

Forecasting peak surface gust wind in association with thunderstorm activity during pre-monsoon season at Delhi

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सार - इस शोध-पत्र में, दिल्ली में गर्जते तूफानों सहित हवा के झोंकों की दिशा और गति के पूर्वानुमान के लिए एक वस्तुपरक पद्धति विकसित करने का प्रयास किया गया है। इस उद्देश्य के लिए वर्ष 1985-90 के अप्रैल, मई और जून (अ.म.जू.) माह के धरातल और उपरितन-वायु के आंकड़ों का उपयोग किया गया है। क्रमवार जाँच पद्धति का प्रयोग करके हवा के झोंकों की दिशा और गति का पूर्वानुमान लगाने के लिए बहुसमाश्रयण समीकरण विकसित किया गया है जिसके लिए कुल 181 संभाव्य पूर्वसूचकों का उपयोग किया गया है। अप्रैल, मई और जून माह के 1994 और 1995 के स्वतंत्र आंकड़ा सेटों से विकसित गतिकीय-सांख्यिकीय निदर्शों का परीक्षण किया गया। विकासात्मक और स्वतंत्र आँकड़ा सेटों से गतिकीय-सांख्यिकीय निदर्शों के संतोषजनक परिणाम प्राप्त हुए हैं। दिशा के मूल माध्य वर्ग त्रुटि में 58° और 77° के मध्य तथा गति पूर्वानुमान में 9 और 12 नॉट के मध्य भिन्नता पाई गई है। कुछेक अवसरों पर पाए गए पूर्वानुमान में व्यापक अंतरों के संभावित कारणों की भी जाँच की गई है।

ABSTRACT. In this study, an attempt is made to develop an objective method for forecasting the direction and speed of the gusty winds associated with thunderstorms at Delhi. For this purpose, surface and upper-air data for April, May and June (AMJ) for the years 1985-90 are utilized. Multiple regression equations are developed for forecasting the direction and speed of the gusty winds, using stepwise screening method, for which a total of 181 potential predictors are utilized. The developed dynamical-statistical models are tested with independent data sets of 1994 and 1995 for April, May and June. The dynamical-statistical models give satisfactory results with the developmental as well as the independent data sets. The root mean square error of the direction vary between 58° and 77° and the speed forecast vary between 9 and 12 knots. Possible reasons for large deviations of the forecast, noticed on a very few occasions, have also been examined.

Key words - Thunderstorm, Gust, Squall, Regression models.

1. Introduction

The thunderstorms during the pre-monsoon season (April-June over northwest India) are severe in nature which are generally experienced during the passage of moving synoptic systems. They are usually associated with gusty/squally winds at the surface. The turbulence associated with such strong winds can produce severe gust load on the aircraft and seriously jeopardise flight safety. The duration of the storm is usually between half an hour to one hour, though on some occasions, it may be for several hours continuously where as the wind gusts associated with the thunderstorms last only for a few minutes. The wind speed at times exceeds 100 kts (200 kmph). Such strong surface wind, usually builds up in a very small interval of time, from an initial low and variable wind. The associated impulsive force becomes

very large and hence destructive. The strong, gusty and squally surface wind can damage the parked and moored aircraft, power transmission lines, communication network, uproot the trees, damage standing crops and cause damage to other structures. It may pick up enough of dust from the ground and cause a dust storm and reduce visibility considerably to affect aviation, surface transportation for light vehicles and other outdoor activities. At times the gusty wind with a cross component to the runway can make the landing/take off of the aircraft difficult. Thus the gusts/squalls associated with the thunderstorms pose a serious hazard to aviation as well as to other commercial activities such as transportation, agriculture, construction, communication, power transmission etc. The forecast of such strong wind would help in taking precautionary measures for protection of life and property.

The thermodynamical instability in the atmosphere is usually relieved by thunderstorms or *vice versa*. The downdrafts in the thunderstorm cell bring the middle tropospheric air down to the surface and in the process the unstable lapse rates in the atmosphere are modified to stable lapse rates. The downdrafts from these cells also reach the ground level and violent surface winds are experienced. These violent winds are also referred as downbursts and have been categorized into micro and macro bursts, depending upon the size of the area affected by such systems.

Some of the studies related to prediction of gusty/squally surface winds associated with thunderstorms can be found in Fawbush and Miller (1952), Johns and Doswell (1992), McCann (1994) and Bartha (1994). The review of the work relating to prediction of peak gust associated with thunderstorm indicated that over Indian regions such studies are very limited. Ram Sanehi and Pant (1985) studied climatology of severe squalls over Delhi and found that the highest frequency of occurrence is in the month of May (mean monthly value of 4.9 days). Further, most of the squalls have a tendency to strike from westerly direction, with the frequency of occurrence being maximum during 1500-2100 hrs local time. The following empirical formulae exist for calculating the squall speed at Delhi.

$$V_{sq} = V + 6T_1^{1/2} \quad (\text{for May}) \quad (1)$$

$$V_{sq} = V + 9T_1^{1/2} \quad (\text{for June}) \quad (2)$$

where V is mean wind speed between 3.0 and 4.5 km above sea level and T_1 is the measure of dry instability. However, this method highly over predicts the observed values of squall speeds.

