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Climatology and trends in near-surface wind speed over India during 1961-2008

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सार – इस शोध पत्र में वर्ष 1961 से 2008 के दौरान भारत में सतह के निकट पवन गति में हुए परिवर्तनों का विश्लेषण किया गया है। 171 स्टेशनों के मासिक पवन गति आंकड़ों के विश्लेषण से प्राप्त परिणाम बताते हैं कि भारत के अधिकतर स्टेशनों पर पवन गति में मासिक और वार्षिक दोनों ही स्थितियों में महत्वपूर्ण रूप से कमी देखी गई है। समूचे भारत में वार्षिक पवन गति माध्य का औसत वर्ष 1961 के 9.7 कि.मी. प्रति घंटा से घटकर वर्ष 2008 में 5.0 कि.मी. प्रति घंटा हो गया है जो 49 प्रतिशत की कमी को दर्शाता है। समूचे भारत में पवन गति के वार्षिक औसत में गिरावट की औसत दर –0.88 कि.मी. प्रति घंटा प्रति दशक पाई गई है। मासिक पैमाने पर सबसे अधिक गिरावट की दर जून में (–1.33 कि.मी. प्रति घंटा प्रति दशक) और सबसे कम अक्तूबर में (–0.60 कि.मी. प्रतिघंटा प्रति दशक) पाई गई है। स्थानिक तौर पर सबसे अधिक गिरावट पश्चिमी भारत, दक्षिणी प्रायद्वीप तथा समुद्र तटीय क्षेत्रों में पाई गई है जबकि मध्य दक्षिण पूर्व एवं पूर्वोत्तर भारत में पवन गति में कम परिवर्तन देखा गया है। पवन गति में महत्वपूर्ण रूप से गिरावट मुख्यतः गुजरात, महाराष्ट्र, तमिलनाडु, उत्तरी कर्नाटक, तटीय उड़ीसा एवं तटीय पश्चिम बंगाल के क्षेत्रों में पाई गई है जिनमें पवन गति का वार्षिक औसत भी अधिक पाया गया है। 15 कि.मी. प्रति घंटा से अधिक वार्षिक औसत वाली पवन गतियां केवल गुजरात और तमिलनाडु में प्रेक्षित की गई हैं। राजस्थान, पश्चिम मध्य प्रदेश, महाराष्ट्र, उत्तरी कर्नाटक तथा समीपवर्ती आंध्र प्रदेश के कुछ भागों और पश्चिमी एवं पूर्वी तटीय किनारों के कुछ भागों में पवन गति 10 से 15 कि.मी. प्रति घंटा रही। उत्तर भारत में वार्षिक औसत पवन गति 10 कि.मी. प्रति घंटा से अधिक वाले स्टेशन नगण्य हैं।

इस शोध पत्र में भारत के विभिन्न क्षेत्रों में पवनों के जलवायु विज्ञान एवं इसके दीर्घ अवधि प्रवृत्तियों का मूल्यांकन किया गया है जहां पवन शक्ति का लाभप्रद तरीके से उपयोग किया जा सकता है। इसके लिए प्रमुख क्षेत्र गुजरात एवं समीपवर्ती मध्य प्रदेश, दक्षिणी राजस्थान, उत्तरी महाराष्ट्र, उत्तरी कर्नाटक, दक्षिणी तमिलनाडु, तटीय आंध्र प्रदेश तथा पश्चिमी तट पर गुजरात से गोवा तक और पूर्वी तट पर कोलकाता से नागपट्नम तक के तटीय क्षेत्र हैं।

ABSTRACT. This study analyses near-surface wind speed changes in India during 1961 to 2008. Consisting of monthly wind speed data of 171 stations, the results show that most of the stations in India have experienced significant weakening of wind speed, both at monthly and annual timescales. All-India averaged annual mean wind speed has decreased from 9.7 kmph in 1961 to 5.0 kmph in 2008 resulting in a 49% decrease. All India averaged rate of decrease in annual mean wind speed is -0.88 kmph/decade. On monthly scale, the largest rate of decline is in June (-1.33 kmph/decade) and the smallest is in October (-0.60 kmph/decade). Spatially, large declines are found in western India, south peninsula and the coastal areas while central, southeast and northeast India have the lesser change in wind speed. Significant weakening of wind speed has occurred primarily in regions along Gujarat, Maharashtra, Tamil Nadu, north Karnataka, coastal Orissa and coastal West Bengal which also have higher annual mean wind speed. Annual mean wind speeds exceeding 15 kmph are observed only over Gujarat and south Tamil Nadu. Some parts of Rajasthan, west Madhya Pradesh, Maharashtra, north Karnataka and adjoining Andhra Pradesh and some pockets along west and east coasts experience wind speeds of 10-15 kmph. Stations having annual mean wind speed exceeding 10 kmph are rare in north India.

The study evaluates climatology of winds and its long-term trends over various regions of India where wind power can be profitably utilised. The prominent regions are in Gujarat and adjoining Madhya Pradesh, south Rajasthan, north Maharashtra, north Karnataka, south Tamil Nadu, coastal Andhra Pradesh and along the west coast from Gujarat to Goa and along the east coast from Kolkata to Nagapatinam.

Key words – Wind speed, Trend, Correlation, Sea surface temperature, Urban, Cyclonic disturbances.

1. Introduction

It is now well accepted by scientists all over the world that the earth has become warmer over the last century. The Inter-governmental Panel on Climate Change (IPCC) has estimated increase in surface temperature during the last hundred years by about 0.6 °C ± 0.2 °C (IPCC, 2001). Heat and moisture are so important in environmental systems that most investigations of climatic variability have focused on temperature and precipitation. But other elements of the climate, including wind, also vary over time (Klink, 2002). However, understanding changes in near-surface wind regimes is of great relevance to studies of climate change as well as to various activities including agriculture, construction, environment and wind energy. However, the wind at a place is governed by the climatology of the place concerned and has large variability in location and season.

Several recent studies have shown decreasing surface wind speed over the United States, Canada, Australia, China and parts of Europe. The near-surface wind speed at coastal stations in Italy has decreased considerably from 1951 to mid-1970s and the decrease has slowed down or leveled-off since 1980 (Pirazzoli and Tomasin, 2003). Annual and winter mean winds at stations along the west coasts of Canada have weakened during the late 1940s to mid-1990s (Tuller, 2004). Annual mean wind speed over China has decreased by 28% during 1969 to 2000 (Xu *et al*., 2006). Reduction in wind speed has been reported over 88% of the weather stations in Australia during 1975–2006 (McVicar *et al*., 2008). Stilling winds have been observed in the contiguous United States during 1973-2005 (Pryor *et al*., 2009). Annual wind speed has declined at 73% of the 822 worldwide stations, dropping by 5-15% over almost all of the land areas examined with the most pronounced effect across Eurasia (Vautard *et al*., 2010). Wan *et al*. (2010) have found significant decreases in wind speed throughout western Canada and most parts of southern Canada in all seasons, with significant increases in the central Canadian Arctic. Guo *et al*. (2010) has attributed weakening of the lower-tropospheric pressure-gradient force as the primary source of change in wind speed over China. In a comprehensive synthesis and review of 148 published studies of wind speed trends all over the world, McVicar *et al*. (2012) have concluded that near-surface wind speed has declined across the globe.

Wind speed is one important climate variable ignored by most climatic change and variability studies. However, changes in wind speed give an indication of the circulation change due to either natural or anthropogenic processes (Guo *et al*., 2010). In this paper, we examine near-surface wind speed recorded at 171 stations under the network of India Meteorological Department (IMD) for the period 1961-2008. The location of wind measuring instruments at these stations is constant but at varying height during the period of study. The main objectives of this study are to describe the monthly and annual variability of observed wind speed and to identify its long-term trends over various observatory stations across India.

2. Data and methodology

2.1. *Wind measurement*

In meteorology, wind direction is considered as the direction from which wind blows and is expressed in degrees measured clockwise from the geographical North or in terms of the points of the compass. The wind direction is measured by an instrument called windvane which is among the oldest meteorological instruments. Wind speed is the rate of movement of air in its instantaneous direction and is measured as kilometers per hour or meter per second or knots. According to meteorological convention, wind is usually defined as the horizontal component of air in motion. Even though there are other methods of measuring wind speed, the rotating cup anemometer is the most commonly used instrument for measuring wind speed in IMD. Wind speed is measured using 3-cup counter anemometers at synoptic hours by noting the counter readings at the beginning and end of a 3-minute period and multiplying the difference by 20 to obtain the wind speed at the hour in kmph. The wind run during the period from 0830 hrs (IST) on the previous day to 0830 hrs (IST) on the current day divided by 24 gives the mean wind speed in kmph for the day. The metadata of surface observatory stations under the network of IMD shows that although the heights of wind measuring instruments are constant for each location, they are different from station to station. Since wind speed generally increase with height above the ground, it is not possible to directly compare the wind speed statistics at stations with different anemometer heights. However, it is possible to analyze the changes in wind statistics over time at a particular site and to make qualitative comparisons between sites (Klink, 2002).

2.2. *Methodology used*

The wind speed data used in this study are taken from the monthly surface meteorological dataset available at National Data Centre (NDC) of IMD located at Pune where all climatological data are archived. Monthly mean wind speed data for 24 hours wind run are selected for 171 stations having at least 30 years data for the period 1961-2008 after omitting stations having large data gaps. Out of 171 stations selected for this study, 147 stations have wind measuring instruments at a height of ~10 meter. The locations of these 171 stations and seven homogeneous

TABLE 1

All India averaged monthly and annual mean (kmph), standard deviation (kmph) and trends (kmph/decade) in average wind speed based upon 171 stations for the period 1961-2008. Trends significant at 99% level of confidence are indicated by '*'

Month	Mean (kmph)	Standard Deviation (kmph)	Coefficient of Variation (%)	Trend (kmph/decade)
January	5.61	0.90	16.0	-0.62*
February	6.21	1.00	16.1	-0.69*
March	6.96	1.15	16.5	-0.80*
April	8.00	1.29	16.1	-0.89*
May	9.54	1.58	16.6	-1.05*
June	10.63	1.96	18.4	-1.33*
July	10.25	1.93	18.8	-1.27*
August	9.20	1.70	18.5	-1.13*
September	7.14	1.36	19.0	-0.90*
October	5.18	0.89	17.2	-0.60*
November	4.99	0.90	18.0	-0.63*
December	5.25	0.93	17.7	-0.64*
Annual	7.42	1.25	16.8	-0.88*

regions, *viz*., Western Himalaya (WH), North West (NW), North Central (NC), North East (NE), West Coast (WC), Interior Peninsula (IP) and East Coast (EC) of India are shown in Fig. 1. Based on monthly time series of these stations, average India monthly and annual means are calculated. The linear trend analysis is performed on monthly and annual mean wind speed and trends are tested for significance at 99% level of significance using *t*-test. Average India mean, standard deviation, coefficient of variation and trend values of wind speed are given in Table 1. Similarly, monthly and annual decadal means and trends in wind speed for 1961-1970, 1971-1980, 1981-1990, 1991-2000 and 2001-2008 decades are given in Table 2. The relationship between the annual means and trends of wind speed for 171 stations is shown in Fig. 2. Numbers of stations having decreasing or increasing trends in monthly and annual mean wind speed out of total 171 stations is given in Table 3. Temporal variations of average India annual means of wind speed for 1961-2008 are shown in Fig. 3. There are four main seasons in India *viz*., winter (the cold weather season), summer (the hot weather season), monsoon (the advancing monsoon) and post monsoon (the retreating monsoon). Spatial patterns of monthly means, standard deviations and trends of wind speed for winter months (December, January and February), summer months (March to May), monsoon months (June to September) and post monsoon months (October and November) are shown in Figs. 4 to 7. Similarly, annual means and trends are shown in Fig. 8. Temporal variations of annual total number of cyclonic

