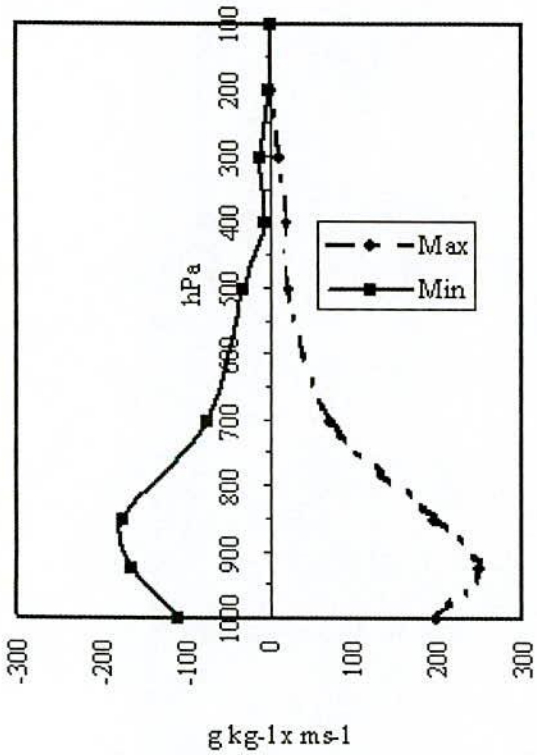

Fig. 5.7: Vertical variation of the maximum and minimum ZFM (g $kg^{-1} \times ms^{-1}$) over Dhaka at 0000 UTC on the dates of occurrence of nor'westers over Bangladesh

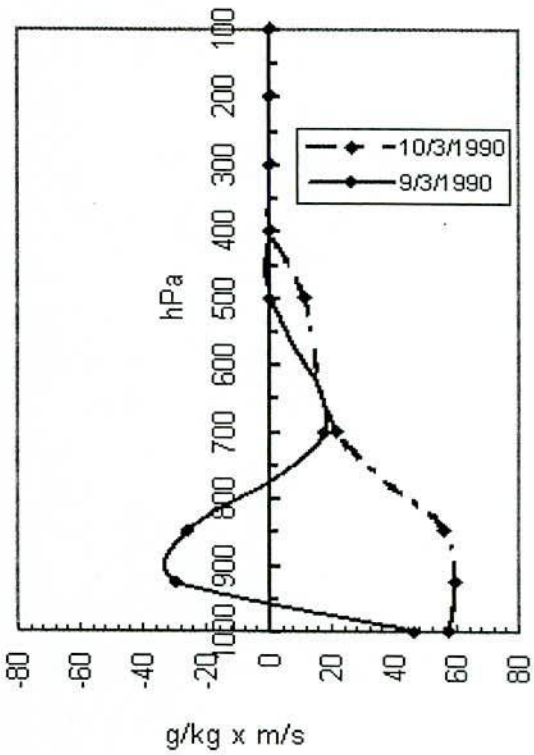

Fig. 5.8: Vertical profiles of the ZFM (g $kg^{-1} \times ms^{-1}$) over Dhaka at 0000 UTC on the date of occurrence (10 March 1990) and the date of non-occurrence (9 March 1990)

5.4.2.2 Meridional fluxes of moisture (MFM) over Dhaka

The MFM over Dhaka at 0000 UTC have been computed at different isobaric levels on the dates of occurrence of about 107 nor'westers over Bangladesh during pre-monsoon season of 1990-1995. The MFM over Dhaka have also been computed for the dates of non-occurrence of nor'westers. A comparative study of the frequency of southerly (positive) fluxes of moisture (SFM) and northerly (negative) fluxes of moisture (NFM) has been made and is given in Table 5.4.

Table 5.4 shows that the SFM dominate from 1000 to about 300 hPa level in most of the cases over Dhaka on the dates of occurrence of nor'westers over Bangladesh, having maximum frequency of SFM in the lower troposphere and the frequency of positive fluxes decreases with height. The frequency of SFM is 92.52% at 1000 hPa and 98.13% at 925-hPa level. The frequency of NFM is less in the lower troposphere having maximum frequency of NFM from 67.29 to 27.10% in the layer from 700 hPa level to about 300 hPa level. In the upper troposphere the MFM become nil in most of the cases.

Table 5.4: %Frequency of SFM and NFM over Dhaka at 0000 UTC on the dates of occurrence of nor'westers in Bangladesh

hPa	Frequency of positive fluxes	Frequency of negative fluxes	Frequency of zero fluxes	Total frequency	%Frequency of positive fluxes	%Frequency of negative fluxes	%Frequency of zero fluxes
1000	99	5	3	107	92.52	4.67	2.80
925	105	2	0	107	98.13	1.87	0.00
850	77	21	9	107	71.96	19.63	8.41
700	26	72	9	107	24.30	67.29	8.41
500	21	47	39	107	19.63	43.93	36.45
400	31	36	40	107	28.97	33.64	37.38
300	37	29	41	107	34.58	27.10	38.32
200	7	3	97	107	6.54	2.80	90.65
100	0	0	107	107	0.00	0.00	100.00

The maximum SFM over Dhaka at 0000 UTC on the dates of occurrence of nor'westers may be 199.4, 250.2, 196.9, 74.9, 23.6, 21.6 and 12.3 gm $kg^{-1} \times ms^{-1}$ at 1000, 925 850, 700, 500, 400, and 300 hPa levels respectively and then the fluxes become unimportant above. The maximum NFM over Dhaka at 0000 UTC may be -109.1, -163.5, -174.1, -74.4 and -31.0 gm $kg^{-1} \times ms^{-1}$ at 1000, 925, 850, 700 and 500 hPa levels respectively and then the

fluxes become unimportant above on the dates of occurrence of nor'westers in Bangladesh. Fig. 5.9 shows, as an example, the variation of maximum and minimum MFM with height. The maximum MFM are always southerly on the dates of occurrence of nor'westers.

The vertical profiles of the meridional fluxes of moisture over Dhaka at 0000 UTC on the dates of occurrence and non-occurrence of nor'westers in Bangladesh are studied and the variation is shown in Fig. 5.10 as an example. It has been found that the fluxes are mainly southerly and more southerly in the lower and middle troposphere on the dates of occurrence of nor'westers as compared to the fluxes on the dates of non-occurrence. The fluxes become nil in the upper troposphere.

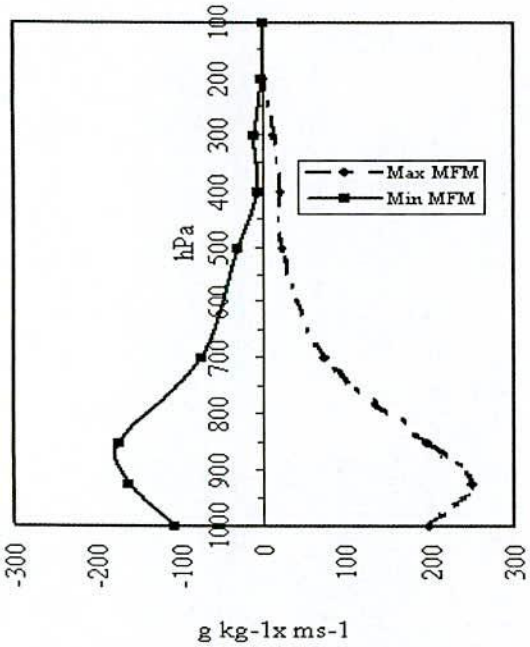

Fig. 5.9: Vertical variation of the maximum and minimum MFM (g kg^{-1} × ms^{-1}) over Dhaka at 0000 UTC on the date of occurrence of nor'westers over Bangladesh

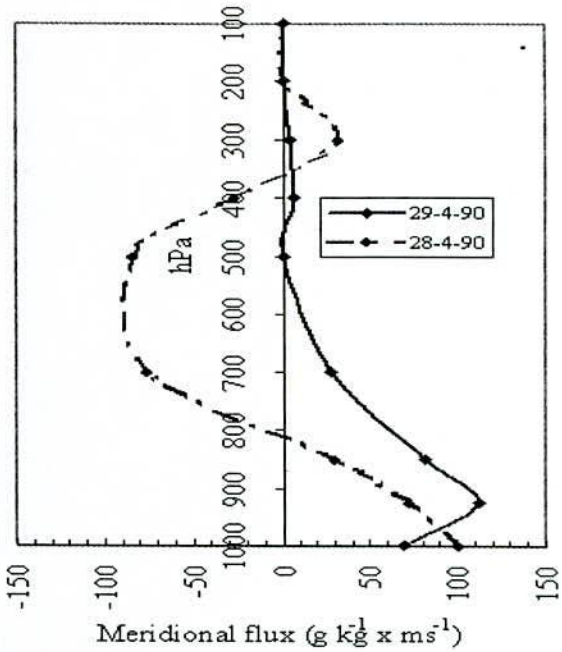

Fig. 5.10: Vertical profiles of the MFM (g kg^{-1} × ms^{-1}) over Dhaka at 0000 UTC on the date of occurrence (29 April 1990) and the date of non-occurrence (28 April 1990)

Above discussion substantiates that the SFM dominate in the troposphere from 1000 to 300-hPa level. The frequency of NFM is less in the lower troposphere having maximum frequency of northerly fluxes in the layer from 700 to about 300 hPa level. In the upper troposphere the MFM become nil in most of the cases. The fluxes are mainly southerly and more southerly in the lower and middle troposphere on the dates of occurrence of nor'westers as compared to the dates of non-occurrence.

5.4.2.3 Vertically integrated zonal and meridional fluxes of moisture over Dhaka

The ZFM and MFM, computed at different isobaric levels over Dhaka at 0000 UTC on the dates of occurrence of nor'westers, have been integrated from 1000 to 400 hPa level by taking the layer mean moisture flux. The vertically integrated ZFM and MFM for 107 nor'westers are shown in Fig. 5.11. This figure shows that the vertically integrated ZFM are much higher than that of the MFM.

The frequency of vertically integrated ZFM and MFM over Dhaka at 0000 UTC on the dates of occurrence of nor'westers in Bangladesh is given in Table 5.5. The table shows that the fluxes are westerly in 97.17% cases and easterly in 3 out of 106 nor'westers. About 83.96% westerly fluxes of moisture are in the range of (10 - 40)× 10^5 kg × ms^{-1} and 7.55% westerly fluxes are in the range of (40 - 60) × 10^5 kg × ms^{-1} on the dates of occurrence of nor'westers in Bangladesh. The vertically integrated MFM are northerly in 19.63% cases and southerly in 80.37% cases. About 39.25% MFM are in the range of (10 - 30) × 10^5 kg × ms^{-1} and 4.67% SFM are in the range of (30 - 50) × 10^5 kg × ms^{-1}.

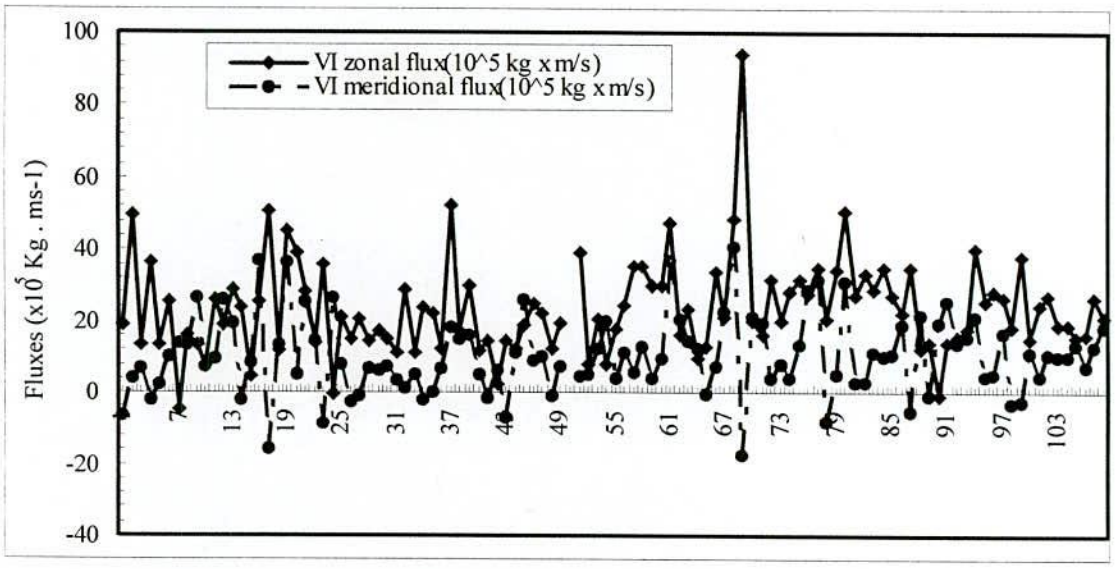

Fig. 5.11: Vertically integrated ZFM and MFM over Dhaka at 0000 UTC on the dates of occurrence of nor'westers in Bangladesh

The vertically integrated ZFM may vary from (-4.84 to 93.78)× 10^5 kg × ms^{-1} and the vertically integrated MFM may vary from (-17.63 to 40.85) × 10^5 kg × ms^{-1} over Dhaka at 0000 UTC on the dates of occurrence of nor'westers in Bangladesh.

Table 5.5: Frequency of vertically integrated ZFM and MFM over Dhaka at 0000 UTC on the dates of occurrence of nor'westers in Bangladesh

Range of fluxes ($\times 10^5$ kg×ms^{-1})	Frequency of vertically integrated ZFM	Frequency of vertically integrated MFM
-20 to -10	0	2
-10 to 0	3	19
0 to +10	6	39
+10 to +20	39	29
+20 to 30	35	13
+30 to +40	15	4
+40 to +50	5	1
+50 to +60	3	0
Total	106	107

5.4.2.4 Spatial distribution of the vertically integrated zonal and meridional fluxes of moisture

The spatial distribution of the vertically integrated ZFM from 925 to 400 hPa level over Bangladesh and its surrounding areas has been analyzed for several cases of nor'westers and one distribution is shown in Fig. 5.12 as an example. It has been found that vertically integrated WFM dominate over Bangladesh on most of the dates of occurrence of nor'westers and the gradient of fluxes is steep over the country. The range of the vertically integrated ZFM for the layer is about (2 - 12) × 10^5 kg × ms^{-1} over Bangladesh in most of the cases. A trough of WFM exists over Bihar, sub-Himalayan West Bengal and northwestern Bangladesh extending to southeastern Bangladesh as can be seen from Fig. 5.12.

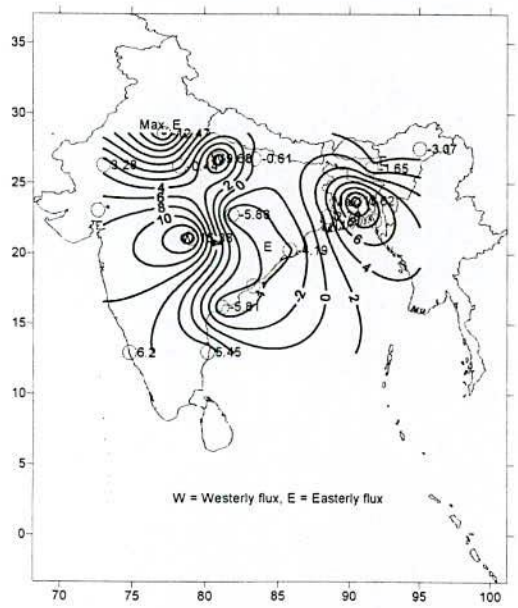

Fig. 5.12: Spatial distribution of vertically integrated ZFM at 0000 UTC on 14 May 1992 (date of occurrence) from 925 to 400 hPa ($\times 10^5$ kg × m/s)

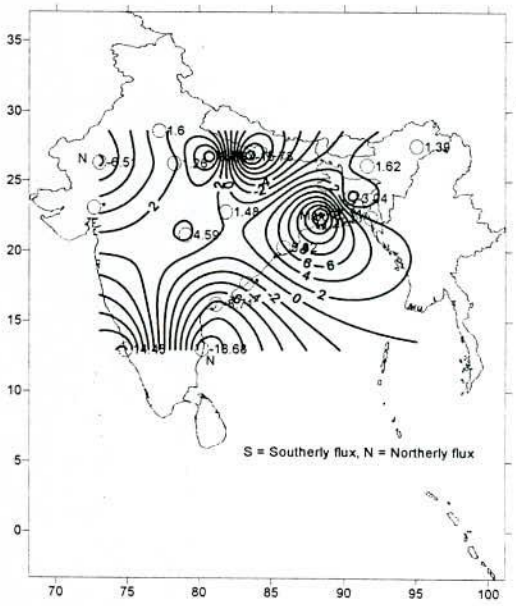

Fig. 5.13: Spatial distribution of vertically integrated MFM at 0000 UTC on 14 May 1992 (date of occurrence) from 925 to 400 hPa ($\times 10^5$ kg × m/s)

The spatial distribution of the vertically integrated MFM from 925 to 400 hPa level over Bangladesh and its surrounding areas has been analyzed for several cases of nor'westers and one distribution is shown in Fig. 5.13 as an example. It has been found that vertically integrated SFM dominate over south-southwestern and adjoining central parts of Bangladesh on the dates of occurrence of nor'westers and the gradient of fluxes is steep over the region. There exist NFM in the northwestern and northeastern parts of the country in many cases. The range of the vertically integrated meridional fluxes for the layer is about $(3 - 14) \times 10^5$ kg $\times$ ms^{-1} in most of the cases. A trough of WFM exists over Bihar, sub-Himalayan West Bengal and northwestern Bangladesh extending to southeastern Bangladesh as can be seen from Fig. 5.13.

CHAPTER 6

ENERGETICS OF THE TROPOSPHERE AND THEIR FLUXES IN RELATION TO NOR'WESTERS

6.1 Introduction

Thunderstorms occur most frequently in the humid continental regions of the tropics. Bangladesh falls in the humid region of the tropics. As a result, the country faces severe thunderstorms especially during the pre-monsoon season. These thunderstorms are known as nor'westers in Bangladesh. The thunderstorm clouds (i.e. cumulonimbus clouds) incur substantial vertical development where their tops usually reach well into the upper levels of the troposphere. However, most cumulonimbus cloud tops are restricted in height by the tropopause. As a norm, cumulonimbus tops reach between 35000 ft and 60000 ft; and when they penetrate the stratosphere their tops can reach 70, 000 ft (Krishnamurti, 2003). In order for a cumulonimbus to develop into a severe storm there needs to be a mechanism to maintain the core of rising air and protect it from the effects of the cold falling precipitation.

Rising air is lifted by an advancing squall line and results in a tilted updraft that is protected from the effects of falling precipitation. The development of severe storm clouds requires a strong feed of warm moist air into the base of the cloud and a contrasting feed of cooler air into the middle layers of the cloud. This mechanism is associated with the changes in the thermodynamic characteristics of the troposphere, especially the sensible heat and latent heat contents of the troposphere. To study the changes in these thermodynamic properties before the occurrence of severe thunderstorms/nor'westers is an important task for a meteorologist in order to predict nor'westers in a country like Bangladesh.

Because of the peculiar geographical location of Bangladesh, a number of nor'westers affect the country every year during the pre-monsoon season. These nor'westers incur loss of lives and properties in Bangladesh. These nor'westers are the manifestations of convective activity in the troposphere. This convective activity is a mechanism by which thermodynamic changes take place over Bangladesh and India during the pre-monsoon season. The

thermodynamic changes take place due to the build up of energy, moisture, their fluxes and different dynamical parameters.

In India-Bangladesh-Pakistan sub-continent, some works on nor'westers and local severe storms have been made by different authors such as Rai Sircar (1953), Koteswaram and Srinivasan (1958), Sen and Gupta (1961), De and Sen (1961), Nandi and Mukherjee (1966), Mukherjee and Bhattacharya (1972), Kumar (1972), Mukherjee *et al.* (1977), and Chowdhury and Karmakar (1986). It may be mentioned that these works are not related to the tropospheric energy. Chowdhury *et al.* (1991) studied some aspects of tropospheric energy in relation to nor'westers over Bangladesh by using data of one year only during March-May and studied a few cases only. They also studied some instability indices of the troposphere for these cases. Das *et al.* (1994) made an investigation on the synoptic conditions and other meteorological conditions associated with the formation, intensity and location of five local severe storms. But no extensive works have so far been made to study the changes in the thermodynamic properties prior to the occurrence of nor'westers in Bangladesh during the pre-monsoon season.

All over the world, different authors have made a lot of works on the computation of energy, moisture and their fluxes. Palmen *et al.* (1958) calculated the kinetic energy released by meridional circulation between the equator and 30°N. They computed the heat transfer and the eddy moisture flow and found that the northward eddy moisture flow is 0.2×10^{15} cal per sec. Henry and Hess (1958) developed methods for determining the contribution of each harmonic wave component to the geostrophic kinetic energy of meridional and zonal motion, and to the geostrophic fluxes of angular momentum and enthalpy. Hastenrath (1966) established the budgets of mechanical energy, latent heat, geopotential energy and sensible heat for the layers 1000-850, 850-700, 700-500 and 500-300 hPa, for both the Caribbean Sea and the Gulf of Mexico. He found that the terms of the mechanical energy are one or two orders of magnitude smaller than those of the other energy forms. According to him there is strong divergence of latent heat, concentrated in the layers 1000-850 hPa and 850-700 hPa over the Caribbean Sea during the winter half-year. Grubber (1970) studied the mean structure and energy budget over Florida Peninsula in order to assess the role played by convective processes in the vertical transfer of heat. He found that the net export of energy mainly in the 300-100 hPa layer. Alestalo and Holopainen (1980) computed the horizontal fluxes of energy at European aerological stations between the surface and 150 hPa level. All these studies of energy fluxes are of different regions and not of Bangladesh-India region and

the studies are not related to thunderstorms. Over the Bangladesh-India region, there are some studies related to the onset and withdrawal of southwest monsoon (Anjaneyulu, 1971; Keshavamurthy, 1968; Krishnamurthy, 1971; Chowdhury and Karmakar, 1980, 1981 and 1983; Karmakar, 1984). But no study has been made on the tropospheric fluxes of energy components related to nor'westers over this region.

In this chapter attempts have been made to study the sensible heat (SH), latent heat energy (LH), potential energy (PE), dry static energy (DSE) and moist static energy (MSE) of the troposphere and their variation over Dhaka before the occurrence of several nor'westers over Dhaka as well as Bangladesh with a view to find out some criteria for their occurrence. The results are likely to be useful in the forecasting of nor'westers.

Attempts have also been made to study the fluxes of energy components of the troposphere over Dhaka as well as its surrounding areas of India before the occurrence of several nor'westers in Bangladesh with a view to find out some criteria for their occurrence.

6.2 Data used

i) Source: Bangladesh Meteorological Department (BMD).

ii) Station: Dhaka and some Indian stations.

iii) Data: Real time rawinsonde data of 0000 UTC at different isobaric heights from 1000 to 100 hPa at Dhaka, Chittagong and different Indian stations have been collected from the Storm Warning Centre (SWC) of Bangladesh Meteorological Department. SWC received these data on real time basis through GTS-Link. For frequency analysis of different fluxes of moisture and energy components, only the data at Dhaka has been considered and for spatial distribution all the available data of 26 stations have been considered. The stations under study are shown in Fig. 6.1. It may be mentioned that data of all the 26 stations were not available on the dates of occurrence of nor'westers.

iv) Period :March through May during 1990 through 1995.

v) Nor'westers: Nor'westers, which occurred in Bangladesh during the pre-monsoon season of 1990-'95 (108 cases).

In some cases, rawinsonde data were not available at one/two levels. In those cases, number of data is less than 108.

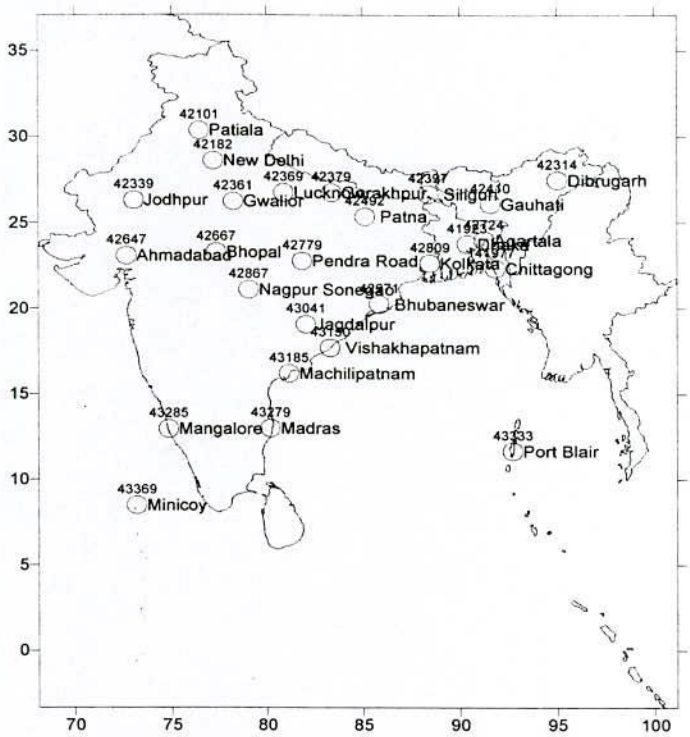

Fig. 6.1: Location of the Rawinsonde Stations under study

6.3 Basic considerations

6.3.1 Energetics of the troposphere

Using the thermodynamic and hydrodynamic equations, the temperature, moisture, geopotential height in geopotential meter and velocity fields may be combined to obtain the equation for total energy of the troposphere. The total energy per unit mass of air may be expressed as

$$E_T = C_pT + gZ + Lq + \tfrac{1}{2}V^2 \qquad (1)$$

Where C_p is the specific heat of air at constant pressure, T the temperature in °K, gZ the potential energy, L the latent heat of phase change, q the specific humidity and V the scalar velocity. The kinetic energy term is normally two orders of magnitude smaller than the other terms and may be neglected. The first term (C_pT) is known as sensible heat energy per unit mass, the second term (gZ) is known as potential energy per unit mass and the third term (Lq) is known as the latent heat energy per unit mass. The sum of the first two terms is

known as Dry Static Energy (DSE) and the sum of the first three terms of Equation (1) is known as Moist Static Energy (MSE). Therefore,

Sensible heat energy (SH) per unit mass	$= C_pT$	(2)
Latent heat energy (LH) per unit mass	$= Lq$	(3)
Potential energy (PE) per unit mass	$= gZ$	(4)
Dry static energy (DSE) per unit mass	$= C_pT + gZ$	(5)
Moist static energy (MSE) per unit mass	$= C_pT + gZ + Lq$	(6)

These energy components are expressed in Joule/gm. The latent heat of phase change (L) is a function of air temperature and is given by

$$L = 597.3 - 0.566\ (T-273) \text{ in Cal/gm} \tag{7}$$

The specific humidity (q) can be computed by using the equation:

$$q = \frac{0.62197 \times e}{(P - 0.37803 \times e)} \tag{8}$$

Where e is the actual vapour pressure (hPa) and can be obtained from the Clausius-Clapeyron equation:

$$\ln\frac{e}{6.11} = \frac{18 \times 4.186 \times L}{8.3144}\left(\frac{1}{273} - \frac{1}{T_d}\right) \tag{9}$$

Where T_d is the dew-point temperature in °K.

6.3.2 Fluxes of energy components

Since DSE and MSE have the major contributions to the total atmospheric energy, their zonal and meridional fluxes with their vertical and spatial distributions are studied during the study period. The zonal fluxes of energy components are the products of the energy components and the zonal wind component. Similarly, the meridional fluxes of energy components are the products of energy components and the meridional wind component. These are given by:

$$F_1 = \left(C_pT + gZ\right)u \tag{10}$$

$$F_2 = (C_pT + gZ + Lq).u \tag{11}$$

$$H_1 = (C_pT + gZ).v \tag{12}$$

$$H_2 = (C_pT + gZ + Lq).v \tag{13}$$

Where F_1 and F_2 are the zonal fluxes of dry static energy (ZFDSE) and moist static energy (ZFMSE), and H_1 and H_2 are the meridional fluxes of dry static energy (MFDSE) and moist static energy (MFMSE), respectively. The units of the fluxes are Joulegm^{-1} × ms^{-1}.

6.3.3 Vertically integrated fluxes of energy components

The vertically integrated zonal and meridional fluxes of DSE and MSE can be computed by using the equations:

$$\text{Vertically integrated ZFDSE} = -\frac{1}{g}\int_{P_1}^{P_2}(C_pT + gZ).udp \tag{14}$$

$$\text{Vertically integrated MFDSE} = -\frac{1}{g}\int_{P_1}^{P_2}(C_pT + gZ).vdp \tag{15}$$

$$\text{Vertically integrated ZFMSE} = -\frac{1}{g}\int_{P_1}^{P_2}(C_pT + gZ + Lq).udp \tag{16}$$

$$\text{Vertically integrated MFMSE} = -\frac{1}{g}\int_{P_1}^{P_2}(C_pT + gZ + Lq).vdp \tag{17}$$

The integration has been done by taking the layer mean values of the fluxes of DSE and MSE from 1000 to 100 hPa level over Dhaka and for spatial distribution from 925 to 100 hPa level. Here 925 hPa has been taken because the surface pressure becomes less than 1000 hPa level in most of the stations during the pre-monsoon season. The units of the integrated fluxes are in kJ×m^{-1}s^{-1}.

6.4 Results and discussion

The daily rawinsonde observations at 0000 UTC over Dhaka from March to May during 1990 through 1995 have been compiled for the standard isobaric heights from the surface to 100 hPa level. The data have been computerized and computer programs have been made to compute the different energy components of the troposphere over Dhaka. The output

results have been used to compute the daily, weekly and monthly mean values of the energy components for 6 years (1990-1995). These mean values for 6 years have been treated as the daily, weekly and monthly normal in this study. The energy components such as SH, LH, PE, DSE and MSE on the dates of occurrence of several nor'westers, which occurred over Dhaka as well as in Bangladesh during the pre-monsoon season of 1990-95, have been compared with the daily, weekly and monthly normal values as well as the normal values of the previous week. Comparison of the above energy components between the dates of occurrence and non-occurrence of several nor'westers has also been made in the present study. The SH, LH, PE, DSE and MSE on the dates of occurrence of several nor'westers over Bangladesh have been compared with the normal values of the previous week. The maximum and minimum values of the energy components at each level of the troposphere over Dhaka for several cases of nor'westers have been picked up and studied graphically for obtaining a criterion for the occurrence of nor'westers. The results have been discussed in the subsequent sub-sections.

6.4.1 Sensible heat content (SH) of the troposphere

6.4.1.1 SH of the troposphere over Dhaka at 0000 UTC during the pre-monsoon season

The vertical cross-section of the SH of the troposphere over Dhaka at 0000 UTC has been studied for the pre-monsoon season. The vertical distribution pattern is shown in Fig. 6.2. The figure shows that the SH of the troposphere decreases with height for obvious reason as the temperature decreases with height.

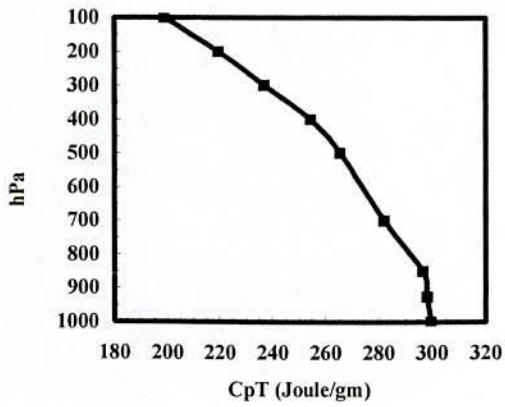

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Fig. 6.2: Vertical cross-section of SH on 23 March 1990 (date of occurrence) over Dhaka at 0000 UTC

Table 6.1: Monthly variation of SH (Joule/gm) of the troposphere over Dhaka at 0000 UTC during the pre-monsoon season

hPa	March	April	May
1000	296.52	298.98	300.05
925	294.18	297.46	297.73
850	290.62	294.75	295.28
700	279.78	282.16	284.40
500	264.18	265.19	268.44
400	252.86	254.02	258.48
300	237.24	239.89	244.42
200	221.06	221.64	223.68
100	199.62	199.31	196.80

During the pre-monsoon season, mean monthly SH of the troposphere has been computed by using the data for the period 1990-1995 and the results are given in Table 6.1. The table shows that the SH of the troposphere increases as the season progresses for obvious reason.

6.4.1.2 Comparison of the SH of the troposphere over Dhaka at 0000 UTC on the dates of occurrence and non-occurrence of nor'westers

The SH of the troposphere over Dhaka at 0000 UTC on the dates of occurrence and non-occurrence of nor'westers has been compared with each other. The vertical cross-section of the difference in SH on the dates of occurrence and non-occurrence has been studied, and some results are shown in Figs. 6.3-6.5.

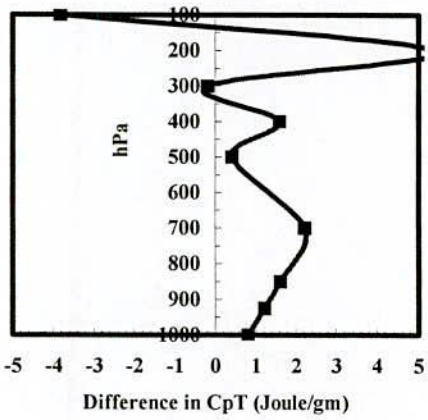


Fig. 6.3: Vertical cross-section of the difference in SH on 23 March (date of occurrence) and 22 March (date of non-occurrence) 1990 over Dhaka at 0000 UTC

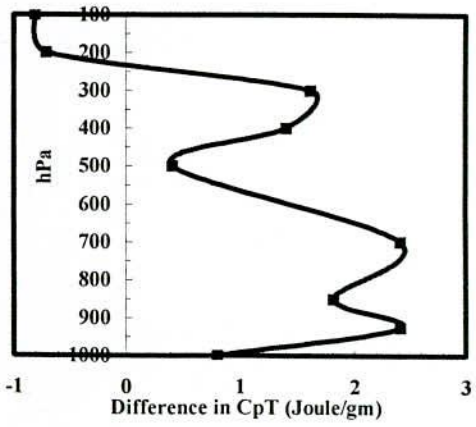


Fig. 6.4: Vertical cross-section of the difference in sensible heat on 7 April (date of occurrence) and 6 April (date of non-occurrence) 1995 over Dhaka at 0000 UTC

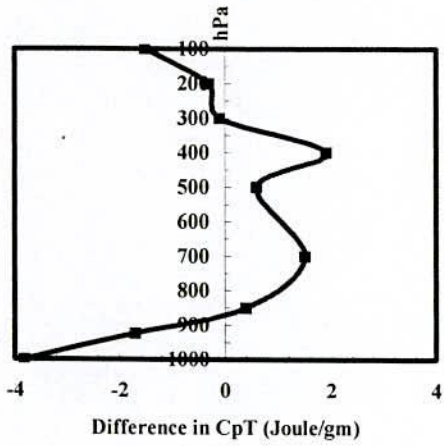


Fig. 6.5: Vertical cross-section of the difference in SH on 10 March (date of occurrence) and 9 March (date of non-occurrence) 1990 over Dhaka at 0000 UTC

It has been found that the SH of the troposphere on the dates of occurrence of nor'westers increases significantly from near the surface to about 300-200 hPa in most of the cases, although it has inter-layer variations. Of course, there are some exceptions especially in the lower troposphere near the surface as can be seen from Fig. 6.5, where there exists decrease in SH of the troposphere at 0000 UTC. These exceptions may be due to the decrease in temperature on some occasions near the surface in the early morning because of cold air advection from the north/northwest.

6.4.1.3 Comparison of the SH of the troposphere over Dhaka at 0000 UTC on the dates of occurrence of nor'westers with the weekly normal

The SH of the troposphere over Dhaka at 0000 UTC on the dates of occurrence of nor'westers has been compared with the weekly normal. The vertical cross-section of the deviation of SH on the dates of occurrence from the weekly normal has been studied and some results are shown in Figs. 6.6-6.7.

It has been found that the SH of the troposphere on the dates of occurrence of nor'westers increases significantly as compared to the weekly normal from near the surface to about 300-200 hPa or more in most of the cases, although it has inter-layer variations. The deviation of SH decreases and becomes normal or negative in the layer between 700 and 500 hPa levels. This may be due to the decrease in temperature in the early morning because of cold air advection from the north/northwest. This cold air advection in this layer from the

north/northwest is very essential to create the required instability for the formation of thunderstorms in conjunction with the warm and moist air advection in the lower troposphere.

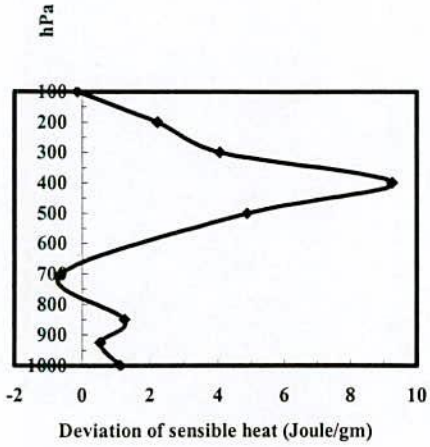


Fig. 6.6: Vertical profile of the deviation of SH of the troposphere over Dhaka at 0000 UTC on 10 April 1990 (date of occurrence) from the weekly normal

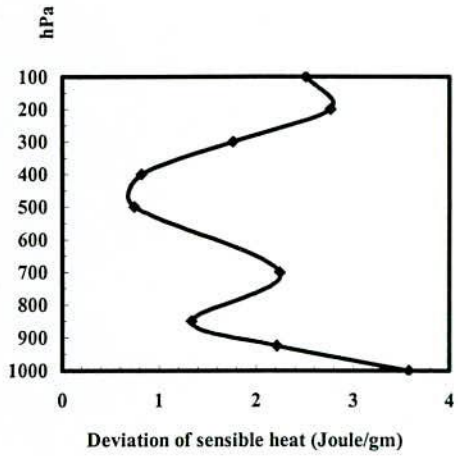


Fig. 6.7: Vertical profile of the deviation of SH of the troposphere over Dhaka at 0000 UTC on 16 May 1992 (date of occurrence) from the weekly normal

6. 4.1.4 Comparison of the SH of the troposphere over Dhaka at 0000 UTC on the dates of occurrence of nor'westers with the monthly normal

The SH of the troposphere over Dhaka at 0000 UTC on the dates of occurrence of nor'westers has been compared with the monthly normal. The vertical cross-section of the deviation of SH on the dates of occurrence from the monthly normal has been studied and the vertical variation pattern is shown in Fig. 6.8 as an example.