It is thus noted that no suitable objective method exists to predict the gust speed and direction associated with the pre-monsoon thunderstorms at Delhi. Therefore, in the present study an objective method using multiple regression analysis has been developed and the performance is evaluated with the dependent as well as independent data sets, for forecasting the gust speed and direction associated with the pre-monsoon thunderstorms over Delhi. A comparison is also made with the realized events to determine the accuracy of the forecasts generated by the empirical method (Eqns.1 & 2) and the developed regression method.

2. Data used

In order to obtain a reliable and relatively long record of continuous data, a meteorological station

situated in the north-eastern periphery of Delhi at a distance of about 15 km from central Delhi (referred to as Delhi in this study) is selected as the exact location to be used, which has been taken as a representative location for north west (NW) India. The months of April, May and June (AMJ) are selected for forecasting strong surface wind as the thunderstorm activities during these months usually gives rise to strong and gusty winds. All cases of maximum surface winds associated with thunderstorm experienced at Delhi are used in the development of the models. The surface and upper-air data of Delhi for AMJ for the period 1985-90 are utilized for development of the forecast model. For testing the developed models, data of AMJ from the recent years of 1994-95 are utilized as independent cases. The total number of potential predictors used in this study are 181 which included drybulb and dewpoint temperatures, dewpoint depression, zonal and meridional components of wind at the standard levels namely, surface, 1000, 850, 700, 500 and 300 hPa; wind shear between the levels namely, 300-850, 500-850 and 700-850 hPa; and lapse rate between levels 1000-850, 850-700, 850-500 and 850-300 hPa. The developed equations are to be used only if a thunderstorm is predicted to occur over Delhi. A model for prediction of occurrence/non-occurrence of thunderstorm at Delhi has already been developed (Ravi *et al.*, 1999). The forecast for occurrence/non-occurrence of thunderstorm is initiated at 0900 hrs (IST), valid for a period of 12 hours. Hence the forecast of gusty wind would also be initiated at 0900 hrs (IST) local time valid for a period of next 12 hrs (IST). It may be noted that the models are developed to forecast only the direction and speed of gusty winds and not the duration of such maximum winds.

3. Characteristic features of gusty/squally winds at Delhi

In general practice, a squall is defined as a sudden increase in wind speed by at least 16 kts (8 ms^{-1}) or more, the minimum speed reaching to 22 kts (11 ms^{-1}) or more and the phenomena lasting for at least one minute. Though the objective of the present study is to forecast the peak gust speed of surface wind associated with thunderstorms, for the purpose of studying characteristic features as well as the development of the models, the above said condition of squall is relaxed and all cases of wind speed of ≥ 16 kts (8 ms^{-1}) associated with thundery activity are included. This limit of 16 kts has been selected since it is felt that wind speed of 16 kts is closer to hazardous level of wind speed for operations of smaller aircraft, paratroop dropping, construction and also in agricultural activities such as spraying of pesticides over crops etc.

The direction and speed of gusty surface wind associated with the thunderstorm depends upon its

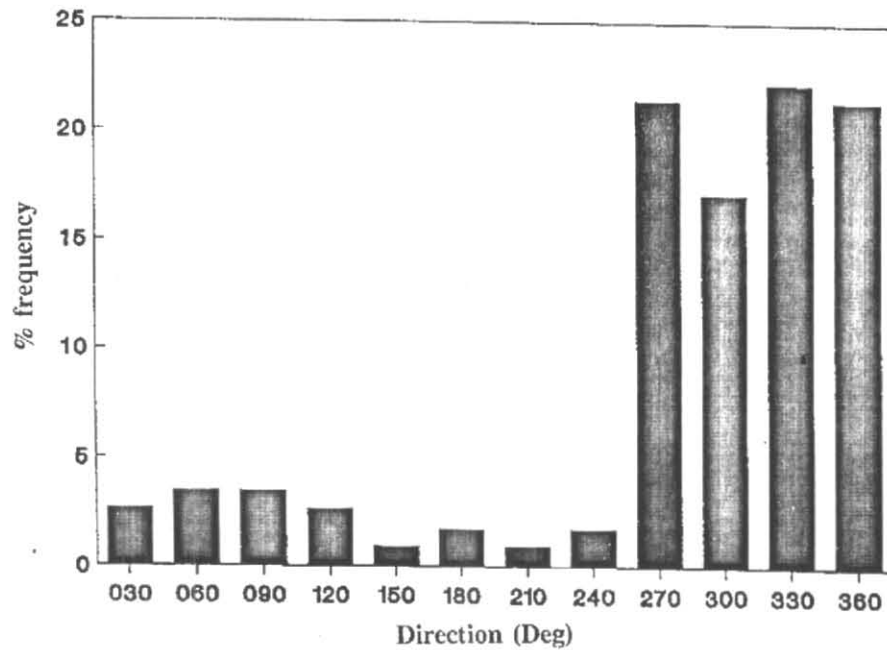


Fig. 1. Frequency distribution of direction of peak gust associated with thunderstorm