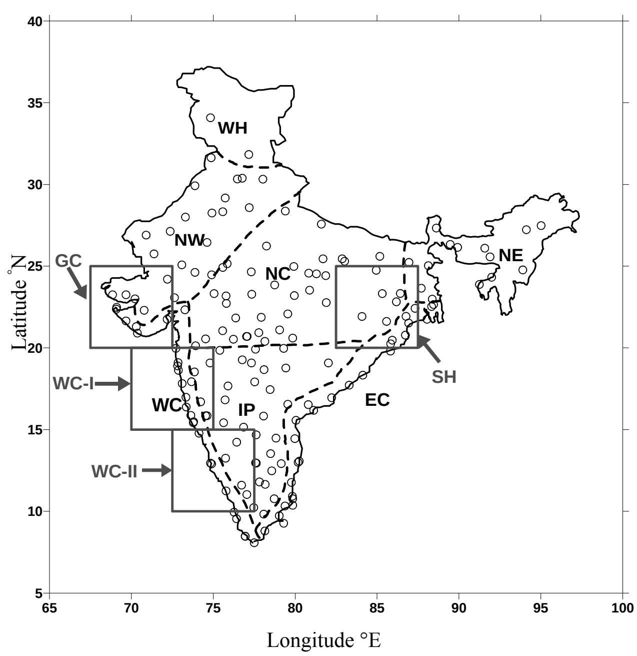


Fig. 1. Spatial distribution of 171 stations belonging to seven homogeneous regions Western Himalaya (WH), North West (NW), North Central (NC), North East (NE), West Coast (WC), Interior Peninsula (IP), East Coast of India selected for study. Four 5° × 5° boxes along Gujarat coast (GC) [20-25° N, 67.5-72.5° E], West Coast–I (WC-I) [15-20° N, 70-75° E], West Coast-II (WC-II) [10-15° N, 72.5-77.5° E] and Sub-Himalayan (SH) [20.0-25.0° N, 82.5-87.5° E] regions where monsoonal flow is studied are also shown

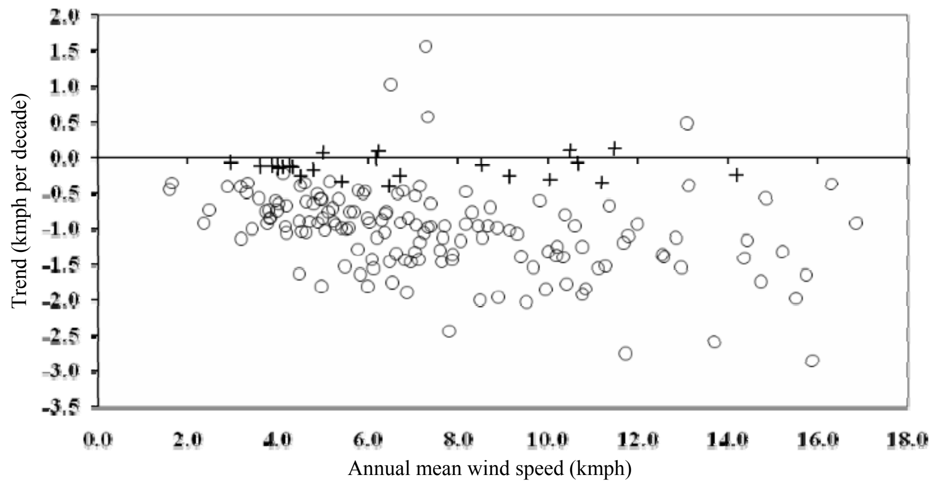


Fig. 2. Trends in annual mean wind speed change at the 171 surface stations relative to their mean wind speeds. Trends statistically not significant are shown by a cross (+) while trends significant at 99% level are shown by circles (○)

TABLE 2

All India averaged decadal mean (kmph) and trends (kmph per decade) in average wind speed based upon 171 stations for the period 1961-2008. Trends significant at 99% level of confidence are indicated by '*'

Month	1961-1970		1971-1980		1981-1990		1991-2000		2001-2008	
	Mean	Trend	Mean	Trend	Mean	Trend	Mean	Trend	Mean	Trend
January	6.90	-0.44	6.10	-0.85	5.49	-1.06*	4.82	-0.44	4.54	-0.77*
February	7.53	-0.56	6.91	-1.46*	6.03	-0.81	5.36	-0.47	5.00	-0.62
March	8.61	-0.58	7.57	-0.67	6.83	-1.10*	5.99	-0.64	5.50	-0.88
April	9.60	-0.72	8.93	-1.91*	7.94	-1.22*	6.88	-0.18	6.29	-0.70
May	11.60	-0.40	10.73	-1.78	9.05	-0.68	8.22	-0.42	7.76	-1.39
June	13.19	-2.10	11.90	-3.59*	10.22	-1.95*	9.12	-0.76*	8.26	-1.85
July	13.00	-0.72	11.21	-2.89*	9.72	-0.55	8.86	-1.04*	8.04	-1.58
August	11.42	-0.48	10.25	-1.74	8.93	-1.79*	7.83	-0.94	7.15	-1.60
September	9.11	-1.23	7.79	-1.35	6.74	-0.57	6.16	-0.64	5.56	-0.75
October	6.28	-0.97	5.79	-1.28*	5.07	-0.39	4.52	-0.47	4.01	-1.13
November	6.18	-0.59	5.56	-0.41	4.92	-0.80*	4.33	-0.79*	3.73	-0.93
December	6.47	-0.73	5.78	-1.16*	5.25	-0.77*	4.50	-0.63*	4.03	-0.86
Annual	9.15	-0.78*	8.22	-1.56*	7.17	-0.95*	6.39	-0.66*	5.84	-1.11

disturbances (including cyclonic storms and severe cyclonic storms) over the Arabian Sea and the Bay of Bengal for the period 1961-2008 are shown in Fig. 9. The coefficients of correlation between annual numbers of cyclonic disturbances over the Arabian Sea, the Bay of Bengal and annual mean wind speed averaged over seven homogeneous regions WH, NW, NC, NE, WC, IP, EC respectively during 1961-2008 are given in Table 4. Annual and seasonal trends in mean wind speed averaged over WH, NW, NC, NE, WC, IP, EC during 1961-2008 are given in Table 5. The trends in annual numbers of cyclonic disturbances over the Bay of Bengal and annual mean wind speed averaged over WH, NW, NC, NE, WC, IP, EC during 1961-2008 are shown in Fig. 10. Using data recorded by Voluntary Observing Ships (VOS) taken from the archives of NDC, temporal variations in annual means

TABLE 3

Numbers of stations having decreasing/increasing trends in monthly and annual mean wind speed (WSP) based on data for period 1961-2008

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann
Decreasing	159	159	160	159	164	165	164	164	164	162	159	158	163
Decreasing significantly	129	133	137	137	136	140	143	141	142	125	125	120	144
Increasing	12	12	11	12	7	6	7	7	7	9	12	13	8
Increasing significantly	3	4	4	3	3	3	2	3	3	2	3	3	4

of sea surface temperature of the Arabian Sea (7° - 24° N, 63° - 75° E) and the Bay of Bengal (7° - 21° N, 78° - 92° E) for the period 1961-2008 are shown in Fig. 11. Further, the 171 stations have been classified into urban (population ≥7.5 lakh) and semi-urban (population <7.5 lakh) stations depending on population as per census 2011 (www.censusindia.gov.in). As per this classification, out of 171 stations, 39 are urban and 132 semi-urban. Temporal variations in annual mean wind speed averaged over the urban and semi-urban stations are shown in Fig. 12. Further, the effect of steady decline in surface wind speed over India on the southwest monsoon flow is examined by preparing time series of wind speed and 850 hPa NCEP/NCAR reanalysis zonal wind speed averaged over four 5° × 5° boxes along Gujarat Coast (GC: 20-25° N, 67.5-72.5° E), West Coast-I (WC-I: 15-20° N, 70-75° E), West Coast-II (WC-II: 10-15° N, 72.5- 77.5° E) and Sub-Himalayan (SH:20-25° N, 82.5-87.5° E) regions for the SW monsoon season June to August (JJA). The trends in wind speed and 850 hPa zonal wind speed over GC, WC-I, WC-II and SH for JJA are shown in Fig. 13. Based upon daily mean wind speed data, numbers of windy days (defined as days with mean wind speed more than 15 kmph) for JJA at stations belonging to 5° × 5° boxes namely GC, WC-I, WC-II and SH are prepared for 1969-2008 (daily data are available in NDC archives from 1969 onwards only). The trends in average 850 hPa level wind speeds and mean numbers of windy days for monsoon season JJA for 1969-2008 are shown in Figs. 14(a-d).

3. Results and discussion

3.1. *All India averaged means and trends of wind speed*

3.1.1. *Monthly and annual means and trends*

All India averaged monthly mean wind speed based upon 171 stations for 1961-2008 is highest in June (10.6 kmph) and lowest in November (5.0 kmph) as given in Table 1. The coefficient of variation is the lowest (16%) for January and the highest (19%) for September

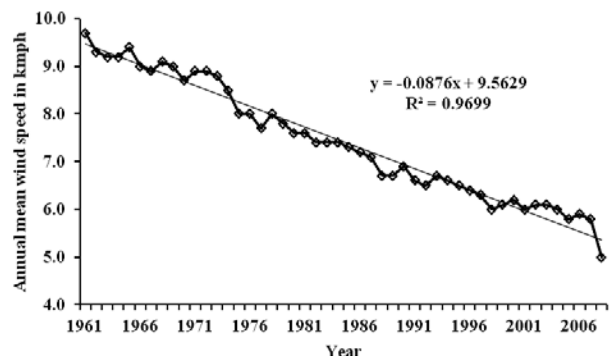


Fig. 3. All India averaged temporal variation and trend (solid line) of annual mean wind speed for the period 1961-2008

indicating smaller inter annual variations in monthly mean wind speeds. The annual march of wind speed over the country is from lower wind speeds in January to higher wind speeds during monsoon months and thereafter once again decreasing till November-December. The annual mean wind speed for the country as a whole is 7.4 kmph with 16.8% coefficient of variation. All India averaged trends in monthly wind speed are decreasing significantly at 99% level of confidence for all months. The highest decrease in monthly wind speed has occurred in June (-1.33 kmph/decade) followed by July (-1.27 kmph/decade). A significantly higher decrease of monsoon winds observed for main monsoon months is a cause of concern for the monsoon season precipitation over the country. The annual decrease in wind speed is at -0.88 kmph/decade which is significant at 99% level of confidence. The rate of decrease in annual mean wind speed is 9.2% per decade. It is clear from Fig. 2 that the decrease in annual mean wind speed at higher rates (> -1.5 kmph/decade) has occurred at stations having higher annual means (> 8.0 kmph) which is similar to results found over Eurasia by Vautard *et al.* (2010). Stations having lower annual mean wind speeds (<5 kmph) have smaller rate of decrease (< -1.0 kmph/decade) in wind speed (Fig. 2).