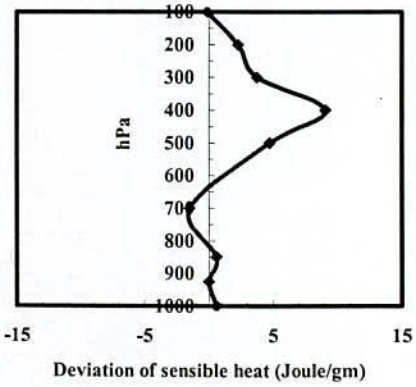


Fig. 6.8: Vertical profile of the deviation of SH of the troposphere over Dhaka on 10 April (date of occurrence) from the monthly normal

It has been seen that the deviation of SH from the monthly normal is positive in the lower troposphere and then it becomes negative in the layer between 850 and 650 hPa levels. Then the deviation increases tremendously in the upper troposphere, having maximum in the layer 400-300 hPa. The negative value in the layer between 850 and 650 hPa levels may be attributed to the cold air advection.

6.4.2 Latent heat (LH) content of the troposphere

6.4.2.1 LH of the troposphere over Dhaka at 0000 UTC during the pre-monsoon season

The vertical cross-section of the LH of the troposphere over Dhaka at 0000 UTC has been studied for the pre-monsoon season. The vertical distribution pattern is shown in Fig. 6.9. The figure shows that the LH of the troposphere decreases with height for obvious reason as the moisture decreases with height. The LH of the troposphere becomes nil at 100 hPa level.

During the pre-monsoon season, mean monthly LH of the troposphere has been computed by using the data for the period 1990-1995 and the results are given in Table 6.2. The table shows that the LH of the troposphere increases as the season progresses for obvious reason. The table also shows that more LH extends up to the top layer of the troposphere as the season progresses.

Table 6.2: Monthly variation of LH (Joule/gm) of the troposphere over Dhaka at 0000 UTC during the pre-monsoon season

hPa	Latent heat (Joule/gm)		
	March	April	May
1000	30.22	38.52	41.90
925	21.56	26.02	34.03
850	15.60	17.10	25.23
700	8.24	10.15	14.37
500	1.89	2.25	3.55
400	0.86	1.03	1.62
300	0.17	0.29	0.53
200	0.006	0.010	0.024
100	0.00	0.00	0.000

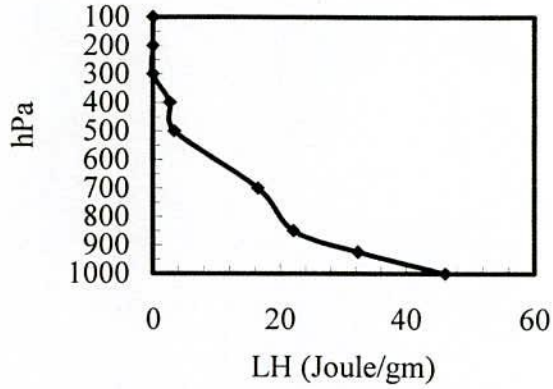


Fig. 6.9: Vertical cross-section of LH on 23 March 1990 over Dhaka at 0000 UTC

6.4.2.2 Comparison of the LH of the troposphere over Dhaka at 0000 UTC on the dates of occurrence and non-occurrence of nor'westers

The LH of the troposphere over Dhaka at 0000 UTC on the dates of occurrence and non-occurrence of nor'westers has been compared with each other. The vertical cross-section of the difference in LH on the dates of occurrence and non-occurrence has been studied, and some results are shown in Figs. 6.10-6.12.

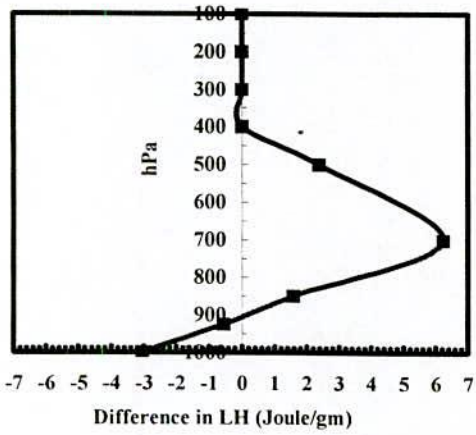


Fig. 6.10: Vertical cross-section of the difference in LH on 10 March (date of occurrence) and 9 March (date of non-occurrence) 1990 over Dhaka at 0000 UTC

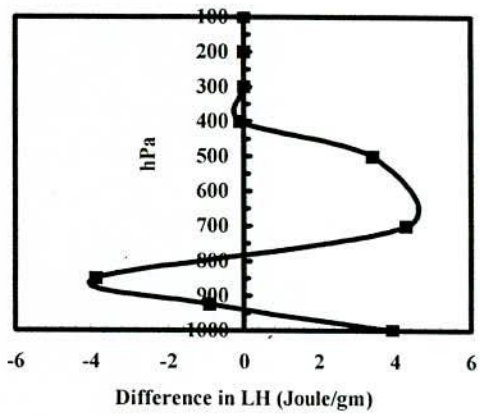


Fig. 6.11: Vertical cross-section of LH on 23 March (date of occurrence) and 22 March (date of non-occurrence) 1990 over Dhaka at 0000 UTC

It has been found that the LH of the troposphere on the dates of occurrence of nor'westers increases significantly from 900 to about 400 hPa or more in most of the cases, although it has inter-layer variations. Of course, there are some exceptions especially in the

lower troposphere as can be seen from figures, where there exists decrease in LH of the troposphere at 0000 UTC. These exceptions may be due to the availability of less moisture in the lower atmosphere on some occasions early in the morning. But there is a significant increase in LH above 900 or 850-hPa level, which extends up to about 400-hPa level. This may be attributed to the LH release due to condensation of moisture near the base of the thunderstorm clouds on the date of occurrence of nor'westers.

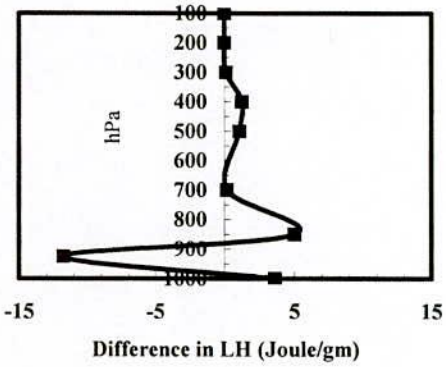


Fig. 6.12: Vertical cross-section of the difference in LH on 7 April (date of occurrence) and 6 April (date of non-occurrence) 1995 over Dhaka at 0000 UTC

6.4.2.3 Comparison of the LH of the troposphere over Dhaka at 0000 UTC on the dates of occurrence of nor'westers with the weekly normal latent heat

The LH of the troposphere over Dhaka at 0000 UTC on the dates of occurrence of nor'westers has been compared with the weekly normal. The vertical cross-section of the deviation of LH on the dates of occurrence from the weekly normal has been studied and some results are shown in Figs. 6.13-6.14.

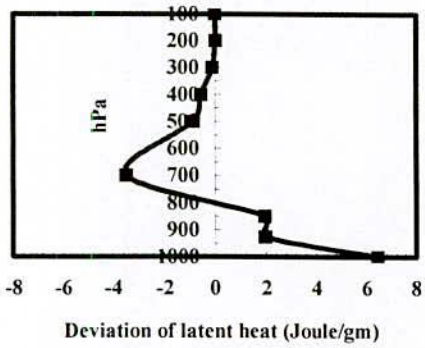


Fig. 6.13: Vertical profile of the deviation of LH of the troposphere over Dhaka on 30 May 1992 (date of occurrence) from the weekly normal

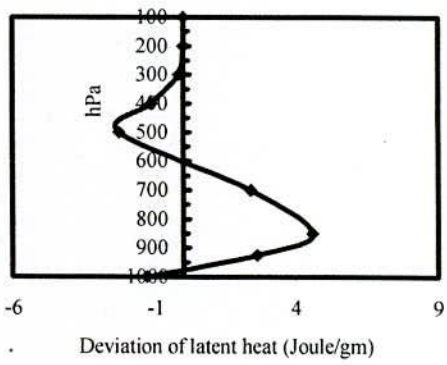


Fig. 6.14: Vertical profile of the deviation of LH of the troposphere over Dhaka on 26 March 1993 (date of occurrence) from the weekly normal

It has been found that the LH of the troposphere on the dates of occurrence of nor'westers increases significantly as compared to the weekly normal in the lower troposphere in most of the cases, although it has inter-layer variations. The deviation of LH decreases and becomes normal or negative in the mid-troposphere. This may be due to the non-availability of moisture and delay of condensation process in the early morning.

6.4.2.4 Comparison of the LH of the troposphere over Dhaka at 0000 UTC on the dates of occurrence of nor'westers with the monthly normal

The LH of the troposphere over Dhaka at 0000 UTC on the dates of occurrence of nor'westers has been compared with the monthly normal. The vertical cross-section of the deviation of LH on the dates of occurrence from the monthly normal has been studied and the vertical variation pattern is shown in Fig. 6.15 as an example.

It has been found that the deviation of LH from the monthly normal is positive and significantly above the monthly normal in the lower troposphere, and then it becomes negative in the mid-troposphere. It becomes nil in the upper troposphere.

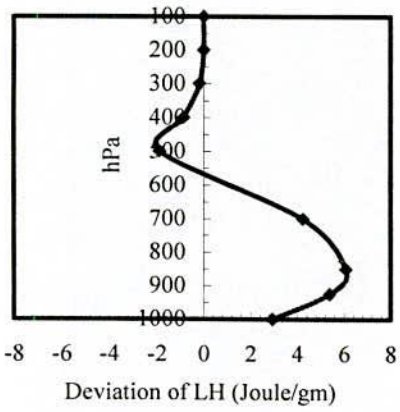


Fig. 6.15: Vertical profile of the deviation of LH of the troposphere over Dhaka on 26 March 1993 (date of occurrence) from the monthly normal

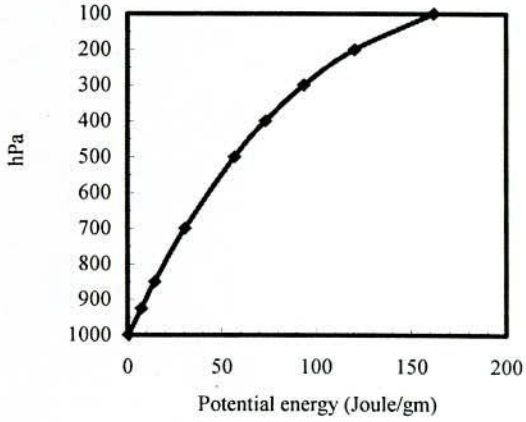


Fig. 6.16: Vertical variation of PE on 23 March 1990 over Dhaka at 00 UTC

6.4.3 Potential energy (PE) of a parcel in the troposphere

6.4.3.1 PE of a parcel of air in the troposphere over Dhaka at 0000 UTC during the pre-monsoon season

The vertical cross-section of the PE of a parcel in the troposphere over Dhaka at 0000 UTC has been studied for the pre-monsoon season. The vertical distribution pattern is

shown in Fig. 6.16. It has been found that the PE of a parcel in the troposphere increases with height for obvious reason.

During the pre-monsoon season, mean monthly PE of a parcel in the troposphere has been computed by using the data for the period 1990-1995 and the results are given in Table 6.3. The table shows that the PE of a parcel decreases in the lower troposphere up to about mid-troposphere and then increases in the upper troposphere. This indicates that contour height decreases in the lower troposphere and increases in the upper troposphere as the season progresses. The decrease in contour height in the lower troposphere is related with the decrease in surface pressure with the advance of the season.

Table 6.3: Monthly variation of PE of a parcel of air in the troposphere over Dhaka at 0000 UTC during the pre-monsoon season

hPa	PE (Joule/gm)		
	March	April	May
1000	0.88	0.63	0.41
925	7.54	7.36	7.15
850	14.69	14.57	14.37
700	30.56	30.66	30.56
500	56.78	56.75	57.15
400	72.90	73.58	74.00
300	93.02	93.43	94.70
200	120.19	120.62	121.88
100	161.64	162.13	163.22

6.4.3.2 Comparison of the PE of a parcel of air in troposphere over Dhaka at 0000 UTC on the dates of occurrence and non-occurrence of nor'westers

The PE at different levels of the troposphere over Dhaka at 0000 UTC on the dates of occurrence of nor'westers in Bangladesh has been compared with that on the dates of non-occurrence of nor'westers (usually one day before) and some results showing the difference in PE between the two dates are given in Figs. 6.17 (a-d).

It has been found that the PE has a decreasing tendency near the surface on the dates of occurrence of nor'westers in many cases and then it shows erratic behaviour in the vertical.

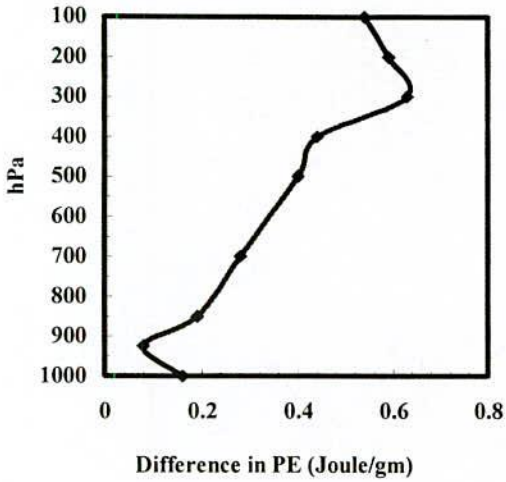


Fig. 6.17 (a): Vertical profile of the difference in PE on 10 March (date of occurrence) and 9 March (date of non-occurrence) 1990 over Dhaka at 0000 UTC

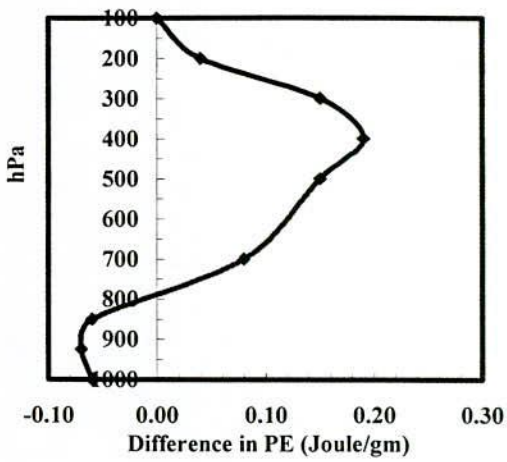


Fig. 6.17 (b): Vertical profile of the difference in PE on 30 March (date of occurrence) and 29 March (date of non-occurrence) 1995 over Dhaka at 0000 UTC

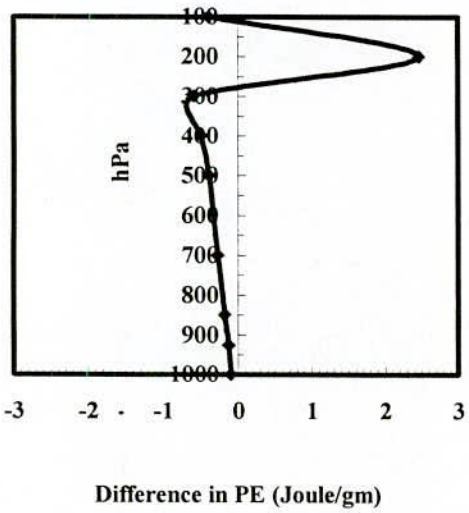


Fig. 6.17 (c): Vertical profile of the difference in PE on 17 April (date of occurrence) and 16 April (date of non-occurrence) 1994 at 0000 UTC over Dhaka

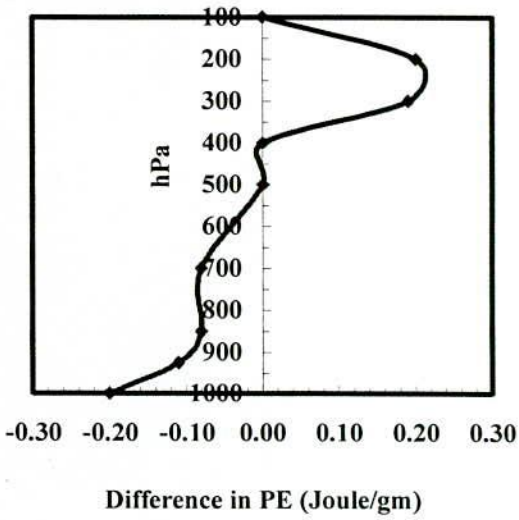


Fig. 6.17 (d): Vertical profile of the difference in PE on 20 April (date of occurrence) and 19 April (date of non-occurrence) 995 over Dhaka at 0000 UTC

6.4.3.3 Comparison of the PE of a parcel of air in troposphere over Dhaka at 0000 UTC on the dates of occurrence of nor'westers with the weekly normal PE

The PE of a parcel of air in the troposphere over Dhaka at 0000 UTC on the dates of occurrence of nor'westers has been compared with the weekly normal potential energy. The vertical cross-section of the deviation of PE on the dates of occurrence from the weekly

normal has been studied and result is shown in Fig. 6.18 as an example. It has been found that the variation of PE is minimum in the lower atmosphere and does not show any definite trend (either above normal or below normal) onwards.

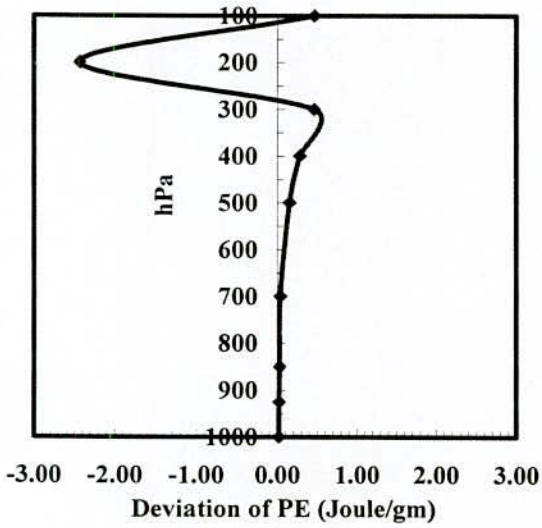


Fig. 6.18: Vertical cross-section of the deviation of PE on 17 April (date of occurrence) 1994 from the weekly normal over Dhaka at 0000 UTC

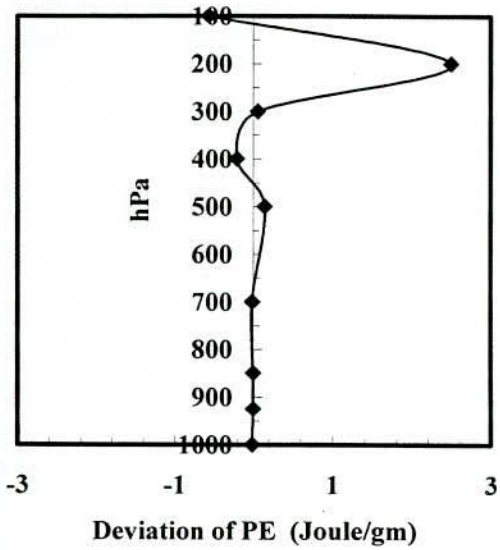


Fig. 6.19: Vertical cross-section of the deviation in PE on 17 April (date of occurrence) 1994 from the monthly normal at 0000 UTC over Dhaka

Table 6.4 gives the comparison of PE with the weekly normal potential energy for about 108 cases. It is seen that the PE is below normal at 1000 hPa level in 54.21% cases and it is normal or above normal from 925 to 500 hPa level in many cases. Then there is no definite trend of variation in PE in the upper troposphere.

Table 6.4: Comparison of PE over Dhaka at 0000 UTC on the dates of occurrence of nor'westers in Bangladesh with that of the weekly normal

hPa	Cases above weekly normal	Cases below weekly normal	Total cases	%Frequency of above weekly normal	%Frequency of below weekly normal
1000	49	58	107	45.79	54.21
925	54	54	108	50.00	50.00
850	55	53	108	50.93	49.07
700	62	46	108	57.41	42.59
500	60	48	108	55.56	44.44
400	51	57	108	47.22	52.78
300	54	54	108	50.00	50.00
200	49	59	108	45.37	54.63
100	55	52	107	51.40	48.60

6.4.3.4 Comparison of the PE of a parcel of air in troposphere over Dhaka at 0000 UTC on the dates of occurrence of nor'westers with the monthly normal PE

The PE of a parcel of air in the troposphere over Dhaka at 0000 UTC on the dates of occurrence of nor'westers has been compared with the monthly normal PE. The vertical cross-section of the deviation of PE on the dates of occurrence from the monthly normal has been studied and result is shown in Fig. 6.19 as an example. It has been found that the variation of PE is minimum in the lower atmosphere and does not show any definite trend (either above monthly normal or below monthly normal).

Table 6.5: Comparison of PE over Dhaka at 0000 UTC on the dates of occurrence of nor'westers in Bangladesh with that of the monthly normal

hPa	Cases above monthly normal	Total cases	%Frequency of above monthly normal
1000	51	107	47.66
925	56	108	51.85
850	56	108	51.85
700	62	108	57.41
500	62	108	57.41
400	51	108	47.22
300	46	108	42.59
200	39	108	36.11
100	54	107	50.47

Table 6.5 gives the comparison of PE with the monthly normal PE for about 108 cases. It is seen that the PE is below normal at 1000 hPa level in 52.34% cases and it is above normal from 925 to 500 hPa level in many cases. Then the PE becomes below monthly normal in many cases up to 200-hPa level.

6.4.4 Dry static energy and moist static energy contents of the troposphere

6.4.4.1 Vertical distribution of monthly normal DSE and MSE components over Dhaka during the pre-monsoon season

The vertical profiles of monthly normal DSE and MSE of the troposphere over Dhaka are shown in Figs. 6.20(a-b) respectively. It can be seen from Fig. 6.20 (a) that the DSE increases with height for obvious reason and also increases from one month to another at all levels up to 200 hPa or more.

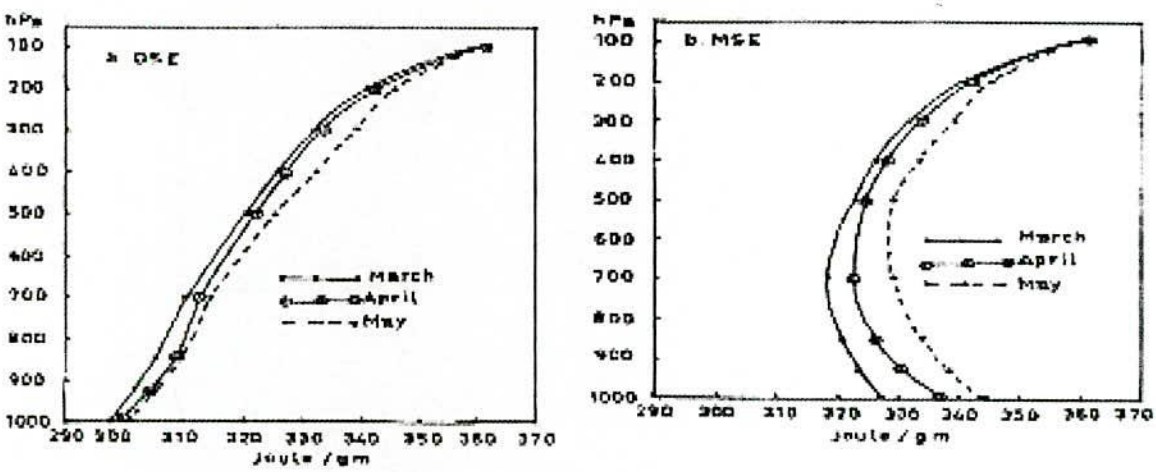


Fig. 6.20 (a-b): Vertical profiles of monthly normal (a) DSE and (b) MSE at 0000 UTC over Dhaka during the pre-monsoon season

In April, the increase in DSE is significant in the lower troposphere below 700 hPa whereas the increase is significant from 850 hPa to 300 hPa in May with respect to that in March. This may be attributed to the increase in SH due to increased seasonal temperature and connective activities. The MSE decreases with height from surface to 700-hPa level and then increases again up to the top of the troposphere [Fig. 6.20 (b)]. The minimum value of MSE at 700 hPa is due to the conditional instability of the troposphere in the tropics. The seasonal trend in the vertical distribution of MSE also indicates that the MSE increases significantly at all levels up to 200 hPa or more from one month to another. This increase in MSE is due to the increase in SH and release of more LH in the troposphere, which is related to the more influx of moisture from the south and its upward transport.

6.4.4.2 Comparison of DSE and MSE components on the dates of occurrence of nor'westers with the normals

6.4.4.2.1 Dry static energy (DSE) - The DSE of each layer from the surface to 100 hPa over Dhaka on the dates of occurrence of 79 nor'westers which occurred at Dhaka has been compared with the monthly, weekly and daily normals. The number and percentage number of cases in respect of the increase and decrease in DSE are given in Table 6.6

Table 6.6 shows that the DSE on the dates of occurrence of nor'westers over Dhaka increases in maximum cases at the surface, 850, 700 and 100 hPa level as compared to the 6-yearly monthly normal values. These increases occur in 53.16, 53.16, 63.16 and 67.09% cases of nor'westers at those levels respectively. The cases of increase in DSE at other levels range from 36.71 to 48.10% having the minimum number at 300-hPa level. The increase in DSE is

mainly due to the increase in SH of the troposphere. As compared to the monthly normal, the DSE decreases in 55.13, 54.43, 54.43, 56.96, 63.29 and 50.63% cases of nor'westers at 1000, 925, 500, 400, 300 and 200 hPa levels respectively. The decrease in DSE at 1000 and 925 hPa levels may be due to the presence of relatively colder air in the morning in absence of the sunlight. In studying 79 cases, it has been found that nor'westers have occurred on many consecutive days in many occasions. In each occasion, there has been increase in DSE in almost all levels on the starting day followed by decrease at almost each level on the subsequent days. This is for obvious reason that the nor'westers generally occur in the afternoon/evening/night and after that occurrence, there exists no source of energy or insolation up to 0000 UTC of the next day. As a result, the DSE remains less at 0000 UTC on the subsequent days of occurrence as compared to the previous weekly normal DSE. As the earth's surface receives sun's insolation with the progress of daytime, energy is assumed to be accumulated in the troposphere thereby creating a favourable condition i.e. instability for the occurrence of nor'westers provided that there must be favourable synoptic conditions and upper air circulation up to a reasonable height. The decrease in DSE occurs in more than 50% cases (i.e. 54.43-63.29%) in the layer 500-300 hPa, which is mainly due to the cold air advection in the middle and adjoining upper troposphere. This cold air advection in the middle and adjoining upper troposphere is necessary in producing the required instability for the occurrence of nor'westers when warm and moist air advection takes place in the lower troposphere as the sun's heating increases with time. Since the increase in DSE in the lower troposphere does not occur in 100% of the cases, the another reason for the corresponding decrease in DSE may be due to the presence of low pressure area where the geopotential height is relatively low and as a result the PE becomes lower which can not be compensated by the increase in SH of the troposphere.

From the comparison of DSE on the dates of occurrence of nor'westers at Dhaka with 6-yearly weekly normal, it can be seen that the DSE increases in 50.63, 50.00, 57.50 and 56.96% of the cases of nor'westers at the surface, 1000, 700 and 100 hPa levels respectively. The increase in DSE at other levels ranges from 40.51 to 49.37% cases. In contrast, the decrease in DSE occurs in maximum cases of 54.43, 55.70, 54.43 and 59.49% at 925, 500, 400 and 300 hPa levels respectively. At other levels, the decrease in DSE ranges from 43.04 to 51.90% cases.

As compared to the daily normal, the DSE increases in 50.00, 53.16 and 54.43/% cases of nor'westers at 1000, 700 and 100 hPa levels respectively (Table 6.6). The increase in

DSE ranges from 35.44 to 46.84% cases at other levels, the minimum being 35.44% cases at 300-hPa level where the decrease occurs in 64.56% cases i.e. the maximum cases.

Table 6.6: Comparison of DSE over Dhaka on the dates of occurrence of nor'westers at Dhaka with the monthly normal, weekly normal and daily normal

Level (hPa)	Cases of nor'westers studied	Monthly normal		Weekly normal		Daily normal	
		Increase in DSE (% cases)	Decrease in DSE (% cases)	Increase in DSE (% cases)	Decrease in DSE (% cases)	Increase in DSE (% cases)	Decrease in DSE (% cases)
Surface	79	53.16	46.84	50.63	49.37	45.57	54.43
1000	78	44.78	55.13	50.00	50.00	50.00	50.00
925	79	45.57	54.43	45.57	54.43	43.04	55.70
850	79	53.16	46.84	48.10	51.90	46.84	53.16
700	78	63.29	36.71	57.50	41.77	53.16	45.57
500	79	45.57	54.43	43.75	55.70	45.57	54.43
400	79	43.04	56.96	45.57	54.43	44.33	55.70
300	79	36.71	63.29	40.51	59.49	35.44	64.56
200	79	48.10	50.63	49.37	50.63	44.30	55.70
100	79	67.09	32.91	56.96	43.04	54.43	45.57

All the results substantiate that the increase in DSE occurs in most cases at 700 hPa level in the lower troposphere and at 100 hPa level in the upper troposphere whereas the decrease in DSE occurs in maximum cases at 300 hPa level as compared to the monthly, weekly and daily normals prior to the occurrence of nor'westers

6.4.4.2.2 Moist static energy (MSE) - The increase and decrease in MSE of the troposphere over Dhaka on the dates of occurrence of nor'westers at Dhaka from the monthly, weekly and daily normals are given in Table 6.7. The table shows that there are increase in MSE from the monthly normal starting from 1000 to 700 hPa level in most of the cases having the maximum value (69.62% of cases) at 925 hPa level followed by a decrease in the layer 500-200 hPa having the decrease in 67.09, 65.82, 63.29 and 54.43 % of cases at 500, 400, 300 and 200 hPa levels respectively. The MSE increases again in 67.09 % of cases at 100-hPa level. The increase in MSE in the lower troposphere is mainly due to the contribution of LH. This means that the increase in MSE takes place within the boundary layer where condensation of moisture takes place and cloud formation starts. The decrease in MSE at 500 hPa and above can be attributed to the dry and cold air advection from the north. At 100 hPa level, the increase in MSE is mainly due to the contribution of SH.

The MSE of the troposphere over Dhaka on the dates of occurrence of nor'westers at Dhaka increases in most of the cases in the lower troposphere as compared to the weekly normal MSE having the maximum of 75.64% cases at 925-hPa level. The increase in MSE occurs in 51.28, 53.25, 75.64, 66.67 and 61.54% of cases at the surface, 1000, 925, 850 and 700 hPa levels respectively. Then the decrease in MSE occurs in most of the cases in the layer 500-200 hPa having 60.26, 62.82, 58.97 and 50.00% of cases at 500, 400, 300 and 200 hPa levels respectively. This decrease in MSE is followed by an increase in 56.41% of cases at 100-hPa level.

The comparison of MSE of the troposphere over Dhaka on the dates of occurrence of nor'westers at Dhaka with the daily normal MSE (Table 6.7) also shows that the increase in MSE occurs in most of the cases starting from the surface to 700 hPa level having the increase in maximum cases of 76.92% at 925 hPa level - the top of the boundary layer. The increase in MSE occurs in 50.00, 57.14, 76.92, 66.67 and 61.54% cases at the surface, 1000, 925, 850 and 700 hPa levels respectively. Increase in MSE also occurs in 55.13% of cases at 100 hPa level as compared to the daily normal. In the layer 500-200 hPa, the MSE decreases in most of the cases having 57.69, 57.69, 62.82 and 53.85% of cases at 500, 400, 300 and 200 hPa levels respectively.

Table 6.7: Comparison of MSE over Dhaka on the dates of occurrence of nor'westers at Dhaka with the monthly normal, weekly normal and daily normal

Level (hPa)	Cases of nor'westers studied	Monthly normal		*Weekly normal		*Daily normal	
		Increase in MSE (% cases)	Decrease in MSE (% cases)	Increase in MSE (% cases)	Decrease in MSE (% cases)	Increase in MSE (% cases)	Decrease in MSE (% cases)
Surface	79	48.10	51.90	51.28	48.72	50.00	48.52
1000	78	55.85	46.15	53.25	45.45	57.14	42.86
925	79	69.62	30.38	75.64	24.36	76.92	23.08
850	79	67.09	32.91	66.67	33.33	66.67	33.33
700	78	62.03	37.97	61.54	31.18	61.54	38.46
500	79	32.91	67.09	39.74	60.26	41.03	57.69
400	79	34.18	65.82	37.18	62.82	42.31	57.69
300	79	36.71	63.29	41.03	58.97	35.90	62.82
200	79	45.57	54.43	50.00	50.00	46.15	53.85
100	79	67.09	32.91	56.41	43.59	55.13	44.87

*No. of cases studied is 1 less than the 2nd column

Table 6.7 substantiates that the MSE of the troposphere over Dhaka on the dates of occurrence of nor'westers at Dhaka increases in most of the cases in the lower troposphere having the increase in maximum cases of 69.62, 75.64 and 76.92% at 925 hPa level as compared to the monthly, weekly and daily normals respectively. This increase in MSE is followed by a decrease in the layer 500-200 hPa that is again followed by an increase at 100 hPa level.

6.4.4.3 Comparison of DSE and MSE components on the dates of occurrence of nor'westers at Dhaka with the previous weekly normal

With a view to finding some criteria for the forecasting of nor'westers, comparison of energy components of the troposphere over Dhaka on the dates of occurrence of nor'westers at Dhaka has been made with the normal of the previous week at each standard isobaric surface including the surface. This comparison gives better results than the previous results discussed in the earlier sections. The results are given in Table 6.8.

6.4.4.3.1 Dry static energy (DSE) - Table 6.8 gives the number of cases of increase and decrease in the DSE of the troposphere over Dhaka on the dates of occurrence of nor'westers at Dhaka as compared to the previous weekly normal DSE.

Table 6.8: Comparison of DSE and MSE over Dhaka on the dates of occurrence of nor'westers at Dhaka with the previous weekly normal

Level (hPa)	No. of cases studied	Previously weekly normal			
		Increase in DSE	Decrease in DSE	Increase in MSE	Decrease in MSE
		% cases	% cases	% cases	% cases
Surface	79	53.16	45.57	54.43	45.57
1000	78	56.41	43.59	57.69	41.77
925	79	46.84	53.16	82.28	17.72
850	79	51.90	48.10	69.62	30.38
700	79	72.15	27.85	68.35	31.65
500	79	56.96	43.04	39.24	60.76
400	79	54.43	45.57	51.90	48.10
300	79	50.67	49.37	54.43	45.57
200	79	58.23	40.51	56.96	43.04
100	79	59.49	40.51	60.76	39.24

The table shows that the increase in DSE on the dates of occurrence of nor'westers at Dhaka occurs in most of the cases at each level except 925 hPa level where the increase in DSE occurs in 46.84% (< 50%) of cases as compared to the previous weekly normal DSE. This increase in DSE in less number of cases at 925 hPa may be attributed to the decrease in geopotential which sometimes becomes significantly low due to the presence of low pressure area. The number of cases, in which the DSE increases, range from 46.84 to 72.15% having the maximum and minimum values of 72.15 and 46.84% cases at 700 and 925 hPa levels respectively.

6.4.4.3.2 Moist static energy (MSE) - The number of cases of increase and decrease in MSE of the troposphere over Dhaka on the dates of occurrence of nor'westers at Dhaka from the previous weekly normal is also given in Table 6.8.

Table 6.8 shows that the increase in MSE on the dates of occurrence of nor'westers at Dhaka occurs in most of the cases at each level except 500 hPa level where the increase in MSE occurs in 39.24% (< 50%) of cases only. This increase in MSE in less number of cases at 500-hPa level is mainly due to the advection of cold and dry air from the north when significantly cold air sometimes advects at 500 hPa level. The number of cases, in which the MSE increases, ranges from 39.24 to 82.28% of cases having the maximum and minimum number of cases i.e. 82.28 and 39.24% at 925 and 500 hPa levels respectively.

6.4.5 Comparison of the DSE and MSE components of the troposphere over Dhaka between the dates of occurrence and non-occurrence of nor'westers

The DSE and MSE at each level of the troposphere over Dhaka on 25 dates of occurrence of nor'westers at Dhaka as well as over Bangladesh have been compared with those on the dates of non-occurrence. The dates of non-occurrence are the dates one day earlier than the dates of occurrence except in one case where it is two days earlier when no nor'wester occurred at Dhaka or the dates on which nor'wester occurred at one/two places over Bangladesh far away from Dhaka. The frequency table for the increase/decrease in DSE and MSE at each level of the troposphere on the dates of occurrence of nor'westers with respect to those on the dates of non-occurrence has been constructed and is given in Table 6.9.