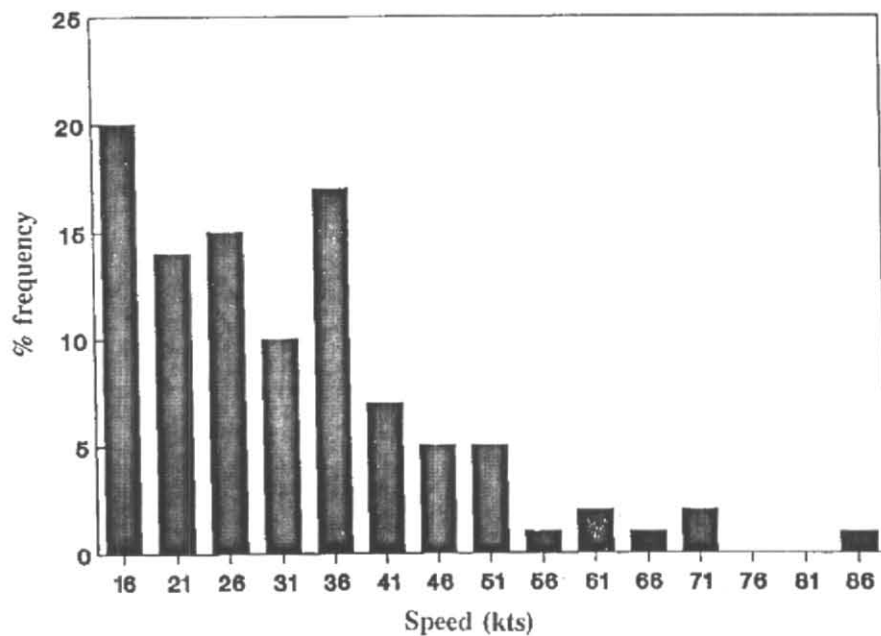


Fig. 2. Frequency distribution of speed of peak gust associated with thunderstorm

location with respect to the station and movement of the thunderstorm cell. In practice, it has been observed that an approaching thunderstorm cell towards the station gives rise to stronger surface wind speed than the cell which is moving away from the station.

The frequency distribution of winds from different directions at an interval of 30° , associated with thunderstorms at Delhi is given in Fig. 1. It is seen from this figure that strong and gusty surface wind at Delhi occurs usually from westerly to northerly direction. The

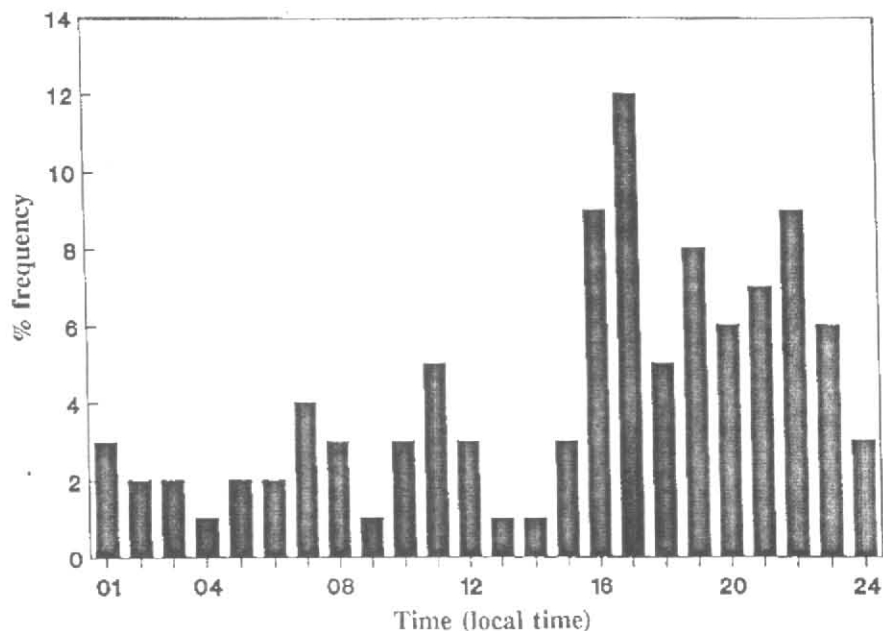


Fig. 3. Hourly distribution of peak gust associated with thunderstorm

frequency distribution of peak gust speeds as given in Fig. 2 indicates that the speeds are usually between 16 to 50 kts (8 to 25 ms^{-1}). Fig. 3 gives the distribution of occurrence of peak gusts at different time intervals of the day. It indicates that the probable time of occurrence of stronger winds is generally during 1600-0100 hrs local time, though some preference for occurrence during the early morning hours around 0700 and 1100 hrs local time is also noticed. This is in agreement with the observed climatology of occurrence of thunderstorm at Delhi (Ram Sanahi & Pant, 1985). It is observed that thunderstorms have a secondary maxima in the early morning hours from 0400-0800 and 1000-1200 hrs local time. Climatological information of squall lines recorded at New Delhi is also given by Pareek and Kalsi (1999).

4. Methodology

The direction and speed of squally/gusty winds associated with the thunderstorm depends upon the location and movement of the thunderstorm with respect to the reporting station, as well as the large scale direction of wind flow at that particular moment. Thus, the peak gust from an approaching thunderstorm could be stronger than that due to the receding thunderstorm. In other words, it would be the resultant of the environmental wind field and the wind field generated by the thunderstorm. Since surface wind is a vector quantity, separate equations have been developed for forecasting squall speed and direction.