TABLE 4

Coefficient of correlation between annual total number of cyclonic disturbances (including cyclonic storms and severe cyclonic storms) over Arabian Sea, Bay of Bengal and annual mean wind speed for seven homogeneous regions Western Himalaya (WH), North West (NW), North Centre (NC), North East (NE), West Coast (WC), Interior Peninsula (IP) and East Coast (EC) of India during the period 1961-2008. Correlation coefficient significant at 99% level are indicated by '*'

	Annual mean wind speed						
	WH	NW	NC	NE	WC	IP	EC
Number of cyclonic disturbances in the Arabian Sea	-0.07	0.10	0.04	0.18	0.12	0.08	0.06
Number of cyclonic disturbances in the Bay of Bengal	0.66*	0.75*	0.74*	0.72*	0.67*	0.73*	0.68*

3.1.2. *Decadal means and trends*

All India averaged monthly and annual means and trends of wind speed for decades 1961-1970, 1971-1980, 1981-1990, 1991-2000 and 2001-2008 are given in Table 2. The decadal monthly and annual means of wind speed clearly indicates steady decrease in wind speed. During this period, monthly mean wind speed has largest decrease in July (-5.0 kmph) followed by June (-4.9 kmph). The decadal trends in monthly mean wind speed are decreasing for all decades but significant for February, April, June, July, October and December during 1971-1980 decade; January, March, April, June, August, November and December during 1981-1990 decade; June, July, November and December during 1991-2000 and for January during 2001-2008 decade. Averaged annual mean wind speed is significantly decreasing for all the decades except 2001-2008.

3.1.3. *Temporal variations*

The temporal variation in all India averaged annual mean wind speed during the period 1961-2008 is shown in Fig. 3. Averaged annual mean wind speed has declined from 9.7 kmph in 1961 to 5.0 kmph in 2008 resulting in a 49% decline in wind speed during the period. Annual mean wind speed over the country has declined at a rate - 0.088 kmph/annum which is significant at 99% level. A closer examination of annual mean wind speed series indicates higher rate of decline in wind speed (-0.095 kmph/annum) during 1961-1998 as compared to the period 1998 to 2007 when the rate of decline fell to -0.031 kmph/annum. The significant decline of surface winds over India is a potential concern for wind power generation, agriculture, air pollution, environment and human comfort. The reduction in wind speed has affected ventilation of pollutants from urban areas in India leading to significant decline in numbers of good visibility days (visibility > 10 km) over the country (Jaswal, 2009).

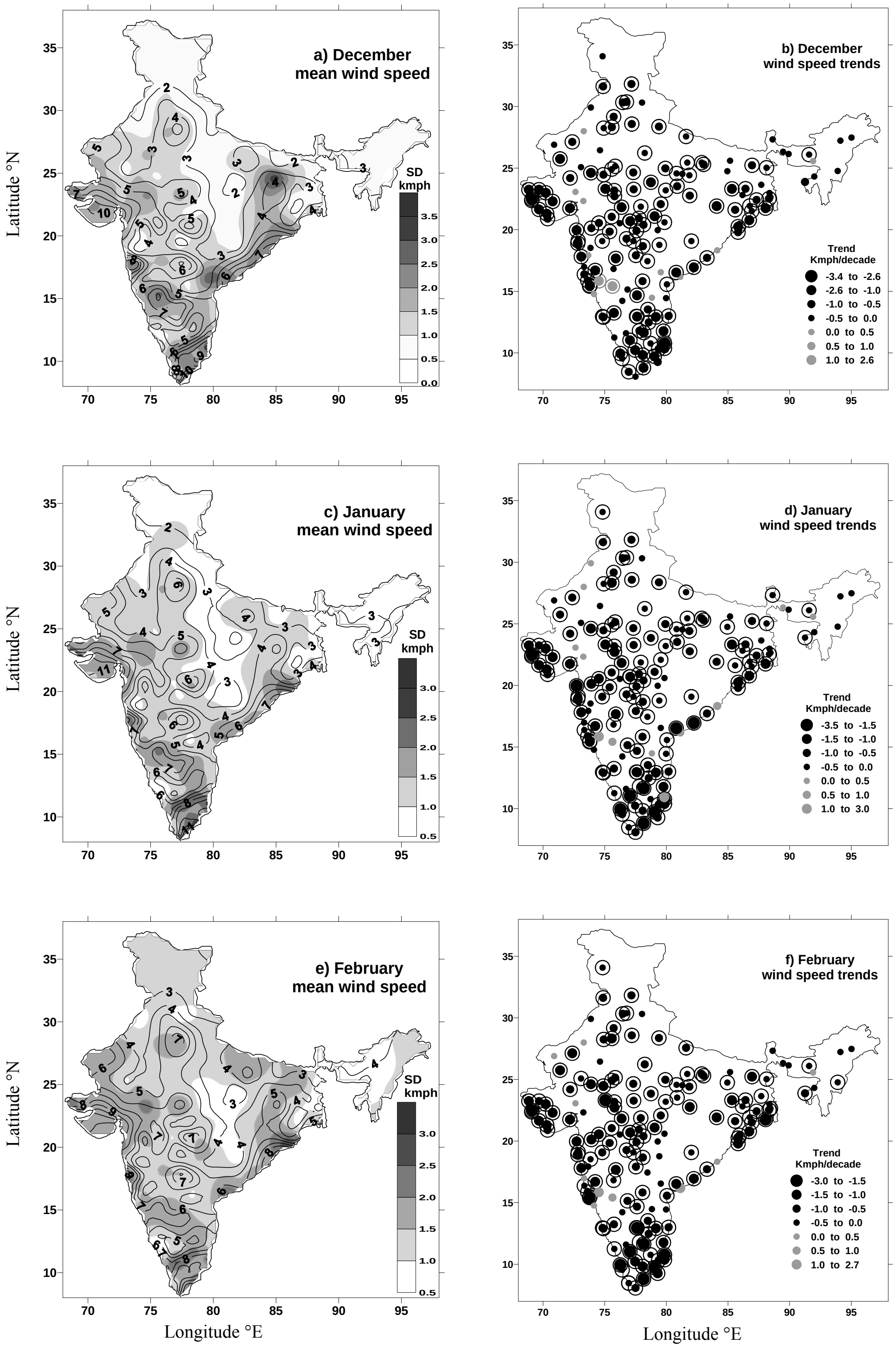
3.2. *Spatial patterns of monthly means and trends of wind speed*

3.2.1. *Winter months*

The winter season in India is from December to February. During this season, the northeast trade winds prevail over the country blowing from land to sea and hence, for most part of the country except Tamil Nadu coast, it is a dry season. The weather is normally marked by clear sky, low temperatures, low humidity and light winds. A characteristic feature of this season is passage of upper-air cyclonic systems over the northern plains called 'western disturbances' causing much needed rain over the plains and snowfall in the Himalayas.

3.2.1.1. December

Spatial patterns of monthly mean wind speed for December [Fig. 4(a)] indicates regions of higher wind speed over Gujarat, Western Ghats, Tamil Nadu and coastal Andhra Pradesh and Orissa. Stations having higher monthly mean wind speed for December (>10 kmph) are Kanyakumari, Pamban, Tuticorin, Okha, Mahabaleshwar, Nagapatinam, Karaikal, Kodaikanal, Bhaunagar, Veraval, Keshod and Tiruchchirappalli. The range of monthly mean wind speeds is from 0.8 kmph to 18.5 kmph. 120 stations are showing significantly decreasing trends in monthly mean wind speed for December as given in Table 3. The spatial patterns of wind speed trends shows general decrease over all parts of the country [Fig. 4(b)] but more coherent over northwest India, Gujarat, north Maharashtra, Western Ghats, Tamil Nadu and coastal Orissa and West Bengal. The monthly mean wind speed trends for December are in the range -3.32 kmph/decade and +2.52 kmph/decade.



Figs. 4(a-f). Spatial variations of monthly means and trends of wind speed for winter months December, January and February based upon period 1961-2008. Spatial variations of standard deviation are shown in the background alongwith mean wind speed in Figs. (a), (c) and (e). Trends significant at 99% are shown by filled circle in Figs. (b), (d) and (f) where black colour indicates decreasing and gray colour indicates increasing trends

TABLE 5

Seasonal wind speed trends (kmph per decade) over Western Himalaya (WH), North West (NW), North Central (NC), North East (NE), West Coast (WC), Interior Peninsula (IP) and East Coast (EC) of India during the period 1961-2008. Trends significant at 99% level of confidence are indicated by '*'

	Seasonal wind speed trends in kmph per decade						
	WH	NW	NC	NE	WC	IP	EC
Winter	-0.44*	-0.74*	-0.63*	-0.36*	-0.66*	-0.68*	-0.87*
Summer	-0.75*	-0.94*	-0.89*	-0.69*	-0.83*	-0.94*	-1.22*
Monsoon	-0.65*	-1.33*	-1.23*	-0.62*	-1.13*	-1.40*	-1.09*
Post monsoon	-0.47*	-0.68*	-0.55*	-0.34*	-0.62*	-0.66*	-0.75*

3.2.1.2. *January*

The spatial patterns of monthly mean wind speeds for January [Fig. 4(c)] clearly shows that winds are weak over most parts of the country except over coastal Gujarat and Tamil Nadu where many stations are having wind speed >10 kmph. The range of mean wind speed is from 0.9 kmph (Baripada) to 18.9 kmph (Kanyakumari). Out of 171 stations, 129 stations are showing significantly decreasing trends (Table 3) and spatial patterns of trends for January show general decrease over all parts of the country [Fig. 4(d)]. The significantly decreasing trends are more coherent over Gujarat, Western Ghats, Tamil Nadu and coastal West Bengal. The trends are between - 3.19 kmph/decade and + 2.94 kmph/decade.

3.2.1.3. *February*

Mean wind speeds are lower over the country except over Gujarat, coastal Orissa and Tamil Nadu as shown in Fig. 4(e). The range of mean wind speed for February is from 1.4 kmph (Baripada) to 15.6 kmph (Tuticorin). Stations having higher mean wind speed (>10 kmph) are Tuticorin, Kanyakumari, Okha and Bhaunagar. As given in Table 3, 133 stations are showing significantly decreasing trends in mean wind speed for February. Spatial patterns of wind speed trends for February shows general decrease over all parts of the country as shown in Fig. 4(f). The significantly decreasing trends are more coherent over south Gujarat, Tamil Nadu, coastal West Bengal and central India. The trends are between -2.77 kmph/decade (Nagapatinam) and +2.68 kmph/decade (Karaikal).