Table 6.9:Comparison of DSE over Dhaka between the dates of occurrence and non-occurrence of nor'westers

Level (hPa)	Increase/decrease in DSE			Increase/decrease in MSE		
	Class (J/gm)	f	Increase in DSE (% cases)	Class (J/gm)	f	Increase in MSE (% cases)
Surface	-6 to -4	1	80.00	-18 to -12	1	84.00
	-4 to -2	0		-12 to -6	1	
	-2 to 0	4		-6 to 0	2	
	0 to 2	16		0 to 6	13	
	2 to 4	3		6 to 12	7	
	4 to 6	1		12 to 18	1	
1000	-6 to -4	1	84.00	-24 to -18	1	80.00
	-4 to -2	1		-18 to -12	0	
	-2 to 0	2		-12 to -6	1	
	0 to 2	16		-6 to 0	3	
	2 to 4	4		0 to 6	13	
	4 to 6	1		6 to 12	4	
				12 to 18	3	
925	-6 to -4	0	68.00	-12 to -6	1	84.00
	-4 to -2	3		-6 to 0	3	
	-2 to 0	5		0 to 6	13	
	0 to 2	13		6 to 12	6	
	2 to 4	4		12 to 18	2	
	4 to 6	0				
850	-6 to –4	0	56.00	-12 to –6	0	76.00
	-4 to –2	3		-6 to 0	6	
	-2 to 0	8		0 to 6	7	
	0 to 2	10		4 to 12	10	
	2 to 4	3		12 to 18	2	
	4 to 6	1				
700	-8 to –6	1	72.00	-18 to –12	1	60.00
	-6 to –4	0		-12 to –6	1	
	-4 to –2	1		-6 to 0	8	
	-2 to 0	5		0 to 6	11	
	0 to 2	15		5 to 12	4	
	2 to 4	3		12 to 18	0	
	4 to 6	0				
500	-6 to –4	1	56.00	-12 to –6	0	56.00
	-4 to –2	4		-6 to 0	11	
	-2 to 0	6		0 to 6	12	
	0 to 2	8		6 to 12	2	
	2 to 4	4		12 to 18	0	
	4 to 6	2				
400	-6 to –4	1	56.00	-12 to –6	0	60.00
	-4 to –2	2		-6 to 0	10	
	-2 to 0	8		0 to 6	14	
	0 to 2	11		6 to12	1	
	2 to 4	2		12 to 18	0	
	4 to 6	1				

Table 6.9 (Cont'd)

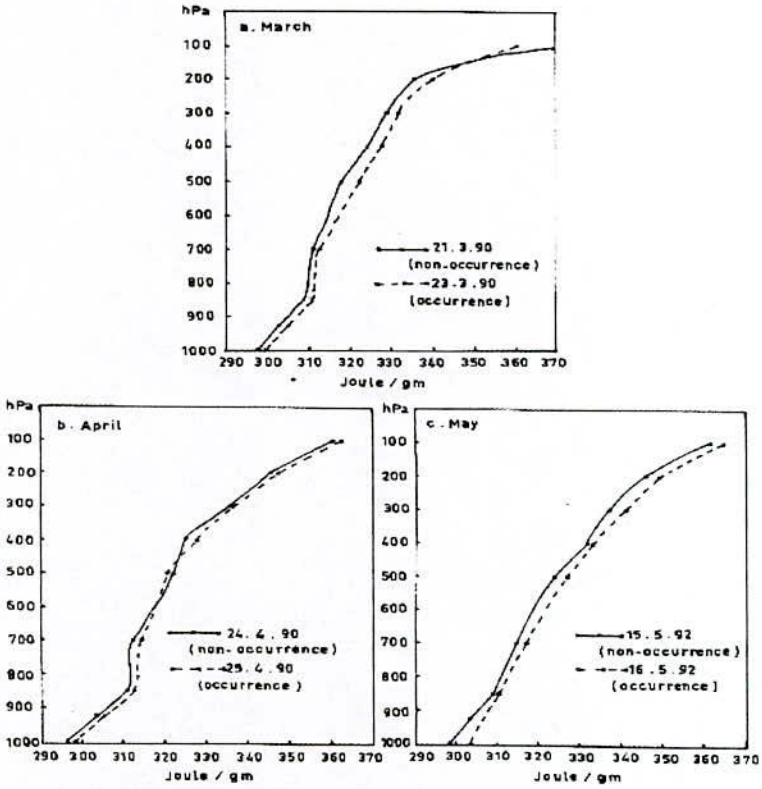
300	-6 to –4	1	64.00	-12 to –6	0	64.00
	-4 to –2	2		-6 to 0	9	
	-2 to 0	6		0 to 6	16	
	0 to 2	11		6 to 12	0	
	2 to 4	2		12 to 18	0	
	4 to 6	3				
200	-8 to -6	1	48.00	-12 to -6	1	48.00
	-6 to -4	1		-6 to 0	12	
	-4 to -2	7		0 to 6	12	
	-2 to 0	4		6 to 12	0	
	0 to 2	5		12 to 18	0	
	2 to 4	6				
	4 to 6	1				
100	-10 to -8	1	44.00	-12 to -6	1	44.00
	-8 to -6	0		-6 to 0	13	
	-6 to -4	1		0 to 6	11	
	-4 to -2	4		6 to 12	0	
	-2 to 0	8		12 to 18	0	
	0 to 2	8				
	2 to 4	3				

f = frequency

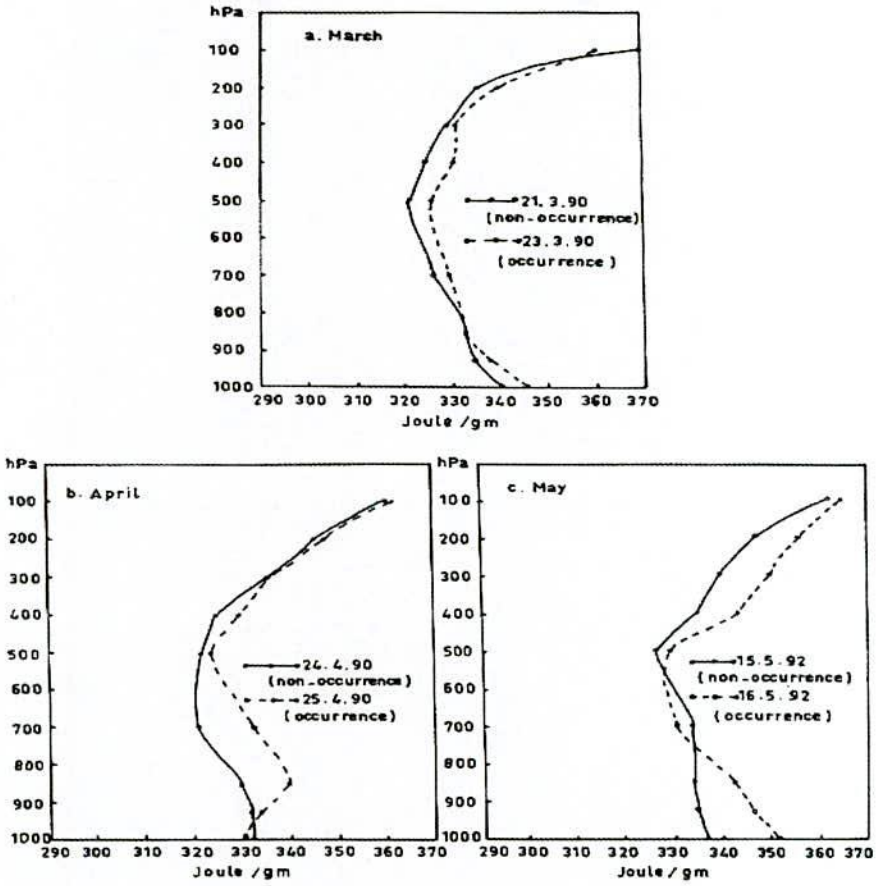
6.4.5.1 Dry static energy (DSE) - Table 6.9 shows the frequency distribution of the changes in DSE at each level of the troposphere over Dhaka on the dates of occurrence of nor'westers from that on the dates of non-occurrence of nor'westers. The table shows that the increase in DSE occurs in most of the cases from the surface to 300 hPa, the maximum being in the lower troposphere on the dates of occurrence as compared to that on the dates of non-occurrence of nor'westers. Sometimes, the increase in DSE occurs up to the top of the troposphere. The DSE increases in 80, 84, 68, 56 and 72% cases at the surface, 1000, 925, 850 and 700 hPa levels respectively. The table also shows that the increase in DSE occurs in the range of 0-2 Joule/gm in most of the cases at each level except at 200 hPa level where the range is 2-4 Joules/gm in most of the cases. The vertical profiles of DSE for some cases are shown in Figs. 6.21 (a-c). The increase in DSE is not so significant. In some cases, the increase in DSE is also found to occur in the range of 2-4 Joules/gm and 4-6 Joules/gm.

6.4.5.2 Moist static energy (MSE) - The Table 6.9 shows that the increase in MSE occurs in most cases from the surface to 300 hPa level on the dates of occurrence of nor'westers as compared to that on the previous days - the dates of non-occurrence. The increase occurs in maximum cases starting from the surface to 300 hPa level having 84, 80, and 84. 76, 60, 56, 60 and 64% cases at the surface, 1000, 925, 850, 700, 500, 400 and 300 hPa levels respectively. The increase in MSE also occurs in 48 and 44% cases at 200 and 100-hPa levels

respectively. The primary and secondary maximum increases in MSE are in the ranges of 0-6 Joule/gm and 6-12 Joules/gm respectively at each level except 850-hPa level where the primary maximum increase is in the range of 6-12 Joules/gm and the secondary maximum in the range of 0-6 Joule/gm. This implies that a significant increase in MSE occurs in the lower atmosphere on the dates of occurrence of nor'westers as compared to that on the dates of non-occurrence. This significant increase in MSE is also evident from the Figs. 6.22 (a-c) for three cases. The increase in MSE on the dates of occurrence of nor'westers is mainly due to the contribution of LH released prior to the occurrence of nor'westers. In one case there is a significant decrease in MSE of magnitudes -16.25 Joules/gm and -19.76 Joules/gm at the surface and 1000-hPa level on 29 April 1990 as compared to that on 28 April 1990. This decrease in MSE may be due to the accumulation of MSE at a distant place, Magura, from Dhaka where a tornado occurred on 29 April 1990.



Figs. 6.21 (a-c): Vertical profiles of DSE over Dhaka at 0000 UTC on the dates of occurrence and non-occurrence of nor'westers



Figs. 6.22 (a-c): Vertical profiles of MSE over Dhaka at 00 UTC on the dates of occurrence and non-occurrence of nor'westers

6.4.6 Comparison of the DSE and MSE components of the troposphere over Dhaka on the dates of occurrence of nor'westers in Bangladesh with the previous weekly normal

The DSE and MSE at each level of the troposphere over Dhaka on the dates of occurrence of 109 nor'westers in Bangladesh have been compared with the previous weekly normal and the deviations of DSE and MSE from the normal have been computed and studied. The frequency table for the deviation of the magnitudes of DSE and MSE from the previous weekly normal at each level of the troposphere over Dhaka on the dates of occurrence has been constructed and is given in Tables 6.10.

6.4.6.1 Dry Static Energy (DSE) - Table 6.10 shows the frequency of deviation in the magnitudes of DSE over Dhaka from the previous weekly normal. The DSE increases in most of the cases ranging from 47.71 to 67.89% throughout the troposphere over Dhaka

having the increase in less than 50% cases at 925 hPa and 300 hPa levels. The maximum increase occurs in 67.89% cases at 700-hPa level.

In studying 109 cases, it has been found that nor'westers have occurred on many consecutive days in many occasions. In each occasion, there has been increase in DSE in almost levels on the starting day followed by decrease at almost each level on the subsequent days. This is for obvious reason that the nor'westers generally occur in the afternoon/evening/night and after that occurrence there exists no source of energy or insolation up to 0000 UTC of the next day. As a result, the DSE remains less at 0000 UTC on the subsequent days of occurrence as compared to the previous weekly normal DSE. As the earth's surface receives sun's insolation with the progress of day time, energy is assumed to be accumulated in the troposphere thereby creating a favourable condition i.e. instability for the occurrence of nor'westers provided that there must be favorable synoptic conditions and upper air circulation up to a reasonable height. At the surface, the maximum increase and decrease in DSE occur in the range of 0 to 3 Joule/gm and -3 to 0 Joule/gm having the frequency of 55 and 35 out of 109 cases respectively. The extreme deviations of DSE from the previous weekly normal are -4.65 Joules/gm and +6.43 Joules/gm (Table 6.10). At 1000 hPa level, the maximum increase and decrease in DSE from the previous weekly normal are found in the range of 0 to 3 Joule/gm and -3 to 0 Joule/gm having the frequency of 59 and 32 out of 108 cases respectively with the extreme deviations of -4.43 Joules/gm and + 4.03 Joules/gm. In the above ranges of deviation, the frequencies at other levels are 41 and 49 at 925 hPa, 48 and 36 at 850 hPa, 69 and 30 at 700 hPa, 50 and 39 at 500 hPa, 43 and 45 at 400 hPa, 38 and 40 at 300 hPa, 45 and 33 at 200 hPa and, 42 and 40 at 100 hPa out of 109 cases.

The extreme deviations of DSE from the previous weekly normal have been found to be -5.15 and +6.43 Joules/gm at 925 hPa, -5.16 and 5.58 Joules/gm at 850 hPa, -3.88 and +9.29 Joules/gm at 700 hPa, -6.60 and +6.97 Joules/gm at 500 hPa, -5.87 and 9.42 Joules/gm at 400 hPa, -9.97 and + 8.33 Joules/gm at 300 hPa, -5.51 and +10.46 Joules/gm at 200 hPa, and -4.90 and +9.48 Joules/gm at 100 hPa. The extreme deviations of DSE on the dates of occurrence of nor'westers from the previous weekly normal are given in Fig. 6.23.

Table 6.10 also shows that the secondary maximum deviations of DSE from the previous weekly normal occur in the range of +3 to +6 Joules/gm and -6 to -3 Joules/gm. The frequencies in these ranges are 10 and 8 at the surface, 5 and 12 at 1000 hPa, 10 and 8 at 925 hPa, 17 and 8 at 850 hPa, 4 and 5 at 700 hPa, 10 and 7 at 500 hPa, 14 and 6 at 400 hPa, 15 and 12 at 300 hPa, 18 and 12 at 200 hPa, and 15 and 10 at 100 hPa out of 109 cases,

indicating the greater positive deviations of DSE in the range of +3 to +6 Joules/gm at 200 hPa (frequency =18) and 850 hPa (frequency =17).

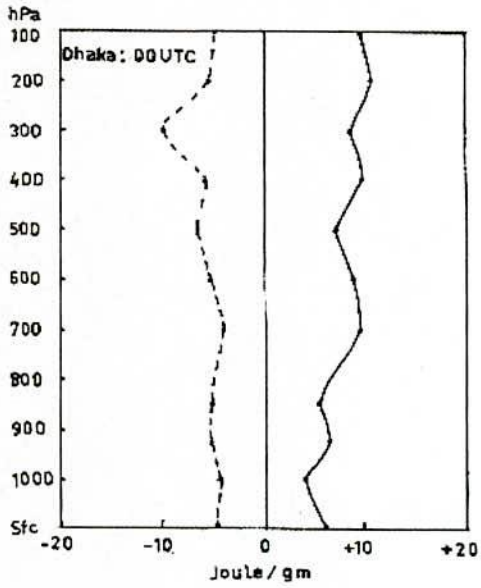


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Fig. 6.23: Vertical profiles of extreme deviation of DSE on the dates of occurrence of nor'westers in Bangladesh from the previous weekly normal

6.4.6.2 Moist static energy (MSE) - Table 6.10 shows that the MSE of the troposphere over Dhaka on the dates of occurrence of nor'westers in Bangladesh increases in most of the cases, as compared to the previous weekly normal MSE, ranging from 37.61 to 77.06% throughout the troposphere having less than 50% at 500 hPa level. The maximum increase occurs in 77.06% cases at 925 hPa and the secondary maximum increase occurs in 68.81% cases at 850-hPa level. Actually, increase in MSE, as compared to the previous weekly normal, occurs in more than 60% cases in the lower troposphere below 500 hPa. At 500-hPa level, the increase MSE in less than 50% cases may be attributed to the cold and dry air advection from the north and less moisture incursion from the south.

Since the increase in MSE has not occurred in 100% cases, the decrease in MSE has been mainly found on the dates when nor'westers have occurred successively after the first date for occurrence due to the reason as mentioned in case of DSE and also due to the varying contributions of latent heat energy. From Table 6.10, it can be seen that maximum increase and decrease in MSE occur in the ranges +6 to +12 Joules/gm and -6 to 0 Joule/gm at the surface having the frequency of 35 and 24 out of 109 cases with the extreme deviations of +19.70 and -14.41 Joules/gm from the previous weekly normal. At 1000 hPa level, the maximum increase and decrease in MSE occur in the same ranges having the frequency of 30

and 20 out of 108 cases with the extreme deviations of +18.19 and -17.51 Joules/gm from the previous weekly normal respectively. At 925 hPa level, the maximum increase and decrease in MSE from the previous weekly normal occur in the ranges of 0 to +6 and -6 to 0 Joule/gm having the frequency of 37 and 17 out of 109 cases with extreme deviations of +16.47 and -12.03 Joules/gm respectively. At 850 hPa level, the maximum increase in MSE from the above normal occurs in the ranges of 0 to +6 Joule/gm and +6 to 12 Joules/gm, having the frequency of 31 in each range out of 109 cases whereas the maximum decrease in MSE occurs in the range of -6 to 0 Joule/gm having the frequency of 22 out of 109 cases. At this level, the extreme deviations of MSE from the previous weekly normal are +19.39 and -16.95 Joules/gm. At other levels, the maximum increase and decrease in MSE from the previous weekly normal have been found in the ranges of +0 to 6 and -6 to 0 Joule/gm having the frequency of 54 and 31 out of 109 cases at 700 hPa, 36 and 66 out of 109 cases at 500 hPa, 54 and 52 out of 109 cases at 400 hPa, 57 and 47 out of 109 cases at 300 hPa, 61 and 45 out of 109 cases at 200 hPa, and 57 and 50 out of 109 cases at 100 hPa respectively. The extreme deviations of MSE from the previous weekly normal are +10.60 and -13.59 Joules/gm at 700 hPa, 9.55 and -6.58 Joules/gm at 500 hPa, +9.26 and -6.54 Joules/gm at 400 hPa, +8.21 and -10.22 Joules/gm at 300 hPa, + 10.45 and -7.56 Joules/gm at 200 hPa, and + 9.48 and -4.90 Joules/gm at 100 hPa. The extreme deviations of MSE on the dates of occurrence of nor'westers in Bangladesh from the previous weekly normal are shown as vertical profiles in Fig. 6.24.

From the above discussion, it may be inferred that the MSE of the troposphere over Dhaka increases from the previous weekly normal in most of the cases of nor'westers which occur in Bangladesh and this increase occurs from the surface to the top of the troposphere except 500 hPa level where the frequency of increase is less than that of decrease. The increase in MSE is significant in the lower troposphere, which may sometimes be in the range of +12 to +18 Joules/gm or even +18 to +24 Joules/gm. The frequency of decrease in MSE is less than that of increase at all levels except 500-hPa level, and though the frequency is lower, the decrease in MSE is also significant in the lower troposphere as in the case of increase in MSE. This significant increase or decrease in MSE is mainly due to the variation of latent heat energy, which is highly variable in character.

Table 6.10: Frequency distribution of the deviation of DSE (J/gm) and MSE (J/gm) over Dhaka on the dates of occurrence of nor'westers in Bangladesh from the previous weekly normal at 0000 UTC

Level (hPa)	Increase/decrease in DSE			Increase/decrease in MSE		
	Class (J/gm)	f	Increase in DSE (% cases)	Class (J/gm)	f	Increase in MSE (% cases)
Surface	-6 to -3	8	59.63	-18 to -12	3	60.55
	-3 to 0	35		-12 to -6	16	
	0 to 3	55		-6 to 0	24	
	3 to 6	10		0 to 6	23	
	6 to 9	1		6 to 12	35	
				12 to 18	6	
				18 to 24	2	
1000	-6 to -3	12	58.33	-18 to -12	4	62.04
	-3 to 0	32		-12 to -6	17	
	0 to 3	59		-6 to 0	20	
	3 to 6	5		0 to 6	22	
	6 to 9	0		6 to 12	30	
				12 to 18	14	
				18 to 24	1	
925	-6 to -3	8	47.71	-18 to -12	1	77.06
	-3 to 0	49		-12 to -6	7	
	0 to 3	41		-6 to 0	17	
	3 to 6	10		0 to 6	37	
	6 to 9	1		6 to 12	27	
				12 to 18	20	
				18 to 24	0	
850	-6 to -3	8	59.63	-18 to -12	5	68.81
	-3 to 0	36		-12 to -6	7	
	0 to 3	48		-6 to 0	22	
	3 to 6	17		0 to 6	31	
	6 to 9	0		6 to 12	31	
				12 to 18	10	
				18 to 24	3	
700	-6 to -3	5	67.89	-18 to -12	1	63.30
	-3 to 0	30		-12 to -6	8	
	0 to 3	69		-6 to 0	31	
	3 to 6	4		0 to 6	54	
	6 to 9	0		6 to 12	15	
	9 to 12	1		12 to 18	0	
500	-9 to -6	1	58.88	-18 to -12	0	37.61
	-6 to -3	7		-12 to -6	2	
	-3 to 0	39		-6 to 0	66	
	0 to 3	50		0 to 6	36	
	3 to 6	10		6 to 12	5	
	6 to 9	2		12 to 18	0	

Table 6.10 (Cont'd)

400	-6 to -3	6	53.21	-18 to -12	0	50.46
	-3 to 0	45		-12 to -6	2	
	0 to 3	43		-6 to 0	52	
	3 to 6	14		0 to 6	54	
	6 to 9	0		6 to 12	1	
	9 to 12	1		12 to 18	0	
300	-12 to -9	1	49.54	-18 to -12	0	54.13
	-9 to -6	2		-12 to -6	3	
	-6 to -3	12		-6 to 0	47	
	-3 to 0	40		0 to 6	57	
	0 to 3	38		6 to 12	2	
	3 to 6	15		12 to 18	0	
	6 to 9	1				
200	-6 to -3	12	57.80	-18 to -12	0	57.80
	-3 to 0	33		-12 to -6	1	
	0 to 3	45		-6 to 0	45	
	3 to 6	18		0 to 6	61	
	6 to 9	0		6 to 12	2	
	9 to 12	1		12 to 18	0	
100	-6 to -3	10	54.13	-18 to -12	0	54.13
	-3 to 0	40		-12 to -6	0	
	0 to 3	42		-6 to 0	50	
	3 to 6	15		0 to 6	57	
	6 to 9	1		6 to 12	2	
	9 to 12	1		12 to 18	0	

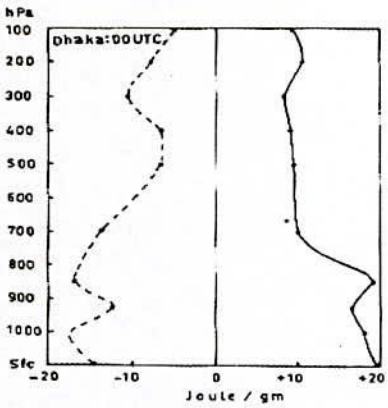
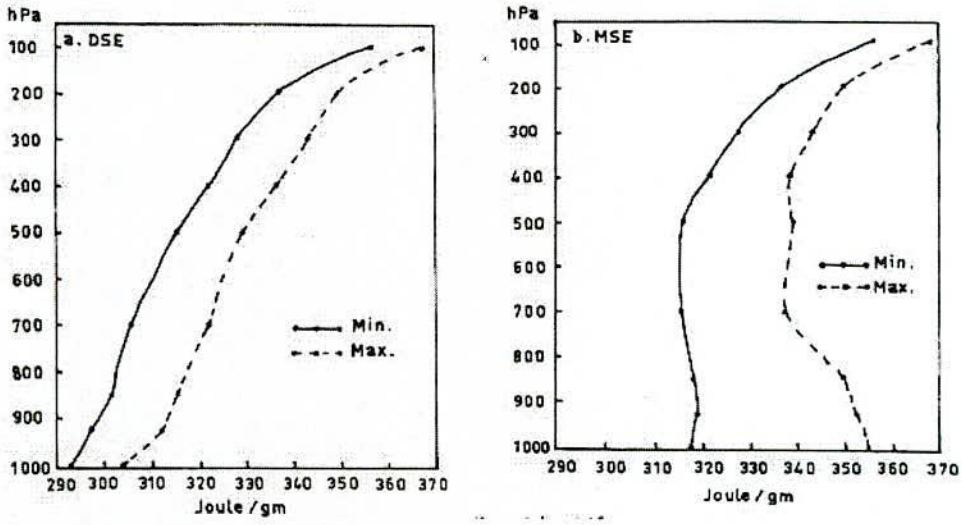


Fig. 6.24: Vertical profiles of extreme deviation of MSE on the dates of occurrence of nor'westers in Bangladesh from the previous weekly normal

6.4.7 Maximum and minimum curves of DSE and MSE components of the troposphere over Dhaka on the dates of occurrence of nor'westers

The DSE and MSE of the troposphere over Dhaka prior to the occurrence of nor'westers have been checked at each level to pick up the maximum and minimum values of these energy components for 79 cases under study. The vertical profiles of the above maximum and minimum energy components are prepared and shown in Figs. 6.25 (a-b).



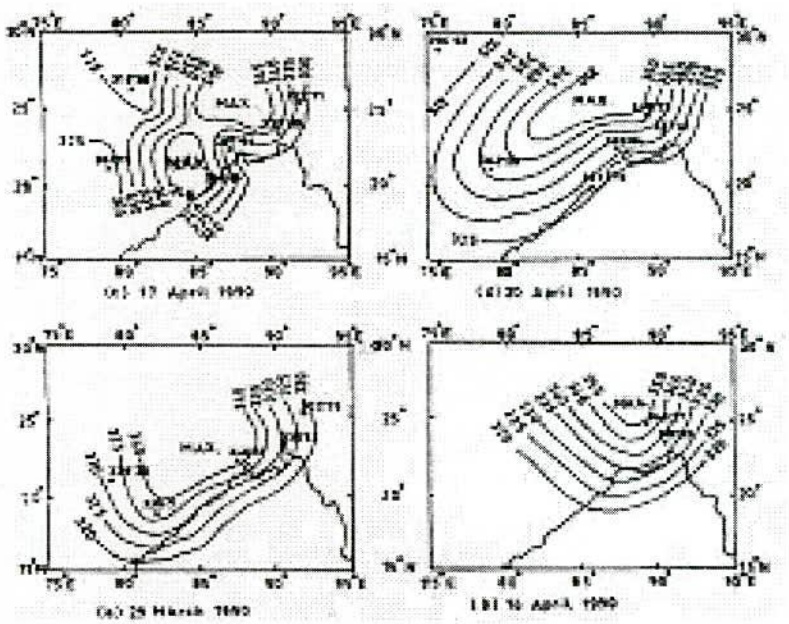
Figs. 6.25 (a-b): Vertical profiles of minimum and maximum (a) DSE and (b) MSE at 0000 UTC over Dhaka on the dates of occurrence of nor'westers

The curves of the minimum and maximum DSE and MSE in the above figures may be used as the criteria for the amount of DSE and MSE required for the occurrence of nor'westers. This means that the DSE and MSE favorable for the occurrence of nor'westers will be within the minimum and maximum values of the curves.

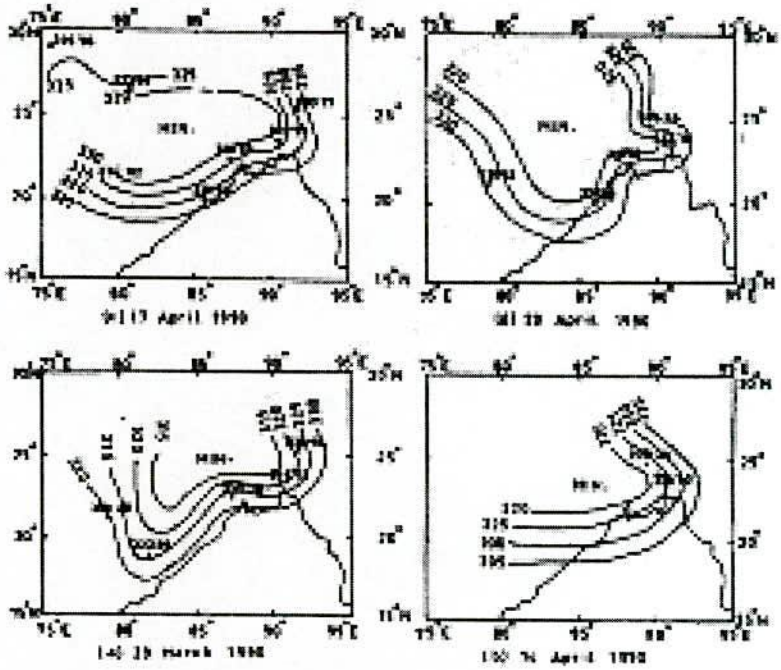
6.4.8 Distribution of moist static energy at 850 and 500 hPa

The MSE of the troposphere over different stations of Bangladesh and India has been computed and their spatial distributions at 850 and 500 hPa levels have been studied for several nor'westers. Some of the analyses for 850 and 500 hPa levels are given in Figs. 6.26 (a-d) and 6.27 (a-d) respectively.

Figs. 6.26 (a-d) show that the area of maximum MSE at 850 hPa level lies over eastern Madhya Pradesh, Bihar, West Bengal and adjoining Bangladesh, where the surface low and low-level circulation exists as has been observed from the analyses of surface and pilot charts (not shown here). The nor'westers have been found to occur at the northeastern or eastern part of the area of maximum MSE where the injection of moisture takes place from the Bay of Bengal. The distribution of MSE at 500 hPa level shows that the area of minimum MSE at 500-hPa lies over the area of maximum MSE at 850-hPa [Figs. 6.27(a-d)].



Figs. 6.26 (a-d): Spatial distribution of MSE (Joule gm^{-1} at 850-hPa level at 0000 UTC



Figs. 6.27 (a-d): Spatial distribution of MSE (Joule gm^{-1}) at 500 hPa level at 0000 UTC

6.4.9 Fluxes of energy components

6.4.9.1 Zonal fluxes of dry static energy (ZFDSE) over Dhaka

The ZFDSE over Dhaka at 0000 UTC have been computed at different isobaric levels on the dates of occurrence of about 107 nor'westers over Bangladesh during pre-monsoon season of 1990-1995. The fluxes over Dhaka have also been computed for the dates of non-occurrence of nor'westers. A comparative study of the frequency of westerly (positive) fluxes

of DSE (WFDSE) and easterly (negative) fluxes of DSE (EFDSE) has been made and is given in Table 6.11.

Table 6.11 shows that the EFDSE dominate at 1000 hPa over Dhaka in 48.60% cases and WFDSE dominate in 41.12% cases on the dates of occurrence of nor'westers over Bangladesh. The WFDSE dominate in the troposphere from 925-hPa level to 100 hPa level having maximum frequency of westerly fluxes from 85.05 to 100% in the layer from 925 to 100 hPa level. The EFDSE become insignificant above 925 hPa.

Table 6.11: Frequency of WFDSE and EFDSE at 0000 UTC over Dhaka on the dates of occurrence of nor'westers in Bangladesh

hPa	Frequency of WFDSE	Frequency of EFDSE	Frequency of zero flux	Total frequency	%Frequency of WFDSE	%Frequency of EFDSE	%Frequency of zero fluxes
1000	44	52	11	107	41.12	48.60	10.28
925	91	14	2	107	85.05	13.08	1.87
850	101	3	3	107	94.39	2.80	2.80
700	107	0	0	107	100.00	0.00	0.00
500	106	0	1	107	99.07	0.00	0.93
400	105	1	1	107	98.13	0.93	0.93
300	105	2	0	107	98.13	1.87	0.00
200	104	3	0	107	97.20	2.80	0.00
100	100	7	0	107	93.46	6.54	0.00

From the study of 107 cases of nor'westers, the maximum WFDSE over Dhaka at 0000 UTC on the dates of occurrence of nor'westers have been found to be 3.87×10^3, 4.22×10^3, 7.90×10^3, 8.99×10^3, 22.03×10^3, 13.60×10^3, 22.85×10^3, 29.02×10^3 and 20.62×10^3 Joule $gm^{-1} \times ms^{-1}$ at standard isobaric heights of 1000, 925, 850, 700, 500, 400, 300, 200 and 100 hPa levels respectively. The maximum EFDSE over Dhaka at 0000 UTC may be -2.12×10^3, -1.24×10^3, -0.36×10^3, 0, -1.23×10^3, -1.36×10^3, -1.60×10^3, and -3.93×10^3 Joule $gm^{-1} \times ms^{-1}$ at 1000, 925, 850, 500, 400, 300, 200 and 100 hPa levels respectively. Fig. 6.28 shows, as an example, the variation of maximum and minimum ZFDSE with height. The maximum ZFDSE are always westerly on the dates of occurrence of nor'westers and the westerly fluxes are significant in the upper troposphere.

The vertical profiles of the ZFDSE over Dhaka at 0000 UTC on the dates of occurrence and non-occurrence of nor'westers in Bangladesh are studied, and the variation is shown in Fig. 6.29 as an example. It has been found that the fluxes of DSE are mainly westerly and more westerly in the lower troposphere on the dates of occurrence of

nor'westers as compared to the fluxes on the dates of non-occurrence. The fluxes of DSE are significantly westerly on both the dates of occurrence and non-occurrence of nor'westers having slightly higher values in the upper troposphere on the dates of occurrence.

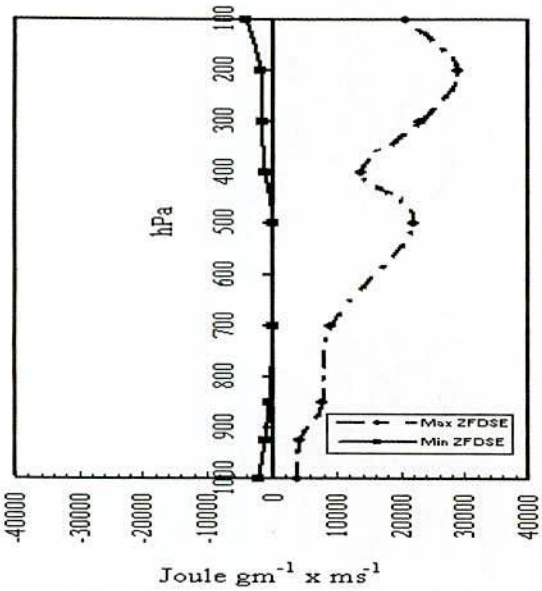


Fig. 6.28: Vertical variation of maximum and minimum ZFDSE over Dhaka at 0000 UTC on the dates of occurrence of nor'westers in Bangladesh

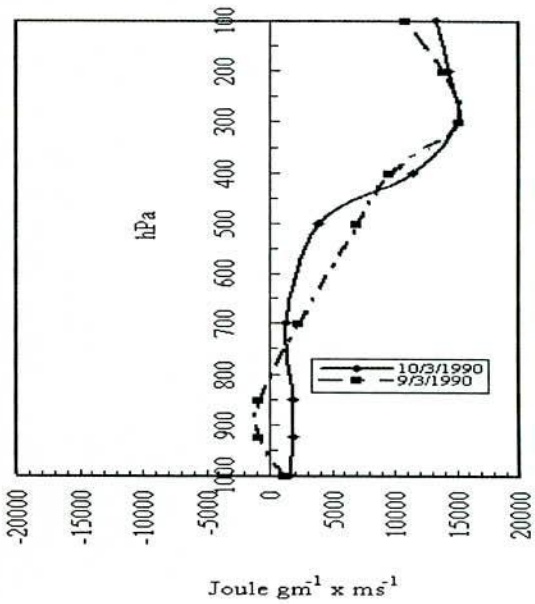


Fig. 6.29: Vertical profiles of the ZFDSE over Dhaka at 0000 UTC on the dates of occurrence (10 March 1990) and non-occurrence (9 March 1990) of nor'westers over Bangladesh

From the above discussion it may be inferred that the EFDSE dominate at 1000 hPa and the WFDSE dominant in the troposphere from 925 to 100 hPa level. The NFDSE decrease with height and the EFDSE become insignificant above 925 hPa. The maximum ZFDSE are always westerly on the dates of occurrence of nor'westers and the westerly fluxes are significant in the upper troposphere. The fluxes of DSE are mainly westerly and more westerly in the lower troposphere on the dates of occurrence of nor'westers as compared to the fluxes on the dates of non-occurrence. The fluxes of DSE are significantly westerly on both the dates of occurrence and non-occurrence of nor'westers having slightly higher values in the upper troposphere.

6.4.9.2 Meridional fluxes of dry static energy (MFDSE) over Dhaka

The MFDSE over Dhaka at 0000 UTC have been computed at different isobaric levels on the dates of occurrence of 107 nor'westers over Bangladesh during pre-monsoon season of 1990-1995. The fluxes of DSE over Dhaka have also been computed for the dates

of non-occurrence of nor'westers. A comparative study of the frequency of southerly (positive) and northerly (negative) fluxes has been made and is given in Table 6.12.

Table 6.12 shows that the SFDSE dominate in the lower and upper troposphere over Dhaka at 0000 UTC on the dates of occurrence of nor'westers over Bangladesh. The frequency of SFDSE is 92.52% at 1000 hPa and 98.13% at 925-hPa level. The frequency of NFDSE is less in the lower and upper troposphere, having maximum frequency of northerly fluxes from 70.09 to 56.07% in the layer from 700 to 400 hPa level.

Table 6.12: Frequency of SFDSE and NFDSE at 0000 UTC over Dhaka on the dates of occurrence of nor'westers in Bangladesh

hPa	Frequency of SFDSE	Frequency of NFDSE	Frequency of zero flux	Total frequency	%Frequency of SFDSE	%Frequency of NFDSE	%Frequency of zero flux
1000	99	5	3	107	92.52	4.67	2.80
925	105	2	0	107	98.13	1.87	0.00
850	77	22	8	107	71.96	20.56	7.48
700	26	75	6	107	24.30	70.09	5.61
500	32	65	10	107	29.91	60.75	9.35
400	38	60	9	107	35.51	56.07	8.41
300	48	51	8	107	44.86	47.66	7.48
200	67	33	7	107	62.62	30.84	6.54
100	57	44	6	107	53.27	41.12	5.61

The maximum SFDSE over Dhaka at 0000 UTC on the dates of occurrence of nor'westers increase with height and may be 35.04×10^2, 39.91×10^2, 52.26×10^2, 45.46×10^2, 37.30×10^2, 59.02×10^2, 51.29×10^2, 103.13×10^2 and 122.41×10^2 Joule $gm^{-1} \times ms^{-1}$ at 1000, 925, 850, 700, 500, 400, 300, 200 and 100 hPa levels respectively. The maximum NFDSE over Dhaka at 0000 UTC may be -25.52×10^2, -39.57×10^2, -41.25×10^2, -48.98×10^2, -87.69×10^2, -47.18×10^2, -66.77×10^2 and -132.60×10^2 Joule $gm^{-1} \times ms^{-1}$ at 925, 850, 700, 500, 400, 300, 200 and 100 hPa levels respectively. The MFDSE are significantly large in the upper troposphere. Fig. 6.30 shows the variation of maximum and minimum MFDSE with height at 0000 UTC at Dhaka on the dates of occurrence of nor'westers in Bangladesh.