(a) Squall/gust wind speed

The difficult task in forecasting of gusty/squally wind speed is that the nature of thunderstorm varies according to the synoptic situation. The parameters that indicate the occurrence of a thunderstorm would also be indicative of the associated strong gust. Since there are a number of meteorological parameters that contribute to the occurrence or non-occurrence of a thunderstorm, it would be advisable to set up a multiple regression equation between peak gust speed and the potential predictor parameters. The significant parameters are selected by stepwise screening regression method. An equation of the type

$$\hat{s} = b_0 + b_1 X_1 + b_2 X_2 + \dots + b_n X_n \quad (3)$$

is assumed where \hat{s} is the value of wind speed obtained by a linear combination of the various predictors x_1, x_2, \dots, x_n and b_1, b_2, \dots, b_n are the regression coefficients, and b_0 is the constant. A total of 181 potential predictors are subjected to screening and six significant predictors out of them are selected. In this study selection of predictors are stopped when none of the remaining predictors would further reduce the variance by 1%.

The developed model equation along with the selected predictors and the variance explained by them is

TABLE 1

Selected predictors and variance explained for forecasting peak gust speed associated with thunderstorm

Speed = 26.4018 + 4.082834*A1 + 2.98324*A2 + 0.02129*A3 - 0.35436*A4 + 0.26117*A5 + 2.10892*A6				
		VE	CVE	CC
A1	Inverse of <i>v</i> component at 500 hPa	21.0	21.0	0.458
A2	Inverse of <i>v</i> component of shear between 300 and 850 hPa	10.5	31.5	0.329
A3	Square of <i>u</i> component at 850 hPa	9.7	41.2	0.353
A4	<i>v</i> component at 500 hPa	4.3	45.5	-0.156
A5	<i>v</i> component at 300 hPa	3.8	49.3	0.087
A6	Inverse of <i>v</i> component of shear between 700 and 850 hPa	2.6	51.9	0.060
MCC = 0.718				

VE - Variance explained (%), CVE - Cumulative VE, CC - Correlation coefficient, MCC - Multiple CC.

given in Table 1. It is seen from Table 1, that all the selected predictors in the equation for forecasting speed of peak gust are upper-air data of Delhi at 0000 UTC, which are derived from the winds at various levels, from 850 to 300 hPa.

An examination of the forecast equation indicates that the predictors A1 (inverse of meridional component of wind at 500 hPa) and A4 (meridional component of wind at 500 hPa) can contribute to a higher gust speed only if the meridional component is positive and small, or negative and large, in magnitude; *i.e.* the wind at 500 hPa either has a small southerly component or a large northerly component. In synoptic terms, such a situation indicates the presence of a trough close to the station at 500 hPa or the trough in the upper air at 500 hPa is about to cross the station. The above stated conditions can also be viewed as a sharp decrease in moisture advection from southern latitudes or increase of dry air advection at 500 hPa level. The drier air at this level is favorable for a stronger gust speed at the surface. It may be noted that the results confirm the study of Colquhoun, 1987, that the drier air at middle tropospheric levels enhances thunderstorm development.

The parameter A2 (inverse of meridional component of shear between 300 and 850 hPa) is required to be positive and large for stronger squall speed. It would amount to that meridional component of shear to be very small or in other words the two meridional wind components at 300 hPa and 850 hPa must compensate each other. In synoptic terms, the center of the circulation at 850 hPa may be to the west of the station and so should

be the trough aloft at 300 hPa. It is a well known fact that troughs in the upper tropospheric westerlies are associated with divergence ahead of the troughline. In other words, presence of a cyclonic circulation close and to the west of the station at 850 hPa level and presence of a trough in the westerlies aloft is one of the favorable synoptic situation for thunderstorm development.

The parameter A3 (square of zonal component of wind at 850 hPa) when viewed in conjunction with A2 indicates that southwesterly wind at 850 hPa is favourable for stronger squall speed. Moreover, stronger the zonal easterly/westerly at 850 hPa, the stronger would be the gust speed at the surface.

It may be noted that the next predictor, A5 (meridional component of wind at 300 hPa) is required to be southerly for stronger gust/squall speed. Thus for stronger gust speeds, the meridional component of wind at 300 hPa may be divergent (southerly), but the southerly component may be marginally higher than that at 850 hPa.

A6 (inverse of meridional component of shear between 700 and 850 hPa) indicates that the wind shear between 700 and 850 hPa may be small but of southerly direction. The southerly wind at 850 & 700 hPa would bring warm moist southerly air over the selected place of study which is also favourable for development of thunderstorm.