3.2.2. *Summer months*

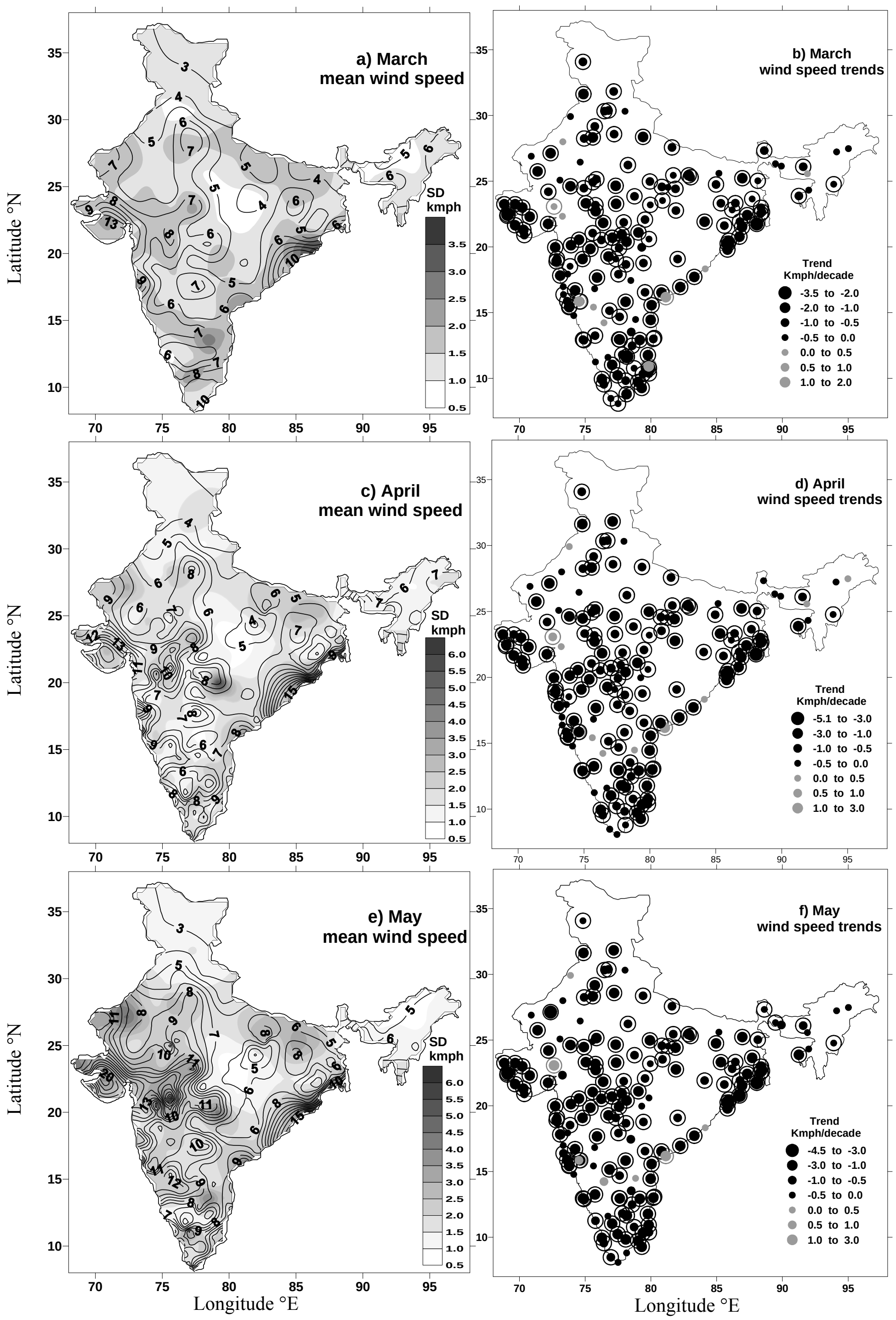
The summer season in India is from March to May during which heat belt shifts northward due to apparent northward movement of the sun. The summer months experience rising temperature and falling air pressure in the northern part of the country. Circulation of air begins to set in around this low pressure area resulting in strong, gusty, hot, dry winds blowing during the day over the north and northwestern India. Dust storms are very common during this season in northern India especially over Rajasthan and many places in the Indo-Gangetic plains. This is also the season for localised thunderstorms, associated with violent winds, torrential downpours, often accompanied by hail known as the 'Kaal Baisakhi'.

3.2.2.1. *March*

Monthly mean wind speed for the month of March is in the range 1.9 kmph to 15.5 kmph. The spatial patterns of monthly mean wind speed for March indicates weak winds over inland stations [Fig. 5(a)]. Gujarat, south Tamil Nadu and coastal Orissa have the highest mean wind speed. Stations having higher mean wind speed (>10 kmph) are Okha, Puri, Rajkot, Veraval, Bhaunagar and Tuticorin. 137 out of total 171 stations are showing significantly decreasing trends in wind speed for March as given in Table 3. Spatial patterns of wind speed trends for March [Fig. 5(b)] shows overall decline over the country but more coherent over central India, Gujarat, Tamil Nadu and coastal West Bengal. The monthly mean wind speed trends for March range between -3.38 kmph/decade and +1.99 kmph/decade.

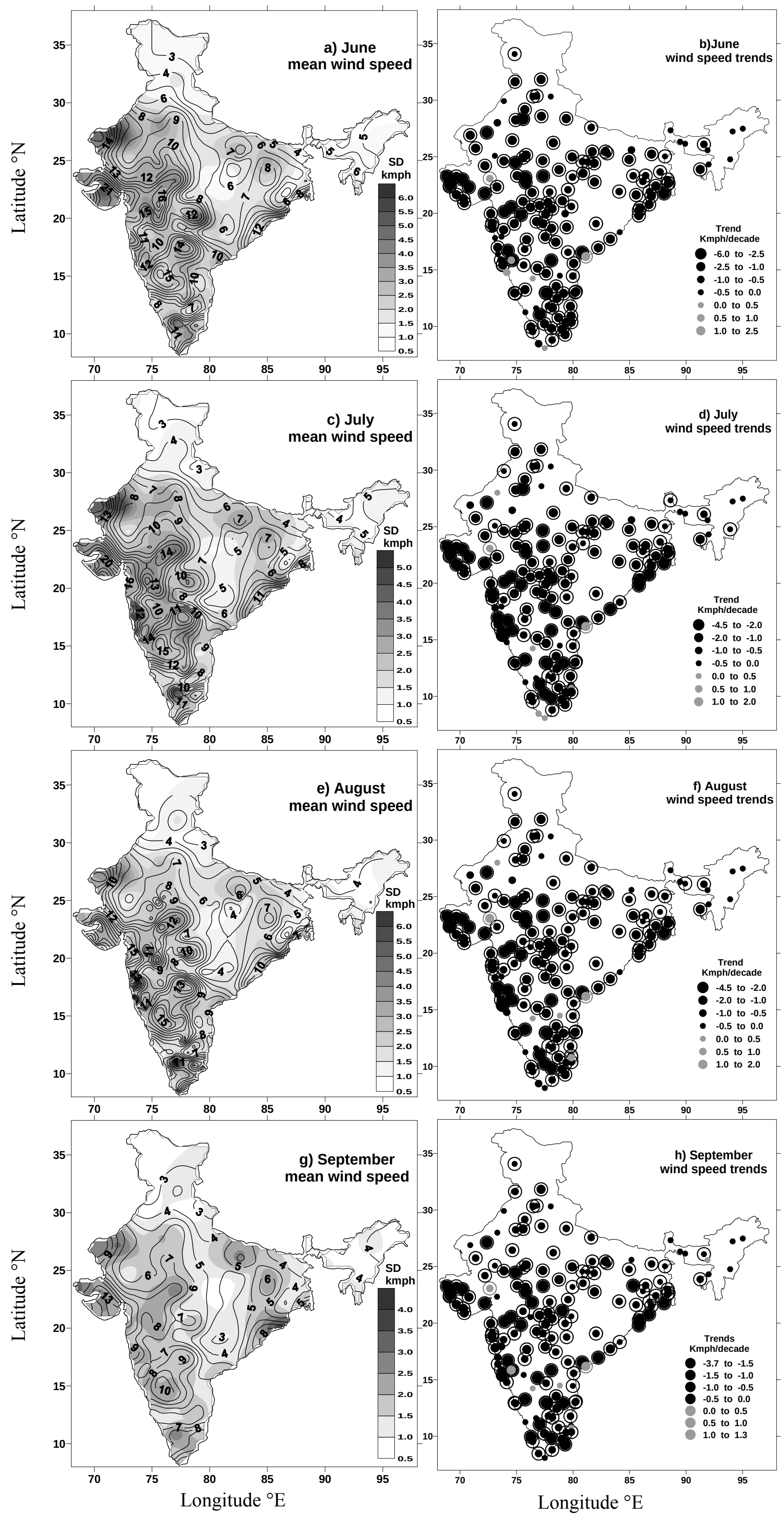
3.2.2.2. *April*

Monthly mean wind speeds for April are still lower over many parts of the country except over Gujarat, north Maharashtra, south Tamil Nadu and Orissa as shown in Fig. 5(c). However, stations having higher mean wind speed are Puri, Rajkot, Sagar Island, New Kandla, Okha and Bhaunagar where mean wind speed is more than 15 kmph. The range of mean wind speed for April is from 2.3 kmph (Sidhi) to 18.6 kmph (Puri). Out of 171 stations,



Figs. 5(a-f). Same as in Fig. 4 but for the summer months of March, April and May

137 stations are showing significantly decreasing trends in mean wind speed (Table 3). The monthly mean wind speed trend values for April are between -5.05 kmph/decade (Sagar Island) and +2.89 kmph/decade (Masulipatnam). Spatial patterns of wind speed trends for April shows decline in wind speed over all parts of the



Figs. 6(a-h). Similar to Fig. 4 but for the monsoon months of June to September country [Fig. 5(d)] but more strongly over south Madhya Pradesh, north Maharashtra, Gujarat, Western Ghats, Tamil Nadu and coastal West Bengal.

3.2.2.3. *May*

Compared to mean wind speed patterns of April [Fig. 5(c)], spatial patterns of May indicate increase in wind speed over the country as shown in Fig. 5(e). Regions over Gujarat, west Rajasthan, south Madhya Pradesh, north Maharashtra, Orissa, coastal West Bengal and Tamil Nadu have mean wind speed more than 15 kmph. The range of mean wind speed for May is from 1.9 kmph (Gangtok) to 23.1 kmph (Rajkot). As given in Table 3, 136 out of 171 stations are showing significantly decreasing trends in wind speed for May. Spatial patterns of wind speed trends show strong decline over all parts of the country [Fig. 5(f)]. Except northeast India, the significantly decreasing trends are spatially more coherent over all parts of the country. The declining trend values of monthly mean wind speed for May are between -4.02 kmph/decade (Sagar Island) and +2.99 kmph/decade (Masulipatnam).