The vertical profiles of the MFDSE over Dhaka at 0000 UTC on the dates of occurrence and non-occurrence of nor'westers in Bangladesh are studied, and the vertical variation is shown in Fig. 6.31 as an example. It has been found that the MFDSE are mainly southerly and/or more southerly in the lower and middle troposphere on the dates of occurrence of nor'westers as compared to the fluxes on the dates of non-occurrence. The

MFDSE are significantly southerly on both the dates of occurrence and non-occurrence of nor'westers having higher values in the upper troposphere.

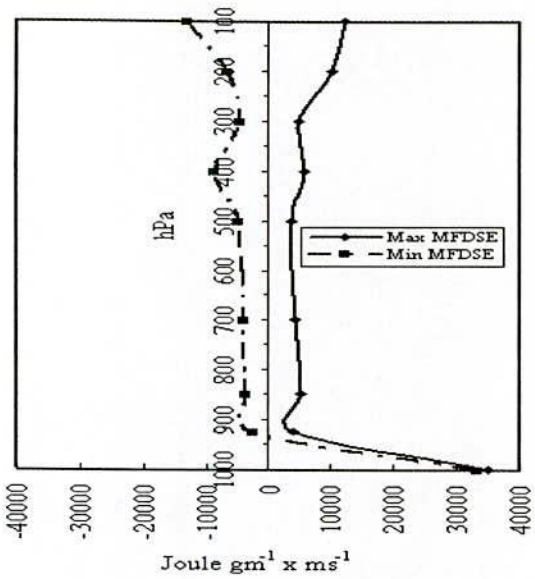


Fig. 6.30: Vertical variation of maximum and minimum MFDSE over Dhaka at 0000 UTC on the dates of occurrence of nor'westers in Bangladesh

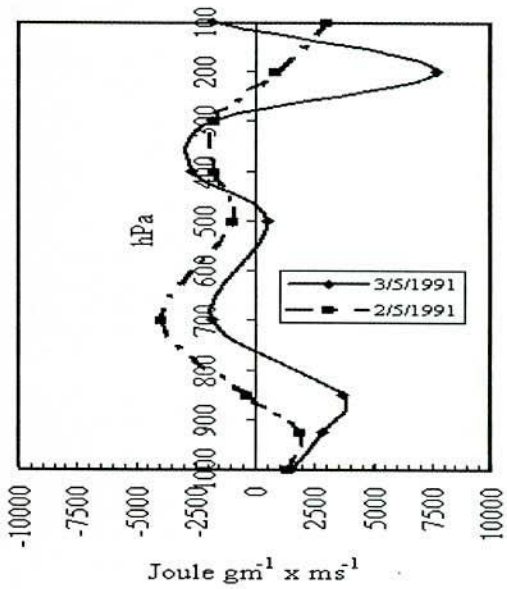


Fig. 6.31: Vertical profiles of the MFDSE over Dhaka at 0000 UTC on the date of occurrence (3 May 1991) and the date of non-occurrence (2 May 1991)

6.4.9.3 Vertically integrated zonal and meridional fluxes of DSE over Dhaka

The ZFDSE and MFDSE, computed at different isobaric levels over Dhaka at 0000 UTC on the dates of occurrence of nor'westers, have been integrated from 1000 to 100-hPa level by taking the layer mean DSE. The vertically integrated zonal and meridional fluxes of DSE for 107 nor'westers are shown in Fig. 6.32. This figure shows that the vertically integrated ZFDSE are significantly higher than that of the MFDSE over Dhaka on the dates of occurrence of nor'westers in Bangladesh. The vertically integrated ZFDSE are always westerly on the dates of occurrence of nor'westers.

The frequency of vertically integrated ZFDSE and MFDSE over Dhaka at 0000 UTC on the dates of occurrence of nor'westers in Bangladesh is given in Table 6.13.

On the dates of occurrence of nor'westers, the vertically integrated ZFDSE may vary from (11.39 - 98.17) $\times 10^{10}$ kJ$\times$m^{-1}s^{-1} and the vertically integrated MFDSE may vary from (-28.96 to 30.36)$\times 10^{10}$ kJ$\times$m^{-1}s^{-1} over Dhaka at 0000 UTC.

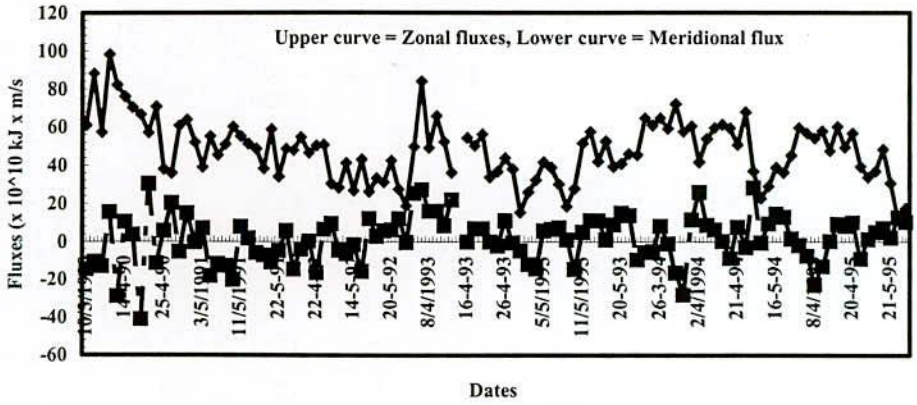


Fig. 6.32: Comparison of vertically integrated ZFDSE and MFDSE over Dhaka at 0000 UTC on the dates of occurrence of nor'westers in Bangladesh

Table 6.13: Frequency of vertically integrated ZFDSE and MFDSE from 1000 to 100 hPa over Dhaka at 0000 UTC on the dates of occurrence of nor'westers in Bangladesh

Range of fluxes ($\times 10^{10}$ kJ$\times$m^{-1}s^{-1})	Frequency of vertically integrated ZFDSE	Frequency of vertically integrated MFDSE
-30 to -20	0	4
-20 to -10	0	18
-10 to 0	0	25
0 to 10	0	38
10 to 20	5	16
20 to 30	9	5
30 to 40	22	1
40 to 50	20	0
50 to 60	29	0
60 to 70	14	0
70 to 80	3	0
80 to 90	4	0
90 to 100	1	0
Total	107	107

The table shows that the vertically integrated ZFDSE are westerly. About 92.52% WFDSE are in the range of (10 - 70) $\times 10^{10}$ kJ$\times$m^{-1}s^{-1} and 7.48% westerly fluxes are in the range of (70 - 100) $\times 10^{10}$ kJ$\times$m^{-1}s^{-1} on the dates of occurrence of nor'westers in Bangladesh. The vertically integrated MFDSE are northerly in 43.93% cases of nor'westers. The MFDSE are southerly in 56.07% cases of which 35.51% cases fall in the range of (0 - 10) $\times 10^{10}$ kJ$\times$m^{-1}s^{-1} and in 20.56% cases the vertically integrated SFDSE are in the range of (10 - 40) $\times 10^{10}$ kJ$\times$m^{-1}s^{-1}.

6.4.9.4 Spatial distribution of the vertically integrated zonal and meridional fluxes of DSE

The spatial distribution of the vertically integrated ZFDSE from 925 to 100 hPa level over Bangladesh and its surrounding areas has been analyzed for 26 cases of nor'westers and one distribution is shown in Fig. 6.33 as an example.

It has been found that vertically integrated WFDSE dominate over Bangladesh and/or eastern Uttar Pradesh, Bihar and Sub-Himalayan West Bengal of India on the dates of occurrence of nor'westers and the gradient of westerly fluxes is significantly steep over the country. The range of the vertically integrated ZFDSE for the layer is about (1 - 16) $\times 10^{10}$ kJ $\times$ m^{-1} s^{-1} over Bangladesh in most of the cases. Sometimes an EFDSE exists over north Orissa, Gangetic West Bengal and adjoining Bangladesh as can be seen from Fig. 6.33.

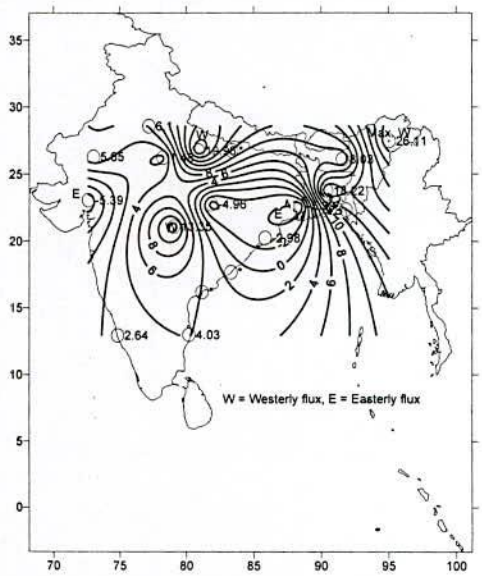


Fig. 6.33: Spatial distribution of vertically integrated ZFDSE ($\times 10^{10}$) in kJ $m^{-1}s^{-1}$ from 925 to 100 hPa at 0000 UTC on 14 May 1992, the date of occurrence of nor'westers in Bangladesh

The spatial distribution of the vertically integrated MFDSE from 925 to 100 hPa level over Bangladesh and its surrounding areas has been analyzed for 26 cases of nor'westers and one distribution is shown in Fig. 6.34 as an example. It has been found that vertically integrated SFDSE dominate over the area from southern India to south southwestern and adjoining central parts of Bangladesh on the dates of occurrence of nor'westers and the

gradient of fluxes is steep over Bangladesh. There exist NFDSE in the northern part of the Bangladesh in many cases. The range of the vertically integrated SFDSE for the layer is about (1 - 5) $\times 10^{10}$ kJ $\times$ $m^{-1}s^{-1}$ and the range of the vertically integrated NFDSE is (-1to –15) 10^{10} kJ $\times$ $m^{-1}s^{-1}$ in most of the cases.

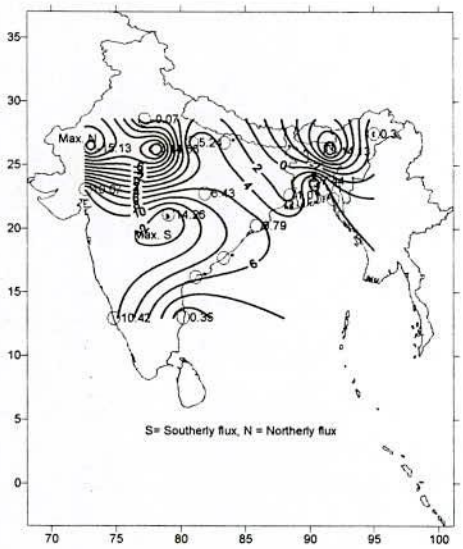


Fig. 6.34: Spatial distribution of vertically integrated MFDSE ($\times 10^{10}$) in kJ $m^{-1}s^{-1}$ at 0000 UTC on 14 May 1992 (date of occurrence)

6.4.9.5 Zonal fluxes of moist static energy (ZFMSE) over Dhaka

The ZFMSE over Dhaka at 0000 UTC have been computed at different isobaric levels on the dates of occurrence of about 107 nor'westers over Bangladesh during pre-monsoon season of 1990-1995. The fluxes over Dhaka have also been computed for the dates of non-occurrence of nor'westers. A comparative study of the frequency of westerly (positive) and easterly (negative) fluxes of MSE has been made. The frequency of positive (westerly) and negative (easterly) ZFMSE at standard isobaric heights on the dates of occurrence of nor'westers is exactly similar to the frequency of ZFDSE.

From the study of 107 cases of nor'westers, the maximum WFMSE over Dhaka at 0000 UTC on the dates of occurrence of nor'westers may be 4.42 $\times$ 10^3, 4.71 $\times$ 10^3, 8.68 $\times$ 10^3, 9.43 $\times$ 10^3, 22.24 $\times$ 10^3, 13.60 $\times$ 10^3, 22.85 $\times$ 10^3, 29.02 $\times$ 10^3 and 20.62 $\times$ 10^3 Joule gm^{-1} $\times$ ms^{-1} at standard isobaric heights of 1000, 925, 850, 700, 500, 400, 300, 200 and 100 hPa levels respectively. The maximum EFMSE over Dhaka at 0000 UTC may be -2.36$\times$ 10^3, -1.38 $\times$ 10^3, -0.39 $\times$ 10^3, 0, -1.23 $\times$ 10^3, -1.37 $\times$ 10^3, -1.60 $\times$ 10^3 and -3.93 $\times$ 10^3 Joule gm^{-1} $\times$ ms^{-1} at 1000, 925, 850, 500, 400, 300, 200 and 100 hPa levels respectively. The variation of

maximum and minimum ZFMSE with height is similar to that of the ZFDSE. The maximum ZFMSE are always westerly on the dates of occurrence of nor'westers and the westerly fluxes are significant in the upper troposphere.

The vertical profiles of the ZFMSE over Dhaka at 0000 UTC on the dates of occurrence and non-occurrence of nor'westers in Bangladesh are studied, and the variation is shown in Fig. 6.35 as an example.

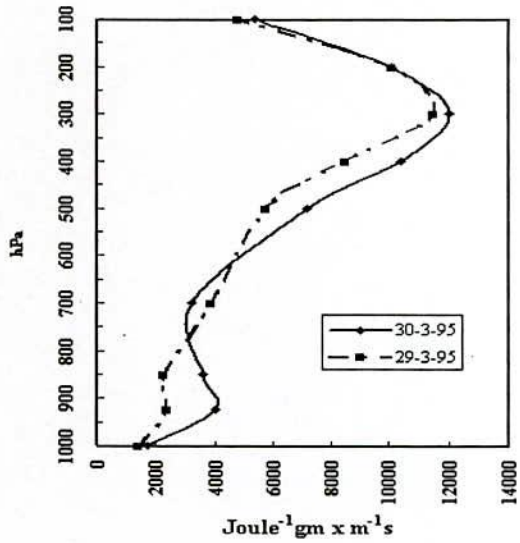


Fig. 6.35: Vertical profiles of the ZFMSE on the date of occurrence (30 March 1995) and the date of non-occurrence (29 March 1995) over Dhaka at 0000 UTC

It has been found that the ZFMSE are mainly westerly and more westerly in the lower troposphere on the dates of occurrence of nor'westers as compared to the ZFMSE on the dates of non-occurrence. The fluxes of MSE are significantly westerly on both the dates of occurrence and non-occurrence of nor'westers having slightly higher values in the upper troposphere

6.4.9.6 Meridional fluxes of moist static energy (MFMSE) over Dhaka

The MFMSE over Dhaka at 0000 UTC have been computed at different isobaric levels on the dates of occurrence and non-occurrence of nor'westers over Bangladesh during pre-monsoon season. A comparative study of the frequency of southerly (positive) and northerly (negative) fluxes has been made. The frequency of positive and negative MFMSE at standard isobaric heights on the dates of occurrence of nor'westers are exactly similar to the frequency of MFDSE.

The maximum SFMSE over Dhaka at 0000 UTC on the dates of occurrence of nor'westers increase with height and may be 44.40 × 10^2, 58.40 × 10^2, 50.27 × 10^2, 39.16 × 10^2, 59.58 × 10^2, 51.84 × 10^2, 103.44 × 10^2, 122.41 × 10^2, and 114.09 × 10^2 Joule $gm^{-1} \times ms^{-1}$ at 1000, 925, 850, 700, 500, 400, 300, 200 and 100 hPa levels respectively. The maximum NFMSE over Dhaka at 0000 UTC may be -28.20 × 10^2, -43.58 × 10^2, -45.52 × 10^2, -48.98 × 10^2, -87.69× 10^2, -47.18 × 10^2, -66.82 × 10^2, -132.60 × 10^2 and -119.66 × 10^2 Joule $gm^{-1} \times ms^{-1}$ at 1000, 925, 850, 700, 500, 400, 300, 200 and 100 hPa levels respectively. The MFMSE are significantly large in the upper troposphere. The variation of maximum and minimum MFMSE with height is similar to that of the MFDSE.

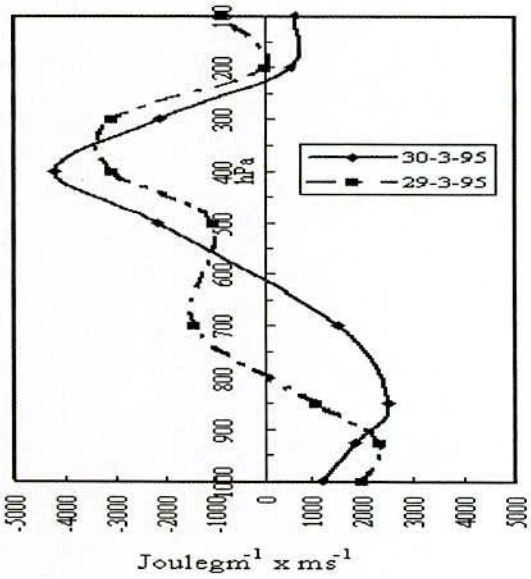


Fig. 6.36: Vertical profiles of the MFMSE on the date of occurrence (30 March 1995) and the date of non-occurrence (29 March 1995) over Dhaka at 0000 UTC

The vertical profiles of the MFMSE over Dhaka at 0000 UTC on the dates of occurrence and non-occurrence of nor'westers in Bangladesh are studied, and the vertical variation is shown in Fig. 6.36 as an example. It has been found that the MFMSE are mainly southerly and/or more southerly in the lower and middle troposphere on the dates of occurrence of nor'westers as compared to the MFMSE on the dates of non-occurrence. The MFMSE are significantly southerly on both the dates of occurrence and non-occurrence of nor'westers having higher values in the upper troposphere.

6.4.9.7 Vertically integrated zonal and meridional fluxes of MSE over Dhaka

The ZFMSE and MFMSE, computed at different isobaric levels over Dhaka at 0000 UTC on the dates of occurrence of nor'westers, have been integrated from 1000 to 100 hPa level by taking the layer mean MSE. The vertically integrated ZFMSE and MFMSE for 107 nor'westers are significantly higher than that of the MFMSE over Dhaka on the dates of occurrence of nor'westers in Bangladesh. The vertically integrated ZFMSE are always westerly on the dates of occurrence of nor'westers like the vertically integrated ZFDSE; the only difference is in magnitudes. The frequency distribution of vertically integrated ZFMSE and MFMSE over Dhaka at 0000 UTC on the dates of occurrence of nor'westers in Bangladesh is shown in Table 6.14.

Table 6.14: Frequency of vertically integrated ZFMSE and MFMSE over Dhaka at 0000 UTC on the dates of occurrence of nor'westers in Bangladesh

Range of fluxes ($\times 10^{10}$ kJ$\times$m^{-1}s^{-1})	Frequency of vertically integrated ZFMSE	Frequency of vertically integrated MFMSE
-30 to -20	0	3
-20 to -10	0	17
-10 to 0	0	24
0 to 10	1	40
10 to 20	5	17
20 to 30	8	6
30 to 40	22	0
40 to 50	20	0
50 to 60	28	0
60 to 70	16	0
70 to 80	3	0
80 to 90	3	0
90 to 100	1	0
Total	107	107

The table shows that the vertically integrated ZFMSE over Dhaka at 0000 UTC are westerly on the dates of occurrence of nor'westers. About 92.52% WFMSE are in the range of (10 - 70) $\times 10^{10}$ kJ$\times$m^{-1}s^{-1} and 6.54% WFMSE are in the range of (70 - 100) $\times 10^{10}$ kJ$\times$m^{-1}s^{-1} having maximum frequency of 61.68% in the range of (30 - 70) $\times 10^{10}$ kJ$\times$m^{-1}s^{-1} on the dates of occurrence of nor'westers in Bangladesh. The vertically integrated MFMSE are northerly in 41.12% cases of nor'westers. The MFMSE are southerly in 58.88% cases of which 37.38% cases fall in the range of (0 - 10) $\times 10^{10}$ kJ$\times$m^{-1}s^{-1} and in 21.50% cases the vertically integrated SFMSE are in the range of (10 - 30) $\times 10^{10}$ kJ$\times$m^{-1}s^{-1}. On the dates of occurrence of

nor'westers, the vertically integrated ZFMSE may vary from (3.44 - 99.11) × 10^{10} kJ×$m^{-1}s^{-1}$ and the vertically integrated MFMSE may vary from (-27.9 to 28.72) × 10^{10} kJ×$m^{-1}s^{-1}$ over Dhaka at 0000 UTC.

Fig. 6.37 shows the variation in the vertically integrated ZFMSE over Dhaka from 1000 to 100-hPa level on the dates of occurrence and the dates of non-occurrence (1 day before) of nor'westers (e.g. 9 March 1990 is the date of non-occurrence and 10 March 1990 is the date of occurrence of nor'westers).

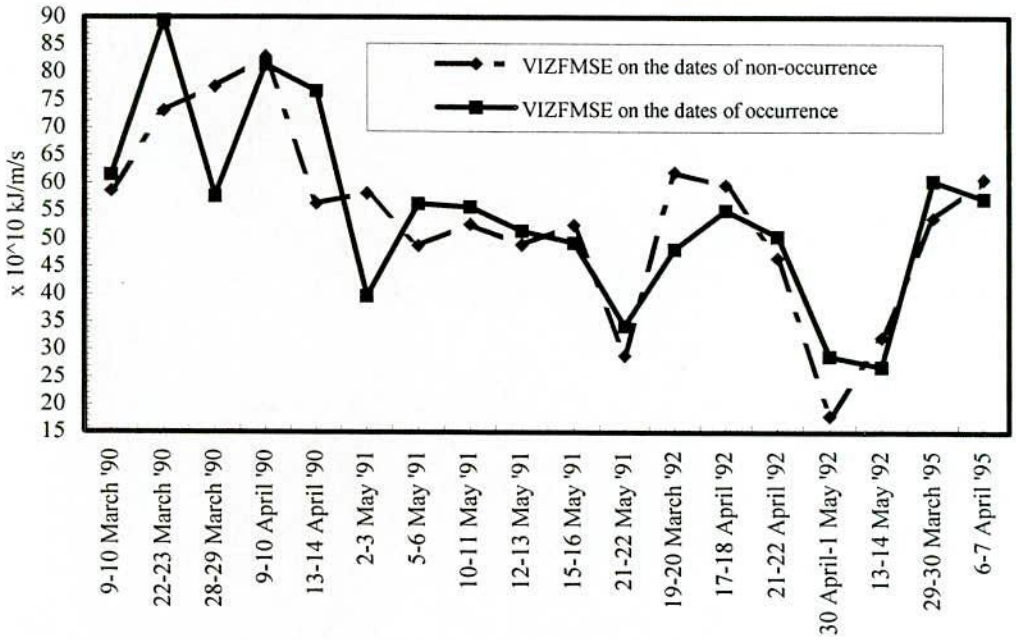


Fig. 6.37: Comparison of the vertically integrated ZFMSE over Dhaka at 0000 UTC on the dates of occurrence and non-occurrence (1 day before) of nor'westers in Bangladesh

It is seen from the figure that the vertically integrated ZFMSE on the dates of occurrence of nor'westers is higher than that on the dates of non-occurrence of nor'westers in many cases (55.56%). The figure also shows that the variation pattern of the fluxes on the dates of occurrence and non-occurrence of nor'westers is almost similar. There exists a correlation between the vertically integrated ZFMSE on the dates of occurrence and non-occurrence of nor'westers. The CC is 0.78565, which is significant at 99% level of significance and the relation between the vertically integrated ZFMSE on the dates of occurrence and non-occurrence is $VIZFMSE_o = 0.7655*VIZFMSE_{non} + 12.233$.

6.4.9.8 Spatial distribution of the vertically integrated zonal and meridional fluxes of MSE

The spatial distribution of the vertically integrated ZFMSE from 925 to 100 hPa level over Bangladesh and its surrounding areas has been analyzed for 26 cases of nor'westers and the distribution pattern is shown in Fig. 6.38 as an example.

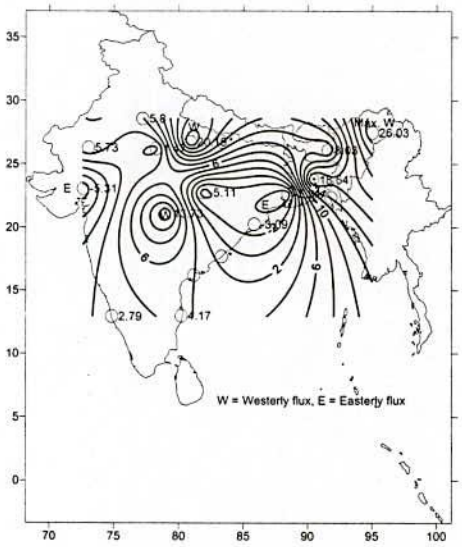


Fig. 6.38: Spatial distribution of vertically integrated ZFMSE ($\times 10^{10}$) in kJ $m^{-1}s^{-1}$ from 925 hPa to 100 hPa at 0000 UTC on 14 May 1992, the date of occurrence of nor'westers in Bangladesh

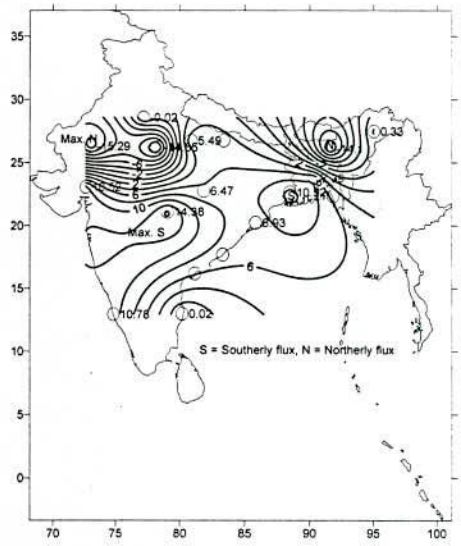


Fig. 6.39: Spatial distribution of vertically integrated MFMSE ($\times 10^{10}$) in kJ $m^{-1}s^{-1}$ from 925 hPa to 100 hPa at 0000 UTC on 14 May 1992, the date of occurrence of nor'wester in Bangladesh

It has been found that vertically integrated WFMSE dominate over Bangladesh and/or eastern Uttar Pradesh, Bihar and adjoining Sub-Himalayan West Bengal of India on the dates of occurrence of nor'westers and the gradient of westerly fluxes is significantly steep over the country. The range of the vertically integrated ZFMSE for the layer is about $(2 - 16) \times 10^{10}$ kJ $\times$ m^{-1} s^{-1} over Bangladesh in most of the cases. An easterly flux of moist static energy exists over north Orissa, West Bengal and adjoining Bangladesh with its trough extending towards north-northeast as can be seen from Fig. 6.38.

The spatial distribution of the vertically integrated MFMSE for the layer 925-100 hPa level over Bangladesh and its surrounding areas has also been analyzed for 26 nor'westers and Fig. 6.39 shows a pattern of distribution of the MFMSE as an example. It has been found that vertically integrated SFMSE dominate over West Bengal of India, south southwestern and adjoining central parts of Bangladesh on the dates of occurrence of nor'westers and the

gradient of fluxes is very steep over Bangladesh. There exist NFMSE in the northern part of the Bangladesh in many cases. The range of the vertically integrated SFMSE for the layer is about (1 - 8) $\times 10^{10}$ kJ $\times$ $m^{-1}s^{-1}$ and the range of the vertically integrated NFMSE is (-1 to – 10) $\times 10^{10}$ kJ $\times$ $m^{-1}s^{-1}$ in most of the cases.

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CHAPTER 7

USE OF RADAR AND SATELLITE IMAGERIES IN THE STUDY OF NOR'WESTERS

7.1 Introduction

Bangladesh is a playground of severe thunderstorms called nor'westers during the pre-monsoon season. These nor'westers cause loss of lives and damage to properties in every year in the country. These nor'westers are meso-scale phenomena, the horizontal dimension of which is of the order of 1-2 × 10^3 km and if sufficient moisture is present, they can cause widespread heavy rain and flooding (Maddox, 1980). Analysis of conventional data both at the surface and the upper air gives the favourable conditions for the formation of thunderclouds even more than 12 hours prior to their occurrence. In the morning, it is not possible to see any cloud formation in and around the country with the help of satellite and radar imageries most of the time. As the day progresses, more and more solar radiation is coming to the earth, cloud formation begins to start as seen from the satellite imageries. Then the combined use of conventional data and satellite imageries gives a better assessment of the atmosphere; these lead to more reliable and accurate warning of local severe storms. Initial state of development, in cumulus stage, cannot be detected by radar observations but it can be identified in satellite imageries. When the thunderclouds develop and come under the radar range, then the movement and intensity can easily be identified by radar observations. Kamble and Kanoujia (1990) studied the multiple squalls over central India. According to them the frequency of occurrence of multiple squalls is maximum in the months of May and June at Nagpur and Bhopal whereas it is maximum in April and May at Jagdalpur. Three-hourly period between 1500-1800 IST is the most favourable period for the development of multiple squalls over central India.

It is well known that convective clouds can grow to great heights, develop vigorous updrafts, and produce heavy rain, lightning and hail when lower atmosphere is sufficiently moist and unstable. These large severe storms may occur individually or more typically in groups associated with synoptic scale fronts or mesoscale convergence zone. Mandal (1989) made satellite and synoptic studies on widespread thunderstorm activity over northwest India on 26 May 1986. According to him, using the satellite cloud imagery and conventional data,

it is possible to identify the area of severe convective activity well in advance. Chatterjee and Prakash (1990) made a study on some aspects of convective clouds around Delhi. They studied the radar data of 55 precipitation echoes from 55 convective clouds during the pre-monsoon and monsoon seasons. According to them, the vertical growth and decay rates as well as the durations of the radar echoes from these clouds varied considerably from day to day and also on the same day on different occasions. Both in the pre-monsoon and monsoon seasons, the average growth rates of the echoes were found to be limited to 6.0 m/sec in 80% cases. However, average decay rates of the echoes were found to be limited to 6.0 m/sec in larger percentage of cases in pre-monsoon than in monsoon season (i.e. 76% and 62% cases respectively). No marked difference was observed in average echo durations in the two seasons (i.e. 39 minutes in pre-monsoon and 36 minutes in monsoon season). The study further suggested that pure collision-coalescence process is responsible for the formation and development of precipitation in at least 50% of the convective clouds forming in Delhi region during the pre-monsoon season. From an analysis of GATE data, Mower (1977) suggested a schematic outline of a squall line over the eastern Atlantic Ocean. According to this analysis, the driving mechanism for the squall line is thought to be an abundant supply of warm moist air in the sub-cloud layer with high enough value of θ_e; the convergence and ascending motion are maintained by downdraft reaching the ground; this seems to originate from a rather low level i.e. 900-800 hPa in this situation. This picture by Mower does not require a large-scale shearing environment for the maintenance of the squall system. In the diagram prepared by him shows inflow and outflow of air at around 600 hPa is about 4 ms^{-1}.

Till now, no satellite and radar studies have yet been made in Bangladesh and a very few studies have been made in this respect in India. In the present study, attempts have been made to use the satellite and radar cloud imageries in the forecasting of nor'westers and their subsequent movement over Bangladesh. Estimation of vertical velocity has also been made from the radar cloud imageries in this chapter.

7.2 Data used

The surface MSL chart, satellite and radar cloud imageries have been collected from the Storm Warning Centre (SWC) of Bangladesh Meteorological Department for the period 2001 through 2004 and are utilized in this study.

7.3 Methodology

7.3.1 Surface MSL charts, radar and satellite imageries

The surface synoptic charts prepared by Storm warning Centre (SWC), radar cloud imageries and satellite cloud imageries obtained by SWC have been critically discussed on the dates of occurrence of nor'westers in Bangladesh.

7.3.2 Vertical velocity at 300 hPa

The radar imageries have been used to obtain the increase in area covered by clouds at different times on the date of occurrence of severe nor'westers on 26-27 April 2002 over Bangladesh. The area of the cloud cover in the radar imageries has been measured by using the arbitrary squares of 5mm×5mm. It is assumed that the increase in cloud area represents the average divergence of the troposphere in the layer 300-100 hPa. The divergence and the vertical velocity have been calculated using the formula given below (Wallace and Hobbs, 1977):

$$\vec{\nabla}.\vec{V} = \frac{1}{A}\frac{dA}{dt} \tag{1}$$

The continuity equation in pressure coordinates is given by:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial \omega}{\partial p} = 0 \tag{2}$$

$$\Rightarrow \quad \vec{\nabla}.\vec{V} + \frac{\partial \omega}{\partial p} = 0$$

$$\Rightarrow \quad \partial \omega = -\vec{\nabla}.\vec{V}\partial p$$

$$\Rightarrow \quad \int_{300}^{100} \partial \omega = -\int_{300}^{100} \vec{\nabla}.\vec{V}\partial p$$

$$\Rightarrow \quad \omega_{100} - \omega_{300} = -\overline{\vec{\nabla}.\vec{V}}(100-300) \tag{3}$$

But the vertical velocity at 100 hPa is usually assumed to be zero. So,

$$\omega_{300} = -\overline{\vec{\nabla}.\vec{V}}.200 \tag{4}$$

The unit of ω is hPa s^{-1}. The relation between ω and w is given by (Holton, 1979):

$$\omega = -\rho g w$$

$$\Rightarrow w = -\frac{\omega}{\rho g}$$

Using equation state, we have:

$$w = -\frac{\omega}{p}\frac{RT}{g} \tag{5}$$

Where R= 287.04 $Jkg^{-1}{}^{\circ}K^{-1}$, T is the temperature at 300 hPa in °K and g=9.80665 ms^{-1}. The unit of w is ms^{-1}.

7.4 Results and discussion

7.4.1 Pseudo-frontal activity

During the pre-monsoon season, two air masses of different temperatures are found over Bangladesh and adjoining West Bengal especially at 0000 UTC on the dates of occurrence of nor'westers and they form a discontinuity line. Sometimes more than one discontinuity lines form over the region. This indicates that '**pseudo-frontal**' activity is found over Bangladesh and its surroundings as can be seen from Fig. 7.1.

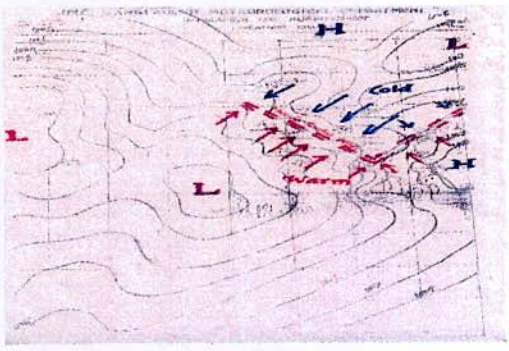

Fig. 7.1: Surface synoptic chart at 0000 UTC on 26 April 2002

When this pseudo-frontal activity is found in the morning, severe thunderstorms/nor'westers occur in the evening or early night. It is interesting to note that the sky over Bangladesh and adjoining areas has been found to remain cloudless/clear from

morning to afternoon in most of the days when the pseudo-frontal activity is present at the surface and on these days nor'westers have been found to occur over Bangladesh provided other conditions must be favourable. In the afternoon/evening, the severe squall lines form and they move like a front. These nor'westers move from northwest to east-southeast up to Chittagong like a front causing a huge damage to crops and properties and loss to human lives.

7.4.2 Study of satellite imagery

GMS satellite imageries, both IR and VIS, have been examined on the dates of occurrence of a number of nor'westers in Bangladesh. It has been found that there exists no cloud mass in the satellite pictures in the morning and noontime in most of the cases. Rather the satellite pictures show almost clear sky over Bihar, West Bengal of India and adjoining areas of Bangladesh during this time except in few cases low clouds appear in the morning of nor'wester day. But in the afternoon, very small mass of bright convective cloud is seen to grow over those areas, which afterwards grow into a large bright convective cloud causing severe thunderstorms / nor'westers over Bangladesh. Some satellite IR cloud imageries on 26 April 2002 are shown in Figs. 7.2 (a-i). The figures show that that there is no bright convective cloud mass at 0000 UTC and 0300 UTC over West Bengal and adjoining areas except west Nepal and adjoining areas. At 0632 UTC, the cloud mass seems to be descended south/southeastwards up to sub-Himalayan West Bengal and at 0932 UTC, a few bright convective cells have appeared over sub-Himalayan West Bengal, adjoining northwestern Bangladesh, West Bengal and Orissa. From 1532 UTC, the cloud mass is seen to diffused. Figs. 7.2(a-i) show the movement of cloud towards east/southeast till 0332 UTC of 27 April 2002.