Thus, it is seen that the most of the predictors selected to form the equation are wind shear related parameters. The most critical environmental factors

TABLE 2

Selected predictors and variance explained for forecasting direction of peak gust associated with thunderstorm

Zonal component				
$\hat{u} = -6.3070 + 1.67886*B1 + 5.85809*B2 - 0.03999*B3 + 4.9751*B4$				
		VE	CVE	CC
B1	Zonal component of wind at 850 hPa	23.4	23.4	0.484
B2	Meridional component of shear between 850 and 300 hPa	13.7	37.1	0.243
B3	Square of zonal component at 850 hPa	7.5	44.6	0.210
B4	Inverse of meridional component at 500 hPa	6.5	51.1	-0.139
		MCC = 0.715		
Meridional component				
$\hat{v} = 1.7344 - 0.028359*C1 - 0.743461*C2 + 0.046648*C3 + 3.797174*C4$				
		VE	CVE	CC
C1	Square of zonal component at 850 hPa	13.8	13.8	-0.290
C2	Meridional component at 300 hPa	10.2	24.0	-0.211
C3	Square of meridional at 300 hPa	8.4	32.4	0.195
C4	Log of square of meridional component of 500 hPa	6.4	38.8	-0.110
		MCC = 0.623		
Direction = arctan $\frac{\hat{v}}{\hat{u}}$				

affecting development of thunderstorm cells involve the strength and nature of lower and middle tropospheric winds. The numerical modelling suggests that the nature of the wind profile in the storm inflow layer and the strength of the wind shear through middle levels are important factors for development and maintenance of severe convective cells (Johns and Doswell, 1992). It is further stated in their study that, stronger the environmental winds in the downdraft entrainment region, the greater the potential contribution to out flow, that is, the downdraft strengthens. With increase in the vertical shear, deep convections are intensified and likely to take the form of self-perpetuating convective systems, i.e. the outflow systematically initiates new updrafts. These systems turn out to be responsible for most severe downdrafts associated with thundery activity. Vertical wind shear also contributes to the strength of the updraft and downdraft owing to the kinetic energy of the air entering the storm (Colquhoun, 1987). Nakamura *et al.* (1996) in their simulation experiment observed that the vertical wind shear is an important factor in the production of convectively generated gusts at the surface.

Thus, it is noticed that the selected predictors in the forecast equation of gust speed, from consideration of the

dynamics of thunderstorms, are important and significant, and in good agreement with similar studies quoted above.

(b) Squall/gust wind direction

In order to develop forecast model for the direction of the gust, stepwise screening method as in the case of the speed is followed. The gusty winds of the developmental sample data are split into zonal (u) and meridional (v) components. Then regression equations are developed for each component, using the 181 potential predictors used earlier, i.e. u and v separately, which take the form,

$$\hat{u} = c_0 + c_1 X_1 + c_2 X_2 + \dots + c_n X_n \quad (4)$$

$$\hat{v} = d_0 + d_1 X_1 + d_2 X_2 + \dots + d_n X_n \quad (5)$$

Initially seven predictors each were selected and incorporated into the developmental equations. However, these predictors are further reduced to four, because the overall results with seven predictors were not found to be significantly superior to the results provided by the first four predictors. The contribution of the last three

TABLE 3

Mean absolute error (MAE) and root mean square error (RMSE) of direction and speed forecast of gusty/squally winds with the developmental (Dev) and independent (Test) data sets

Error statistic	Direction (degrees)		Speed (knots)			
	Dev	Test	Regression model		Empirical model	
			Dev	Test	Dev	Test
MAE	30	58	8.2	9.6	12.2	15.8
RMSE	46	77	9.8	11.7	30.1	32.5

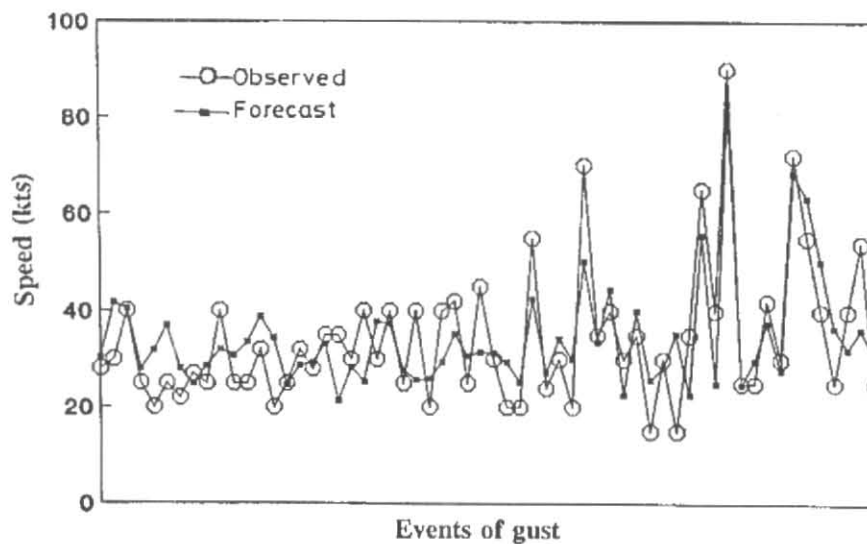


Fig. 4. Observed (O) and forecast (■) of peak gust speed with the developmental data

predictors to the total reduction of variance was also not significant. The developed equations for \hat{u} and \hat{v} are given in Table 2. From the forecast values of \hat{u} and \hat{v} , the direction of squall is calculated by using the relation

$$\theta = \arctan\left(\frac{\hat{v}}{\hat{u}}\right) \quad (6)$$

5. Results and discussion

The multiple regression equations for peak gust speed (Table 1) and direction (Table 2) are used to generate the forecasts of speed and direction with the developmental (1985-90) as well as independent data sets (1994 and 1995) for the months of April, May and June (AMJ). The derived forecasts are then compared with the

realized values. A comparison has also been made between the speed forecasts derived using the regression model (Table 1) and the empirical model, namely equations 1 and 2. A few specific cases with large deviations of forecast from the observed values are also analyzed and presented in this section to find out possible reasons for large error in some of the forecasts. The mean absolute error (MAE) and the root mean square error (RMSE) of the forecast from both the developmental and independent data sets are calculated and presented in Table 3.