3.2.3. *Monsoon months*

The prominent features of wind climatology in India are the circulations influenced by the strong southwest monsoon, when cold, humid air moves towards land. The monsoon season over India starts by early June and ends by the end of September. During this season, the low-pressure condition over the northern plains intensifies by attracting the trade winds of the southern hemisphere. These trade winds originate over the warm subtropical areas of the southern oceans, cross the equator and blow in a southwesterly direction entering the Indian peninsula as the south-west monsoon. These winds are strong and blow at an average velocity of 30 kmph. With the exception of the extreme northwest, the monsoon winds cover the country in about a month. Many low pressure areas are formed in the Bay of Bengal and Arabian Sea in this season which cross over to the mainland. The spatial patterns of monthly mean, standard deviation and trend of wind speed for monsoon months June, July, August and September are shown in Figs. 6(a-h).

3.2.3.1. *June*

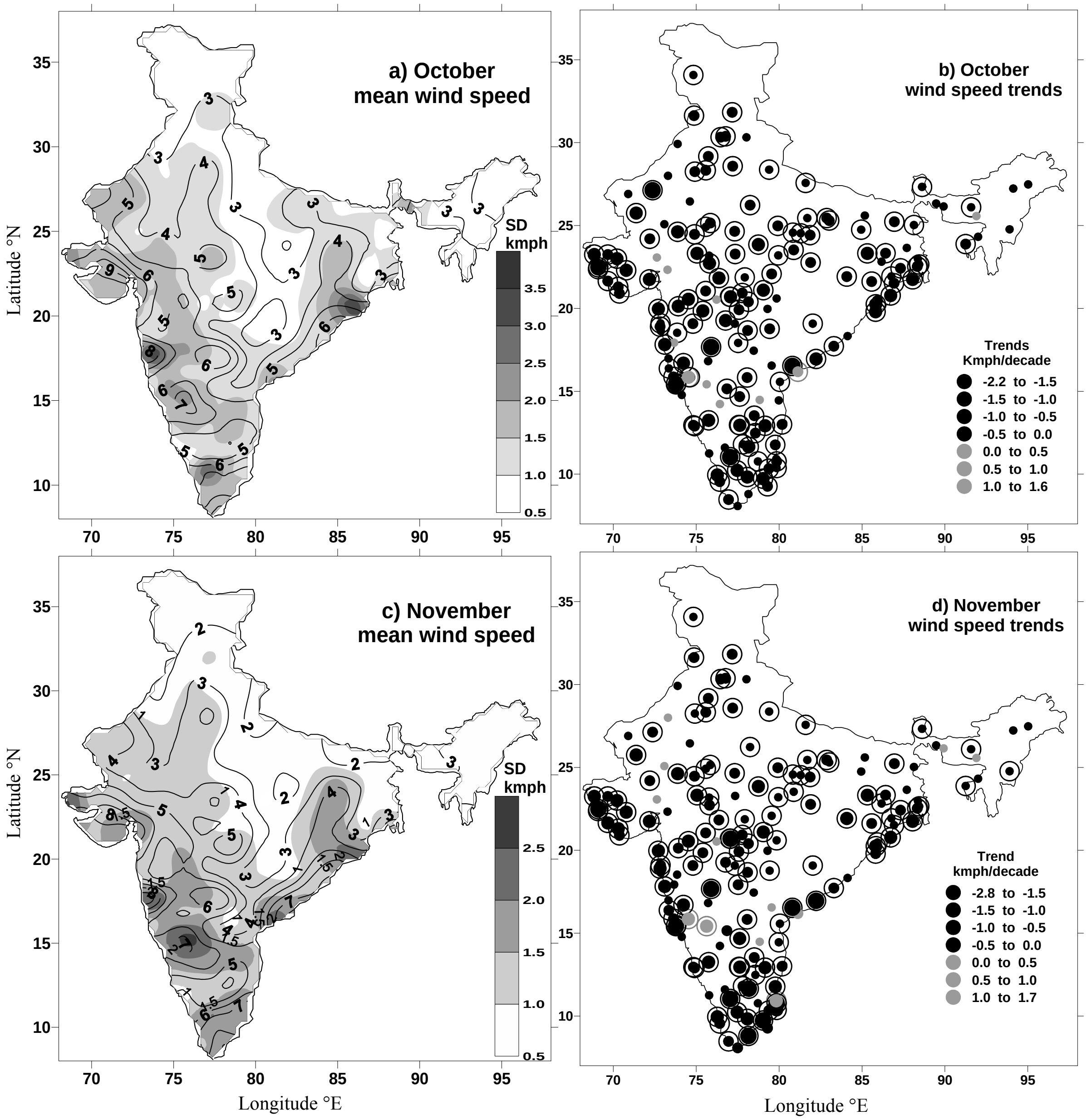
Spatial patterns of monthly mean wind speeds for June shown in Fig. 6(a) indicate overall increase in wind speed over the country except over north, east and northeast India where wind speed is still less than 10 kmph. The range of mean wind speed is 1.1 kmph (Gangtok) to 23.4 kmph (Rajkot). Stations in Gujarat (Rajkot, New Kandla, Veraval, Keshod, Bhaunagar), Maharashtra (Alibaug, Jalgaon, Mahabaleshwar, Aurangabad), Rajasthan (Jaisalmer), Karnataka (Bidar, Gadag), Tamil Nadu (Kanyakumari, Coimbatore, Pamban), Andhra Pradesh (Hyderabad), Orissa (Puri) and West Bengal (Sagar Island) have mean wind speed more than 15 kmph. Out of total 171 stations, 140 stations are showing significantly decreasing trends in wind speed (Table 3). Spatial patterns of wind speed trends show significant decrease over all parts of the country [Fig. 6(b)] which are more coherent over Gujarat, north Maharashtra, Tamil Nadu and coastal West Bengal. The trends are in the range -5.69 kmph/decade (Phalodi) and +2.39 kmph/decade (Masulipatnam).

3.2.3.2. *July*

Fig. 6(c) shows spatial patterns of monthly mean wind speeds for July which are higher over all parts of the country except over north, east and northeast India. Mean wind speeds for this month are highest over Gujarat, Western Ghats, north Maharashtra, Tamil Nadu and coastal Orissa. Stations having mean wind speed more than 20 kmph are Veraval, Alibaug, Devgad, Keshod, New Kandla, Mahabaleshwar, Dwarka, Rajkot and Okha. The range of mean wind speed is from 0.8 kmph (Gangtok) to 28.2 kmph (Veraval). 143 out of 171 stations are showing significantly decreasing trends in wind speed for July (Table 3). Spatial patterns of wind speed trends for July shows strong decline over all parts of the country but more coherently over Gujarat, north Maharashtra, Tamil Nadu and coastal regions of Orissa and West Bengal [Fig. 6(d)]. The monthly mean wind speed trends are in the range -4.37 kmph/decade (Coimbatore) and +1.93 kmph/decade (Masulipatnam).

3.2.3.3. *August*

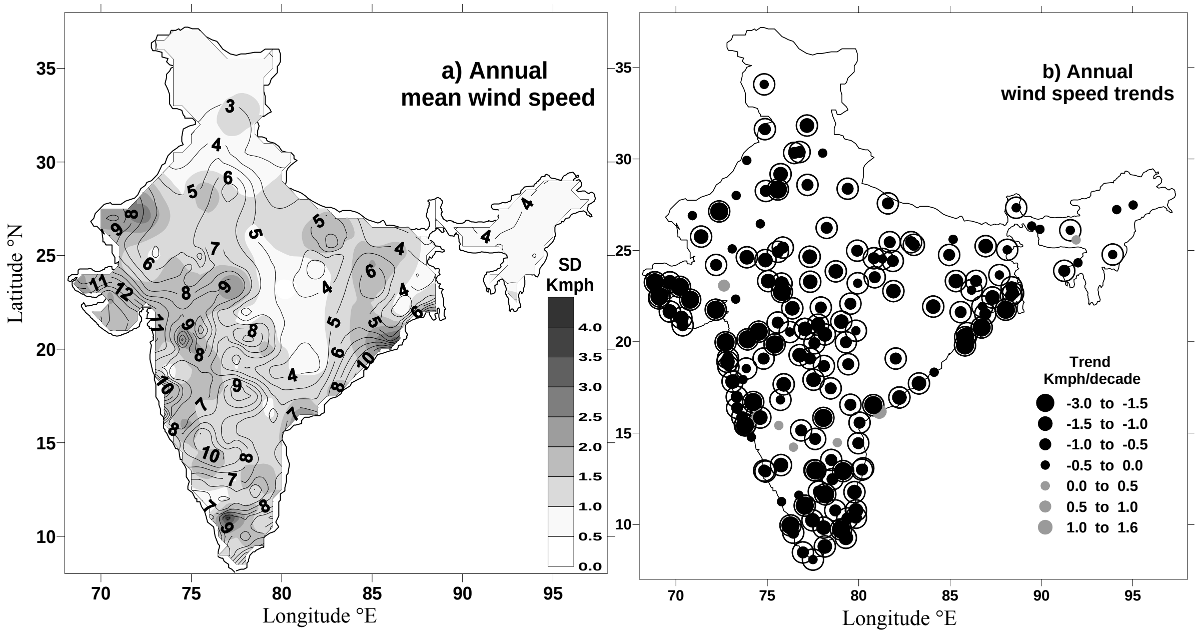
Spatial patterns of monthly mean wind speed for August [Fig. 6(e)] indicate regions of stronger winds over Gujarat, north Maharashtra, Tamil Nadu and coastal Orissa and West Bengal. Stations having stronger monthly mean wind speed (>20 kmph) are Veraval, Alibaug, Devgad, New Kandla and Mahabaleshwar. The range of monthly mean wind speed is from 0.7 kmph (Gangtok) to 23.6 kmph (Veraval). Out of 171 stations, 141 stations are showing significantly decreasing trends in monthly mean wind speed for August (Table 3). The spatial patterns of wind speed trends for August show general decrease over all parts of the country but more coherent over northwest India, Gujarat, north Maharashtra, Tamil Nadu and coastal Orissa and West Bengal [Fig. 6(f)]. The monthly mean wind speed trends are in the range -4.46 kmph/decade (Coimbatore) and +1.51 kmph/decade (Masulipatnam).



Figs. 7(a-d). Similar to Fig. 4 but for the post monsoon months of October and November

3.2.3.4. *September*

Spatial trends of monthly mean wind speed for September [Fig. 6(g)] indicates regions of stronger winds over Gujarat, north Maharashtra, Tamil Nadu and coastal regions of Orissa and West Bengal. Stations having stronger monthly mean wind speed (>15 kmph) are Kanyakumari, New Kandla, Veraval and Rajkot. The range of monthly mean wind speed is from 0.8 kmph (Gangtok) to 17.5 kmph (Kanyakumari). As given in Table 3, 142 stations are showing significantly decreasing trends in monthly mean wind speed. The spatial patterns of wind speed trends show general decrease over all parts of the country [Fig. 6(h)] but more coherent over northwest India, Gujarat, north Maharashtra, Tamil Nadu and coastal regions of Orissa and West Bengal. The



Figs. 8(a&b). Spatial variations of means and trends of annual wind speed for the period 1961-2008. Spatial variations of standard deviation are shown in the background alongwith mean wind speed in Fig (a). Trends significant at 99% are shown by filled circle in Fig. (b) where black colour indicates decreasing and gray colour indicates increasing trends

monthly mean wind speed trends for September are in the range -3.68 kmph/decade (Coimbatore) and +1.26 kmph/decade (Masulipatnam).

