

Recent climatology and trends in surface humidity over India for 1969-2007

A. K. JASWAL and A. L. KOPPAR

India Meteorological Department, Pune – 411 005, India

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e mail : akjaswal@imd pune.gov.in

सार – इस शोध पत्र में भारत के 215 स्टेशनों की विशिष्ट आर्द्रता, सापेक्षिक आर्द्रता और शुष्क बल्ब तापमान की वार्षिक और मौसमी प्रवृत्तियों के विषय में अध्ययन किया गया है। इन प्रवृत्तियों के विशलेषण से प्राप्त हुए परिणामों से 90 प्रतिशत से अधिक स्टेशनों पर 1969–2007 के दौरान भारत में हवा की नमी में बढ़ोतरी के प्रमाण मिले हैं जिससे विशिष्ट आर्द्रता में वृद्धि की प्रवृत्ति का पता चला है। देश की विशिष्ट आर्द्रता और सापेक्षिक आर्द्रता जलवायविक माध्य क्रमशः 14.1 ग्रा. प्रति कि. ग्रा. और 63.9 प्रतिशत हैं और मानसून वर्षा ऋतु में सापेक्षिक आर्द्रता को छोड़कर सभी मौसमों में प्रवृत्तियों में विशेष बढ़ोतरी देखी गई है। विशिष्ट आर्द्रता, सापेक्षिक आर्द्रता और शुष्क बल्ब तापमान में वार्षिक प्रवृत्तियाँ क्रमशः +0.23 ग्रा./कि. ग्रा. प्रति दशक, +0.85 प्रतिशत प्रति दशक, +0.04 डिग्री से. प्रति दशक पाई गई है। विशिष्ट आर्द्रता, सापेक्षिक आर्द्रता और शुष्क बल्ब तापमान में ऋतुनिष्ठ प्रवृत्तियों के आकड़ें महत्वपूर्ण हैं और ग्रीष्म ऋतु (+0.30 ग्रा./कि.ग्रा. प्रति दशक), शीत ऋतु (+1.49 प्रतिशत प्रति दशक) और मानसून ऋतु (+0.11 से. प्रति दशक) में सबसे अधिक हैं। स्थानिक रूप से विशिष्ट आर्द्रता और सापेक्षिक आर्द्रता में प्रवृत्तियों में बढ़ोतरी उत्तर, उत्तर पश्चिम, मध्य और दक्षिण पूर्व भारत में अधिक स्पष्ट रूप से पाई गई है। सापेक्षिक आर्द्रता और शुष्क बल्ब तापमान में स्थानिक पैटर्न की प्रवृत्तियाँ पूरक हैं और प्रभावी रूप से संबद्ध हैं। जम्मू कश्मीर और उत्तर पूर्वी भारत में सापेक्षिक आर्द्रता की प्रवृत्तियों में लगातार कमी पाई गई है।

देश के अधिकांश भागों में ग्रीष्म ऋतु में सापेक्षिक आर्द्रता और मानसून ऋतु में शुष्क बल्ब तापमान में प्रवृत्तियों की बढ़ोतरी के परिणामस्वरूप लोगों को अधिक बेचैनी का सामना करना पड़ता है। इस बढ़ोतरी के कारण होने वाली बेचैनी के स्थानिक पैटर्न से पता चलता है कि जैसे-जैसे मौसम ग्रीष्म ऋतु से मानसून ऋतु की ओर बढ़ता है तो उत्तर और पश्चिम दिशा की ओर भी बेचैनी की स्थिति में वृद्धि होती है।

ABSTRACT. Annual and seasonal trends in specific humidity, relative humidity and dry bulb temperature based upon 215 stations across India are studied. The results of trend analysis show evidence of an increase in air moisture content over India during 1969-2007 with more than 90% stations showing increasing trends in specific humidity. Climatological means of specific humidity and relative humidity for the country are 14.1 g/kg and 63.9% respectively and trends are significantly increasing for all periods except for relative humidity in monsoon season. Annual trends in specific humidity, relative humidity and dry bulb temperature are +0.23 g/kg per decade, +0.85% per decade and +0.04° C per decade respectively. Seasonal trends in specific humidity, relative humidity and dry bulb temperature are statistically significant and highest in summer (+0.30 g/kg per decade), winter (+1.49% per decade) and monsoon (+0.11° C per decade) respectively. Spatially, the increasing trends in specific humidity and relative humidity are more coherent over north, northwest, central and southeast India. Spatial patterns of trends in relative humidity and dry bulb temperature are complementary and strongly correlated. Relative humidity trends are consistently decreasing over Jammu and Kashmir and northeast India.