(a) Squall/gust wind speed

The developed regression model is used to generate the forecasts of speed with the developmental as well as

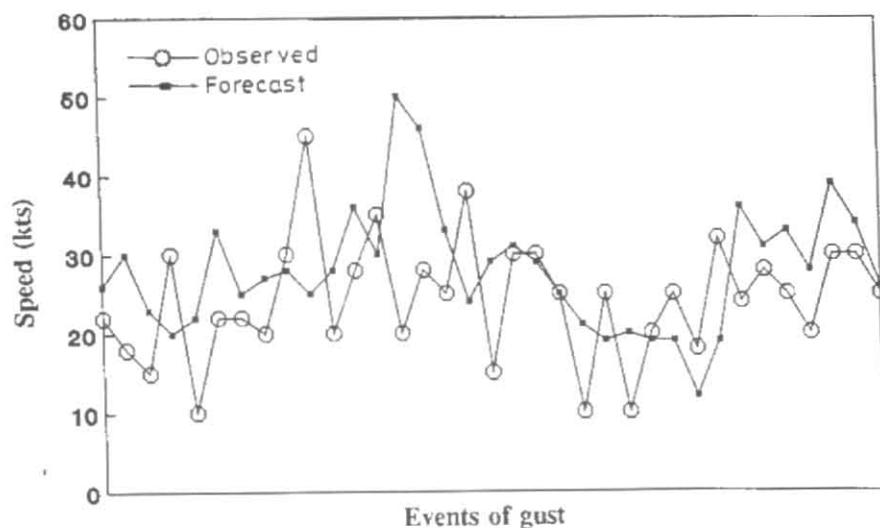


Fig. 5. Same as Fig. 4 but for independent data

independent data sets. The performance is evaluated and presented.

(i) *Performance with developmental data*

The forecasts of gust speed produced by the regression model (Table 1) and the corresponding realized values are presented in Fig. 4. It is seen from the figure that the forecast generated by the model agrees reasonably well with the realized values. Further analysis of the individual cases of the realized and forecast values of speed indicates that, in the developmental data, 43% of the forecasts lie within the error range of ± 5 kts, 70% of the forecasts lie within the range ± 10 kts and 92% within ± 15 kts. Thus, there are large number of occasions when the forecast agreed very well with the realized values. For example, on 3 April 1987 (forecast 40 kts, realized 40 kts), 19 May 1986 (forecast 25 kts, realized 25 kts), 13 June 1986 (forecast 45 kts, realized 40 kts) and 15 June 1987 (forecast 82 kts, realized 90 kts) are some of the days when the forecasts matched reasonably well with the realized values of speed. However, on a very few occasions, large deviations are noticed. In 7 out of a total of 63 occasions, deviations of the forecasts from the realized values are noticed. The deviations varied from 14 to 20 kts. For example, on 18 May 1986, the forecast is 34 kts whereas the realized value of speed is 20 kts; on 4 June 1986, the forecast speed is 50 kts and the realized speed is 70 kts.

In order to find out the reasons for the large deviation in the forecasts, the individual cases are analyzed. The analysis of the predictors on 4 June

1986 indicated that the value of the zonal component of wind at 850 hPa is found to be smaller on this day, which is lower than the previous and subsequent days. This alone has resulted in the forecast speed being lower than the realized value. In addition, the meridional component at 300 hPa was negative and large (northwesterly wind) and thus unfavorable for higher values of gust speed. It is already stated in section 4 that this predictor is required to be positive for higher gust speed. Thus, it is found that in most of the cases, the lower values of the zonal component of wind at 850 hPa and the higher negative values of meridional component at 300 hPa levels led to large deviation of the forecasts.

The MAE and the RMSE of the speed forecast with the developmental data are 8.2 and 9.8 kts respectively (Table 3). The MAE and RMSE of the empirical method with the same data set is 12.2 and 15.8 kts respectively.

(ii) *Performance with independent data*

The forecasts of gust speed with the independent data set produced by the regression model (Table 1) and the realized values are analyzed and presented. It is once again noticed that the speed forecasted by the regression model agrees reasonably well with the realized speeds. The forecast and realized values of wind speed are presented in Fig. 5.