3.2.4. *Post monsoon months*

The post monsoon season in India is from October to November during which, the low-pressure trough over the northern plains becomes weaker and is gradually replaced by a high-pressure system. With the withdrawal of monsoon, October-November months form a period of transition from hot rainy season to dry winter conditions. This season is characterized by clear skies and rise in temperature. Parts of southern India are influenced by the northeast winter monsoon, which starts in October, when cold, dry air moves towards Ocean. The low-pressure conditions get transferred to the Bay of Bengal by early November resulting in formation of cyclonic storms and depressions. These cyclones generate high wind speed along their paths and generally cross the eastern coasts of India causing heavy and widespread rain. The spatial patterns of monthly means, standard deviation and trends of wind speed for post monsoon months October and November are shown in Figs. 7(a-d).

3.2.4.1. *October*

Spatial variations of monthly mean wind speed for October [Fig. 7(a)] indicate regions of higher wind speed over Gujarat, Tamil Nadu and coastal regions of Orissa and West Bengal. Stations having monthly mean wind speed (>10 kmph) are Mahabaleshwar, Kanyakumari, Tuticorin, Okha, Bhaunagar, Veraval, Rajkot and Dwarka. The range of monthly mean wind speed is from 0.8 kmph (Baripada) to 13.9 kmph (Mahabaleshwar). Out of 171 stations, 125 stations are showing significantly decreasing trends in monthly mean wind speed (Table 3). The spatial patterns of wind speed trends show decrease over all parts of India [Fig. 7(b)] but more coherent over northwest, Gujarat, north Maharashtra, Tamil Nadu and coastal regions of Orissa and West Bengal. The monthly mean wind speed trends are between -2.14 kmph/decade (Coimbatore) and +1.50 kmph/decade (Belgaum).

3.2.4.2. *November*

Fig. 7(c) shows spatial patterns of monthly mean wind speeds for November which are weak over most parts of the country except over coastal regions of Gujarat, Maharashtra and Tamil Nadu. Stations having higher mean wind speed (>10 kmph) are Mahabaleshwar, Okha, Pamban, Kanyakumari, Tuticorin, Karaikal, Bhaunagar, Veraval and Nagapatinam. The range of monthly mean wind speed is from 0.8 kmph (Baripada) to 14.9 kmph (Mahabaleshwar). Out of 171 stations, 125 stations are showing significantly decreasing trends in wind speed (Table 3). Spatial patterns of wind speed trends show general decrease over all parts of the country [Fig. 7(d)].

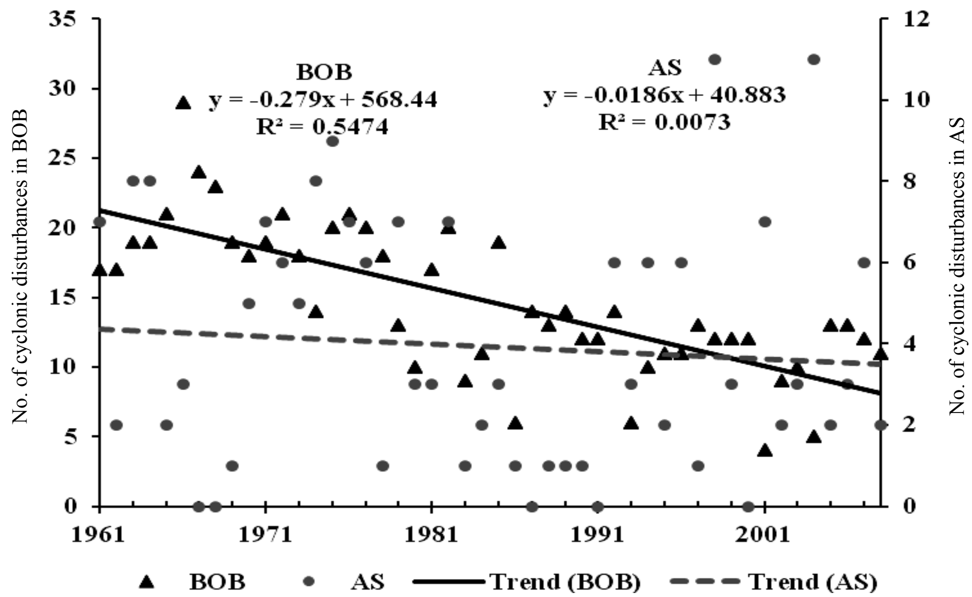


Fig. 9. Trends in annual numbers of cyclonic disturbances (including cyclonic storms and severe cyclonic storms) in the Arabian Sea (AS) and Bay of Bengal (BOB) during the period 1961-2008

The monthly mean wind speed trends for November are between -2.78 kmph/decade (Okha) and +1.68 kmph/decade (Karaikal).

3.3. *Annual means and trends*

Spatial variations of annual mean wind speed [Fig. 8(a)] suggest regions of higher wind speed over Gujarat, west Rajasthan, north Maharashtra, Tamil Nadu and coastal regions of Maharashtra, Andhra Pradesh, Karnataka, Orissa and West Bengal. Large number of stations in Gujarat, Rajasthan, Madhya Pradesh, Maharashtra, Karnataka, Tamil Nadu, Andhra Pradesh, Orissa and West Bengal are having higher annual mean wind speed (>10 kmph). Stations having annual mean wind speed more than 15 kmph are Kanyakumari, Veraval, Okha, Rajkot, New Kandla while stations having annual mean wind speed between 10 to 15 kmph are Keshod, Mahabaleshwar, Tuticorin, Bhaunagar, Devgad, Dwarka, Karaikal, Alibaug, Puri, Porbandar, Harnai, Pamban, Jalgaon, Sagar Island, Gadag, Tiruchchirappalli, Nagapatinam, Bidar, Chitradurga, Marmugao, Dahanu, Baroda, Indore, Kalingapatnam, Coimbatore, Tondi, Bhopal, Bhuj, Jaisalmer, Panjim, Ozar, Naliya, Aurangabad, Hyderabad and Kodaikanal. The range of annual mean wind speed over India is from 1.3 kmph (Gangtok) to 16.2 kmph (Kanyakumari). Out of total 171 stations, 144 stations are showing significantly decreasing trends in annual mean wind speed as given in Table 3. Stations showing significant increase in annual mean wind speed are Masulipatnam, Karaikal, Belgaum and Ahmedabad. Higher annual mean wind speed over Jaisalmer in Rajasthan indicates wind power generation over this region as suggested by Bishnoi (2011). The spatial patterns of annual wind speed trends show overall decline over all parts of the country [Fig. 8(b)]. The decreasing trends are spatially more coherent over northwest India, Gujarat, north Maharashtra, Tamil Nadu and coastal regions of Maharashtra, Orissa and West Bengal. The annual mean wind speed trends are in the range -2.85 kmph/decade (Okha) and +1.56 kmph/decade (Masulipatnam). The decreasing trends in annual mean wind speed over India are similar to trends over Canada (Tuller, 2004), China (Xu *et al*., 2006; Guo *et al*., 2010), USA (Pryor *et al*., 2009) and Australia (McVicar *et al*., 2008).

3.4. *Seasonal trends over seven homogeneous regions of India*

Seasonal trends in mean wind speed averaged over the seven homogeneous regions WH, NW, NC, NE, WC, IP, EC of India during the period 1961-2008 are significantly decreasing at 99% level of confidence for all seasons (Table 5). In the seven homogeneous regions of India, seasonal highest decrease in mean wind speed (per decade) has taken place over WH in summer (-12.7%), over NW in post monsoon (-10.1%), over NC in monsoon and post monsoon (each -11.8%), over NE in monsoon (-12.7%), over WC in monsoon (-7.2%), over IP in monsoon (-10.6%) and over EC in summer (-9.9%).

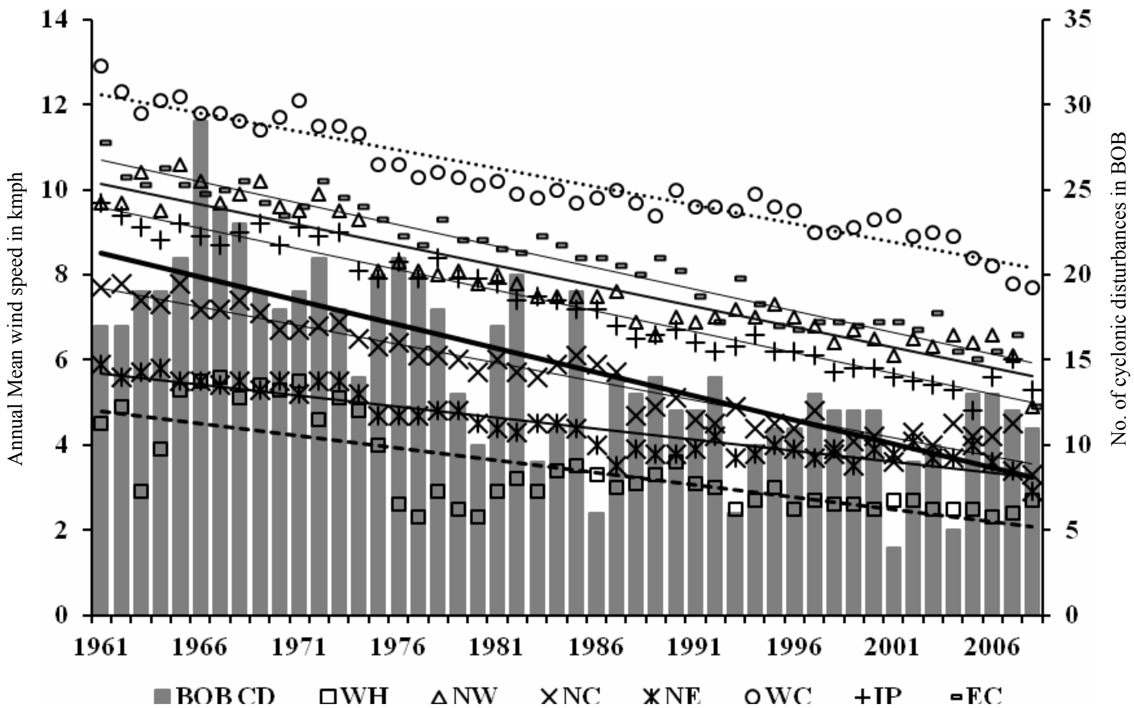


Fig. 10. Trends in annual total number of cyclonic disturbances (including cyclonic storms and severe cyclonic storms) in the Bay of Bengal (BOB CD) and annual mean wind speed over seven homogeneous regions Western Himalaya (WH), North West (NW), North Central (NC), North East (NE), West Coast (WC), Interior Peninsula (IP), East Coast (EC) of India during the period 1961-2008

The highest decrease in mean wind speed in winter has occurred over EC (-0.87 kmph/decade) followed by NW (-0.74 kmph/decade). Lowest decrease in mean wind speed in winter has occurred over NE (-0.36 kmph/decade). In summer season, EC, NW and IP are showing higher decline in mean wind speed (-1.22 kmph/decade, -0.94 kmph/decade, -0.94 kmph/decade respectively) while NE is having lower decline at -0.69 kmph/decade. Out of seven homogeneous regions of India, IP, NW and NC are having higher decreasing trend (-1.40 kmph/decade, -1.33 kmph/decade, -1.23 kmph/ decade respectively) in monsoon season mean wind speed. The southwest monsoon season accounts for nearly 80% of the rainfall in India, the strong decrease in mean wind speed in this season over large parts of the country is noteworthy. Post monsoon season trends over seven homogeneous regions of India show higher decrease in mean wind speed over EC (-0.75 kmph/decade) followed by NW (-0.68 kmph/ decade) while NE (-0.34 kmph/decade) is exhibiting lower decrease in wind speed. The significant decreasing trends in monsoon season mean wind speed are a cause of worry which needs further investigation.