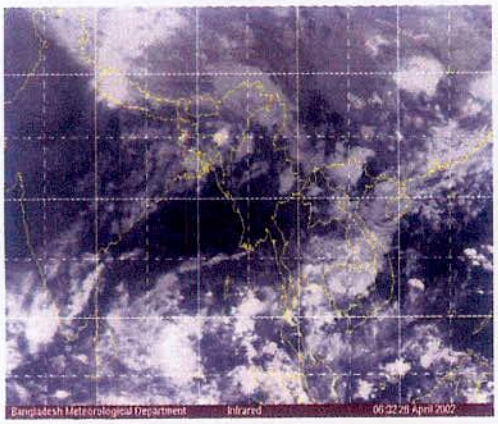

Fig. 7.2 (a): 00:32 UTC, 26 April 2002

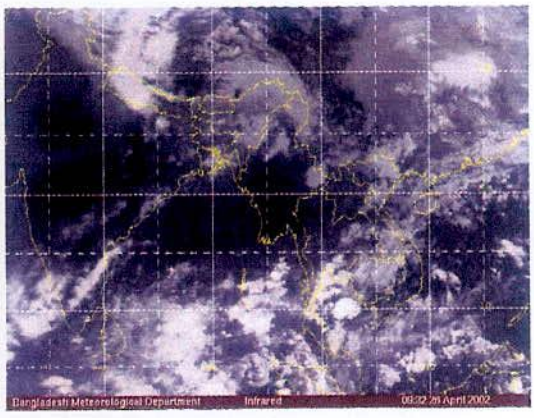

Fig. 7.2 (b): 03:32 UTC, 26 April 2002

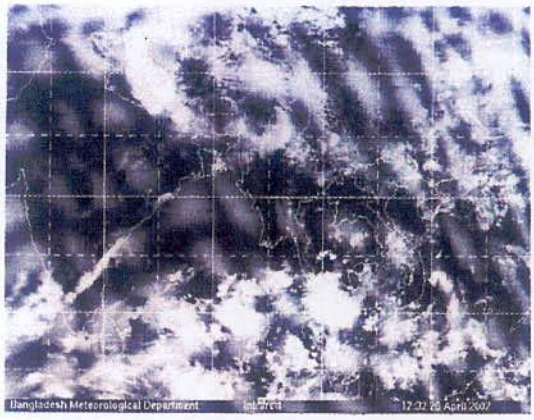

Fig. 7.2(c): 06:32 UTC, 26 April 2002

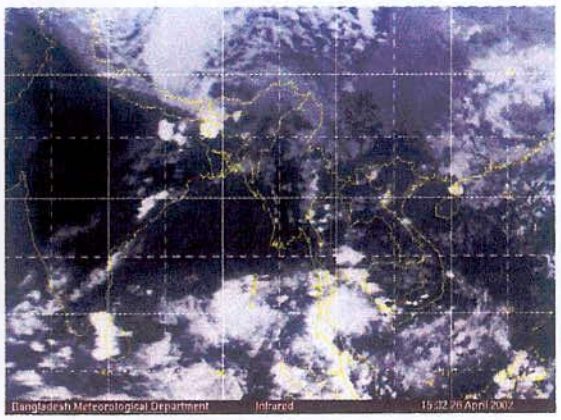

Fig.7.2 (d): 09:32 UTC, 26 April 2002

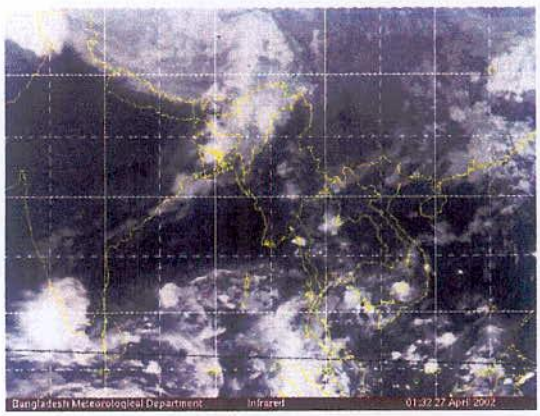

Fig. 7.2 (e): 15:32 UTC, 26 April 2002

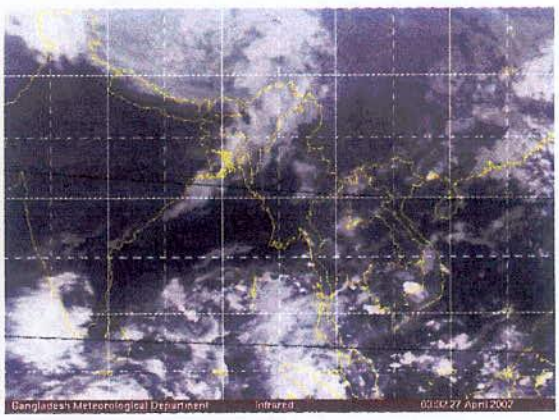

Fig. 7.2 (f): 21:32 UTC, 26 April 2002

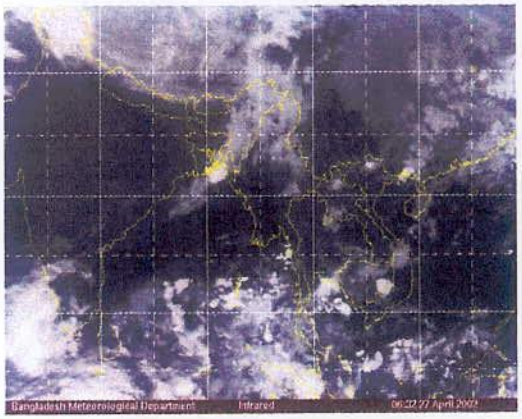

Fig. 7.2 (g): 00:32 UTC, 27 April 2002

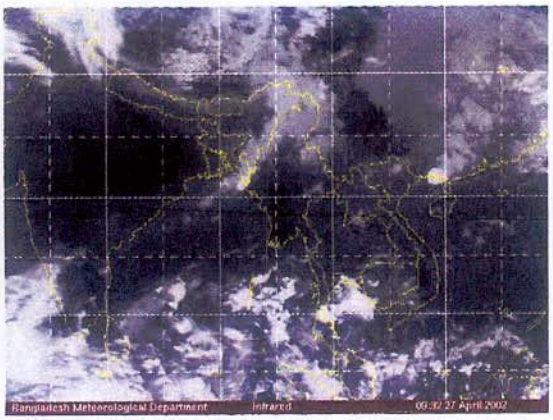

Fig. 7.2 (h): 03:32 UTC, 27 April 2002

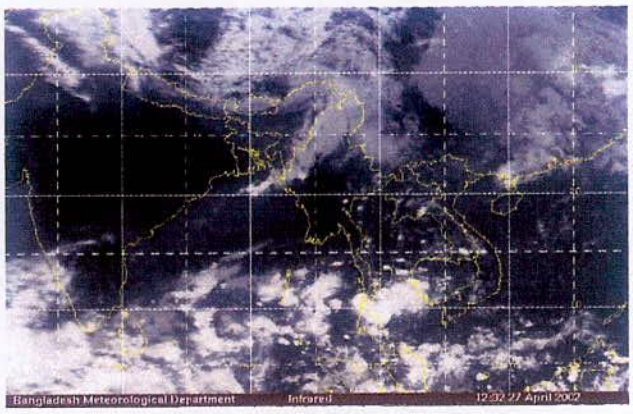

Fig. 7.2 (i): 06:32 UTC, 27 April 2002

Figs. 7.2(a-i): Satellite cloud imageries in the morning on the dates of occurrence of nor'westers 26-27 April 2002

7.4.3 Study of Radar Imagery

Radar imageries at Dhaka have been examined on the dates of occurrence of a number of nor'westers in Bangladesh. It has been found that there exists no cloud mass in the radar pictures in the morning and noontime in most of the cases. Rather the radar pictures show almost clear sky over Bihar, West Bengal of India and adjoining areas of Bangladesh during this time. But in the afternoon, very small mass of convective cloud is seen to grow over those areas, which afterwards grow into large convective clouds causing severe thunderstorms/nor'westers together with squall lines over Bangladesh. Some radar cloud imageries on 26 April 2002 are shown in Figs. 7.3 (a-h). The figures show that small cloud mass appears at 0800 UTC (Fig. 7.3a) over northwestern Bangladesh. The cloud area begins to expand from 1101 UTC forming multiple cells and squall lines moving east-southeastwards (Fig. 7.3b). Then the convective cloud area has expanded more and more up to 1700 UTC on 26 April and the cloud area is seen to decrease afterwards. The movement of clouds/squalls towards east/southeast till 2309 UTC of 26 April 2002 (i.e. 0309 BST of 27 April). The pseudo frontal activity as described in section 7.4.1 is confirmed by the radar cloud imageries.

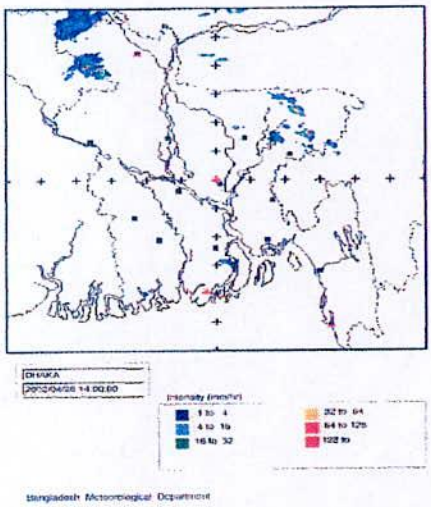

Fig. 7.3 (a): 1400 BST on 26 April 2002

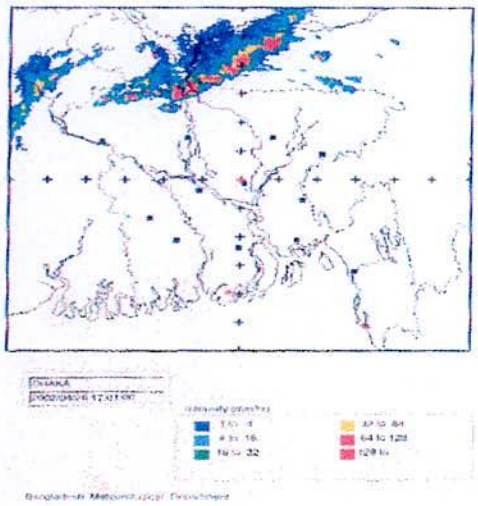

Fig. 7.3 (b): 1701 BST on 26 April 2002

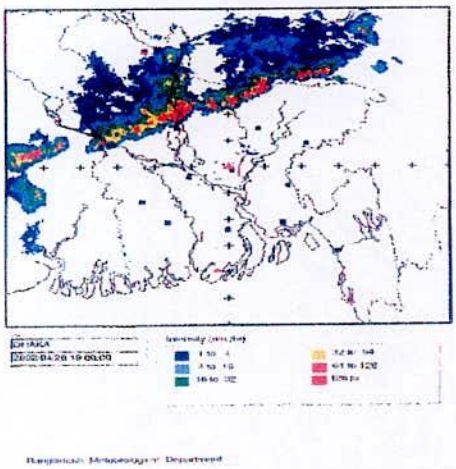

Fig. 7.3 (c): 1900 BST on 26 April 2002

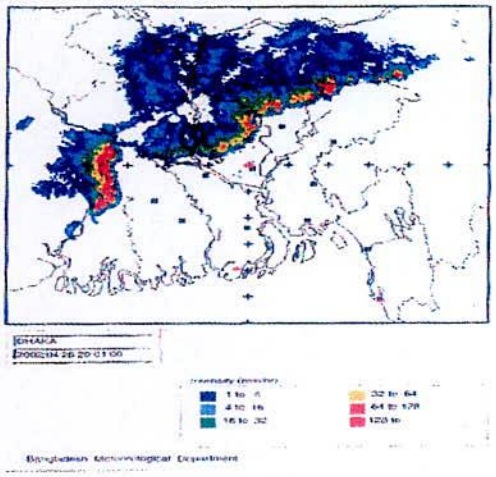

Fig. 7.3 (d): 2001 BST on 26 April 2002

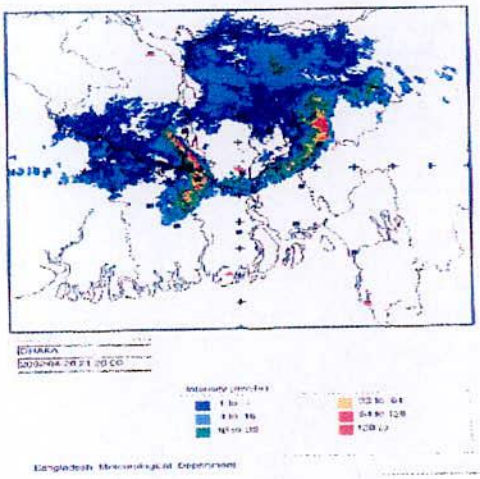

Fig. 7.3 (e): 2020 BST on 26 April 2002

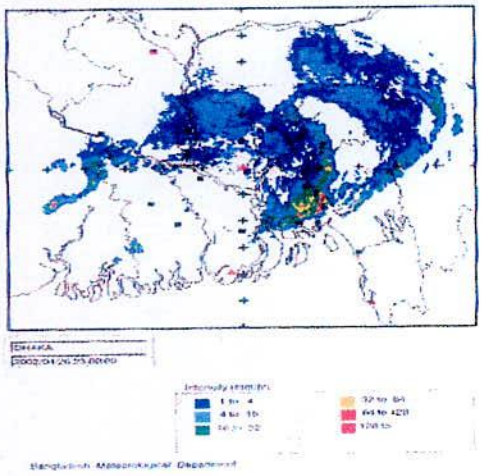

Fig. 7.3 (f): 2300 BST on 26 April 2002

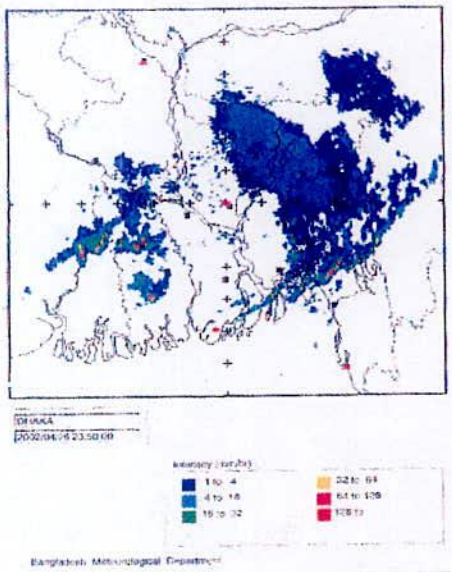

Fig. 7.3 (g): 2350 BST on 26 April 2002

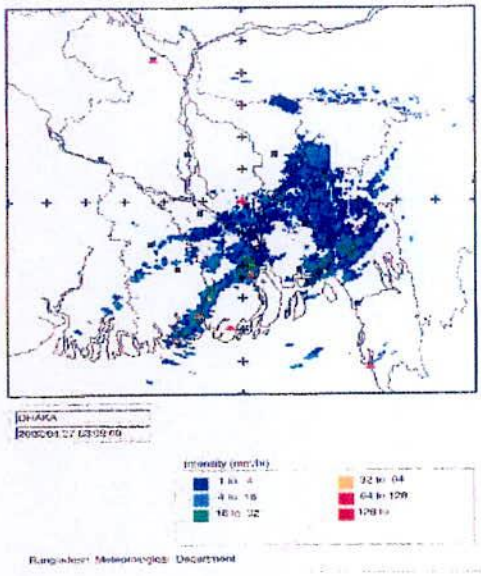

Fig. 7.3 (h): 0309 BST on 27 April 2002

Figs. 7.3(a-h): Radar pictures on 26-27 April 2002 at different observation times

7.4.4 Vertical velocity at 300 hPa

The radar imageries as shown in Figs. 7.3 (a-h) have been used to obtain the increase in area covered by clouds at different times on the date of occurrence of severe nor'westers on 26-27 April 2002 over Bangladesh. The increase in cloud area represents the average divergence of the troposphere in the layer 300-100 hPa. The divergence in the layer 300-100 hPa and the vertical velocity at 300 hPa have been calculated using the above radar imageries. The temporal variation of vertical velocity at 300 hPa is shown in Fig. 7.4.

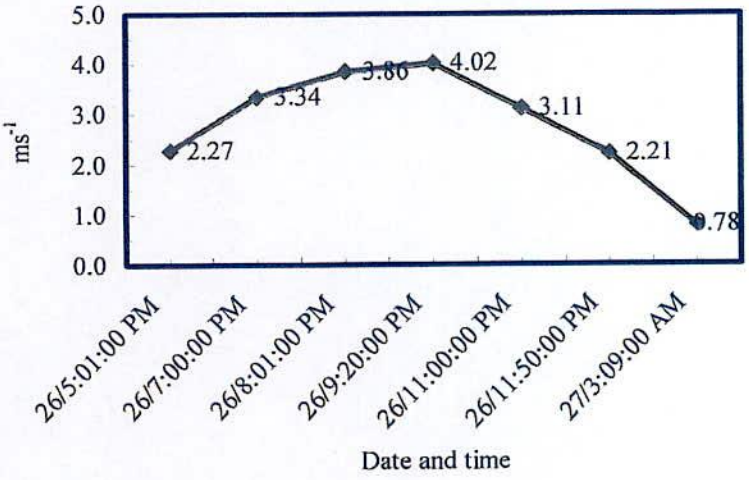

Fig. 7.4: Temporal variation of vertical velocity at 300 hPa calculated from radar imageries on 26-27 April 2002

The Fig. 7.4 shows that the vertical velocity associated with nor'wester increases with time from 1101 UTC to 1520 UTC on 26 April 2002 (i.e. for about 4 hours 19 minutes) and then begins to decrease till 2309 UTC. The maximum vertical velocity has been estimated to be 4.02 ms^{-1}. This value is almost identical to the inflow of air as indicated by Mower (1977).

CHAPTER 8

AVAILABLE INSTABILITY ENERGY AND VERTICAL WIND SHEAR ASSOCIATED WITH NOR'WESTERS

8.1 Introduction

Tropical disturbances or weather systems can be classified into five categories according to their space and time scales. The smallest weather system is the individual cumulus with a life span of only a few hours. The cumulus clouds are generally parallel to the wind direction rather than being randomly distributed. Such cumulus clouds may aid the development of a larger disturbance if up- and downdrafts intensify convection during distributed weather conditions. The second category is the mesoscale system particularly associated with land/sea boundaries, heated oceanic islands, or topography. Mesoscale systems are intermediate in size and life span between synoptic disturbances and individual cumulonimbus cells. They include thunderstorm and organized convective systems like the squall lines. The third category is the cloud cluster, a distinctive feature of the tropics that has been identified from satellite imagery. The cloud cluster is of sub-synoptic scale and may persist for 1-3 days. The fourth category includes synoptic scale wave disturbances and cyclonic vortices. The final and the fifth category of tropical disturbances is the planetary wave. These waves are very large with a wavelength from 10,000 to 40,000 km and occur in the equatorial upper troposphere and stratosphere. The waves do not, however, appear to influence weather directly though they may interact with lower tropospheric systems (Ayoade, 1983).

For the peculiar geographical condition of Bangladesh with the Bay of Bengal to the south and Himalayan ranges to the north, the meso-scale systems such as severe thunderstorms occur in different parts of the country during pre-monsoon season. Due to the apparent position of the sun, the lower troposphere over Bangladesh and adjoining countries gets heated and the air near the surface of the earth rises up. As a result a low pressure develops over Bihar, West Bengal of India and adjoining Bangladesh. Moist and warm air from Bay of Bengal moves towards the centre of the low pressure and at the same time cold

and dry air comes from the north/north-west for which a significant instability grows in the atmosphere. Because of these meteorological conditions and circulation in the atmosphere strong cumulus cloud forms and severe thunderstorm occurs. During pre-monsoon season, most of the thunderstorm proceeds from northwest direction and as such they are known as nor'westers in Bangladesh and adjoining Indian states. When the instability of the atmosphere is very significant, a portion of thunderstorm cloud descends as a pendant reaching near the surface of the earth like a funnel cloud or elephant trunk, which has severe twisting effects. This type of cloud is the tornado cloud. The severe thunderstorm/nor'westers have great damaging effects on agricultural crops and cause huge loss to lives and properties over this region. At the same time, if no nor'wester occurs over this region during the pre-monsoon season there is scarcity of rain and as a result drought may occur. Therefore, early forecasting of severe thunderstorms/nor'westers is essential in this region.

Various meteorological aspects of severe thunderstorms/nor'westers have been studied by different authors like Sen (1931), Chatterjee and Sur (1933), Malurkar (1949), Bose (1955), Koteswaram and Srinivasan (1958), Saha (1960), Sen and Basu (1961), Chowdhury (1961), Mukherjee and Bhattacharya (1972), and Mukherjee *et al.* (1977), Chowdhury and Karmakar (1986), Chowdhury *et al.* (1991), Das *et al.* (1994), and Akram and Karmakar (1998). In all these studies, a number of important results have been obtained as regards formation, structure, timing and devastation of nor'westers, etc. There has been, of course, some difference of opinions among the authors as well. Koteswaram and Srinivasan (1958) have shown in their investigation that the nor'westers fail to occur in the Gangetic West Bengal and by inference over Bangladesh and Assam in the absence of southerly winds up to at least 1 km in spite of the other conditions being fulfilled. However, it is possible that the initial shallow layer of moist air can even become deep due to the stretching of the lower layer by convergence.

In this chapter, attempts have been made to study available instability energy or instability energy of the troposphere, its relation with the gusty wind and vertical wind shear associated with nor'westers in Bangladesh during the pre-monsoon season.

8.2 Data used

Data on gusty wind over Dhaka during the months of March through May of 1995-2004 and gusty wind at other stations of Bangladesh Meteorological Department (BMD) during March-May 2004, rawinsonde data of 0000 UTC at different isobaric levels over

Dhaka, Chittagong and some Indian stations during 1990-2004 have been collected from BMD and utilized in the study.

8.3 Basic computation

8.3.1 Available instability energy

Rawinsonde observations at Dhaka on the dates of occurrence have plotted on Tephigrams and analysed. The positive and negative areas on Tephigram have been determined by considering the low level moisture and temperature at 925 hPa to study the instability of the troposphere. From the positive areas, the available instability energy (I) per unit area has been determined (Sheet, 1969) by using the equation:

$$I = C_v g^{-1} \int_{P_0}^{P_h} (T_* - T_{env})\, dp$$

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Where $C_v = 7.201\times10^2$ Jkg^{-1} $°C^{-1}$,

$g = 9.8$ ms^{-2},

T^* = Temperature of the ascending parcel.

T_{env} = Temperature of the environment

8.3.2 Vertical wind shear

The vertical wind shear is defined as the difference in the zonal wind components at two levels. In this study the vertical wind shears in the layers 925-500 and 850-200 hPa have been computed specially for spatial distribution on the dates of occurrence of nor'westers. The vertical wind shear (VWS) between 500 and 925 hPa is given by:

$$VWS_{500\text{-}925} = u_{500} - u_{925}$$

Similarly, for the layer 850-500 hPa,

$$VWS_{500\text{-}850} = u_{500} - u_{850}$$

8.4 Results and discussion

8.4.1 Gusty wind speed

The maximum, minimum and average gusty wind speed associated with nor'westers recorded in March, April and May at Dhaka during 1995-2004 have been analysed and the results are shown in Figs. 8.1-8.3 respectively.

It has been found from the figures that the minimum gust wind ranges from 28 to 52 kph, the maximum gusty wind ranges from 38 to about 78 kph with the average gusty wind of 38-56 kph in March (Fig. 8.1). In April, the minimum gusty wind ranges from 22 to 42 kph, the maximum gusty wind ranges from 45 kph to about 106 kph with the average gusty wind of 40-64 kph (Fig. 8.2). Whereas in May, the minimum gusty wind ranges from 23 to 40 kph, the maximum gusty wind ranges from 45 to about 105 kph with the average gusty wind of 42-61 kph (Fig. 8.3). This indicates that the nor'westers with greater gusty wind occurred in April and May as compared to that in March and this may be attributed to the increased instability of the troposphere.

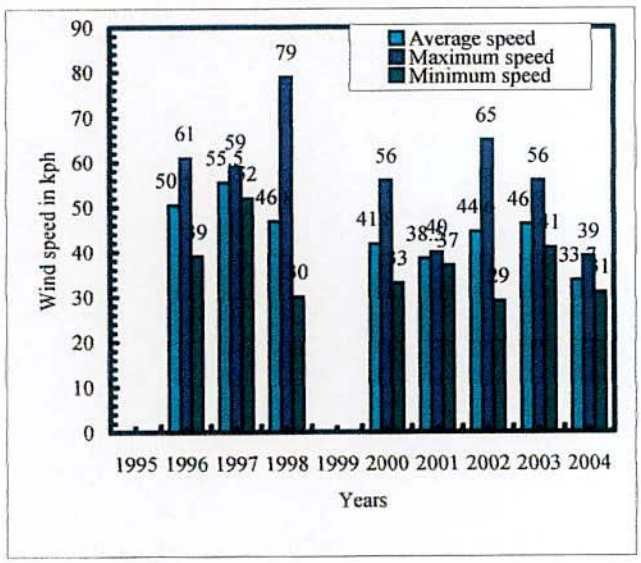

Fig. 8.1: Gusty wind speed recorded in Dhaka in March during 1995-2004

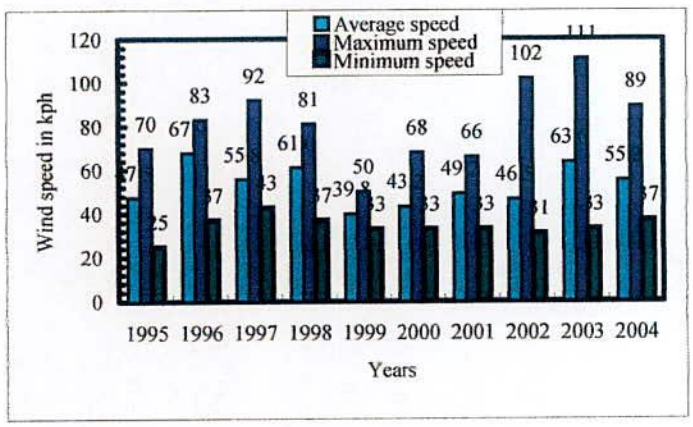

Fig. 8.2: Gusty wind recorded in Dhaka in April during 1995-2004

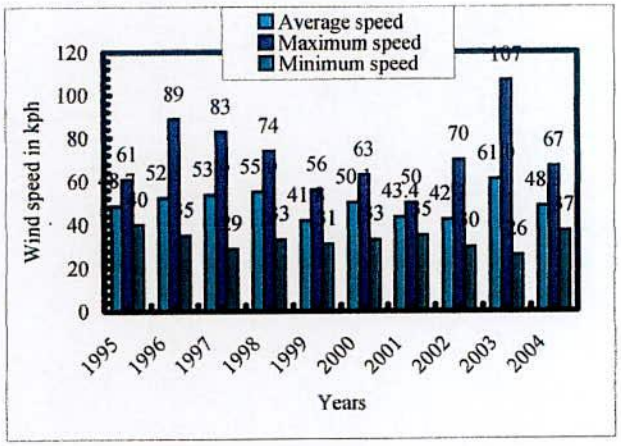

Fig. 8.3: Gusty wind recorded in Dhaka in May during 1995-2004

8.4.2 Available instability energy over Dhaka

In 2004, the number of nor'westers recorded in March, April and May are 6, 17 and 9 respectively. The analysis of Tephigram has shown that there have been positive areas at 0000 UTC mostly on the dates of occurrence of nor'westers during the pre-monsoon season of 2004. This means that the atmosphere was unstable at 0000 UTC on most of the days of occurrence of nor'westers. From the Tephigram analysis, the available instability energy over Dhaka on dates of non-occurrence and dates of occurrence of nor'westers in April and May has been calculated by using the integrated equation of Sheet (1969). The available instability energy over Dhaka is given in Table 8.1.

Table 8.1: Available instability of the troposphere over Dhaka at 0000 UTC in the pre-monsoon season of 2004

Range of available instability energy ($\times 10^5$ Jm^{-2})	Frequency		
	March	April	May
0	21	2	10
>0 to 25	4	1	6
25 to 50	2	1	6
50 to 75	1	3	2
75 to 100	1	1	3
100 to 125	1	2	2
125 to 150	0	5	1
150 to 175	0	1	0
175 to 200	1	5	1
200 to 225	0	3	0
225 to 250	0	1	0
250 to 300	0	4	0
>300	0	1	0
Total	31	30	31

It is seen from the Table 8.1 that the atmosphere over Dhaka was absolutely stable on 21 days in March, 2 days in April and 10 days having zero instability energy in May at 0000 UTC in 2004. Higher instability energy was available in April than that in May. It is also clear from the Fig. 8.4 that the available instability was significantly higher in April 2004. As a result, more nor'westers occurred in April 2004. In April, the range of the available instability energy is 35.18×10^5 Jm^{-2} to 300.51×10^5 Jm^{-2} mainly and in May the range is 5.88×10^5 Jm^{-2} to 176.53×10^5 Jm^{-2}.

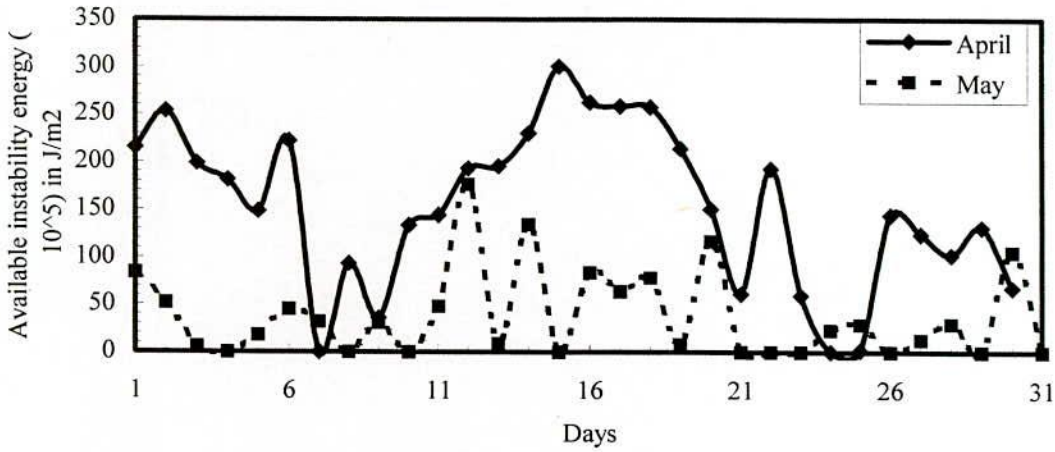

Fig. 8.4: Comparison of available instability energy between April and May at 0000 UTC over Dhaka in 2004

8.4.3 Relation between available instability energy and maximum gusty wind over Dhaka

The available instability energy of the troposphere over Dhaka at 0000 UTC and the maximum gusty wind recorded at Dhaka as well as at other stations has been compared for the months of March through May 2004 and the results are shown in Figs. 8.5-8.9. Fig. 8.5 for March indicates some erratic results. In March there was no instability energy in the morning but nor'westers occurred on 7 and 9 March. This may be due to fact that this month is the starting month for nor'westers; atmosphere was stable in the morning and instability developed in the afternoon. The Fig. 8.6-8.9 show that there seems to have some correlation between the available instability energy and the gusty wind associated with nor'westers. The higher the available instability energy of the troposphere, the greater is the possibility of occurrence of nor'westers, provided the other conditions especially the synoptic conditions are favourable.

It has been found from the figures in April and May that although there were few days with available instability energy but no nor'wester occurred on those days over Dhaka. On those days nor'westers occurred in other places (Figs. 8.8 and 8.9). This might be due to the absence of other favourable conditions in the atmosphere. Again there were few days when there was no available instability energy at 0000 UTC, but nor'westers occurred at Dhaka on those days. This may be attributed to the fact that the atmosphere was stable in the morning and the atmosphere became unstable afterwards due to insolation and moisture influx.

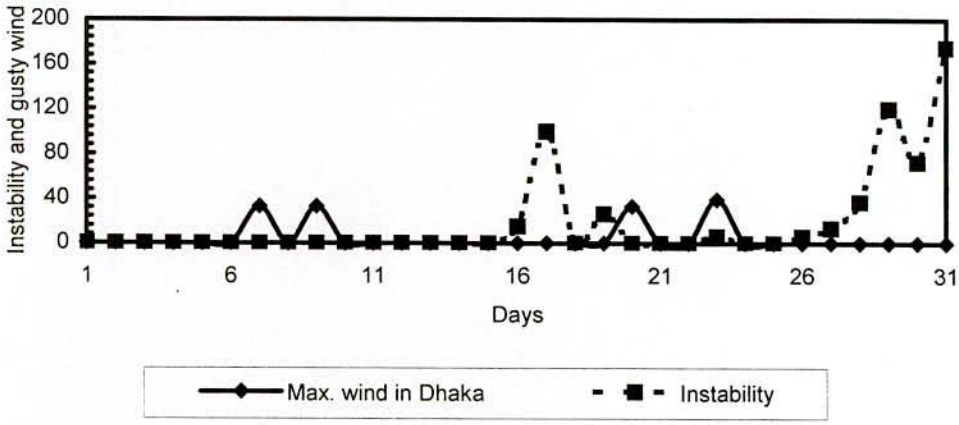

Fig. 8.5: Temporal variation of maximum wind speed (km/hr) and available instability energy ($\times 10^5$ J/m^2) at 0000 UTC over Dhaka in March 2004

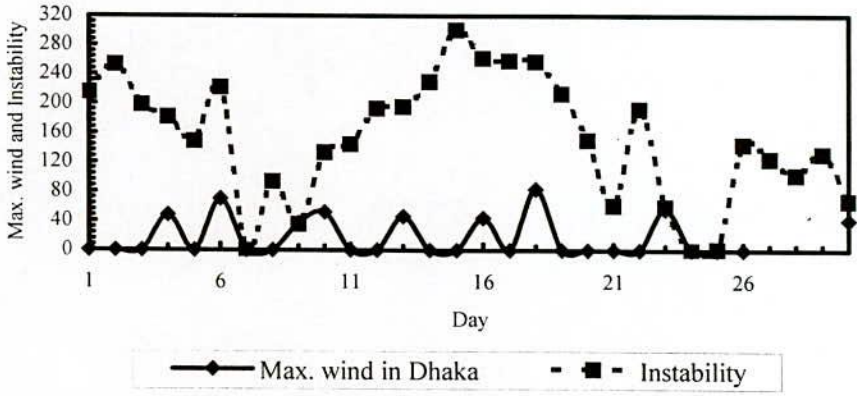

Fig. 8.6: Temporal variation of maximum wind speed (km/hr) and available instability energy ($\times 10^5$ J/m^2) at 0000 UTC over Dhaka in April 2004

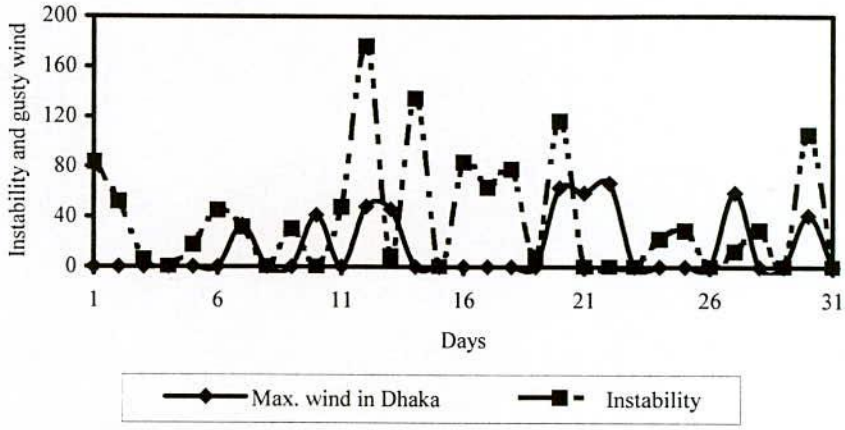

Fig. 8.7: Temporal variation of maximum wind speed (km/hr) and available instability energy ($\times 10^5$ J/m^2) at 0000 UTC over Dhaka in May 2004

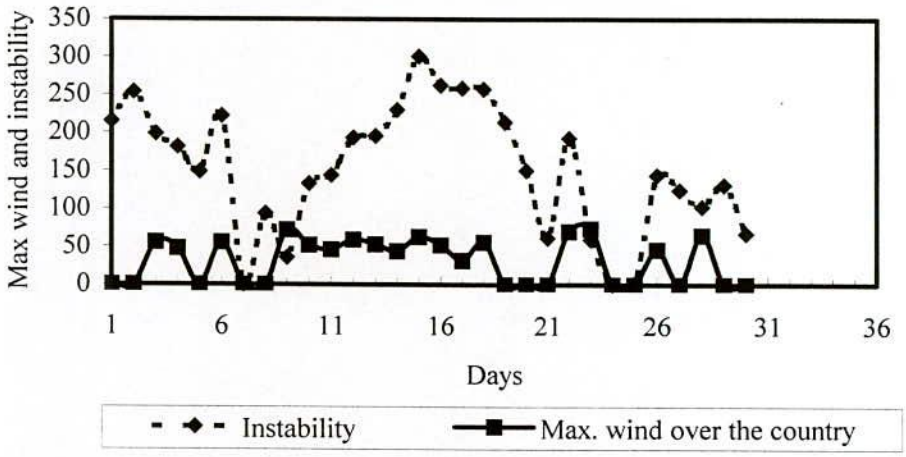

Fig. 8.8: Temporal variation of maximum wind speed (km/hr) recorded in Bangladesh except Dhaka and available instability energy ($\times 10^5$ J/m^2) at 0000 UTC over Dhaka in April 2004

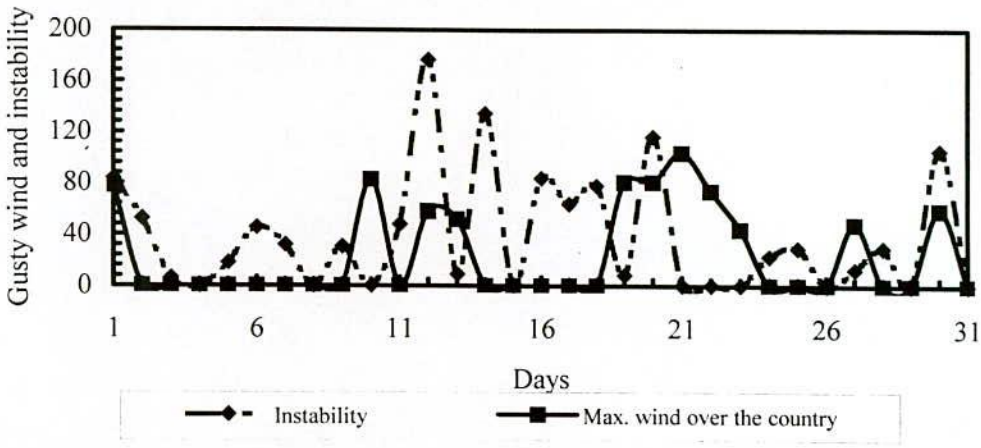

Fig. 8.9: Temporal variation of maximum wind speed (km/hr) recorded in Bangladesh except Dhaka and available instability energy ($\times 10^5$ J/m^2) at 0000 UTC over Dhaka in May 2004