The analysis of the forecast and realized values of the speeds indicated that 31% of the forecasts lay within the error range of ± 5 kts, 74% of the forecasts were within ± 10 kts and 91% within

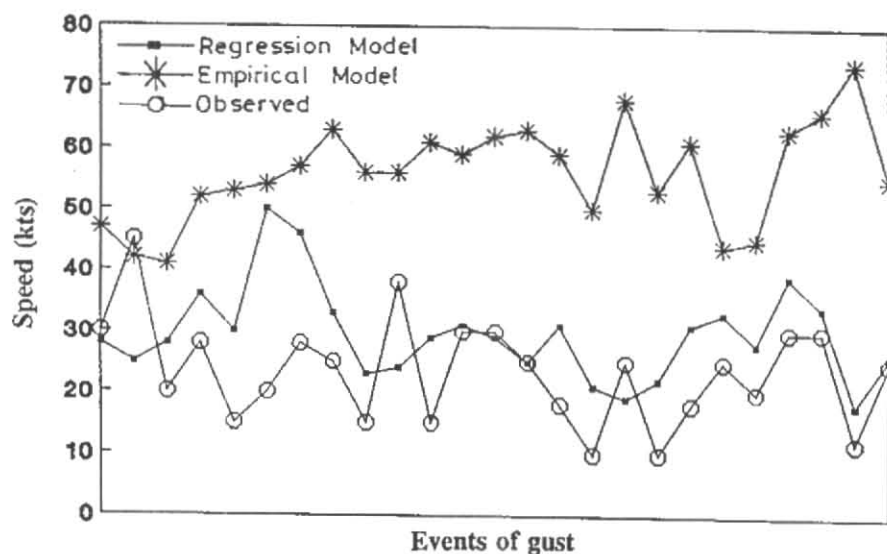


Fig. 6. Observed (O) and forecasts of peak gust speed by regression method (■) and the empirical method (*)

± 15 kts. Thus in majority of the cases, the predicted speed agreed well with the realized values (for example, on 2 April 1994, forecast 26 kts, realized 22 kts; 6 May 1994, forecast 31 kts, realized 35 kts; and 20 June 1995, forecast 33 kts, realized 30 kts). However, there are two occasions where the model produced large deviation of 18 and 31 kts. On 7 May 1994 (forecast 51 kts, realized 20 kts) and 8 May 1994 (forecast 46 kts, realized 28 kts) are the days when the large deviations occurred. On these two occasions, the model over predicted the realized values of speed. The examination of the predictors for these days indicated that the larger contribution by the zonal component of wind at 850 hPa level alone contributed to the over prediction.

The winds at 850 hPa level on 7 and 8 May 1994 are found to be higher than the previous and subsequent days. The wind at 850 hPa at 0000 UTC, between 6 and 9 May 1994 respectively are $305^\circ/10$ kts, $295^\circ/37$ kts, $295^\circ/31$ kts and $205^\circ/15$ kts. Thus the zonal component of wind on 7 May 1994 yielded higher contribution to the forecast and hence large deviation. Such strengthening of winds could be attributed to two factors, namely, thundery activity in the vicinity of the observation site which could modify the environmental winds; or passage of a synoptic system. It is found from the current weather observations that thunderstorm activity took place between 2100 hrs (IST) of 6 May 1994 and 0400 hrs (IST) of 7 May 1994. Thus, the strengthening of

winds at 850 hPa level could be attributed to the thundery activity.

The forecasts of wind speed for the months of May and June 1994-95 from the regression model is also compared with the forecasts that are generated using the empirical method (Eqns. 1 and 2) for the same period. The results are presented in Fig. 6. It is seen that the regression model could predict the observed speed more realistically as compared to the forecasts derived by the empirical method. In most of the cases, the empirical method over estimated the gust speed values.

The mean absolute error and the root mean square error of the speed forecasts generated using the regression and empirical model are presented in Table 3. The MAE and RMSE of the regression method with the independent data sets are 9.6 and 11.7 kts respectively. The MAE and RMSE of the empirical method with the same independent data sets are found to be 15.8 and 32.5 kts respectively. The possible reason for the large forecast error in the empirical model could be due to the fact that this model was developed using only the cases of gust/squall speed of 40 kts or more.

(b) Squall/gust wind direction

The developed regression models are also used to generate the forecast of direction of realized gusts with the