3.5. *Declining surface winds and monsoonal flow*

Quite a few studies have also reported a weakening trend in the intensity of the southwest summer monsoon circulation during the recent decades (Joseph and Simon, 2005; Fan *et al*., 2010). Scientific work published so far is not yet clear whether the weakening of the monsoonal flow and the SST warming of the north Indian Ocean are related to the global warming phenomena.

The strength of monsoonal flow as it enters the Indian peninsula is investigated by selecting four 5° × 5° boxes over the Indian coastline and sub Himalayan region (Fig. 1). The trends in near-surface wind speed and 850 hPa zonal wind speed averaged over 5° × 5° boxes over GC, WC-I, WC-II and SH for monsoon season JJA for the period 1961-2008 are shown in Fig. 13. Monsoon season near-surface wind speed is decreasing significantly over the four boxes (GC, WC-I, WC-II and SH) with coefficient of determination 0.85, 0.77, 0.87 and 0.81 respectively. However, 850 hPa zonal wind speed trends for JJA are weak and increasing over GC and decreasing over WC-I, WC-II and SH. Similarly, trends in mean

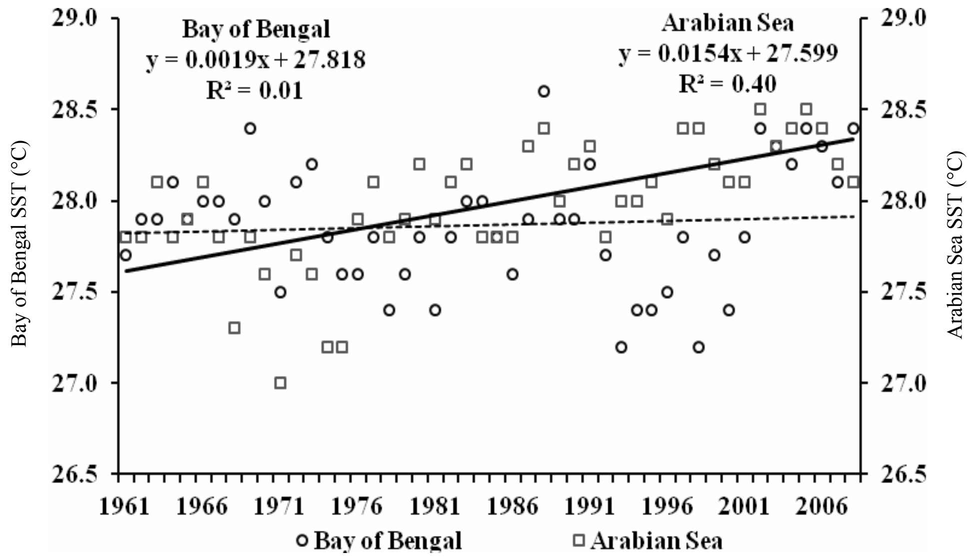


Fig. 11. Temporal variations in annual mean sea surface temperature (SST) of the Arabian Sea (AS) and Bay of Bengal (BOB) during the period 1961-2008

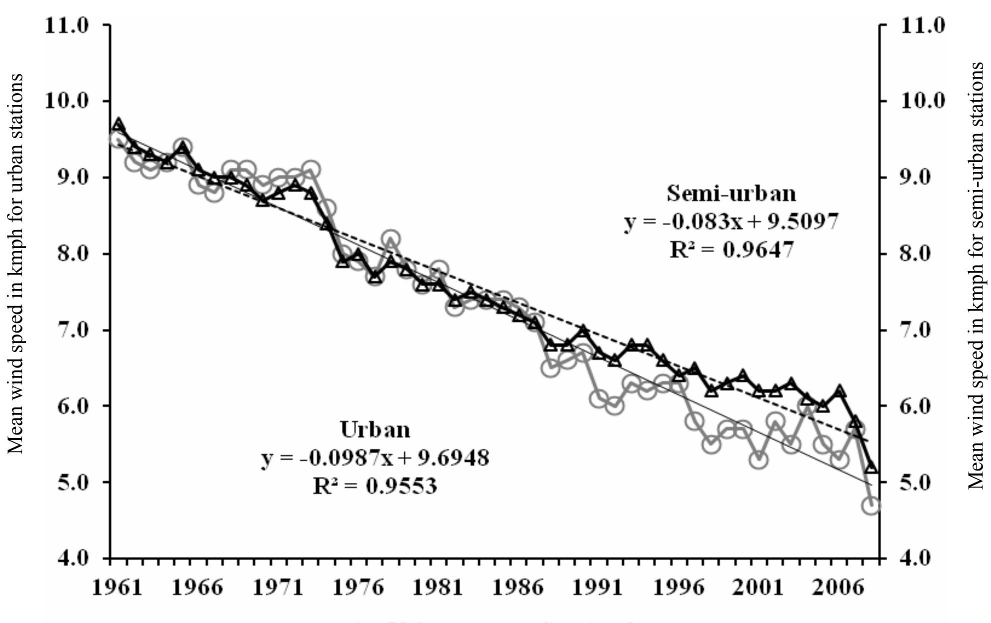
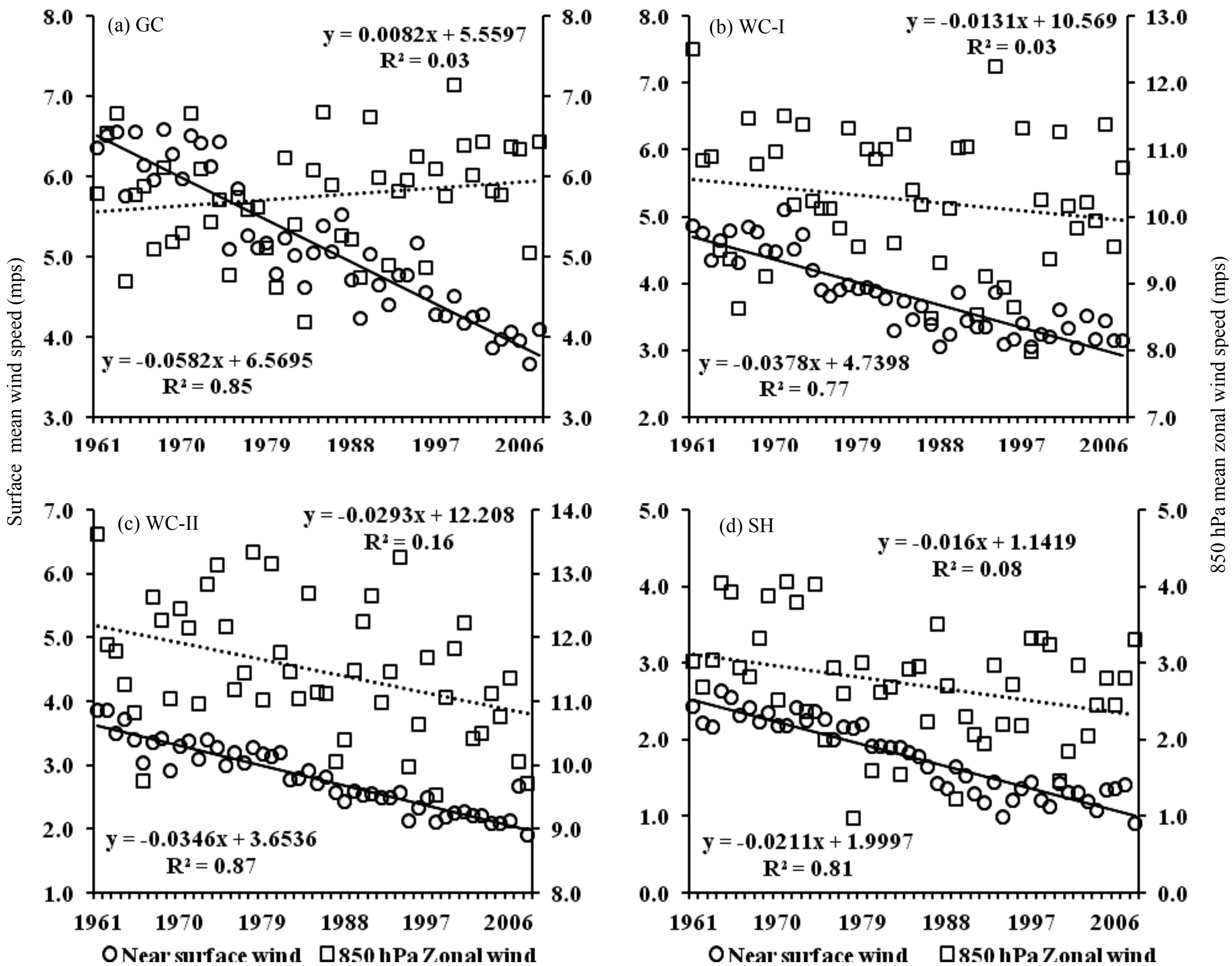


Fig. 12. Temporal variations in annual mean wind speed averaged over 39 urban (population ≥7.5 lakh) and 132 semi-urban (population <7.5 lakh) stations of India during 1961-2008

monthly near-surface wind speed and numbers of windy days (days with mean wind speed > 15 kmph) averaged over GC, WC-I, WC-II and SH for JJA for 1969-2008 are shown in Figs. 14(a-d). It is clear from Figs. 14(a-d) that surface wind speeds as well as numbers of windy days are significantly decreasing over GC, WC-I, WC-II and SH having coefficient of determination more than 0.6 for both the time series.