8.4.4 Vertical wind shear on the dates of occurrence of nor'westers

The spatial distribution of wind shear for the layer 925-500 and 850-500 hPa for 26 cases of nor'westers have been analysed and some of the results are shown in Figs. 8.10-8.16 as examples. The distribution patterns in both the layers are the same having maximum positive shear over Bangladesh and adjoining West Bengal of India in 20 out of 26 cases (76.92%) and over eastern Uttar Pradesh and adjoining Bihar only in 6 cases (i.e. 23.08% cases). Practically, wind shear is large along Uttar Pradesh, Bihar, West Bengal and Bangladesh on the dates of occurrence of nor'westers. The wind shear in the layer 925-500 hPa is higher than that in the layer 850-500 hPa. The ranges of the wind shear are 12.9-34.9 ms^{-1} and 6.2-23.2 ms^{-1} in the layers 925-500 hPa and 850-500 hPa, respectively except in one case when the wind shear is 43.2 ms^{-1} in the layer 850-500 hPa. This is also evident from Table 8.2

Table 8.2: Maximum vertical wind shear along eastern Uttar Pradesh, Bihar and Bangladesh on the dates of occurrence of nor'westers during 1990-1995

Range of VWS (ms^{-1})	Frequency in the layer 925-500 hPa	Frequency in the layer 850-500 hPa
5-10	0	4
10-15	5	9
15-20	11	8
20-25	8	4
25-30	0	0
30-35	1	0
35-40	0	0
40-45	0	1
Total	25	26

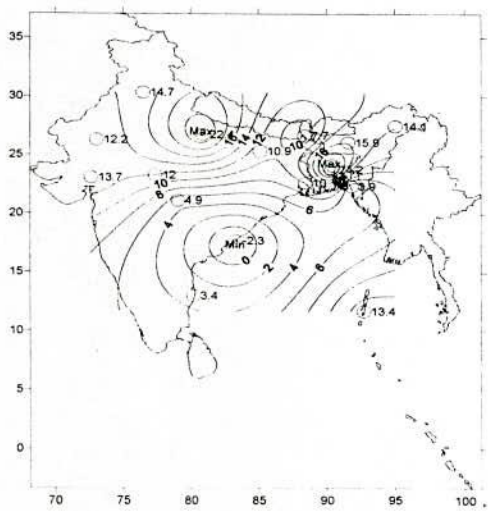

Fig.8.10: Spatial distribution of wind shear (ms^{-1}) between 850 and 500 hPa on 10 April 1993

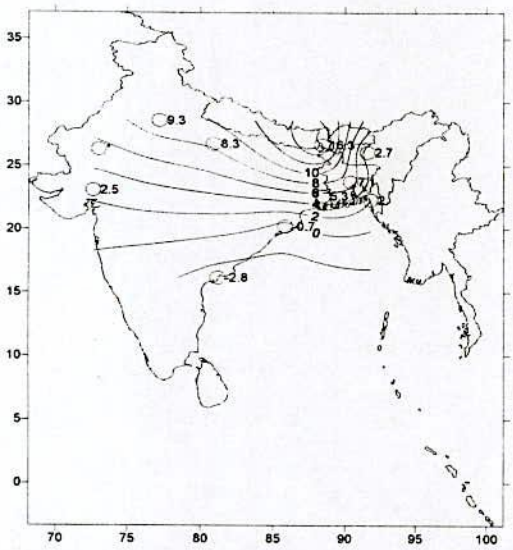

Fig. 8.11: Spatial distribution of wind shear (ms^{-1}) between 850 and 500 hPa on 16 April 1993

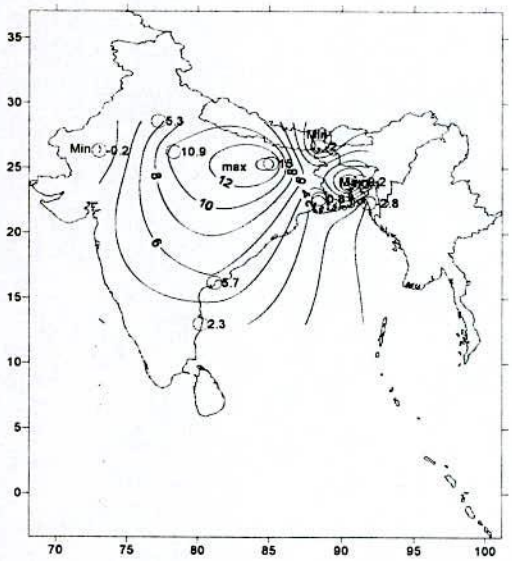

Fig. 8.12: Spatial distribution of wind shear (ms^{-1}) between 850 and 500 hPa on 21 April 1993

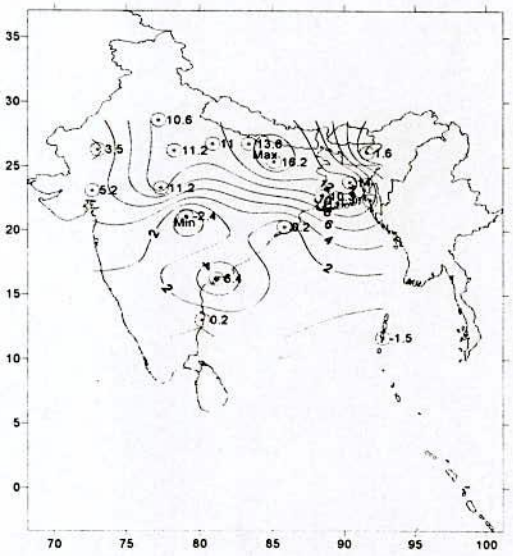

Fig. 8.13: Spatial distribution of wind shear (ms^{-1}) between 850 and 500 hPa on 23 April 1993

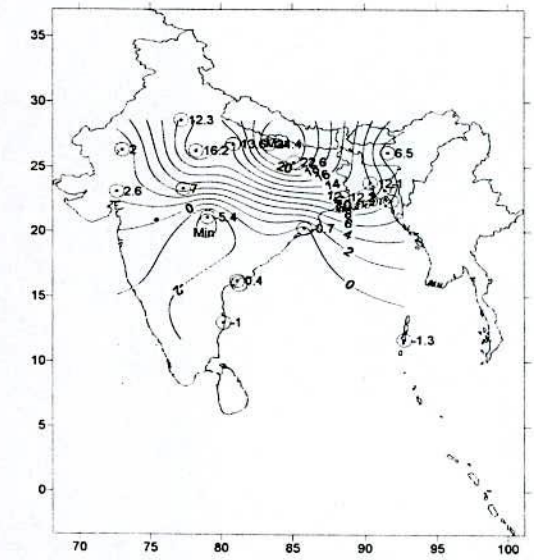

Fig. 8.14: Spatial distribution of wind shear (ms^{-1}) between 925 and 500 hPa on 23 April 1993

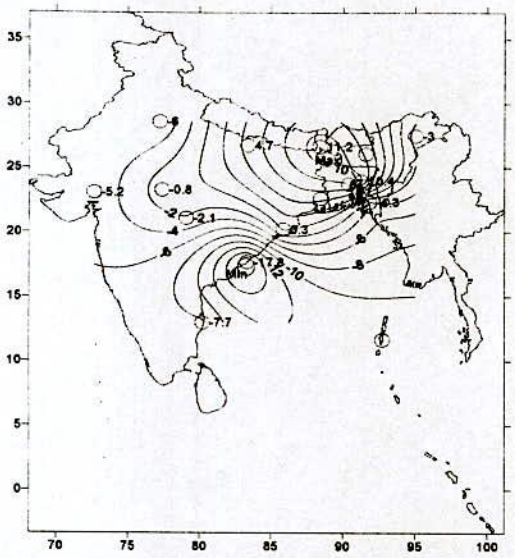

Fig. 8.15: Spatial distribution of wind shear (ms^{-1}) between 850 and 500 hPa on 6 May 1993

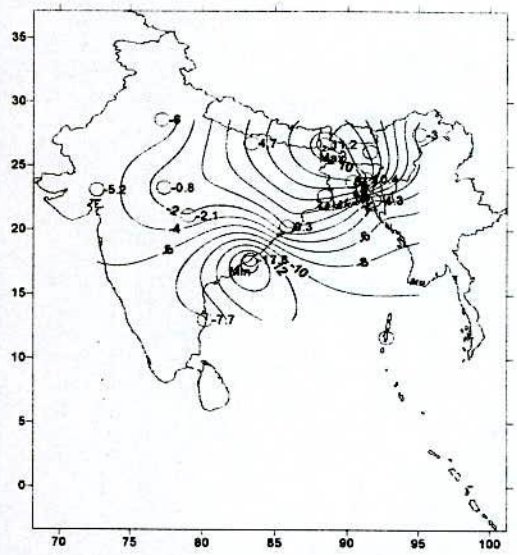

Fig. 8.16: Spatial distribution of wind shear (ms^{-1}) between 850 and 500 hPa on 6 May 1993

CHAPTER 9

SIMULATION OF SURFACE WIND AND RAINFALL FIELDS ASSOCIATED WITH NOR'WESTERS IN BAGLADESH

9.1 Introduction

During the pre-monsoon season, nor'westers bring the first relief-giving rain after a prolonged dryness in Bangladesh. Low-level circulation develops over Bihar, sub-Himalayan West Bengal, Gangetic West Bengal and adjoining Bangladesh or Orissa or eastern Madhya Pradesh and as a result moisture influx occurs from the Bay of Bengal, sufficient instability develops in the atmosphere over Bangladesh and adjoining area causing nor'westers over the country. Simulation of this low-level circulation and rainfall over Bangladesh and adjoining area is important for the Meteorologist. In the present chapter, wind and precipitation fields are obtained by RegCM. RegCM is a Regional Climate Model developed by International Centre for Theoretical Physics (ITCP), Italy. RegCM is a hydrostatic model. To obtain the required parameters, RegCM is run in 60 × 60 km horizontal grids at 18 vertical levels. For the map projection, Rotated Mercator Coordinate (ROTMER) has been preferred in this study. Grell Scheme with Arakawa-Schubert assumption is used in RegCM run. More than 18 parameters such as surface pressure, surface wind (at 10 m), surface temperature, humidity, solar radiation, geopotential meter, convection rainfall, cloud coverage, water run-off etc. i.e. all common meteorological parameters can be obtained from the output. The RegCM is a binary data file, which can be analyzed using special type of meteorological software like GrADS (Grid Analysis and Display System), Ferret, NCL, GMT, etc. In the present study, GrADS has been used to analyze the data of wind and precipitation and to display them.

To use the data in GrADS, there are two basic common files in which one contains data and the other is a control file. The data file is linked in the control file and that control file is opened by using 'GrADS command' – 'grids' from the command line in the Linux OS (Operating System).

To make the work easier GrADS script file has been preferred. This file contains the GrADS control file and other common GrADS commands. The GrADS script provides the

required meteorological parameters in meta-format. That format is converted into post-script format. Finally, the post-script format is converted into common graphics format like JPEG (Joint Photographic Expert Group) using Ghost script.

In this chapter, the surface winds at 10 m height and rainfall from 0000 UTC to next 0000 UTC have been simulated on the dates of nor'westers in Bangladesh.

9.2 Data used

For the simulation of surface wind and rainfall fields, NCEP 6-hrly interval LBC (Lateral Boundary Condition) data is used as an input of RegCM on 25 selected dates of occurrence of nor'westers in Bangladesh. The RegCM output comes with 3-hrly intervals for all common meteorological parameters in different levels. These 3-hrly data for surface wind (at 10 m height) and rainfall are processed from 0000 UTC to next 0000 UTC for the calculation of 1 day results. These outputs give the 24 hrs average rainfall and wind fields in a particular region.

9.3 Results and discussion

The average wind filed at 10 m height and average rainfall field from 0000 UTC to next 0000 UTC over the regions bonded by Lat. 8-32° N and Long. 70-110° E on the dates of occurrence of 25 nor'westers have been obtained using NCEP LBC data and are given in Figs. 9.1-9.25.

9.3.1 Simulated average wind fields

Figs. 9.1-9.25 show the simulated average surface wind fields (at 10 m) over the region for 24 hours. The figures reveal the circulation patterns over eastern Uttar Pradesh, Bihar, Sub-Himalayan West Bengal or Orissa of India with south/southwesterly winds over Bangladesh. The wind speeds range is 3-10 ms^{-1} on most of the days of occurrence of nor'westers in Bangladesh. These circulation patterns are favourable for the occurrence of nor'westers.

9.3.2 Simulated average rainfall fields

Figs. 9.1-9.25 show the simulated average rainfall fields over the region for 24 hours from 0000 UTC to next 0000 UTC. The rainfall estimated from the figures has been compared with the actual 24 hours rainfall over Bangladesh. The comparison of rainfall is given in Table 9.1.

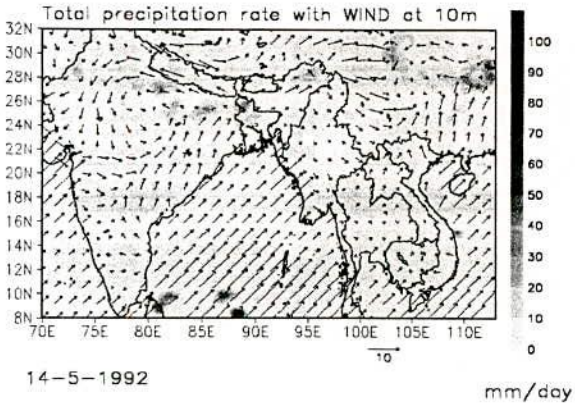

Fig. 9.1: Average surface wind and rainfall fields for 24 hrs valid from 0000 UTC on 14 May 1992

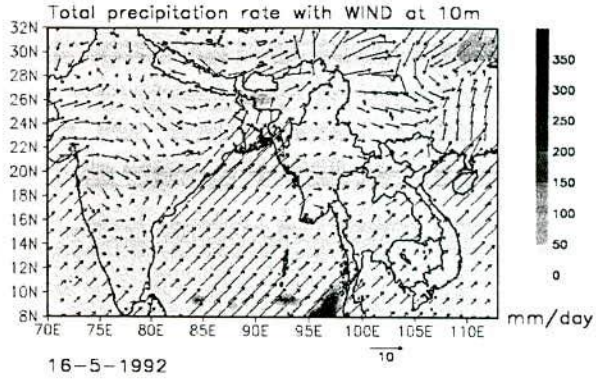

Fig. 9.2: Average surface wind and rainfall fields for 24 hrs valid from 0000 UTC on 16 May 1992

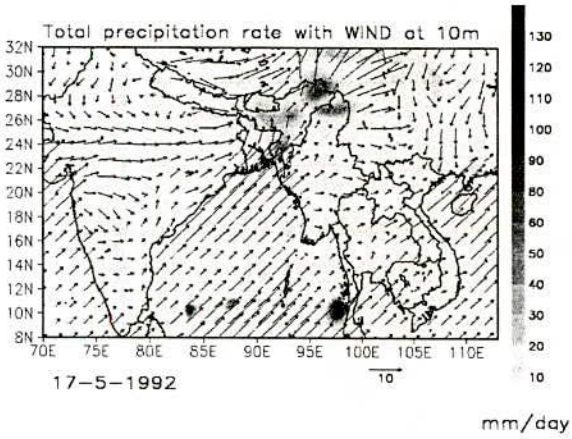

Fig. 9.3: Average surface wind and rainfall fields for 24 hrs valid from 0000 UTC on 17 May 1992

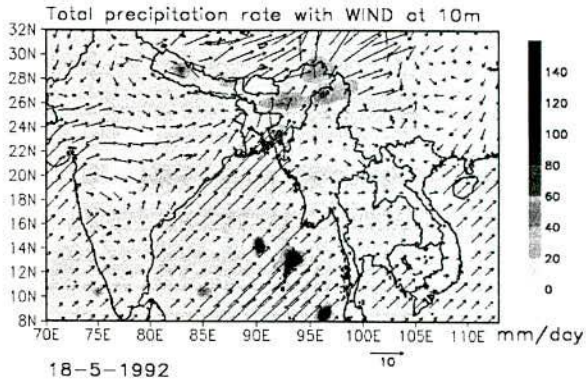

Fig. 9.4: Average surface wind and rainfall fields for 24 hrs valid from 0000 UTC on 18 May 1992

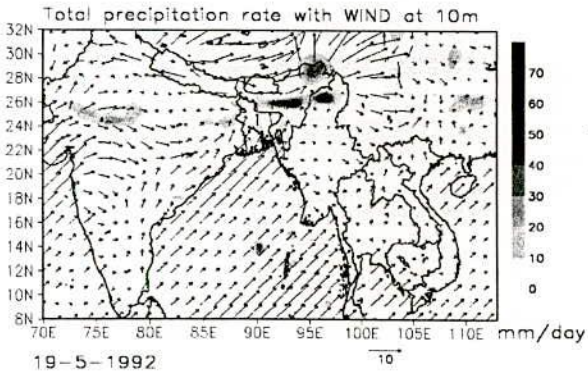

Fig. 9.5: Average surface wind and rainfall fields for 24 hrs valid from 0000 UTC on 19 May 1992

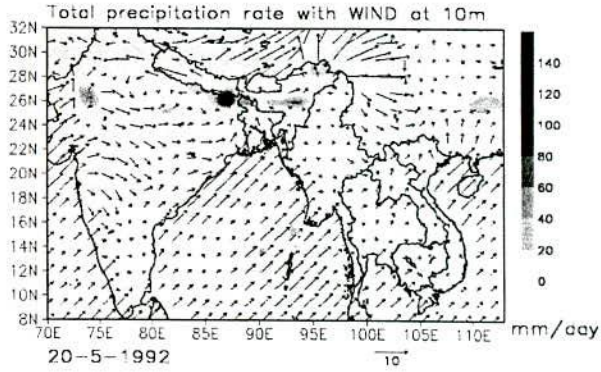

Fig. 9.6: Average surface wind and rainfall fields for 24 hrs valid from 0000 UTC on 20 May 1992

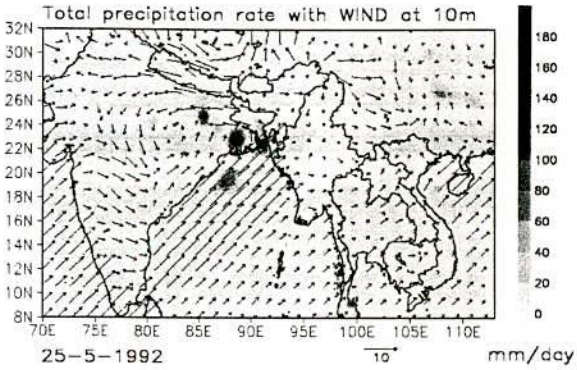

Fig. 9.7: Average surface wind and rainfall fields for 24 hrs valid from 0000 UTC on 25 May 1992

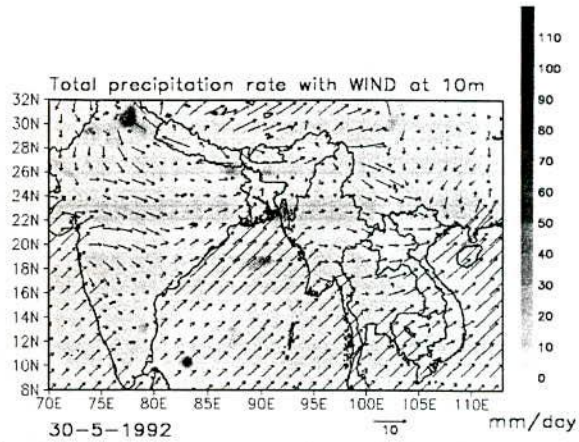

Fig. 9.8: Average surface wind and rainfall fields for 24 hrs valid from 0000 UTC on 30 May 1992

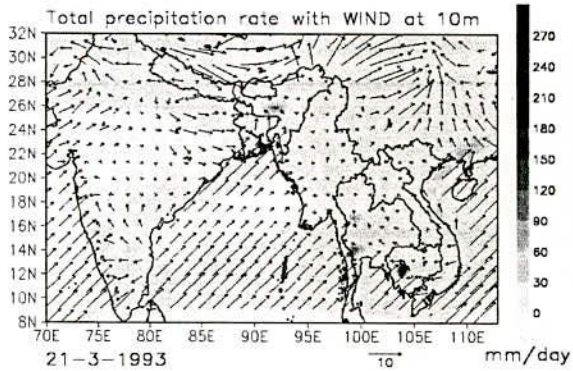

Fig. 9.9: Average surface wind and rainfall fields for 24 hrs valid from 0000 UTC on 21 March 1993

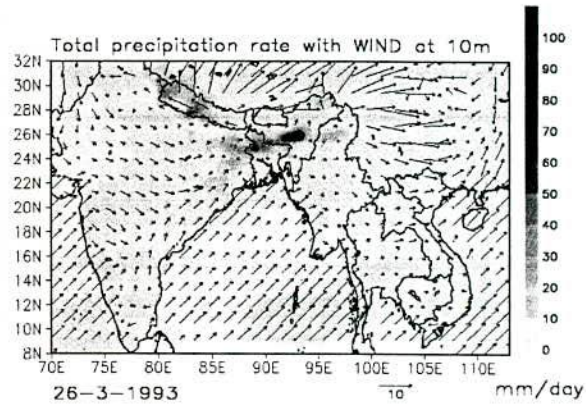

Fig. 9.10: Average surface wind and rainfall fields for 24 hrs valid from 0000 UTC on 26 March 1993

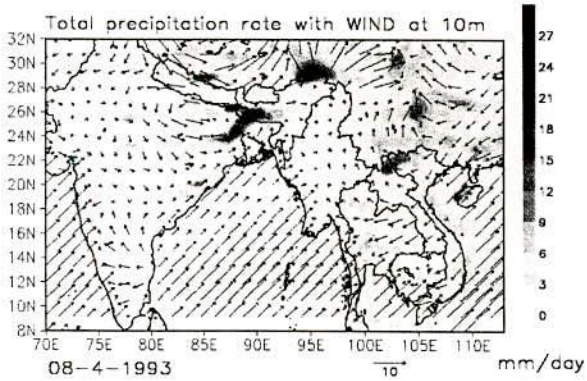

Fig. 9.11: Average surface wind and rainfall fields for 24 hrs valid from 0000 UTC on 8 April 1992

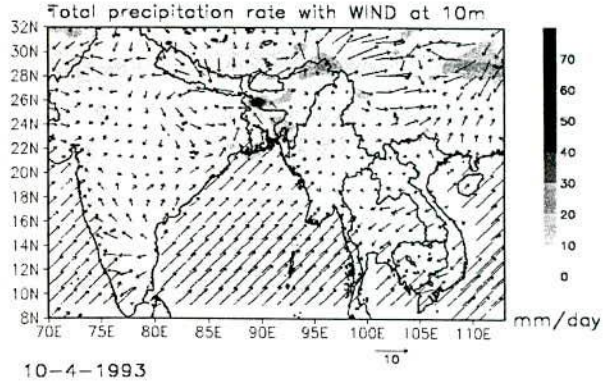

Fig. 9.12: Average surface wind and rainfall fields for 24 hrs valid from 0000 UTC on 10 April 1993

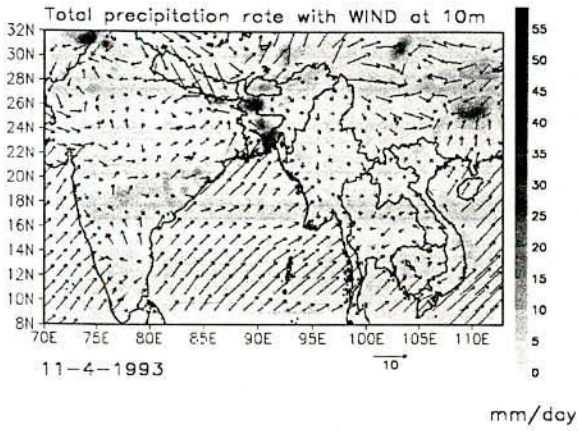

Fig. 9.13: Average surface wind and rainfall fields for 24 hrs valid from 0000 UTC on 11 April 1993

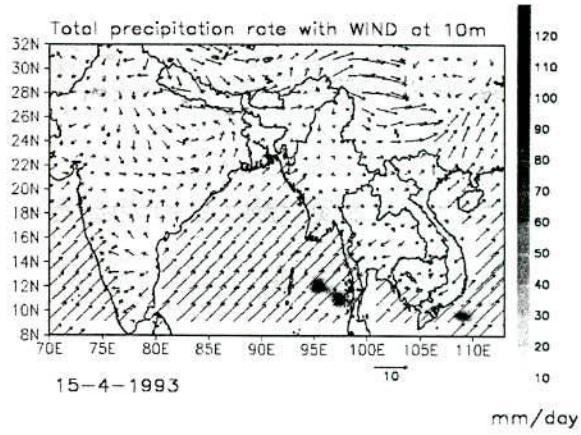

Fig. 9.14: Average surface wind and rainfall fields for 24 hrs valid from 0000 UTC on 15 April 1993

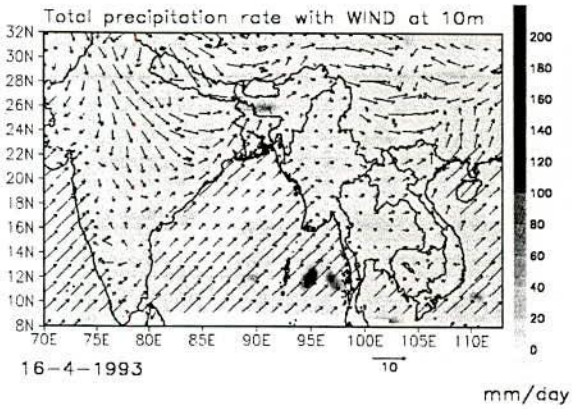

Fig. 9.15: Average surface wind and rainfall fields for 24 hrs valid from 0000 UTC on 16 April 1993

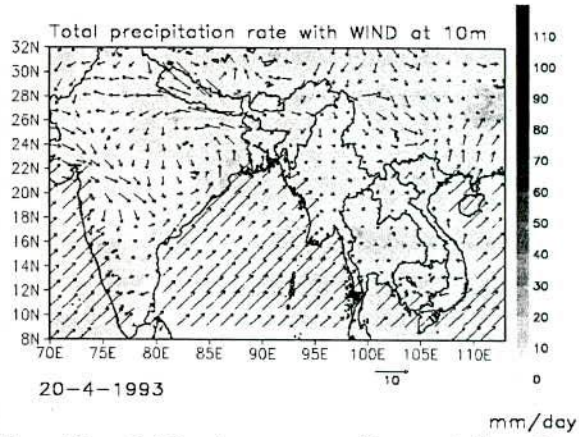

Fig. 9.16: Average surface wind and rainfall fields for 24 hrs valid from 0000 UTC on 20 April 1993

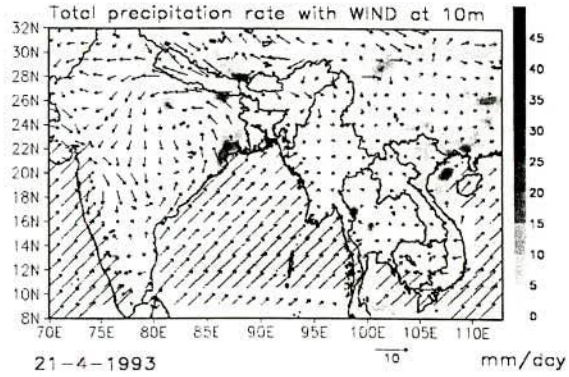

Fig. 9.17: Average surface wind and rainfall fields for 24 hrs valid from 0000 UTC on 21 April 1992

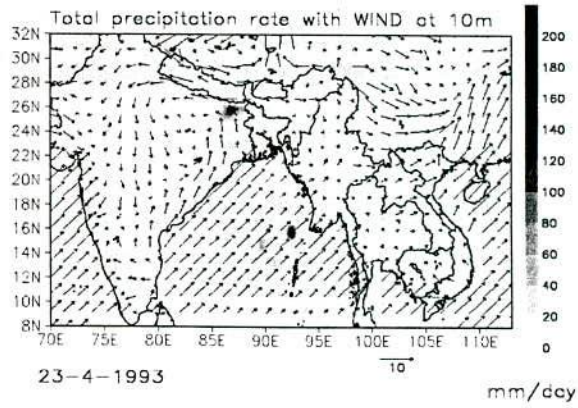

Fig. 9.18: Average surface wind and rainfall fields for 24 hrs valid from 0000 UTC on 24 April 1993

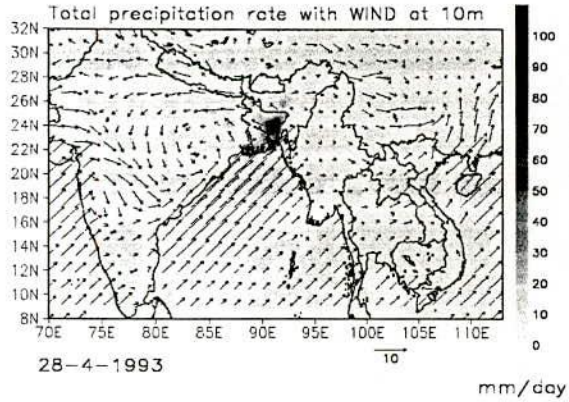

Fig. 9.19: Average surface wind and rainfall fields for 24 hrs valid from 0000 UTC on 28 April 1993

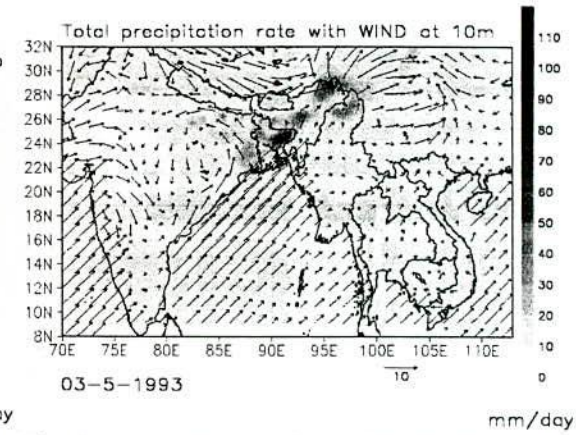

Fig. 9.20: Average surface wind and rainfall fields for 24 hrs valid from 0000 UTC on 03 May 1992

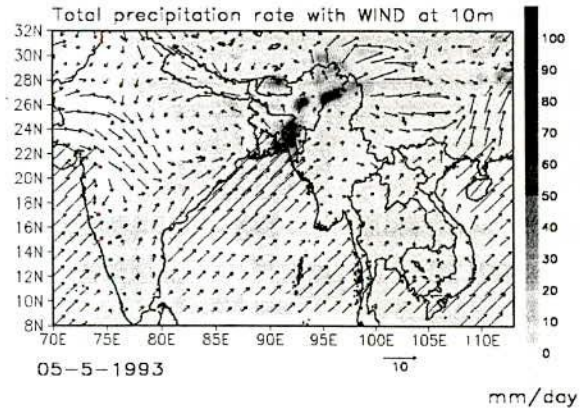

Fig. 9.21: Average surface wind and rainfall fields for 24 hrs valid from 0000 UTC on 5 May 1992

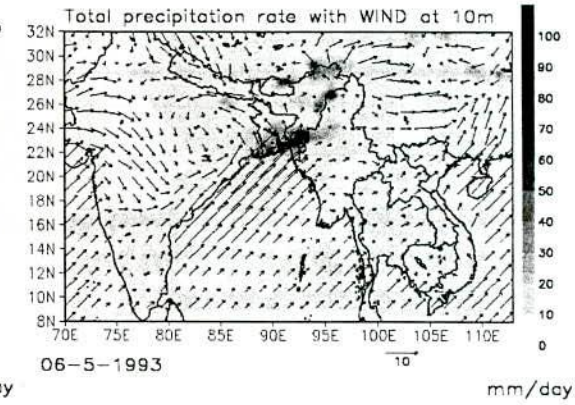

Fig. 9.22: Average surface wind and rainfall fields for 24 hrs valid from 0000 UTC on 6 May 1993

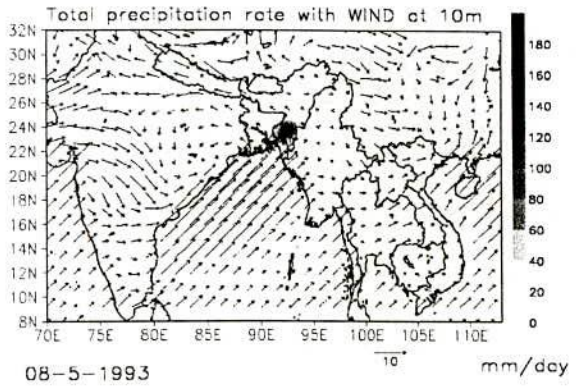

Fig. 9.23: Average surface wind and rainfall fields for 24 hrs valid from 0000 UTC on 8 May 1993

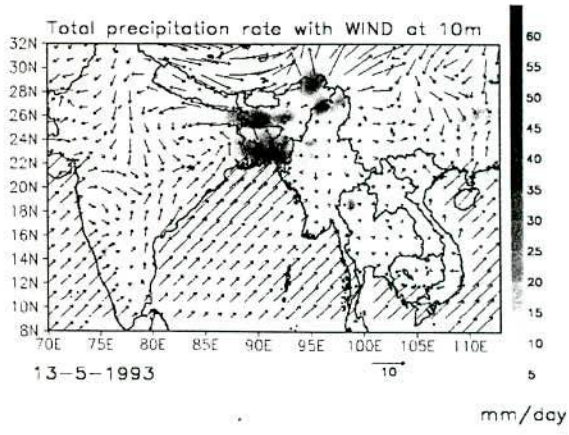

Fig. 9.24: Average surface wind and rainfall fields for 24 hrs valid from 0000 UTC on 13 May 1993

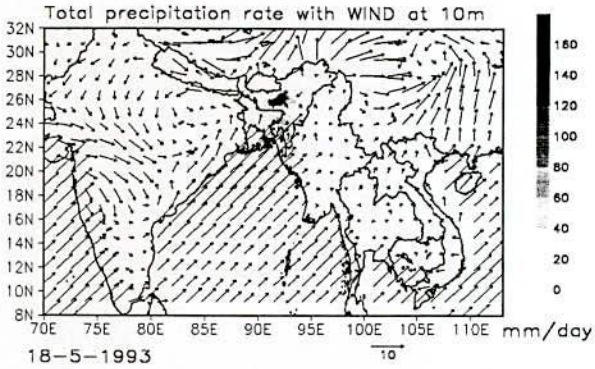

Fig. 9.25: Average surface wind and rainfall fields for 24 hrs valid from 0000 UTC on 18 May 1993

Table 9.1: Comparison of simulated average rainfall and actual rainfall in Bangladesh

Dates of simulation	Actual rainfall and places of rainfall	Simulated average rainfall and areas of rainfall from 0000 UTC to next 0000 UTC
14 May 1992	00	20-30 mm over NW-Bangladesh, Bogra and Tangail.
16 May 1992	Srimangal-57 mm, Rajshahi Division: 14-16 mm.	50-100 mm over extreme NW-Bangladesh.
17 May 1992	Sylhet=67 mm, Comilla-Chittagong region: 1-27 mm	60-80 mm Comilla-Tripura region
18May 1992	Sylhet-190 mm, Srimangal-38 mm, Dinajpur-9 mm, Rangpur-19 mm, Mymensingh-2 mm, Dhaka-9 mm, Kutubdia-2 mm, Cox's Bazar-16 mm, Sayedpur-11 mm.	60-80 mm Comilla-Tripura region.
19 May 1992	Rangpur-42 mm, Bogra-24 mm, M.Court-9 mm.	30-40 mm Chittagong region.
20May 1992	Rangamati-28 mm, Rangpur-Rajshahi region: 1-25 mm.	20-40 mm over extreme NW-Bangladesh.
25 May 1992	Rangamati-22 mm, Khulna-1 mm, Syedpur-10 mm.	120-140 mm over Khulna region, 40-60 mm Bhola-Chittagong.
30 May 1992	Feni-56 mm, Sandwip-45 mm, Rajshahi-17 mm.	40-50 mm over Chittagong region, 0-10mm over NW-Bangladesh
21 March 1993	M. Court-58 mm, Kutubdia-51 mm, Rangamati-40 mm, Cox's Bazar-13 mm.	0-30 mm over Noakhali-Chittagong region
26-March 1993	Hatiya-103 mm, Rajshahi Division: 4-16 mm and whole Bangladesh.	40-60 mm over Rajshahi Division.
8 April 1993	No rain over Bangladesh.	24-27 mm over Rajshahi region.
10 April 1993	Sylhet-20mm.	20-40 mm over NW-Bangladesh, Comilla-Noakhali region.

Table 9.1(Cont'd)

Dates of simulation	Actual rainfall and places of rainfall	Simulated average rainfall and areas of rainfall from 0000 UTC to next 0000 UTC
11 April 1993	Mymensingh-12 mm, Sylhet-15 mm, Srimangal-25 mm, Dhaka-16 mm, Chandpur-1 mm, Feni-5 mm, Sitakunda-3 mm.	30-40 mm over NW-Bangladesh, Dhaka Division, 20-25mm over Sylhet-Srimangal, 30-35 mm over Noakhali-Chittagong region.
15 April 1993	Rajshahi-15 mm	10-20 mm over NW-Bangladesh.
16 April 1993	Rajshahi Division-6-25 mm, Dhaka Division-6-14 mm, other places: 2-12 mm.	40-60 mm over NW-Bangladesh.
20 April 1993	Khulna, Madaripur-4mm	0-10 mm over extreme northwestern and southwestern Bangladesh.
21 April 1993	Rajshahi div-6-15mm, Dhaka division-1-6 mm, Khulna div-9-12mm, Chandpur-6mm, Barisal –3	15-20 mm over Gangetic WB, Sub-Himalayan West Bengal and 0-5 mm over Bangladesh.
23 April 1993	Faridpur-2 mm	0-10 mm over NW-Bangladesh.
28 April 1993	Sylhet-4 mm, Srimangal-44 mm, Feni-122 mm, Faridpur-1 mm, Madaripur-7 mm, M. Court-3 mm, Sitakunda-32 mm, Chittagong-21 mm, Kutubdia-39 mm, Cox's Bazar-33 mm, Teknaf-14 mm, Rangmati-39 mm.	100-110 mm over Comilla, Noakhali-Chittagong, Sylhet-Srimangal and south Khulna region.
3 May 1993	Dhaka-99 mm, Chittagong-71 mm, M. Court-55 mm, Khulna-52 mm, Cox's Bazar-52 mm, Chadpur-35 mm, Satkhira-35, Sandwip-32 mm, Kutubdia-27 mm, Madaripur-26 mm, Srimangal-24 mm, Bhola-21 mm, Barisal-20, Khepupara-18 mm, Sitakunda-15 mm, Ishurdi-11 mm, Patuakhali-8 mm, Comilla-6 mm, Rangamati-5 mm, Mongla-3 mm Faridpur-2 mm, Sayedpur-2 mm, Tangail-1 mm, Jessore-1 mm, Feni-1 mm.	90-100 mm over Srimangal-Sylhet region, 30-40 mm over Rajshahi-Dhaka-Khulna Divisions, 10-20 mm over Chittagong Division.
5 May 1993	Srimangal-56 mm, Sylhet-32 mm, Mymensingh-3 mm, Feni-8 mm, Chandpur-4 mm, Bhola-3 mm, Teknaf-3 mm, Sitakunda-1 mm, Chittagong-1 mm, Rangamati-1 mm, Dhaka-1 mm, Bogra-1 mm, Sayedpur-1 mm.	50-60 mm over Comilla and Chittagong regions.
6 May 1993	RajShahi-121 mm, Sylhet-68 mm, Rangamati-51, Feni-33 mm, Srimangal-31 mm, Chandpur-6 mm, Sitakunda-6, Comilla-5 mm, Dhaka-4 mm, Chittagong-3 mm, Kutubdia-1 mm, Ishurdi-1 mm, Cox's Bazar-1 mm.	50-70 mm over the regions of Dhaka, Comilla, Chittagong, Barisal.