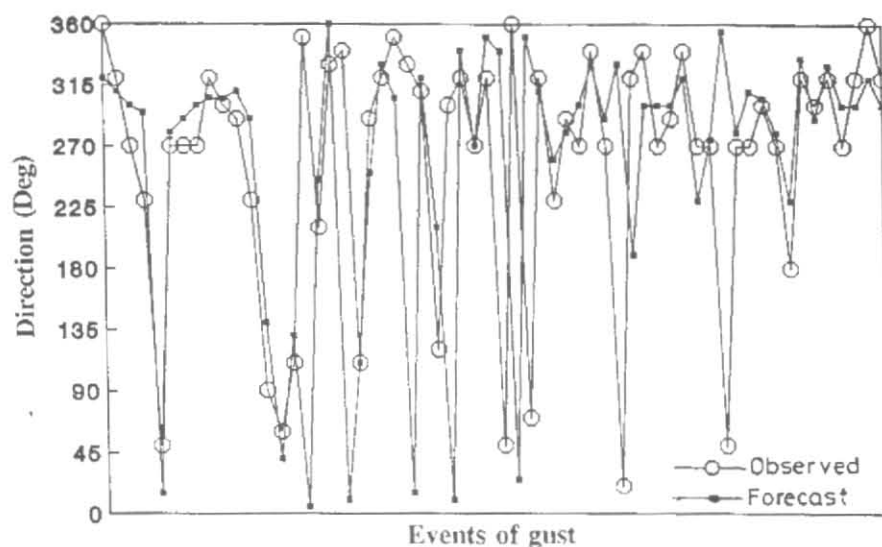


Fig. 7. Observed (O) and forecast (■) of direction with the developmental data

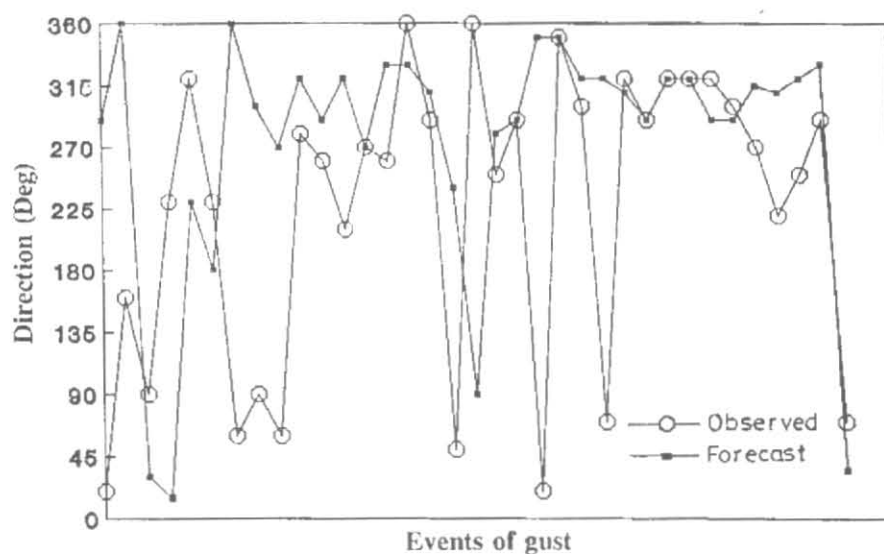


Fig. 8. Same as Fig. 7 but for independent data

developmental as well as independent data sets and the results as follows.

(i) *Performance with development data*

The forecast of \hat{u} and \hat{v} components are generated using equations of Table 2 with the developmental data set (AMJ, 1985-90) and the

forecasts are then compared with the realized values. The forecast and the realized values of direction of the gust are presented in Fig. 7. It is observed that on large number of occasions, the forecasts match well with the realized values (31 May 1985 – forecast 300°, realized 310°, 1 May 1987 - forecast and realized 110°; 3 June 1987 forecast and realized 270°). There are a few occasions when large

deviations of the order of 70-130° are observed (3 May 1990 – forecast 340°, realized 50°; 25 June 1986 - forecast 190°, realized 320°, 17 May 1988 - forecast 210°, realized 120°). The MAE and RMSE of the direction forecast with the developmental data set are 30° and 46° (given in Table 3) respectively. It is further noticed that 68% of the forecasts are within the error range of $\pm 30^\circ$, 89% of the forecasts are within $\pm 60^\circ$ and 98% of the forecasts are within $\pm 90^\circ$. Since the wind direction measurement is circular in nature, the direction error is calculated in such a way that when a forecast is 340° and the realized value is 30°, the error is calculated to be 50° and not 310°.

(ii) *Performance with independent data*

The developed equations for \hat{u} and \hat{v} components (Table 2) are utilized to generate the forecasts of gust direction on the independent data sets (1994-95). The forecast and realized values of direction are illustrated in Fig. 8. From this figure it is seen that the model could predict the realized values of direction reasonably well (on 6 May 1994, forecast and realized 270°). However, a few cases of large deviations of the order of 140-170° are also observed (on 12 April 1994, forecast 360°, realized 160°). Further analysis of the direction forecasts indicated that 43% of the forecast lay within $\pm 30^\circ$, 63% of the forecasts were within $\pm 60^\circ$ and 80% within $\pm 90^\circ$ respectively. The MAE and RMSE of the direction forecast of the independent data are 58° and 77° respectively.

The possible reasons for the large errors in direction forecast in the developmental and the independent data using the \hat{u} and \hat{v} method could be attributed possibly to two reasons. The first reason could be due to the fact that the equations for \hat{u} and \hat{v} have their own standard errors, which could contribute to the final error in the forecast. The other reason may be due to the large variations in the direction itself which lead to large errors in estimation. It is, therefore, felt that the forecast of direction may serve as guidance to a forecaster to indicate the general direction from which the storm could approach the station and hence the direction of gusty surface wind.

6. Conclusions

The analysis of the results and evaluation of performance of the dynamical-statistical models with the

development and independent data sets lead to the following broad conclusions.

- (i) The period of occurrence of gusty/squally winds are in agreement with the period of occurrence of thunderstorm at Delhi, predominantly between 1600-2300 hrs local time.
- (ii) Majority of strong gusts associated with thundery activity approach from southwest to northerly direction with speed range between 25-45 kts.
- (iii) The performance of the dynamical-statistical models for forecasting direction and speed of gusty/squally winds in association with thunderstorm yielded satisfactory results with the developmental as well as independent data sets.
- (iv) The developed regression model gives more realistic forecasts of peak gust speed than the empirical method.

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