Increasing trends in summer season relative humidity and monsoon season dry bulb temperature over large parts of the country contribute significantly to upward trend in human discomfort. The spatial patterns of discomfort index show that the aerial extent of uncomfortable conditions increases both north and westwards as season progresses from summer to monsoon.

Key words – Air temperature, Dew point temperature, Relative humidity, Specific humidity, Vapour pressure, Saturation vapour pressure, Discomfort index, Trend, Correlation.

1. Introduction

Climate plays an important role in every aspect of human life. Change in climate has been documented in many locations throughout the world but most of these studies focus on changes in temperature and precipitation only. However atmospheric water vapor is one of the most important factors in determining Earth's weather and climate and hence warrants a thorough investigation to understand its behaviour. Water vapor plays a dominant role in the radiative budget of the troposphere as it is the most important contributor to the natural greenhouse effect and is strongly coupled with clouds. The main sources of water vapor in the lower atmosphere are evaporation from the Earth's surface and transpiration by plants. Since surface humidity and temperature regulate evaporation and transpiration processes, they are connected to both the hydrological cycle and surface energy budget. An important feedback for the warming predicted by climate models due to an increase in greenhouse gas concentration is an increase in atmospheric water vapor (Philipona *et al.* 2005). As temperatures rise, the atmosphere's water holding capacity increases. The surface temperature of the Earth has increased at a rate of about 0.13° C per decade during the past 50 years and the average atmospheric water vapour has increased over land and ocean as well as in the upper troposphere (IPCC 2007). There is strong evidence of increase in temperatures over India as reported by number of authors (Hingane *et al.* 1985; Srivastava *et al.* 1992; Rupa Kumar *et al.* 1994; De and Rajeevan 1997; Sahai 1998; Kothawale and Rupa Kumar 2005; Dash *et al.* 2007; Jaswal 2010a).

There are number of regional and global studies of long-term changes in surface water vapor content over land and ocean (Oort 1983; Peixoto and Oort 1996; Gaffen and Ross 1999; Robinson 2000; Sun *et al.* 2000; Groisman *et al.* 2004; Schönwiese and Rapp 1997; New *et al.* 2000; Wang and Gaffen 2001; Philipona *et al.* 2004; Dai 2006; Vincent *et al.* 2007; Willett *et al.* 2007). Long-term mean distributions of surface specific humidity show large seasonal and spatial variations (Oort 1983), while the variations in surface relative humidity are relatively small over the oceans (Peixoto and Oort 1996) but considerable over the United States (Gaffen and Ross 1999). Increased surface specific humidity and dew point temperature during the second half of the twentieth century have been reported over the contiguous United States by Robinson (2000), Sun *et al.* (2000) and Groisman *et al.* (2004). Increase in surface water vapor is also found over Europe (Schönwiese and Rapp 1997; New *et al.* 2000; Philipona *et al.* 2004), the former Soviet Union and China (Sun *et al.* 2000; Wang and Gaffen 2001), Canada (Vincent *et al.* 2007) and Japan (New *et al.*

2000). Investigating changes in global surface humidity, Dai (2006) has reported increase in both specific and relative humidity over United States, India and China.

In India, Kothawale and Rupa Kumar (2005) have reported marked acceleration of warming trends in surface air temperatures and they have found significant increase by 0.2° C per decade in the annual mean, maximum as well as minimum temperatures during the last three decades of 1901-2003. Dash *et al.* (2007) have found increase by 1° C in winter maximum temperature over India during 1901-2003 while in a recent study, Jaswal (2010a) has reported higher significant increase in maximum temperature (+0.29° C/decade) in February over North India as compared to South India (+0.19° C/decade) for 1970-2007.