Table 9.1(Cont'd)

Dates of simulation	Actual rainfall and places of rainfall	Simulated average rainfall and areas of rainfall from 0000 UTC to next 0000 UTC
8 May 1993	Comilla-118 mm, Feni-74 mm, Madaripur-69 mm, Bogra-66 mm, M. Court-50 mm, Rangamati-48 mm, Chandpur-45 mm, Sitakunda-45 mm, Chittagong-43 mm, Sandwip-43 mm, Dhaka-42 mm, Khepupara-39 mm, Mongla-38 mm, Satkhira-36 mm, Patuakhali-36 mm, Bhola-35 mm, Barisal-34 mm, Cox's Bazar-34 mm, Kutubdia-32 mm, Khulna-32 mm, Jessore-28 mm, Faridpur-28 mm, Dinajpur-25 mm, Mymensingh-19 mm, Tangail-18 mm, Teknaf-17 mm, Srimangal-3 mm, Rangpur-1 mm.	120-140 mm over Tripura-Comilla region, 20-40 mm over Khulna-Barisal region, and 10-20mm over other places.
13 May 1993	Chittagong-63 mm, Sitakunda-43 mm, Sandwip-28 mm, M. Court-24 mm, Comilla-23 mm, Sylhet-22 mm, Kutubdia-20 mm, Rangamati-17 mm, Tangail-15 mm, Feni-15 mm, Teknaf-10 mm, Srimangal-8 mm, Bhola-7 mm, Cox'sBazar-6 mm, Chandpur-6 mm, Dhaka-6 mm, Chuadanga-2 mm, Madaripur-2 mm, mm, Faridpur-1 mm, Bogra-1 mm.	50-60 mm over NW-Bangladesh, Dhaka Division, Khulna Division, Barisal Division and Chittagong Division, 20-25 mm over Sylhet-Srimangal region.
18 May 1993	Rangpur-52 mm, Bogra-45 mm, Mymensingh-34 mm, Sylhet-39 mm, Dinajpur-26 mm, Srimangal-25 mm, Comilla-18 mm, Madaripur-10 mm, Dhaka-6 mm, Chandpur-4 mm, Rajshahi-1 mm, Faridpur-1 mm.	60-80 mm over Comilla-Tripura region and Sylhet-Srimangal region, 20-40 mm over northwestern and northern Bangladesh.

Table 9.1 shows that the areas of simulated rainfall and its quantity do not comply fully with the areas and quantity of actual rainfall over Bangladesh but the simulated field gives a unique signature for rainfall over the country. This indication for the rainfall will be very useful to the Meteorologists for issuing forecasts.

CHAPTER 10

PREDICTION TECHNIQUES FOR THE NOR'WESTERS AND ASS0CIATED MAXIMUM WIND SPEED AND RAINFALL

10.1 Introduction

Nor'westers are the most frequent events during the pre-monsoon season (March-May) in Bangladesh. They are the manifestations of the instability of the troposphere where significant changes in thermodynamic characteristics take place. Because of these changes in the thermodynamic characteristics, giant cumulonimbus clouds form in the atmosphere resulting in severe thunderstorms whose fury at times is comparable with that of a tornado and cause extensive damage to property and loss of lives in Bangladesh. Sometimes, tornadoes are embedded in the mother clouds, which are produced due to the presence of great instability and sufficient moisture influx in the troposphere. The damage is caused mainly due to maximum wind speed associated with nor'westers/tornadoes. Not many studies have been made on the maximum peak gust associated with thunderstorms over Bangladesh and India. Pendse et al. (1967) observed that the most probable peak speed that a thunder squall at Nagpur on any day is likely to attain is in the range of 50-79 $kmhr^{-1}$.

The problem for the meteorologist is to determine the maximum wind speed associated with nor'westers. In Bangladesh, the meteorologists use the Tephigram analysis for the determination of maximum gust due to nor'westers following the method of Miller (1967). There is no empirical method for the determination of maximum gust due to nor'westers. It is, therefore, imperative to develop some empirical method so that the maximum wind speed associated with nor'westers can be forecasted.

Lewellen (1976) developed the theoretical model of the tornado vortex. In his study, it mentioned the ultimate source of tornado's energy is the buoyant potential energy derived from condensing water vapour in an unstable environment. Air with dew point temperature around 20 °C has ≈15 gm of water vapour/kilogram. If all of the energy released when this water vapour condenses were to be converted to kinetic energy of the air, it would correspond to

$$V_{max} \approx 260 \text{ ms}^{-1} \qquad \text{(A)}$$

Another possible way of estimating the maximum velocity is to assume that the thunderstorm acts as a heat engine in converting the latent heat of vaporization into kinetic energy. If the heat engine operates between a surface temperature of ≈ 305 K and the tropopause temperature of 225 K, then the maximum ideal Carnot efficiency of the process would be 26%. Reducing this by 50% to account for turbulence dissipation leads to 13% which, when combined (A) leads to

$$V_{max} \approx 95 \text{ ms}^{-1} \qquad \text{(B)}$$

This method gives a reasonable maximum wind speed.

During the pre-monsoon season, rainfall associated with nor'westers is very important for the agricultural activities in the country and also for the comfort of human being. Keeping in view of this fact, it is essential to develop linear multiple regression equations for the rainfall associated with nor'westers in Bangladesh.

One of the most difficult problems faced by the operational Meteorologists is whether to forecast thunderstorms/nor'westers or severe nor'westers or severe nor'westers accompanied by tornadoes. For most part, the same parameters will be present, in varying degree of intensity, for either phenomenon. Reasonable discrimination depends on certain synoptic features. The area over which nor'westers are likely to occur varies from one day to the other mostly depending on the synoptic situation at the surface and upper level. Identification of this are with positive threat of the storms is one of the difficult tasks faced by the Meteorologists. However, in the present study, a broad investigation has been made to find out the favourable criteria for the occurrence of nor'westers in Bangladesh with to overcoming the problems. These criteria may be used as the forecasting techniques for the occurrence of nor'westers.

In this chapter, attempts have been made to correlate the maximum wind speed associated with nor'wester/thunderstorms, which occurred at Dhaka with a number of meteorological parameters in order to develop a multiple regression formula suitable for the forecasting of maximum gusty wind speed associated with nor'westers/thunderstorms. Linear multiple regression equations have also been developed for the forecasting of 24 hrs rainfall associated with nor'westers.

Attempts have also been made to verify the developed regression equations for the rainfall and the maximum gusty wind speed by using data on the dates of occurrence of

nor'westers during the pre-monsoon season of 2005. Synoptic and statistical techniques for the forecasting of nor'westers and associated maximum gusty wind and rainfall have been developed.

10.2 Data used

Maximum wind speed recorded at Dhaka due to nor'westers, rawinsonde data at different isobaric height, MSL pressure at 0000 UTC on the dates of occurrence of nor'westers during the period March-May of 1990-1995 have been utilized to find out an empirical formula for the determination of maximum gusty wind speed associated with nor'westers. The rawinsonde data has been used to derive a lot of parameters with which multiple regressions have been made.

The rawinsonde data at 0000 UTC over Dhaka, maximum gusty wind over Dhaka, MSL pressure and the next 24 hours rainfall at 34 stations over Bangladesh on the dates of occurrence of several nor'westers during March-May 2005 have been used to verify the developed regression equations, for the prediction of maximum gusty wind speed and the rainfall associated with nor'westers. The data have been collected from the Storm Warning Centre (SWC) of Bangladesh Meteorological Department (BMD).

10.3. Methodology

The maximum wind speed and rainfall associated with nor'westers over Dhaka have been correlated with a number of parameters with a view to forecasting them by using multiple regression equation as given below:

$$Y = a_1 + a_2X_1 + a_3X_2 + a_4X_3 + \ldots\ldots\ldots\ldots + a_nX_n$$

Where

X_1 = Modified Vertical Total Index (MVT) over Dhaka at 0000 UTC,

X_2 = Modified Cross Total Index (MCT) over Dhaka at 0000 UTC,

X_3 = Modified Total Totals Index (MTT) over Dhaka at 0000 UTC,

X_4 = Modified K-Index (MKI) over Dhaka at 0000 UTC,

X_5 = Difference between latent heat at 1000 and 500 hPa levels (LH_{1000}- LH_{500}) over Dhaka at 0000 UTC,

X_6 = 24-hour change in geopotential height (ΔZ_{24}) at 925 hPa over Dhaka at 0000 UTC,

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X_7 = 24-hour change in geopotential height (ΔZ_{24}) over Dhaka at 0000 UTC at 1000 hPa,

X_8 = Zonal wind component at 850 hPa (u_{850}) over Dhaka at 0000 UTC,

X_9 = Meridional wind component at 850 hPa (v_{850}) over Dhaka at 0000 UTC,

X_{10} = Zonal wind component at 200 hPa (u_{200}) over Dhaka at 0000 UTC,

X_{11} = Meridional wind component at 200 hPa (v_{200}) over Dhaka at 0000 UTC,

X_{12} = Vertical wind shear (u_{200} - u_{850}) over Dhaka at 0000 UTC,

X_{13} = Wind speed at 200 hPa [$(u^2_{200}+ v^2_{200})^{0.5}$] over Dhaka at 0000 UTC,

X_{14} = Ratio of the MVT and MCT over Dhaka at 0000 UTC,

X_{15} = Modified Severe Weather Threat Index (MSWI) over Dhaka at 0000 UTC,

X_{16} = Showalter Stability Index (SI) over Dhaka at 0000 UTC,

X_{17} = Lifted Index (LI) over Dhaka at 0000 UTC,

X_{18} = Dew-Point Index (DPI) over Dhaka at 0000 UTC,

X_{19} = Dry Instability Index (DII) over Dhaka at 0000 UTC,

X_{20} = Energy Index (EI) over Dhaka at 0000 UTC,

X_{21} = 24-hour pressure change (P_{24}) at Dhaka at 0000 UTC over Dhaka at 0000 UTC,

X_{22} = Wind speed at 700 hPa (V_{700} in km/hr) over Dhaka at 0000 UTC,

X_{23} = Wind speed at 500 hPa (V_{500} in km/hr) over Dhaka at 0000 UTC,

X_{24} = Wind speed at 300 hPa (V_{300} in km/hr) over Dhaka at 0000 UTC,

X_{25} = Average wind speeds at 700, 500 and 300 hPa [$(V_{700} + V_{500} +V_{300})/3$] over Dhaka at 0000 UTC,

X_{26} = Day's maximum upper air wind speed in km/hr ($V_{maxUpper}$) over Dhaka at 0000 UTC,

X_{27} = Temperature difference between 500 and 200 hPa (T_{500}- T_{200}) over Dhaka at 0000 UTC,

X_{28} = Dew point depression [DPD=($T - T_d$)] at 1000 hPa over Dhaka at 0000 UTC,

a_1, a_2, a_3, ...a_n are regression co-efficients.

10.4 Significance test

After obtaining the multiple regression equation for maximum wind speed associated with nor'westers, values of the maximum wind speed have been computed. The scatter diagrams for the computed maximum wind speed and the actual maximum wind speed have been prepared to obtain the values of R^2. Then the significance test has been made with the help of F-distribution as given below:

$$F = \frac{\frac{R^2}{k}}{\frac{(1-R^2)}{(N-k-1)}}$$

Where $df_{total} = N-1$

$df_{explained} = (k+1)-1$

$df_{unexplained} = N-(k+1)$

k = No. of regressors

N = No. of observations

10.5 Results and discussion

The frequency distribution of maximum wind speed associated with nor'westers at Dhaka has been studied. The maximum wind speed and rainfall associated with nor'westers at Dhaka have been correlated with different parameters using rawinsonde data at 0000 UTC over Dhaka as described in section 10.3 and a number of experiments has been conducted to find out an empirical formula for forecasting the maximum wind speed and rainfall associated with nor'westers. Some of the results are described in this chapter.

10.5.1 Frequency of maximum wind speed of nor'westers at Dhaka

The frequency of maximum wind speed associated with nor'westers at Dhaka during the period 1990-1995 is shown in Table 10.1. The table shows that maximum frequency of wind speed is in the range of 50-60 km/hr and is 10. Most of the gusts/maximum wind speed at Dhaka occurs in the range of 50-110 km/hr.

Table 10.1: Frequency distribution of maximum wind speed associated with nor'westers/thunderstorms at Dhaka

Range (km/hr)	Frequency
30-40	1
40-50	4
50-60	10
60-70	9
70-80	7
80-90	7
90-100	4
100-110	6
110-120	2
120-130	1
Total	51

10.5.2 Multiple regression of maximum wind speed with different parameters

10.5.2.1 Experiment-1: Multiple regression of maximum wind speed with different parameters

Multiple regression of maximum wind speed recorded at the Storm Warning Centre due to nor'westers has been made with 10 parameters and the result is given by the following equation:

$$V_{max} = -375.61 - 12.953*X_1 + 17.94*X_2 + 0.8505*X_5 + 0.41807*X_8 + 0.14943*X_{10} + 306.65*X_{14} - 0.03698*X_{15} - 1.6615*X_{16} + 1.1208*X_{19} - 0.19784*X_{27} \quad (1)$$

Where

$X_1 = MVT$

$X_2 = MCT$

$X_5 = LH_{1000} - LH_{500}$

$X_8 = u_{850}$

$X_{10} = u_{200}$

$X_{14} = \frac{MVT}{MCT}$

$X_{15} = MSWI$

X_{16} = Showalter Stability Index (SI)

X_{19} = Dry Instability Index (DII)

$X_{27} = .T_{500} - T_{200}$

The R^2 value is 0.2771 (correlation coefficient is 0.52640) and the F-value is 1.53 ($F_{0.95}$ = 2.08 for df (10,40)), which is not statistically significant. The standard error of estimate is 17.91 $kmhr^{-1}$. The variation of the actual maximum wind speed and the computed maximum wind speed is shown in Fig. 10.1. It is seen from the Fig. 10.1 that the variation of computed maximum wind speed has some similarity in many cases.

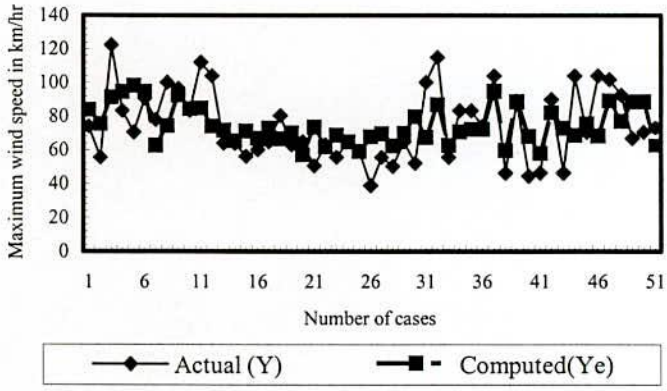

Fig. 10.1: Comparison of peak gust associated with nor'westers over Dhaka and the peak gust computed from developed multiple regression model (Experiment-1)

10.5.2.2 Experiment-2: Multiple regression of maximum wind speed with different parameters

In experiment-2, multiple regression of maximum wind speed recorded at the Storm Warning Centre due to nor'westers has been made with 20 parameters and the result is given by the following equation:

$$V_{max} = -299.12 - 9.3787*X_1 + 15.343*X_2 - 0.46988*X_4 + 0.78063*X_5 + 0.26462*X_6 - 0.22429*X_7 + 0.52926*X_8 - 0.22914*X_9 + 0.55434*X_{10} - 0.46351*X_{13} + 244.93*X_{14} - 0.02678*X_{15} - 1.4485*X_{16} + 1.4192*X_{19} - 0.13369*X_{22} + 0.03405*X_{23} - 0.03913*X_{24} + 0.0207*X_{26} - 0.359*X_{27} - 2.1434*X_{28} \quad (2)$$

Where

X_1 = MVT

X_2 = MCT

X_4 = MKI

$X_5 = LH_{1000} - LH_{500}$

$X_6 = \Delta Z_{24}$ at 925 hPa

$X_7 = \Delta Z_{24}$ at 1000 hPa

$X_8 = u_{850}$

$X_9 = v_{850}$

$X_{10} = u_{200}$

$X_{13} = \left(u_{200}{}^2 + v_{200}{}^2\right)^{\frac{1}{2}}$

$X_{14} = \dfrac{MVT}{MCT}$

X_{15} = MSWI

X_{16} = Showalter Stability Index (SI)

X_{19} = Dry Instability Index (DII)

$X_{22} = V_{700}$ in km/hr

$X_{23} = V_{500}$ in km/hr

$X_{24} = V_{300}$ in km/hr

X_{26} = Day's maximum upper air wind speed in km/hr over Dhaka

$X_{27} = T_{500} - T_{200}$

X_{28} = Dew point depression [DPD ($T - T_d$)] at 1000 hPa

The R^2 value is 0.3498 (correlation coefficient is 0.59144) and the F-value is 0.81, which is ($F_{0.95}$=1.93 with df (19, 31)) not statistically significant. The standard error of estimate is 16.99 $kmhr^{-1}$. However, the result is encouraging. The variation of the actual maximum wind speed and the computed maximum wind speed is shown in Fig. 10.2.

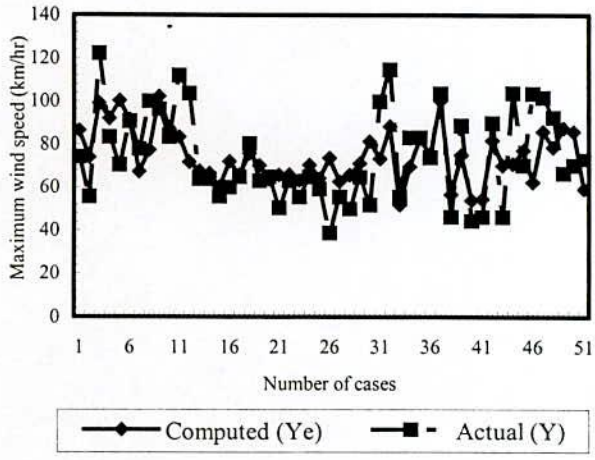

Fig. 10.2: Comparison of peak gust associated with nor'westers over Dhaka and the peak gust computed from developed multiple regression model (Experiment-2)

The figure shows that the pattern of the variation of actual and computed maximum wind speed is almost the same in most of the cases.

10.5.2.3 Experiment-3: Multiple regression of maximum wind speed with different parameters

24 parameters derived from the rawinsonde data and surface data have been correlated with maximum wind speed associated with nor'westers. The multiple regression equation obtained for the maximum gusty wind speed associated with nor'westers by Experiment-3 is:

$$V_{MaxExpt\text{-}3} = -286.28 - 9.4394*MVT + 15.124*MCT - 0.48523*MKI + 0.90451*(LH_{1000} - LH_{500}) + 0.27351*\Delta Z_{(925)24} - 0.21913*Z_{(1000)24} + 0.50031*u_{850} - 0.25579*v_{850} + 0.53726*u_{200} - 0.00232*v_{200} - 0.42981*(u^2_{200} + v^2_{200})^{0.5} + 237.26*(MVT/MCT) - 0.02244*MSWI - 1.77519*SI - 0.00813*LI - 0.22326*DPI + 1.4652*DII + 0.3815*EI + 0.05769*\Delta P_{24} - 0.10143*V_{700} + 0.02644*V_{500} - 0.03397*V_{300} - 0.37227*V_{maxUpper} - 2.0172*(T_{500}-T_{200}) \quad (3)$$

Where $V_{MaxExpt\text{-}3}$ is the computed maximum gusty wind speed in Experiment 3. The correlation coefficient is 0.59102 ($R^2 = 0.3493$)[$F_{cal} = 0.58$, $F_{0.95} = 1.95$, df (24,26)] and the coefficient of correlation is not statistically significant.

10.5.2.4 Experiment-4: Multiple regression of maximum wind speed with different parameters

In this experiment, only 7 parameters have been correlated with the maximum wind speed associated with nor'westers.

The multiple regression equation obtained for the maximum gusty wind speed associated with nor'westers in Experiment-4 is:

$$V_{Max\text{-}Expt\text{-}4} = -553.38 - 19.392*MVT + 24.89*MCT + 0.64226*(LH_{1000}-LH_{500}) - 0.44853*V_{850} - 1.5239*SI + 467.46*(MVT/MCT) + 0.55567*DII \quad (4)$$

Where $V_{MaxExp\text{-}4}$ is the computed maximum gusty wind speed in Experiment 4. The correlation coefficient is 0.49325 ($R^2 = 0.2433$)[$F_{cal} = 1.98$, $F_{0.95} = 2.23$, df (7, 43)], which is not significant statistically.

10.5.3 Linear multiple regression equations for the rainfall due to nor'westers

Linear multiple regression equations have been developed for the prediction of country-averaged 24 hrs rainfall, maximum 24 hrs rainfall in Bangladesh and 24 hrs rainfall at Dhaka over Dhaka using different meteorological parameters and rainfall due to nor'westers.

10.5.3.1 Linear multiple regression equations for the country-averaged 24 hrs rainfall

The linear multiple regression equation for the 24 hrs country-averaged rainfall with 15 different parameters is given below:

$$R_{CA} = -47.593 + 0.31651*W + 0.30343*TT - 0.01198*SWI - 2.0397*CT + 0.7502*VT + 0.33778*EI + 0.15477*KI + 2.9652*(q_{1000} - q_{500}) - 3.9788*(q_{1000}-q_{850}) + 0.25286*MTT + 0.02877*MSWI + 1.15478*MCT - 0.15745*MVT + 0.98992*MEI - 0.26142*MKI \quad (5)$$

Where R_{CA} is the country-averaged 24 hrs rainfall over Bangladesh, $(q_{1000} - q_{500})$ is the difference in specific humidity between 1000 and 500 hPa, and $(q_{1000}-q_{850})$ is the difference in specific humidity between 1000 and 850 hPa. The correlation coefficient is 0.62777 (R^2 = 0.3941), which is significant at 100% level of significance [F_{cal} = 3.86, F = 2.27, df (15, 89)]. The correlation coefficient is statistically significant at 100% level.

10.5.3.2 Linear multiple regression equations for the 24 hrs maximum rainfall in Bangladesh

15 parameters have been correlated with 24 hrs maximum rainfall in Bangladesh. The linear multiple regression equation for the 24 hrs maximum rainfall in Bangladesh with different parameters is given below:

$$R_{Max} = -124.31 + 1.1452*W + 1.2214*TT + 0.03735*SWI - 6.3362*CT + 1.3432*VT + 1.543*EI - 2.3201*KI + 10.597*(q_{1000} - q_{500}) - 12.985*(q_{1000} - q_{850}) + 1.7561*MTT + 0.01551*MSWI + 2.6342*MCT - 0.7697*MVT + 2.6175*MEI + 1.1728*MKI \quad (6)$$

Where R_{Max} is the 24 hrs maximum rainfall in Bangladesh. The correlation coefficient is 0.56125 (R^2 = 0.3150), which is significant at 100% level of significance [F_{cal} = 2.73, F = 2.27, df (15, 89)]. The correlation coefficient is statistically significant at 100% level.

10.5.3.3 Linear multiple regression equations for the 24 hrs rainfall at Dhaka

The linear multiple regression equation for the 24 hrs rainfall at Dhaka with 15 different parameters is given below:

$$R_{Dha}=-331.26 + 0.81183*W + 0.56864*TT - 0.053*SWI - 2.6421CT + 4.8911*VT + 7.13248*EI + 1.0439*KI + 18.716*(q_{1000} - q_{500}) - 19.79**(q_{1000}-q_{850}) - 1.422*MTT + 0.09023*MSWI + 2.4528*MCT + 3.1014*MVT + 1.0352*MEI - 0.85393*MKI \quad (7)$$

Where R_{Dha} is the 24 hrs rainfall at Dhaka. The correlation coefficient is 0.56391 (R^2 = 0.3180), which is significant at 100% level of significance [F_{cal} = 2.77, F = 2.27, df (15, 89)]. The correlation coefficient is statistically significant at 100% level.

10.5.4 Correlation between the actual maximum wind speed and the computed maximum wind speed

The correlation between the computed maximum wind speeds obtained by the empirical formula of Experiments 1 and 2 and the actual maximum wind speed associated with nor'westers has been made through scatter diagrams as shown in Figs. 10.3 and 10.4. The R^2 values are 0.275 and 0.3474, which correspond to the F-values of 9.10344 and 12.77597, indicating statistically significance at 95% level.

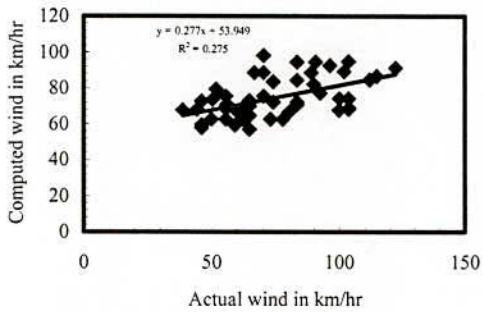

Fig. 10.3: Scatter diagram between actual and computed maximum wind speeds (Experiment-1)

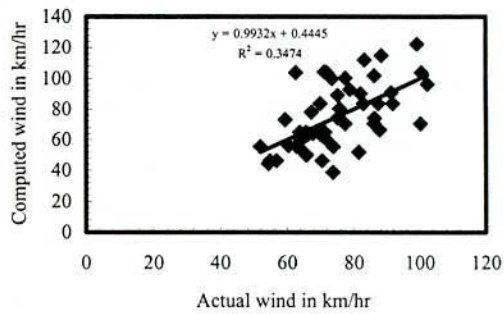

Fig. 10.4: Scatter diagram between actual and computed maximum wind speeds (Experiment-2)

10.6 Validation of the linear multiple regression equations for maximum gusty wind speed associated with nor'westers

10.6.1 Experiment-1 &2 for the multiple regression of maximum gusty wind

The linear multiple regression equations (1) and (2) developed for the maximum gusty wind speed have been used to compute the maximum gusty wind speed using the different parameters derived from the rawinsonde data and MSL pressure over Dhaka for the pre-monsoon season of 2005. The computed maximum gusty wind at Dhaka and the actual maximum gusty wind at Dhaka have been compared and are given in Table 10.2.

It can be seen from the Table 10.2 that the results are encouraging with standard error of estimates ± 21.03078 kph and ± 15.92911 kph for the regression equations (1) and (2) respectively. Though the standard error of estimate is larger in Experiment-1than that of Experiment-2. The second regression equation is more acceptable.

Table 10.2: Comparison between the actual maximum wind speed at Dhaka and the computed maximum wind speed by linear multiple regression models (Expt-1 and Expt-2) based on the data during March-May of 2005

Dates	Actual maximum wind speed	Computed maximum wind speed in Expt-1	Standard error of estimate in Expt-1	Computed maximum wind speed in Expt-2	Standard error of estimate in Expt-2
09-04-2005	46	60.92	± 21.03078	58.12	± 15.92911
20-04-2005	83	145.88		120.02	
24-04-2005	41	65.80		56.61	
25-04-2005	96	80.17		75.66	
26-04-2005	48	78.17		61.83	
27-04-2005	87	88.53		86.81	
29-04-2005	56	76.92		73.83	
05-05-2005	56	67.73		61.09	
20-05-2005	59	62.96		51.36	
22-05-2005	87	93.00		83.93	

The regression equations (1) and (2) for the maximum gusty wind speed have also been used to compute the maximum gusty wind speed using data over Dhaka during 1-16 May 2005. The computed maximum gusty wind at Dhaka and the actual maximum gusty/maximum wind at Dhaka have been compared and are given in Table 10.2A.

Table 10.2A: Comparison between the actual maximum wind speed at Dhaka and the computed maximum wind speed by linear multiple regression models (Expt-1 and Expt-2) based on the data during 1-16 May 2005

Dates	Actual maximum wind speed (kph)	Maximum wind speed (kph) at other places	Computed maximum wind speed in Expt-1	Standard error of estimate in Expt-1	Computed maximum wind speed in Expt-2	Standard error of estimate in Expt-2
01-05-2005	46		64.95	±16.80554	59.38	±17.97481
02-05-2005	9		46.38		43.20	
03-05-2005	13		63.02		52.31	
04-05-2005	41	Bogra:78	76.40		63.96	
05-05-2005	56	Khepupara:109	67.73		61.09	
06-05-2005	11	Rangpur:63	58.13		56.77	
07-05-2005	6		77.50		64.71	
08-05-2005	13	Sitakunda:61	62.76		54.08	
09-05-2005	9	Chittagong:45	56.71		53.07	
10-05-2005	13	Sylhet:78	61.03		51.73	
11-05-2005	13	Sylhet:55	78.07		68.49	
12-05-2005	46		88.05		61.83	
13-05-2005	111		*		*	
14-05-2005	13	Sylhet:56	66.24		42.60	
15-05-2005	17	Sylhet:41	84.80		81.10	
16-05-2005	50	Sylhet:48	79.24		62.11	

It can be seen from the Table 10.2A that the results are encouraging with standard errors of estimates ± 16.80554 kph and ± 17.97481kph for the regression equations (1) and (2) respectively. During the period, nor'westers did not occur on all days at Dhaka but they occurred at other places over Bangladesh on most of the days. As a result the parameters derived from the rawinsonde data over Dhaka were conducive for the occurrence of nor'westers in Bangladesh.

10.6.2 Experiments-3 & 4 for the multiple regression of maximum gusty wind

The linear multiple regression equations (3) and (4) developed for the maximum gusty wind speed have been used to compute the maximum gusty wind speed using the different parameters derived from the rawinsonde data and MSL pressure over Dhaka for the pre-monsoon season of 2005. The computed maximum gusty wind at Dhaka and the actual maximum gusty wind at Dhaka have been compared and are given in Table 10.3.

Table 10.3: Comparison between the actual maximum wind speed at Dhaka and the computed maximum wind speed by linear multiple regression models (Expt-3 and Expt-4) based on the data during March-May of 2005

Dates	Actual maximum wind speed (kph)	Computed maximum wind speed (kph) in Expt-3	Standard error of estimate in Expt-3 (kph)	Dates	Actual maximum wind speed (kph)	Computed maximum wind speed (kph) in Expt-4	Standard error of estimate in Expt-4 (kph)
09-04-2005	46	61.33616	± 14.86753	09-04-2005	46	51.74006	± 13.60994
20-04-2005	83	112.0576		24-04-2005	41	66.99843	
24-04-2005	41	55.17920		25-04-2005	96	85.04686	
25-04-2005	96	72.47564		26-04-2005	48	74.58799	
26-04-2005	48	60.86529		27-04-2005	87	79.06972	
27-04-2005	87	85.25223		29-04-2005	56	71.24613	
29-04-2005	56	74.1205		01-05-2005	46	70.54016	
05-05-2005	56	58.76267		05-05-2005	56	63.90696	
20-05-2005	59	54.70419		20-05-2005	59	59.08976	
22-05-2005	87	85.1565		22-05-2005	87	92.39565	

It can be seen from the Table 10.3 that the results are encouraging with standard error of estimates ± 14.86753 kph and ± 13.60994 kph for the regression equations (3) and (4) respectively. The standard errors of estimates in Experiment-3 and Experiment-4 are appreciably smaller. The second regression equation (4) is more acceptable.

The regression equations (3) and (4) for the maximum gusty wind speed have also been used to compute the maximum gusty wind speed using data over Dhaka during 1-16 May

2005. The computed maximum gusty wind at Dhaka and the actual maximum gusty/maximum wind at Dhaka have been compared and are given in Table 10.3A.

Table 10.3A shows that the standard errors of estimates ± 16.18183 kph and ± 20.11473 kph for the regression equations (3) and (4) respectively. The equations give the indication for the occurrence of gusty wind, though the standard error of estimate in case of equation (3) is a bit larger.

Table 10.3A: Comparison between the actual maximum wind speed at Dhaka and the computed maximum wind speed by linear multiple regression models (Expt-3 and Expt-4) based on the data during 1-16 May of 2005

Dates	Actual maximum wind speed	Maximum wind speed (kph) at other places	Computed maximum wind speed in Expt-3	Standard error of estimate in Expt-3	Computed maximum wind speed in Expt-4	Standard error of estimate in Expt-4
01-05-2005	46		50.41881	±16.18183	70.54014	±20.11473
02-05-2005	9		35.62106		58.87444	
03-05-2005	13		19.3699		66.05296	
04-05-2005	41	Bogra:78	49.74071		75.74063	
05-05-2005	56	Khepupara:109	58.76267		63.90696	
06-05-2005	11	Rangpur:63	27.66681		62.90925	
07-05-2005	6		29.71028		96.57262	
08-05-2005	13	Sitakunda:61	44.48693		67.05542	
09-05-2005	9	Chittagong:45	45.50451		61.27074	
10-05-2005	13	Sylhet:78	52.80647		72.34519	
11-05-2005	13	Sylhet:55	65.2309		83.51335	
12-05-2005	46		77.79463		91.17259	
13-05-2005	111		*		*	
14-05-2005	13	Sylhet:56	34.54752		68.64662	
15-05-2005	17	Sylhet:41	53.14062		88.37976	
16-05-2005	50	Sylhet:48	45.77299		82.36009	

10.7 Validation of the regression equations for 24 hrs rainfall

10.7.1 Validation of the simple regression equations for the country-averaged rainfall in Bangladesh

In case of verification of the regression equations for rainfall, it has been found that there are trace amount of rainfall on one or two days. Trace amount of rainfall is defined as the rainfall below 0.5 mm. In this study, 0.25 mm is taken as the trace amount of rainfall. Based on the data during the pre-monsoon season of 1990-95, the regression equations developed for the country-averaged rainfall with precipitable water and MSWI in Chapter 5 are given below:

$$R_{CA} = 0.306W - 1.3696 \quad (8)$$

$$R_{CA} = 0.0207*MSWI - 0.1335 \quad (9)$$

Where R_{CA} is the 24 hours country-averaged rainfall over Bangladesh, W is the precipitable water content of the troposphere at 0000 UTC over Dhaka and MSWI is the Modified SWEAT Index. The correlation coefficients are 0.24915 (t_{cal} = 2.64837, n= 108) and 0.30425 (t_{cal} =

3.28832, n= 108), which are significant at 95% level of significance. Table 10.4 gives the comparison between the actual country-averaged rainfall and the computed rainfall.

Table 10.4: Comparison between the actual country-averaged rainfall and the computed rainfall based on the data during March-May of 2005

R_{CA} = 0.306*W - 1.3696				R_{CA} = 0.0207*MSWI - 0.1335			
Dates	Actual country-averaged rainfall	Computed country-averaged rainfall	Standard error of estimate	Dates	Actual country-averaged rainfall	Computed country-averaged rainfall	Standard error of estimate
09-04-2005	5.45	7.29	± 3.17845	09-04-2005	5.45	9.57	±3.73266
23-04-2005	4.66	8.29		20-04-2005	0.21	2.89	
24-04-2005	3.77	8.66		23-04-2005	4.66	3.49	
25-04-2005	4.27	9.45		24-04-2005	3.77	8.6	
27-04-2005	7.45	10.08		25-04-2005	4.27	6.71	
29-04-2005	11.02	9.74		27-04-2005	7.44	10.27	
30-04-2005	5.78	7.82		29-04-2005	11.01	10.93	
04-05-2005	7.56	10.71		30-04-2005	5.78	15.21	
12-05-2005	3.86	7.86		01-05-2005	1.47	7.91	
13-05-2005	5.03	7.55		12-05-2005	3.86	9.72	
20-05-2005	7.54	10.11		20-05-2005	7.54	9.22	
21-05-2005	9.41	10.79		21-05-2005	9.41	13.77	
22-05-2005	19.38	12.29		22-05-2005	19.38	13.99	

Table 10.4A: Comparison between the actual country-averaged rainfall and the computed rainfall based on the data during 1-16 May 2005

R_{CA} = 0.306*W - 1.3696				R_{CA} = 0.0207*MSWI - 0.1335			
Dates	Actual country-averaged rainfall	Computed country-averaged rainfall	Standard error of estimate	Dates	Actual country-averaged rainfall	Computed country-averaged rainfall	Standard error of estimate
01-05-2005	1.47059	8.819128	± 4.91021	01-05-2005	1.47059	7.91	±5.82094
02-05-2005	1.31618	8.849087		02-05-2005	1.31618	6.09362	
03-05-2005	2.77941	8.970458		03-05-2005	2.77941	5.82810	
04-05-2005	7.55882	10.71371		04-05-2005	7.55882	8.30796	
05-05-2005	21.26471	9.195805		05-05-2005	21.26471	10.8621	
06-05-2005	6.28676	8.331965		06-05-2005	6.28676	6.04545	
07-05-2005	6.22059	7.323643		07-05-2005	6.22059	3.41862	
08-05-2005	12.77941	11.69405		08-05-2005	12.77941	10.37259	
09-05-2005	6.00735	9.776341		09-05-2005	6.00735	6.70992	
10-05-2005	6.76471	13.5953		10-05-2005	6.76471	12.32352	
11-05-2005	1.41176	10.46153		11-05-2005	1.41176	11.56108	
12-05-2005	3.86029	7.860169		12-05-2005	3.86029	12.0627	
13-05-2005	5.02941	7.55229		13-05-2005	5.02941	*	
14-05-2005	2.15441	6.219991		14-05-2005	2.15441	13.10391	
15-05-2005	6.03676	7.989058		15-05-2005	6.03676	14.55365	
16-05-2005	4.02206	10.13149		16-05-2005	4.02206	11.47202	

The table shows the encouraging results with standard errors of estimates ± 3.17845 and ± 3.73266 mm for the regressions R_{CA} = 0.306W - 1.3696 and R_{CA} = 0.0207*MSWI - 0.1335 respectively. These equations can be used to predict country-averaged 24 hrs rainfall associated with nor'westers.