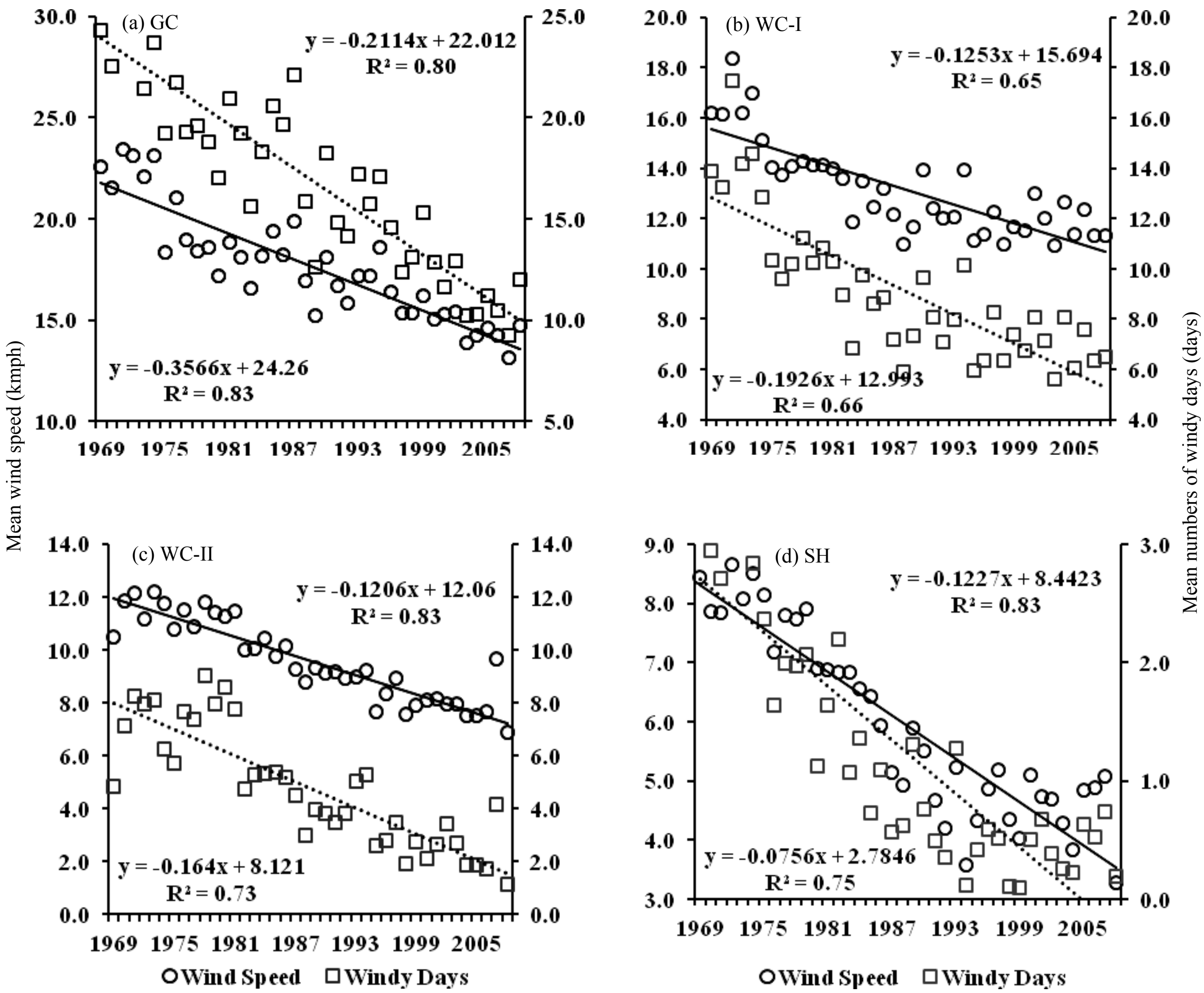


Figs. 13(a-d). Surface wind speed and 850 hPa mean zonal wind speed trends over (a) Gujarat coast (GC) [20-25° N, 67.5-72.5° E], (b) West Coast-I (WC-I) [15-20° N, 70-75° E], (c) West Coast-II (WC-II) [10-15° N, 72.5-77.5° E] and (d) Sub-Himalayan (SH) [20.0-25.0° N, 82.5-87.5° E] regions during 1961-2008. Time series is 5° × 5° averaged near surface wind speed (mps) and 850 hPa averaged NCEP-NCAR reanalysis zonal wind speed (mps) for monsoon season June to August

3.6. *Some of the probable causes of decline in wind speed*

The near-surface wind field is produced by a complex interplay of forces at the global, regional, and local scales (Klink, 2002). Over the course of a year, winds over India reflect general pattern of the large-scale atmospheric circulation and its seasonal variation, with stronger winds in the summer and monsoon and weaker winds in the winter season. The movement of synoptic scale weather systems also plays a prominent role in driving wind over a region. The reduction in wind speed can be caused by many factors, such as global warming, changes in regional and global atmospheric circulation, change in land use patterns and other anthropogenic factors. Topography, urbanization, sea breezes and other localized circulations can alter winds on an hourly basis (Klink, 2002). Local changes, such as building locations or vegetation cover at observation site can also change near-surface wind speeds. Vautard *et al*. (2010) have attributed increasing amounts of vegetation, causing up to 60% of slowing in wind speed across the Northern Hemisphere. Urban heat island effects may enhance near-surface wind speeds, while the higher roughness of urban versus rural areas may reduce speeds (Bornstein and Johnson, 1977; Balling and Cerveney, 1987).

The significant decrease in wind speed over India during 1961-2008 is coincident with the decrease in cyclonic disturbances (including cyclonic storms and



Figs. 14(a-d). Surface wind speed and windy days trends over (a) Gujarat coast (GC) [20 - 25° N, 67.5 - 72.5° E], (b) West coast-I (WC-I) [15 - 20° N, 70 - 75° E], (c) West coast-II (WC-II) [10 - 15° N, 72.5 - 77.5° E] and (d) Sub-Himalayan (SH) [20.0 - 25.0° N, 82.5 - 87.5° E] during 1969-2008. Time series is 5° × 5° averaged surface wind speed (kmph) and mean numbers of windy days (days having daily mean wind speed > 15 kmph) for monsoon season June to August

severe cyclonic storms) over the Bay of Bengal and the Arabian Sea (Fig. 9). Even though the decrease of cyclonic disturbances over the Arabian Sea during 1961-2008 is not significant (-0.02 per year), there is significant decrease in annual number of cyclonic disturbances over the Bay of Bengal (-0.15 per year). The coefficients of correlation (CC) between annual total number of cyclonic disturbances over Arabian Sea, Bay of Bengal and annual mean wind speed for seven homogeneous regions of India during the period 1961-2008 are given in Table 4. The CC values are >+0.6 which are significant at 99% for all regions suggesting a strong relationship between the decrease in cyclonic disturbances over the Bay of Bengal and the decrease in wind speed over the country. Fig. 10 shows temporal variations of annual total number of cyclonic disturbances in the Bay of Bengal and annual mean wind speed over seven homogeneous regions of India indicating steady decreasing trends during the period of study. Winds are a function of the temperature contrasts over land and sea. Temporal variations in annual means of Sea Surface Temperature (SST) of the Arabian Sea and the Bay of Bengal for 1961-2008 (Fig. 11) indicate significant increasing trends over the Arabian Sea (+0.015 °C per year) as compared to the Bay of Bengal (+0.006 °C per year). The observed greater warming over the Arabian Sea relative to land surface warming may also be a factor in the overall decline of wind speed over the country, which needs more investigation.

Some of the decreases in wind speed observed in this study are probably due to local effects such as urbanization and changes in land use patterns. There is large-scale increase in urbanization in India especially during the past three decades. Urbanization has a great impact on winds of a place as wind speed is considerably reduced in urban areas versus open areas (Bornstein and Johnson, 1977). Large-scale unplanned and denser structures in the urban areas increase the roughness of the surface and exert a drag on the low-level air flow. This leads to decline in wind speed near the ground in the long run. Fig. 12 shows temporal variations of annual mean wind speed averaged over urban and semi-urban stations of India out of 171 stations selected for study. The calculated trend in annual mean wind speed over urban stations is -0.099 kmph/year as compared to -0.083 kmph/year over semi-urban stations. A closer examination of Fig. 12 reveals that wind speed over urban stations decreased more sharply from 1986 onwards as compared to semi-urban stations which is similar to results obtained over China by Guo *et al.* (2010). There is also a possibility that due to urbanization near the IMD observatories, the exposure of the wind measuring instruments have been vitiated. However wind decrease over semi-urban stations suggests that this effect could be only small and overall decrease in wind speed is real rather than due to exposure. The significant decline of surface wind observed in many regions of the country especially over the wind farming areas along Gujarat and west coast is a potential concern for wind power generation. Besides the wind power industry, the slower surface winds can have significant impacts on environment, agriculture, air pollution and human comfort. Many authors have attributed weakening surface wind speed as a major factor causing decreases in surface evaporation (Liu *et al*., 2004; Chen *et al*., 2006; Shenbin *et al*., 2006; Zhang *et al*., 2007). The significant decline in wind speed may also be a factor in the significant decreasing trends in pan evaporation over India (Jaswal *et al*., 2008). Reductions in wind speed will adversely affect the environment by inefficient ventilation of pollutants from urban areas, lesser heat and moisture transfers between the earth's surface and the atmosphere and decline in wind energy (Pryor *et al*., 2009; Vautard *et al*., 2010). The stilling effect on ventilation of pollutants over India has resulted in large-scale decrease in sunshine duration and visibility (Jaswal, 2009). A comprehensive analysis of land and ocean parameters is required in future studies to unravel the causes of decline in wind speed over India.

4. Conclusions

The spatial variability and long-term trends in wind speeds over India based on 171 well distributed stations for 1961-2008 are studied. The results show that wind speed is significantly declining over India as well which is similar to the reported trends world over. The prominent regions of India where wind power can be profitably utilised are in Gujarat and adjoining Madhya Pradesh, south Rajasthan, north Maharashtra, north Karnataka, south Tamil Nadu, coastal Andhra Pradesh, along the west coast from Gujarat to Goa and along the east coast from Kolkata to Nagapatinam. The main results of this study are given below:

(*i*) All India averaged mean monthly and annual wind speed has decreased significantly at 99% level of confidence. The rate of decrease in annual mean wind speed is -0.88 kmph/decade while monthly wind speed has the largest rate of decline in June (-1.33 kmph/decade) followed by July (-1.27 kmph/decade).

(*ii*) In the seven homogeneous regions of India, significantly highest decrease in mean wind speed (per decade) has taken place over WH in summer (-12.7%), over NW in post monsoon (-10.1%), over NC in monsoon and post monsoon (each -11.8%), over NE in monsoon (-12.7%), over WC in monsoon (-7.2%), over IP in monsoon (-10.6%) and over EC in summer (-12.7%) season.

(*iii*) Spatially, large declines are found in Gujarat and adjoining Madhya Pradesh, north Maharashtra, south Rajasthan, Tamil Nadu, Andhra Pradesh, north Karnataka and Orissa and West Bengal coasts which primarily have higher mean wind speed.

(*iv*) Annual mean wind speeds exceeding 15 kmph are observed only over Gujarat and south Tamil Nadu. Some parts of Rajasthan, western Madhya Pradesh, Gujarat, Maharashtra, north Karnataka and adjoining Andhra Pradesh and the coastal belts experience mean wind speeds of 10-15 kmph.

(*v*) Correlations between annual mean wind speed over seven homogeneous regions of India and annual total numbers of cyclonic disturbances over the Arabian Sea and the Bay of Bengal suggest a strong relationship between decrease in cyclonic disturbances over the Bay of Bengal and decrease in wind speed.

Given the relevance of wind as a possible indicator of global climate change and its importance to efficient wind power generation, it is fundamentally important to install high quality wind sensors and have best exposure conditions at observation sites in India.

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