Temperature and rainfall trends over India have been studied by number of authors but very little work has been done on humidity data. Increasing trends in winter season air temperature and surface humidity at most of the airport stations in India have been reported by De *et al.* (2001). Rao *et al.* (2004) have studied trends in annual mean relative humidity at 15 urban stations and found significant increasing trends at 11 stations. Singh *et al.* (2008) have studied annual trends in relative humidity over nine river basins in northwest and central India and have found increasing trends (1 to 18% per 100 years) in six river basins and decreasing trends (-1 to -13% per 100 years) in three river basins. Jaswal (2010b) has reported significantly decreasing trends at four stations (-0.10% to -0.38% per year) and significantly increasing trends at two stations (~ +0.14% per year) in annual mean relative humidity over Jammu and Kashmir.

The main aims of this paper are to present annual and seasonal surface humidity distributions over India for the climatic normal period 1971-2000 and to document trends in humidity and temperature over the period 1969–2007. Further, the effects of temperature and humidity on human comfort are studied for summer and monsoon seasons by using discomfort index given by Giles *et al.* (1990). The data and methodologies are presented in section 2 followed by results and discussion in section 3 of the paper.

2. Data and methodology

Humidity is a general term used to indicate moisture in the atmosphere. The specific humidity (g/kg) is the mass of water vapor contained within a unit mass of moist air which means the higher the amount of water vapor, the higher the specific humidity. The commonly used term relative humidity can be defined as the ratio (%) of the actual vapor pressure of the air to the saturation vapor

TABLE 1

All India mean and trend per decade for annual and seasonal specific humidity (g/kg), relative humidity (%) and dry bulb temperature (°C) based upon 215 stations for 1969-2007. Trends significant at 95% level are marked by “*” sign

	Specific Humidity (g/kg)		Relative Humidity (%)		Dry Bulb Temperature (°C)	
	Mean	Trend/ decade	Mean	Trend/ decade	Mean	Trend/ decade
Annual	14.1	+0.23*	63.9	+0.85*	26.3	+0.04
Winter	9.8	+0.25*	60.4	+1.49*	21.1	+0.02
Summer	13.3	+0.30*	51.4	+1.10*	29.7	-0.06
Monsoon	18.3	+0.21*	74.7	+0.25	28.2	+0.11*
Post monsoon	13.7	+0.22*	65.7	+0.79*	25.2	+0.03

pressure at the same pressure and temperature. In other words, it is a measure of the actual amount of water vapor in the air compared to the total amount of vapor that can exist in the air at its current temperature. On the other hand, the dew point temperature provides a measure of the actual amount of water vapor in the air. It is the temperature to which the air must be cooled in order for that air to be saturated. Dew point temperature and relative humidity are obtained daily from the dry and wet bulb temperatures at standard times in India Meteorological Department (IMD). The consistency in the methods of observation in IMD ensures that the quality of surface meteorological observations is generally good.

Surface meteorological data analysed here are taken from the archives of National Data Centre (NDC) of IMD located at Pune. Variability and trends in specific humidity and relative humidity over India are studied along with corresponding changes in dry bulb temperature for 1969-2007. The period of study is restricted to 1969 onwards as computation of daily specific humidity requires daily surface observations which are available in the database of IMD from 1969 onwards only. Based upon data availability and completion of records, a total number of 215 stations well spread over India are selected. In this study, observations recorded at 0300 and 1200 UTC are used for calculating mean monthly specific humidity, relative humidity, dry bulb temperature and dew point temperature. Daily specific humidity values in g/kg are calculated using following relation originally given by Tetens (1930) and simplified by Murray (1967).

$$e_w = 6.1078 \times \exp \left(\frac{17.269388 \times (dpt - 273.16)}{(dpt - 35.86)} \right)$$

Here e_w is vapour pressure in hPa and dpt is dew point temperature in °K. The specific humidity sph in g/kg is calculated by the following relation

$$sph = \frac{622 \times e_w}{slp - 0.378 \times e_w}$$

where, slp is the station level pressure in hPa at the time of observation.