The above equations have also been used to obtain country-averaged rainfall amount by using the data for the period 1-16 May 2005 and the results are given in Table 10.4A. The results are encouraging too with standard errors of estimates ± 4.91021 and ± 5.82094 for the equations (8) and (9) respectively.

10.7.2 Validation of the simple regression equations for the 24 hours rainfall at Dhaka and maximum rainfall in Bangladesh

The regression equations for the 24 hrs rainfall at Dhaka and the maximum rainfall in Bangladesh with precipitable water and SWI in Chapter 5 are given below:

$$R_{Dha} = 0.7261*W - 11.136 \quad (10)$$

$$R_{Max} = 0.0859*SWI + 33.154 \quad (11)$$

Where R_{Dha} is the 24 hours rainfall at Dhaka, R_{Max} is the 24 hrs maximum rainfall in Bangladesh, W is the precipitable water content of the troposphere at 0000 UTC over Dhaka and SWI is the SWEAT Index. The correlation coefficients are 0.246601 (t_{cal} = 2.619817, n= 108) and 0.29504 (t_{cal} = 3.17912, n=108), which are significant at 95% level of significance. Table 10.5 gives the comparison between the actual 24 hrs rainfall at Dhaka and maximum 24 hrs rainfall in Bangladesh and the computed rainfall.

The table shows the encouraging results with standard errors of estimates ± 12.3388 and ± 8.5680 mm for the regressions R_{Dha} = 0.7261*W - 11.136 and R_{Max} = 0.0859*SWI + 33.154 respectively. Though the standard error of estimate is a bit larger in case of 24 hrs rainfall at Dhaka, the correlation coefficient is statistically significant at 95% level. The standard error of estimate is significantly smaller in case of maximum rainfall in Bangladesh. These equations can be used to predict 24 hrs rainfall at Dhaka and 24 hrs maximum rainfall in Bangladesh associated with nor'westers.

The above equations have also been used to obtain 24 hrs rainfall at Dhaka and the maximum rainfall over Bangladesh by using the data for the period 1-16 May 2005 and the results are given in Table 10.5A. The standard errors of estimates are ± 11.32064 and ± 20.35842 for the equations (10) and (11) respectively. These values are larger and the equation (10) overestimates the rainfall at Dhaka.

Table 10.5: Comparison between the actual 24 hrs rainfall at Dhaka and maximum rainfall in Bangladesh with the computed rainfall by linear multiple regression model based on the data during March-May of 2005

$R_{Dha} = 0.7261*W - 11.136$				$R_{Max} = 0.0859*SWI + 33.154$			
Dates	Actual 24 hrs rainfall at Dhaka	Computed 24 hrs rainfall at Dhaka	Standard error of estimate	Dates	Actual 24 hrs maximum rainfall in Bangladesh	Computed 24 hrs maximum rainfall in Bangladesh	Standard error of estimate
03-04-2005	3	4.734761	± 12.3388	09-04-2005	45	47.81688	± 8.5680
24-04-2005	6	12.65868		23-04-2005	44	43.7197	
25-04-2005	23	14.52668		26-04-2005	45	53.78718	
26-04-2005	45	17.19629		27-04-2005	61	59.4394	
29-04-2005	8	15.23611		29-04-2005	58	53.01408	
29-04-2005	8	15.23611		26-04-2005	45	53.78718	
04-05-2005	6	17.53619		27-04-2005	61	59.4394	
05-05-2005	16	13.93439		29-04-2005	58	53.01408	
12-05-2005	8	10.76509		01-05-2005	23	47.82572	
16-05-2005	10	16.15467		04-05-2005	45	55.0716	
19-05-2005	38	14.4815		19-05-2005	51	47.82572	
21-05-2005	28	17.71635		22-05-2005	75	73.07181	

Table 10.5A: Comparison between the actual 24 hrs rainfall at Dhaka and maximum rainfall in Bangladesh with the computed rainfall by linear regression model based on the data during 1-16 May 2005

$R_{Dha} = 0.7261*W - 11.136$				$R_{Max} = 0.0859*SWI + 33.154$			
Dates	Actual 24 hrs rainfall at Dhaka	Computed 24 hrs rainfall at Dhaka	Standard error of estimate	Dates	Actual 24 hrs maximum rainfall in Bangladesh	Computed 24 hrs maximum rainfall in Bangladesh	Standard error of estimate
01-05-2005	0	13.04059	±11.32064	01-05-2005	23	47.82572	± 20.35842
02-05-2005	0	13.11167		02-05-2005	20	55.98240	
03-05-2005	0	13.39967		03-05-2005	41	57.28001	
04-05-2005	6	17.53619		04-05-2005	45	55.07160	
05-05-2005	16	13.93439		05-05-2005	64	51.93174	
06-05-2005	0.25	11.88461		06-05-2005	67	53.57720	
07-05-2005	0	9.49199		07-05-2005	75	41.88144	
08-05-2005	7	19.86242		08-05-2005	85	64.17257	
09-05-2005	10	15.31193		09-05-2005	45	51.89738	
10-05-2005	0	24.37385		10-05-2005	52	81.06802	
11-05-2005	0	16.93781		11-05-2005	25	50.00758	
12-05-2005	8	10.76509		12-05-2005	23	42.75762	
13-05-2005	38	10.03454		13-05-2005	64	*	
14-05-2005	0	6.87316		14-05-2005	29	55.63001	
15-05-2005	0.25	11.07093		15-05-2005	53	55.23864	
16-05-2005	10	16.15467		16-05-2005	41	55.00930	

10.7.3 Validation of the linear multiple regression equations for 24 hrs rainfall

10.7.3.1 Validation of the linear multiple regression equation for the country averaged 24 hrs rainfall in Bangladesh

The linear multiple regression equation (5) developed for the 24 hrs country-averaged rainfall has been used to compute the country-averaged rainfall using the different parameters derived from the rawinsonde data for the pre-monsoon season of 2005. The computed rainfall and the actual country-averaged rainfall have been compared and are given in Table 10.6.

Table 10.6: Comparison between the actual country-averaged 24 hrs rainfall over Bangladesh and the computed country-averaged 24 hrs rainfall by linear multiple regression model based on the data during March-May of 2005

Dates	Actual 24 hrs country-averaged rainfall	Computed 24 hrs country-averaged rainfall	Standard error of estimate
20-04-2005	0.213235	0.73598	± 4.88887
23-04-2005	4.661765	1.68209	
27-04-2005	7.441176	13.27330	
04-05-2005	7.558824	10.88451	
05-05-2005	21.26471	19.82743	
12-05-2005	3.860294	3.50041	
19-05-2005	18.68382	8.71816	
21-05-2005	9.411765	14.84800	
22-05-2005	19.38235	16.84446	

The table shows the encouraging results with standard errors of estimates ± 4.88887 mm for the regression equation (5). The standard error of estimate is appreciably small in case of 24 hrs country-averaged rainfall. The correlation coefficient is statistically significant at 100% level.

The linear multiple regression equation (5) for the 24 hrs country-averaged rainfall has also been used to compute the country-averaged rainfall using the different parameters derived from the rawinsonde data for the period 1-16 May 2005 and the results are given in Table 10.6A. The results indicate overestimation of country-averaged rainfall but the standard error of estimate is small. This may be due to the fact that upper air data over Dhaka has been used but nor'westers did not occur everyday over Dhaka during the period and so the rainfall was nil at Dhaka on those days.

Table 10.6A: Comparison between the actual country-averaged 24 hrs rainfall over Bangladesh and the computed country-averaged 24 hrs rainfall by linear multiple regression model based on the data during 1-16 May 2005

Dates	Actual 24 hrs country-averaged rainfall	Computed 24 hrs country-averaged rainfall	Standard error of estimate
01-05-2005	1.47059	49.92861	± 16.5491
02-05-2005	1.31618	45.55627	
03-05-2005	2.77941	46.67122	
04-05-2005	7.55882	10.88451	
05-05-2005	21.26471	19.82743	
06-05-2005	6.28676	44.91881	
07-05-2005	6.22059	40.39667	
08-05-2005	12.77941	52.03174	
09-05-2005	6.00735	44.46584	
10-05-2005	6.76471	56.76882	
11-05-2005	1.41176	49.52407	
12-05-2005	3.86029	48.50462	
13-05-2005	5.02941	*	
14-05-2005	2.15441	58.44353	
15-05-2005	6.03676	57.35232	
16-05-2005	4.02206	51.71071	

10.7.3.2 Validation of the linear multiple regression equation for the maximum 24 hrs rainfall in Bangladesh

The linear multiple regression equation (6) developed for the 24 hrs maximum rainfall over Bangladesh has been used to compute the maximum rainfall using the different parameters derived from the rawinsonde data for the pre-monsoon season of 2005. The computed maximum rainfall and the actual maximum rainfall over Bangladesh have been compared and are given in Table 10.7.

Table 10.7: Comparison between the actual maximum 24 hrs rainfall over Bangladesh and the computed maximum rainfall by linear multiple regression model based on the data during March-May of 2005

Dates	Actual 24 hrs maximum rainfall in Bangladesh	Computed 24 hrs maximum rainfall in Bangladesh	Standard error of estimate
23-04-2005	44	28.34561	± 13.7856
27-04-2005	61	60.32335	
29-04-2005	58	81.67821	
04-05-2005	45	70.60152	
05-05-2005	64	79.08987	
12-05-2005	23	41.58225	
16-05-2005	41	57.43384	
19-05-2005	51	47.58950	
21-05-2005	74	70.01947	
22-05-2005	75	79.41671	

Table 10.7 shows the encouraging results with standard errors of estimates ± 13.7856 mm for the regression equation (6). The standard error of estimate, though ± 13.7856 mm, is appreciably small in case of 24 hrs maximum rainfall in Bangladesh. The correlation coefficient is statistically significant at 100% level.

Equation (6) has also been used to compute maximum 24 hrs rainfall over Bangladesh using the different parameters derived from the rawinsonde data for the period 1-16 May 2005 and the results are given in Table 10.7A. Though the standard error of estimate, ±18.74894, is larger, the results are encouraging.

Table 10.7A: Comparison between the actual maximum 24 hrs rainfall over Bangladesh and the computed maximum rainfall by linear multiple regression model based on the data during 1-16 May 2005

Dates	Actual 24 hrs maximum rainfall in Bangladesh	Computed 24 hrs maximum rainfall in Bangladesh	Standard error of estimate
01-05-2005	23	51.18412	±18.74894
02-05-2005	20	66.82858	
03-05-2005	41	52.28165	
04-05-2005	45	70.60152	
05-05-2005	64	79.08987	
06-05-2005	67	57.7472	
07-05-2005	75	53.11457	
08-05-2005	85	77.25829	
09-05-2005	45	60.78061	
10-05-2005	52	90.00668	
11-05-2005	25	50.76479	
12-05-2005	23	42.79809	
13-05-2005	64	*	
14-05-2005	29	64.48098	
15-05-2005	53	59.12044	
16-05-2005	41	56.27658	

10.7.3.3 Validation of the linear multiple regression equation for the 24 hrs rainfall at Dhaka

The linear multiple regression equation (7) developed for the 24 hrs rainfall at Dhaka has been used to compute the rainfall at Dhaka using the different parameters derived from the rawinsonde data over Dhaka for the pre-monsoon season of 2005. The computed 24 hrs rainfall at Dhaka and the actual 24 hrs rainfall at Dhaka have been compared and is given in Table 10.8.

It can be seen from the Table 10.8 that the results are encouraging with standard error of estimates ± 17.68258 mm for the regression equation (7). Though the standard error of estimate is larger, the correlation coefficient is statistically significant at 100% level.

Regression equation (7) has been used to compute 24 hrs rainfall at Dhaka using the different parameters derived from the rawinsonde data for the period 1-16 May 2005 and the results are given in Table 10.8A. The equation overestimates the rainfall at Dhaka. This may be due to fact that nor'westers did not occur over Dhaka everyday and so the rainfall was nil at Dhaka on many days.

Table 10.8: Comparison between the actual 24 hrs rainfall at Dhaka and the computed rainfall by linear multiple regression model based on the data during March-May of 2005

Dates	Actual 24 hrs rainfall at Dhaka	Computed 24 hrs rainfall at Dhaka	Standard error of estimate
20-04-2005	1	0	± 17.68258
23-04-2005	0.25	10.86923	
25-04-2005	23	56.02599	
26-04-2005	45	23.14266	
04-05-2005	6	27.86984	
12-05-2005	8	7.145565	
16-05-2005	10	20.13828	
19-05-2005	38	28.61759	
21-05-2005	28	40.26875	
22-05-2005	72	51.31122	

Table 10.8A: Comparison between the actual 24 hrs rainfall at Dhaka and the computed rainfall by linear multiple regression model based on the data during 1-16 May 2005

Dates	Actual 24 hrs rainfall at Dhaka	Computed 24 hrs rainfall at Dhaka	Standard error of estimate
01-05-2005	0	17.77362	±12.68621
02-05-2005	0	7.83511	
03-05-2005	0	2.785359	
04-05-2005	6	27.86984	
05-05-2005	16	28.55987	
06-05-2005	0.25	3.851844	
07-05-2005	0	3.680979	
08-05-2005	7	21.86741	
09-05-2005	10	11.45558	
10-05-2005	0	28.59975	
11-05-2005	0	20.79278	
12-05-2005	8	16.4179	
13-05-2005	38	*	
14-05-2005	0	16.67731	
15-05-2005	0.25	24.4093	
16-05-2005	10	59.75897	

10.8 Synoptic techniques for the prediction of nor'westers

10.8.1 Synoptic techniques for the prediction of nor'westers in Bangladesh

Nor'westers generally occur over Bangladesh in the afternoon/evening/early night to midnight. The Meteorologists are to issue forecast nor'westers based on the data at 0000 and

0300 UTC about 9 to 12 hours before the occurrence of nor'westers. To see the basic favourable conditions being fulfilled, a Meteorologist within a short span of time has to adopt certain quick techniques to decide whether a nor'wester is likely to occur or not. These techniques, based on the morning analysis of meteorological data, are:

i) to locate the low pressure system over Bihar, sub-Himalayan West Bengal and adjoining Bangladesh, Gangetic West Bengal and adjoining Bangladesh, Orissa and southwestern Bangladesh,

ii) to find out the 24 hrs or 12 hrs pressure change over Bangladesh and adjoining areas and to find out the negative pressure change,

iii) to determine the area of negative pressure departure,

iv) to locate the area of low-level convergence and its vertical extension from Pilot Balloon charts,

v) to locate the area of moist and dry zones at the surface and the point of intersection of the axes of these zones,

vi) to locate the area warm air advection at the surface and the area of increase in minimum temperature,

vii) to delineate the area of pseudo-frontal activity at the surface in the magnified synoptic chart,

viii) to compute different instability indices,

ix) to delineate the positive and negative areas on the thermodynamic chart,

x) to find out the middle and upper level jet shear,

xi) to determine the point of intersection of the axes of low-level maximum wind and upper-level jet stream,

xii) to see whether there is moisture incursion up to 1 km or more with south/southeasterly or southwesterly wind over Bangladesh,

xiii) to see whether the southerly wind speed has increasing tendency in the lower troposphere,

xiv) to find the number of isobars passing across Bangladesh coming from the south,

xv) to see whether the isobars passing over Bangladesh turns towards the east or west,

xvi) to determine the LFC, CCL, wet-bulb zero height and their tendency as compare to their past 24 hrs values,

xvii) to see the trough in the upper-air westerlies and jet streams,

xviii) to see the movement of the easterly low pressure systems over the southern peninsula of India or the Arabian Sea,

xix) to determine the position of the western disturbance and its conjugation with easterly low pressure system or easterly trough,

xx) to see in the satellite or radar imageries whether there is any bright cloud mass developing the west of Bangladesh

xxi) to see whether there increase in moisture in the lower troposphere over Bangladesh,

xxii) to see whether there is increase in the precipitable water content of the troposphere over Bangladesh,

xxiii) to see whether there is increase in energy components and total energy per unit mass in the troposphere,

xxiv) to whether there is increase in the westerly and southerly fluxes of moisture and energy in the lower troposphere.

10.8.2. Key forecasting parameters and intensity of nor'westers in Bangladesh

The key parameters, which are related with the intensity of nor'westers, are given in the tabular form:

Table 10.9: Key forecasting parameters and intensity of nor'westers

Sl. No.	Parameters		Nor'westers	Severe Nor'westers	Tornado
1.	Synoptic conditions	Presence of low pressure over Bihar, Sub-Himalayan West Bengal, Gangetic West Bengal, northern Orissa and adjoining Bangladesh.	1-2 closed isobars	2 or more closed isobars	2 or more closed isobars
		Low-level circulation in the Pilot chart	1 km	1-2 km	2-3 km or more
		Pressure fall in 24 hours	1-2 hPa	2-3 hPa	3-6 hPa
		Pressure departure	1 hPa below normal	2-3 hPa below normal	3-5 hPa below normal
		Trough in the upper westerly over Bihar/Sub-Himalayan West Bengal/northern Bangladesh	Prominent trough at 300 hPa	Prominent trough at 300 hPa or below	Prominent trough at 300 hPa or below
2.	Rise in minimum temperature		2-3°C	3-4°C	3-4°C
3.	Temperature contrast in the pseudo-frontal zone		2-3°C	3-4°C	3-5°C

Table 10.9 (cont'd)

Sl. No.	Parameters	Nor'westers	Severe Nor'westers	Tornado
4.	Area of the rise in minimum temperature/warm area	South / southwestern Bangladesh	South / southwestern Bangladesh	South / southwestern Bangladesh
5.	Vertical wind shear Between 500 and 850 hPa	10-15 ms^{-1}	15-20 ms^{-1}	15-20 or more ms^{-1}
6.	Point of intersection of the axes of moist zone and dry zone	Near the place of occurrence	Near the place of occurrence	Near the place of occurrence
7.	Point of intersection of the axes of low-level maximum wind and upper level jet stream	Near the place of occurrence	Near the place of occurrence	Near the place of occurrence
8.	Specific humidity in the lower troposphere	Average 2-3 gm kg^{-1} increase from the previous day	Average 3-4 gm kg^{-1} increase from the previous day	Average 3-4 gm kg^{-1} or more increase from the previous day
9.	Specific humidity near the surface on the dates of occurrence of nor'westers.	15-20 g kg^{-1}	15-20 g kg^{-1}	15-20 g kg^{-1}
10.	Weighted average specific humidity between 1000 hPa and 500 hPa	8-12 g kg^{-1}	8-12 g kg^{-1}	8-12 g kg^{-1}
11.	Precipitable water between 1000 and 500 hPa	25-45 mm hr^{-1}	25-45 mm hr^{-1}	25-45 mm hr^{-1}
12.	SI	$\leq 3°C$	$\leq -3°C$	$\leq -3°C$
13.	LI	$\leq -3°C$	$\leq -3°C$	$< -3°C$
14.	DPI	$\leq -3°C$	$\leq -4°C$	$<-4°C$
15.	DII	$\leq 0°C$	$<-4°C$	$<-4°C$
16.	CT	$\geq 14°C$	$\geq 16°C$	$\geq 23.6°C$
17.	VT	$\geq 24°C$	$\geq 26°C$	$\geq 28°C$
18	TT	$\geq 40°C$	$\geq 40°C$	$\geq 49.5°C$
19.	EI	≤ 0	≤ -3	≤ -10
20.	SWI	> 200	> 250	> 400
21.	KI	$\geq 34°C$	$\geq 34°C$	$\geq 42.5°C$
22.	MCT	$\geq 20°C$	$\geq 22°C$	$\geq 24°C$
23.	MVT	$\geq 26°C$	$\geq 28°C$	$> 30°C$
24.	MTT	$\geq 48°C$	$\geq 54°C$	$\geq 55.0°C$
25.	MSWI	≥ 300	≥ 300	≥ 500
26.	MEI	< -3	≤ -9	≤ -11
27.	MKI	$\geq 42°C$	$\geq 48°C$	$>58°C$
28.	DSE and MSE at low level on the dates of occurrence of nor'westers	Increase in DSE and MSE	Increase in DSE and MSE	Increase in DSE and MSE
29.	Instability energy	Increase in instability energy	Increase in instability energy	Increase by 44.75421×10^5 Jm^{-2} to 90.931003×10^6 Jm^{-2}
30.	Vertical velocity at 300 hPa	Increases with time	Increases with time	Increases with time and may be maximum of 4.02 ms^{-1}.

CHAPTER 11

CONCLUSIONS

Based on the present study, the following conclusions can be drawn:

(i) The frequency of nor'westers increases sharply from noontime and becomes maximum in the evening/early night between 6 p.m. and 10 p.m. (BST) and then decreases again. The mean frequency of thunderstorms and thunderstorm days over Bangladesh increases significantly as the season progresses from March to May and is maximum in May.

(ii) The mean monthly and seasonal thunderstorm frequencies and thunderstorm days are maximum over Sylhet region and minimum over southern and extreme southeastern parts of Bangladesh, Dinajpur-northern Rajshahi region and Rangamati-Maijdi Court-Comilla region. There are two other regions of maximum monthly and seasonal thunderstorms namely Jessore-Faridpur-Rajshahi and Chittagong-Cox's Bazar regions.

(iii) The CV of monthly thunderstorms and thunderstorm days over Bangladesh is maximum in March and decreases sharply as the season progresses. The CV of monthly thunderstorms is maximum over extreme southern part of Bangladesh, Rangamati-Maijdi Court region and Dinajpur-Bogra-Rajshahi region and minimum over western Sylhet-eastern Mymensing-northern Dhaka region, Jessore-Rajshahi region and Chittagong-Cox's Bazar region. In March and April, the areas of secondary and tertiary minimum CV of thunderstorms are Jessore-Rajshahi and Chittagong-Cox's Bazar regions whereas in May the reverse is true. The CV of seasonal thunderstorms show the same pattern of distribution as that of the monthly thunderstorms having the lowest value at Sylhet and highest value at Teknaf. The CV of both monthly and seasonal thunderstorm days are minimum over the areas of maximum frequency of mean thunderstorm days and vice-versa.

(iv) There exists 3-7 years cycles of variation in the monthly and seasonal frequency of thunderstorms over Bangladesh. The country-averaged monthly and seasonal frequency of thunderstorms during the pre-monsoon season has increasing trends. The rates of increase in the frequency of thunderstorms are 0.1912, 0.1059 and 0.2365/year in March, April and May respectively and 0.4566/year during the pre-monsoon season.

(v) There exists a belt of increasing trends in the monthly and seasonal frequency of thunderstorms from northwestern part of Bangladesh towards southeast up to Rangamati across Bogra, Mymensingh, Srimangal, Comilla, Feni and Maijdi Court.

(vi) The existence of a low pressure over eastern Uttar Pradesh and Bihar/West Bengal of India with its axis extending in the west-east direction across the plains is favourable for the occurrence of nor'westers in Bangladesh. Nor'westers have been found to occur over Bangladesh near the trough line in the surface synoptic charts and near the point of intersection of the axes of moist and dry areas. Nor'wester activities have been found to increase over Bangladesh if the low-pressure systems persist for the whole season. In these cases the surface sub-tropical highs have been found to be weak over the Bay of Bengal and adjoining areas.

(vii) Early nor'westers have been found to occur over Bangladesh when the easterly low-pressure systems penetrate through the southern tip of India. For the late occurrence of nor'westers in Bangladesh, the easterly low-pressure systems have been found to move more westwards over the Arabian Sea.

(viii) On the dates of occurrence of severe nor'westers or tornado:

a) A very small warm area of minimum temperature has been found near the place of occurrence or there exists an interaction of relatively very cold air mass with warm air mass near the place of occurrence of tornado.

(b) The minimum temperatures have been found to rise as compared to minimum temperatures on the dates of non-occurrence of nor'westers (1 day before occurrence) over the northwestern and southwestern parts of the country.

(c) Severe drying of the atmosphere near the surface occurs in the afternoon and the gradient of humidity increases significantly.

(ix) The humidity is found to be higher over the south and southwestern parts of the country and this humidity extends northeastwards up to central Bangladesh or more northeastwards in most of the cases on the dates of occurrence of nor'westers at 0000 UTC or 0300 UTC.

(x) When trough in the upper air westerly jet stream is present over Bihar/West Bengal of India or over Bangladesh, severe nor'westers are found to occur in Bangladesh. Severe nor'westers have been found to occur near the point of intersection of the axis of the maximum jet stream at 300/200 hPa and the axis of maximum wind at 850-hPa level.

(xi) On the dates of occurrence of tornadoes, intrusion of warm air through the southwestern part of the country and presence of cold air just in the northeast are observed.

(xii) Significant increase in the moisture content of the troposphere over Dhaka at 0000 UTC is observed in the lower level on the dates of occurrence of tornadoes.

(xiii) On the dates of occurrence of tornadoes the westerly winds over Dhaka at 0000 UTC were found very strong in the middle and upper troposphere and vertical wind shears were positive and large on the dates of occurrence.

(xiv) The frequency of different Stability Indices reveals that the atmosphere may be stable in the morning on date of occurrence of a few nor'westers but this stability may be thought of being destroyed with the advancement of the day.

(xv) The critical values of different stability indices viz. SI $\leq$ 3°C, LI $\leq$ 3°C, DPI $\leq$ -3°C, DII $\leq$ 0°C, CT $\geq$ 14°C, VT $\geq$ 24°C, TT $\geq$ 40°C, EI $\leq$ 0, SWI > 200,

KI ≥ 34°C may be considered to occur nor'westers in Bangladesh. The critical values of different stability indices viz. SI ≤ -3°C, LI ≤ -3°C, DPI ≤ -4°C, DII ≤ -4°C, CT ≥ 16°C, VT ≥ 26°C, TT ≥ 40°C, EI ≤ -3, SWI > 250, KI > 34°C may be considered for severe to very severe nor'westers to occur in Bangladesh.

(xvi) Normally, nor'westers have been found to occur over the maximum unstable area or at the northeastern or eastern part of the area of maximum instability.

(xvii) The Modified Instability Indices at 0000 UTC over Dhaka such as MCT, MVT, MTT, MSWI, MKI and MEI show greater instability of the troposphere in the morning as compared to CT, VT, TT, SWI, KI and EI on the dates of occurrence of nor'westers.

(xviii) The critical values of modified instability indices at 0000 UTC over Dhaka are: MCT ≥ 20°C, MVT ≥ 26°C, MTT ≥ 48°C, MSWI > 300, MKI ≥ 42°C and MEI < 0 respectively for the nor'westers to occur in Bangladesh. For severe to very severe nor'westers, the critical values of MCT, MVT, MTT, MSWI, MKI and MEI at 0000 UTC over Dhaka are: MCT ≥ 22°C, MVT ≥ 28°C, MTT ≥ 54°C, MSWI ≥ 300, MKI ≥ 48°C and MEI < -9 respectively. For tornadoes in Bangladesh, the critical values of different indices are: MCT ≥ 24°C, MVT > 30°C, MTT ≥ 55.0°C, MSWI ≥ 500, MEI ≤ -11 and MKI>58°C over Dhaka at 0000 UTC.

(xix) The SI has moderate to good correlation with different instability indices except DPI, VT, MVT and MKI also LI has moderate to good correlation with different instability indices except DII, KI and MVT.

(xx) Instability indices have moderate to strong correlation with the corresponding modified instability indices, having 99% level of significance. The CC of VT and MVT, SWI and MSWI, and KI and MKI are comparatively large. Standard errors of estimate are small in almost all the cases except the SWI and MSWI.

(xxi) Maximum number of nor'westers occurs when the precipitable water is 25-45 mm hr^{-1} up to 500 hPa, the maximum frequency being 48 in the range of 35-45 mm hr^{-1}. It has been found that the maximum precipitable water is concentrated over the area near the places of nor'westers.

(xxii) The precipitable water content of the troposphere at 0000 UTC over Dhaka has significant correlation with different instability indices namely TT, SWI, SWI/TT, MSWI, EI and MEI of the troposphere at 0000 UTC over Dhaka. The regression equations developed corresponding to the significant correlation may be useful in the computation of precipitable water content of the troposphere.

(xxiii) The specific humidity has been found to increase on the dates of occurrence of nor'westers in Bangladesh on most occasions. Maximum number of nor'westers occurs when the WAq between the surface and 500 hPa is 8-12 g kg^{-1}. Nor'westers have been found to occur near or at the eastern end of maximum WAq, the maximum WAq being 14 g kg^{-1}.

(xxiv) On the dates of occurrence of nor'westers over Bangladesh the WFM dominate in the troposphere over Dhaka at 0000 UTC from 925 to 200-hPa level. In the upper troposphere the ZFM become nil in most of the cases. The ZFM over Dhaka at 0000 UTC are mainly westerly or westerly in the lower and middle troposphere on the dates of occurrence of nor'westers as compared to the dates of non-occurrence.

(xxv) On the dates of occurrence of nor'westers over Bangladesh the SFM dominate in the troposphere over Dhaka at 0000 UTC from 1000 to 300 hPa level. In the upper troposphere the MFM become nil in most of the cases. The MFM are mainly southerly or southerly in the lower and middle troposphere on the dates of occurrence of nor'westers as compared to the dates of non-occurrence.

(xxvi) The vertically integrated ZFM over Dhaka at 0000 UTC from 1000 to 100 hPa on the dates of occurrence of nor'westers in Bangladesh are much higher than that of the meridional fluxes.

(xxvii) The spatial distribution of the vertically integrated ZFM and MFM from 925 to 400 hPa level over Bangladesh and its surrounding areas at 0000 UTC indicates that WFM dominate over Bangladesh and/or eastern Uttar Pradesh, Bihar, and Sub-Himalayan west Bengal of India whereas SFM dominate over south-southwestern and adjoining central parts of Bangladesh on the dates of occurrence of nor'westers and the gradient of fluxes is steep over the region.

(xxviii) During the pre-monsoon season, the SH and monthly mean LH of the troposphere increases as the season progresses. The SH of the troposphere on the dates of occurrence of nor'westers increases significantly as compared to the weekly normal from near the surface to about 300-200 hPa or more in most of the cases, although it has inter-layer variations. There are some exceptions especially in the lower troposphere near the surface where there exists decrease in SH of the troposphere at 0000 UTC.

(xxix) On the dates of occurrence of nor'westers the SH is above the monthly normal value in the lower troposphere and below normal in the layer between 850 and 650 hPa levels. It is significantly above the monthly normal in the upper troposphere, having maximum in the 400-300 hPa layer.

(xxx) The LH of the troposphere on the dates of occurrence of nor'westers increases significantly from about 900 to about 400 hPa or more in most of the cases, although it has inter-layer variations. There is a significant increase in LH above 900 or 850 hPa level, which extends up to about 400 hPa level.

(xxxi) The LH of the troposphere on the dates of occurrence of nor'westers increases significantly as compared to the weekly normal in the lower troposphere in most of the cases, although it has inter-layer variations. The LH on the dates of occurrence of nor'westers is significantly above the monthly normal in the

lower troposphere, and then it becomes below of monthly normal in the mid-troposphere.

(xxxii) The increase in DSE occurs in most of the cases at 700 and 100 hPa level over Dhaka whereas the decrease in DSE occurs in maximum cases at 300 hPa level as compared to the monthly, weekly and daily normal prior to the occurrence of nor'westers at Dhaka.

(xxxiii) The MSE of the troposphere over Dhaka, on the dates of occurrence of nor'westers at Dhaka, increases in most of the cases in the lower troposphere having the increase in maximum cases of 69.62, 75.64 and 76.92 % at 925 hPa level as compared to the monthly, weekly and daily normal respectively.

(xxxiv) The increase in DSE and MSE of the troposphere over Dhaka occurs in most cases from the surface to 300 hPa level on the dates of occurrence of nor'westers as compared to that on the dates of non-occurrence, the maximum being in the lower troposphere.

(xxxv) The DSE and MSE of the troposphere over Dhaka has significant positive anomalies with respect to the previous weekly normal on the dates of occurrence of nor'westers in Bangladesh in most of the cases.

(xxxvi) The area of maximum MSE at 850 hPa level lies over the area where the surface low and low-level circulation exist. Nor'westers occur at the northeastern or eastern part of the area of maximum MSE. The area of minimum MSE at 500-hPa level lies over the area of maximum MSE at 850 hPa level.

(xxxvii) On the dates of occurrence of nor'westers over Bangladesh at 0000 UTC EFDSE dominate over WFDSE over Dhaka at 1000 hPa level and for 925-100 hPa level the case is reversed.

(xxxviii) The ZFDSE and ZFMSE at 0000 UTC over Dhaka are mainly westerly or westerly in the lower troposphere on the dates of occurrence of nor'westers as compared to the zonal fluxes on the dates of non-occurrence. The ZFDSE at

0000 UTC over Dhaka are significantly westerly on both the dates of occurrence and non-occurrence of nor'westers but have slightly higher values in the upper troposphere on the dates of occurrence.

(xxxix) On the dates of occurrence of nor'westers over Bangladesh at 0000 UTC, the SFDSE dominate over NFDSE between 1000 – 850 and 200 – 100 hPa levels and in the other levels NFDSE dominate over SFDSE.

(xl) The MFDSE over Dhaka at 0000 UTC are mainly southerly or southerly in the lower and middle troposphere on the dates of occurrence of nor'westers as compared to the fluxes on the dates of non-occurrence of nor'westers in Bangladesh. The MFDSE are significantly southerly on both the dates of occurrence and non-occurrence of nor'westers but have higher values in the upper troposphere on the dates of occurrence.

(xli) The vertically integrated ZFDSE and ZFMSE from 1000 hPa to 100 hPa over Dhaka at 0000 UTC are significantly higher than that of the MFDSE and MFMSE respectively on the dates of occurrence of nor'westers in Bangladesh. The vertically integrated ZFDSE and ZFMSE are always westerly on the dates of occurrence of nor'westers.

(xlii) The spatial distribution of vertically integrated WFDSE dominate over EFDSE over Bangladesh on the dates of occurrence of nor'westers and the gradient of westerly fluxes is significantly steep over the country. The spatial distribution of the vertically integrated SFDSE dominate over NFDSE over the area from southern India to south-southwestern and adjoining central parts of Bangladesh on the dates of occurrence of nor'westers and the gradient of fluxes is steep over Bangladesh. There exist NFDSE in the northern part of the Bangladesh in many cases.

(xliii) The vertically integrated ZFMSE over Dhaka at 0000 UTC from 1000 to 100 hPa level are westerly and higher than that on the dates of occurrence of nor'westers.

(xliv) There exists a correlation between the vertically integrated ZFMSE on the dates of occurrence and non-occurrence of nor'westers. The correlation co-efficient is 0.78565, which is significant at 99% level of significance.

(xlv) The vertically integrated WFMSE from 925 to 100 hPa level dominate over Bangladesh and/or eastern Uttar Pradesh, Bihar, and Sub-Himalayan west Bengal of India on the dates of occurrence of nor'westers and the gradient of westerly fluxes is significantly steep over the country.

(xlvi) The vertically integrated SFMSE from 925 to 100 hPa level dominate over West Bengal of India, south southwestern and adjoining central parts of Bangladesh on the dates of occurrence of nor'westers and the gradient of fluxes is very steep over Bangladesh.

(xlvii) When pseudo-frontal activity is found over Bangladesh in the morning, severe thunderstorms / nor'westers occur in the evening or early night.

(xlviii) When the pseudo-frontal activity is present at the surface and other conditions are favourable to occur nor'westers in Bangladesh, severe squall lines form in the afternoon/evening and they move like a front causing nor'westers in Bangladesh. These nor'westers move from northwest to east-southeast up to Chittagong like a front.

(xlix) No cloud mass is found in radar and satellite imageries, both IR and VIS in most of the cases. But in the afternoon, very small mass of bright convective cloud is seen to grow over those areas, which afterwards grow into large bright convective clouds causing severe thunderstorms / nor'westers over Bangladesh.

(l) Nor'westers with greater gusty wind speed occur in April and May as compared to that in March and this may be attributed to the increased instability of the troposphere. The higher the available instability energy of the troposphere, the greater is the possibility of occurrence of nor'westers,

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provided the other conditions especially the synoptic conditions are favourable.

(li) The distribution patterns of wind shear for the layers 925-500 and 850-500 hPa are the same having maximum positive shear over Bangladesh and adjoining West Bengal of India. The wind shear in the layer 925-500 hPa is higher than that in the layer 850-500 hPa.

(lii) The maximum frequency of wind speed associated with nor'westers is in the range of 50-60 km/hr. Most of the gusts/maximum wind speed at Dhaka occurs in range of 50-110 km/hr.

(liii) The RegCM's output for average surface wind field gives a better circulation patterns similar to the actual circulation patterns favourable for the occurrence of nor'westers in Bangladesh. The averaged rainfall output over the country can be used as a basis for the forecast of rainfall.

(liv) The proposed regression equations are useful in the estimation of maximum gusty wind speed associated with nor'westers in Bangladesh. Using them, the computed values of maximum gusty wind speed have statistically significant correlation with the actual maximum gusty wind speed and are comparable with the observed.

(lv) The multiple regression equations developed for the estimation of 24 hrs country-averaged rainfall, 24 hrs maximum rainfall in Bangladesh and the 24 hrs rainfall at Dhaka are likely to be useful in the operational forecasting purposes.

(lvi) Hopefully the techniques and the key parameters identified for the occurrence of nor'westers will be useful for the operational Meteorologist in Bangladesh and provide better forecasting tool.

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