Before preparing monthly means, the calculated specific humidity, relative humidity, dry bulb temperature and dew point temperature data values for all 215 stations were subjected to a range check and standard deviation based quality checks to exclude any outliers. From the monthly means, annual and seasonal means of specific humidity (SPH), relative humidity (RH) and dry bulb temperature (DBT) are computed considering annual as January to December, winter as December to February, summer as March to May, monsoon as June to September and post monsoon as October to November. Climatology of humidity for 1971-2000 is prepared for annual and four seasons and spatial variations of mean SPH and RH over the country are shown in Figs. 1(a-e) and 2(a-e) respectively. All India averaged temporal variations in SPH & RH as anomalies from 1971-2000 means are shown in Figs. 3(a-e). Table 1 shows all India averaged annual and seasonal means and trends in SPH, RH and DBT. The trends in annual and seasonal means of SPH, RH and DBT are calculated and tested for all 215 stations by the method of least squares at 95% level of confidence using Student’s *t*-test and spatial patterns of trends for annual and four seasons are shown in Figs. 4(a-e) to 6(a-e) where black circles indicate decreasing trends, grey circles indicate increasing trends and statistically significant

TABLE 2
Numbers of stations showing decreasing or increasing trends in specific humidity (SPH), relative humidity (RH) and dry bulb temperature (DBT) for 1969-2007

		Numbers of stations		
		Specific humidity	Relative humidity	Dry bulb temperature
a. Annual	Decreasing	20	34	34
	Decreasing significantly	4	20	7
	Increasing	46	44	63
	Increasing significantly	145	117	111
b. Winter	Decreasing	19	36	48
	Decreasing significantly	2	10	11
	Increasing	54	54	66
	Increasing significantly	140	115	90
c. Summer	Decreasing	36	37	72
	Decreasing significantly	10	23	16
	Increasing	45	47	80
	Increasing significantly	124	108	47
d. Monsoon	Decreasing	26	68	11
	Decreasing significantly	4	22	1
	Increasing	55	80	95
	Increasing significantly	130	45	108
e. Post monsoon	Decreasing	27	41	53
	Decreasing significantly	3	12	10
	Increasing	80	75	86
	Increasing significantly	105	87	66

trends are indicated by an outer circle at the station. Table 2 gives numbers of stations showing increasing/decreasing trends in SPH, RH and DBT. Numbers of stations having positive or negative correlation between SPH & DBT and RH & DBT are given in Tables 3 and 4.

It is well known that meteorological parameters like air temperature and relative humidity affect public health concerning human comfort. The bioclimatic index, the discomfort index of Thom (1959) reflects the proportionate contribution of air temperature and relative humidity on the human thermal comfort. For estimating discomfort index (DI) in °C the following equation given by Giles *et al.* (1990) is used to calculate daily values of DI for each station.

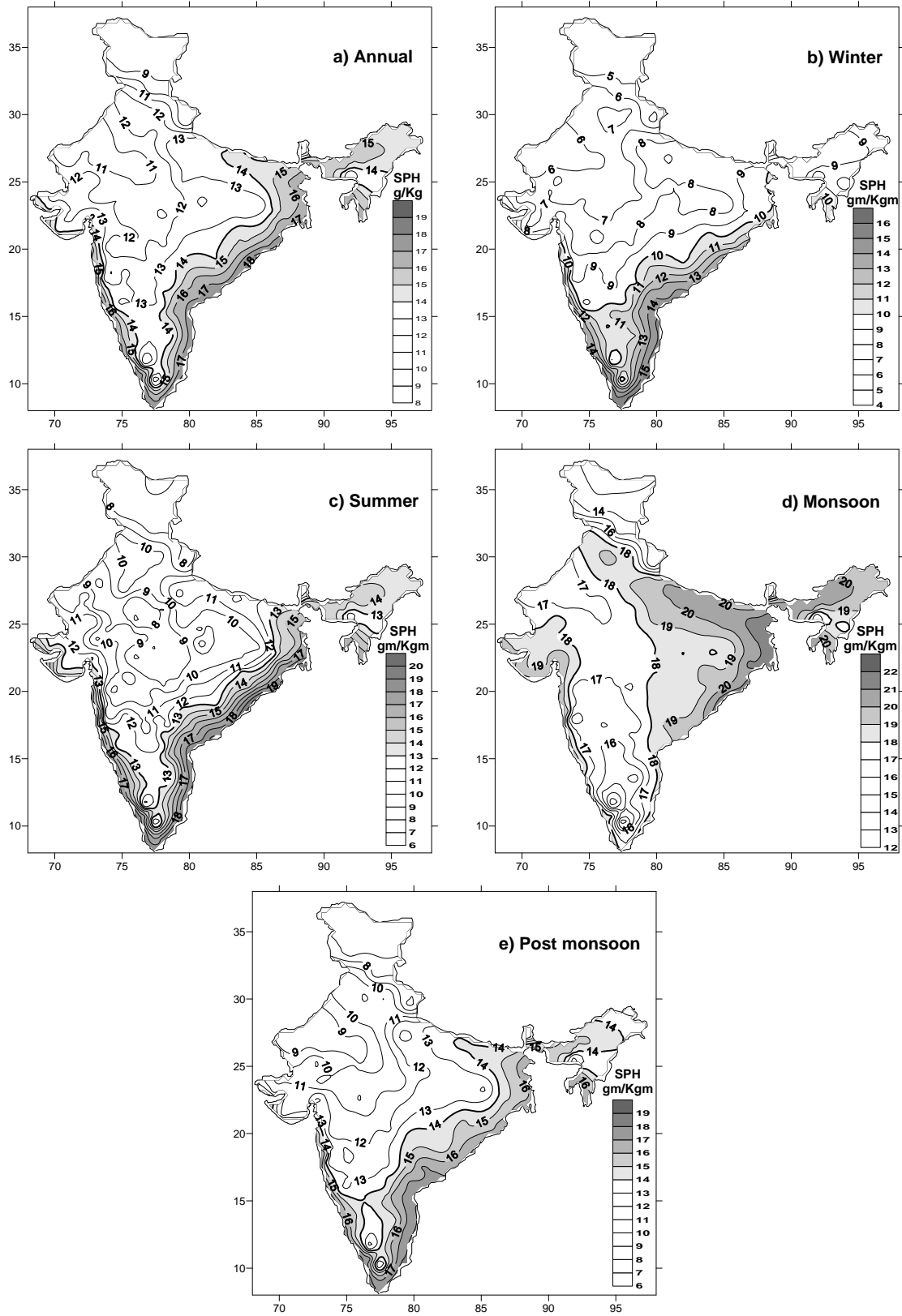
$$DI = dbt - 0.55 \times (1.0 - 0.01 \times rh) \times (dbt - 14.5)$$

In this equation dbt is the air temperature in °C and rh in % is the corresponding value of relative humidity. From the calculated daily values of mean DI, monthly mean indices are calculated for all 215 stations for summer and monsoon seasons. Figs. 7(a&b) shows temporal variations in all India averaged DI, DBT and RH for summer and monsoon seasons while spatial patterns of means and trends of DI are shown in Figs. 8(a-d).

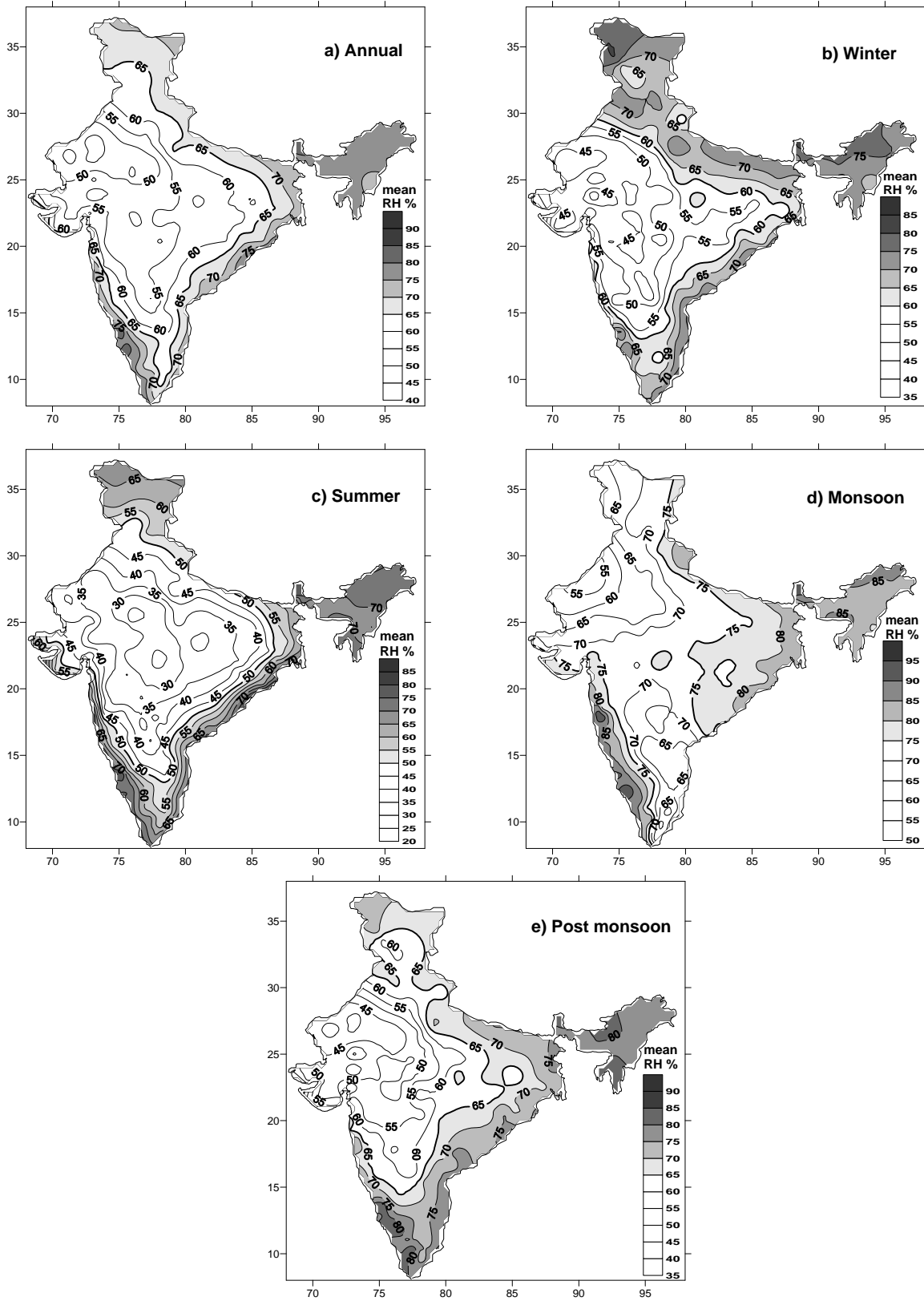
3. Results and discussion

3.1. Humidity climatology

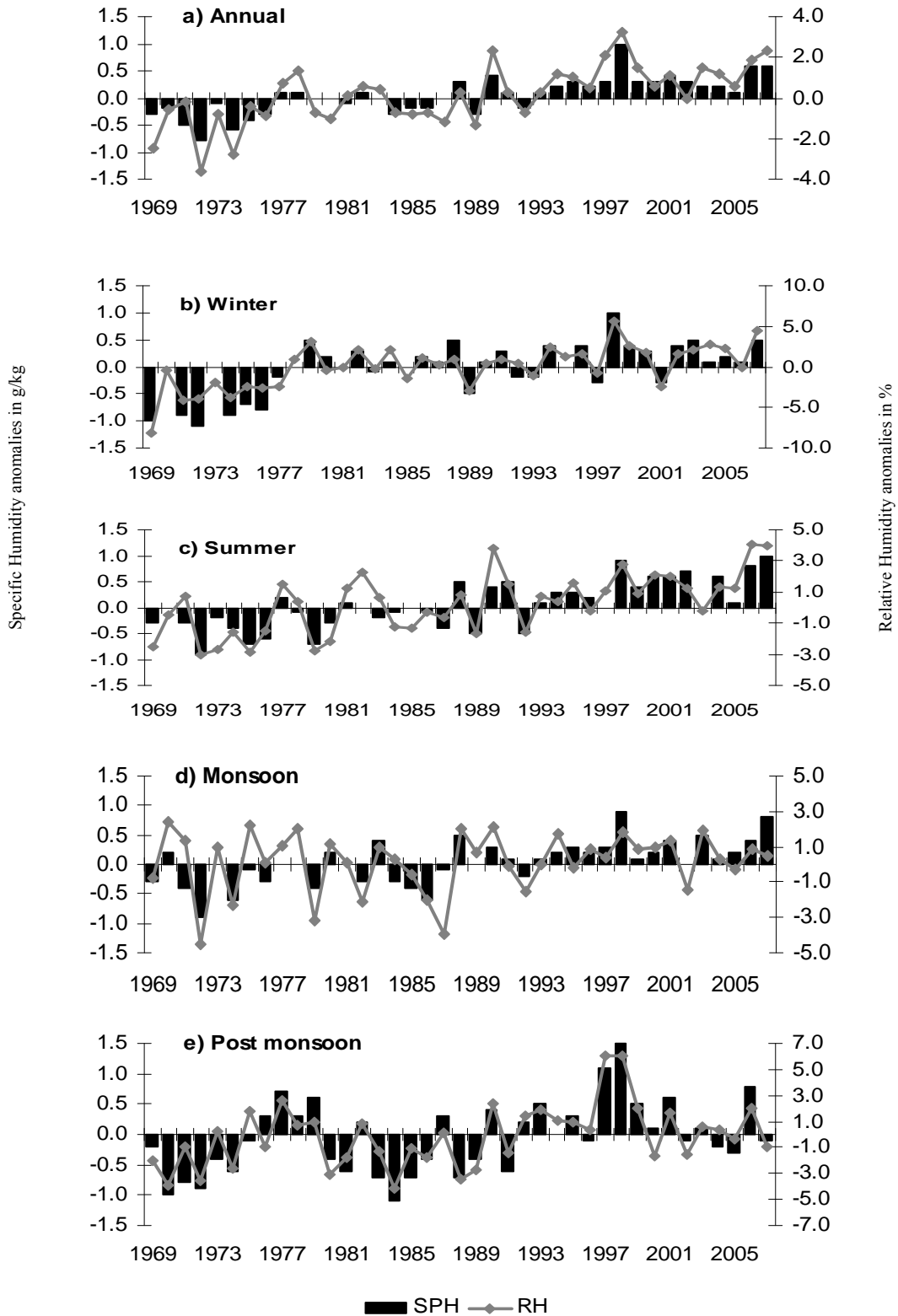
In Indian subcontinent, relative and specific humidity tend to increase dramatically during the monsoon season when onshore winds carry moisture laden air from the ocean to land areas. Therefore seasonal humidity variations in India depend on seasonal changes



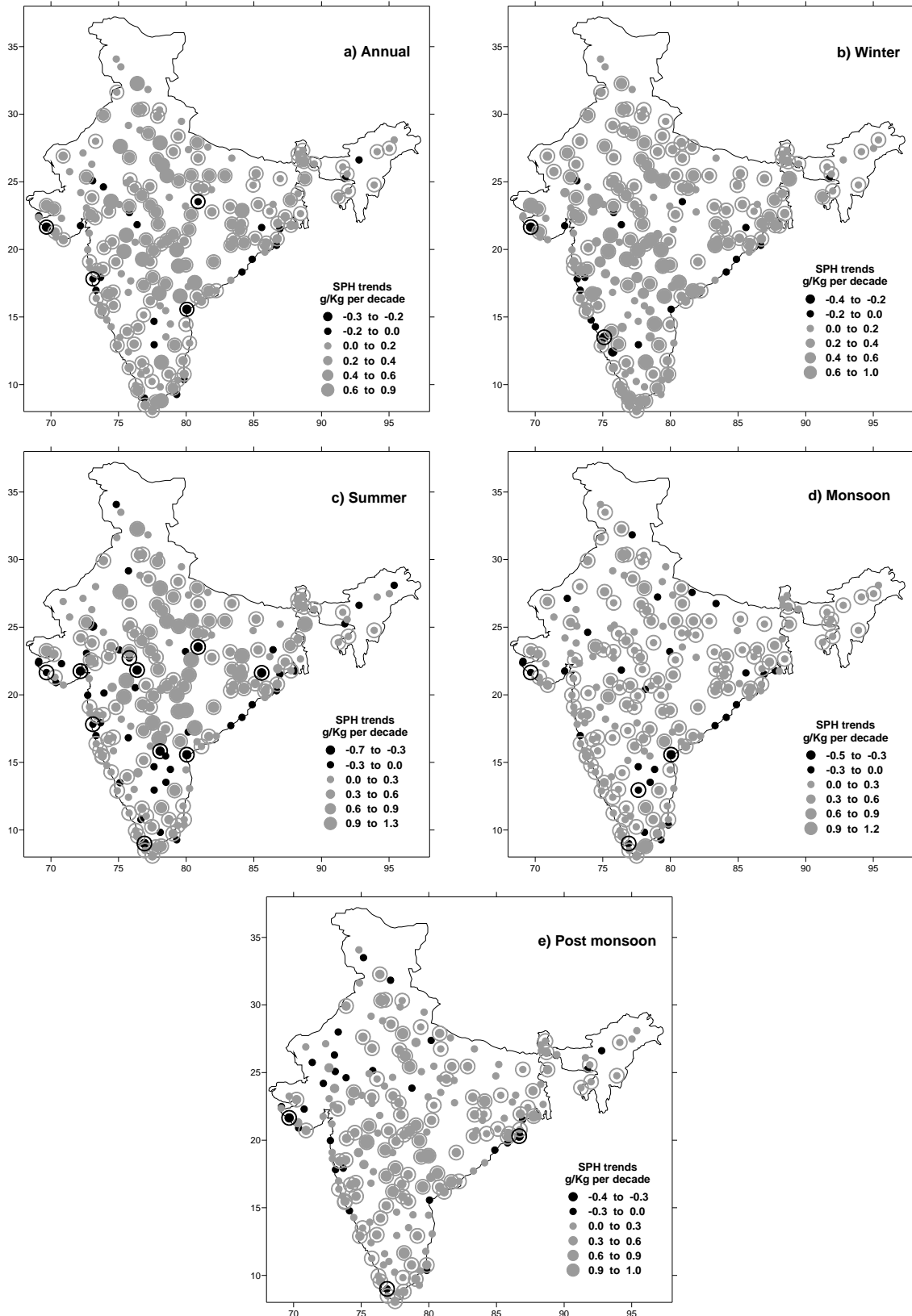
Figs. 1(a-e). Spatial distribution of mean specific humidity (SPH) in g/kg for 1971-2000. Contours of mean SPH greater than equal to the respective annual or seasonal climatological mean are shaded



Figs. 2(a-e). Spatial distribution of mean relative humidity (RH) in % for 1971-2000 data. Contours of mean RH greater than equal to the respective annual or seasonal climatological mean are shaded



Figs. 3(a-e). Temporal variations in averaged India specific humidity (SPH) and relative humidity (RH) during 1969-2007. Data series are anomalies from 1971-2000 averages



Figs. 4(a-e). Spatial distribution of trends in specific humidity (SPH) in g/kg per decade for 1969-2007. Trends significant at 95% level are shown by an outer circle

in temperature and atmospheric circulation. Climatology of both specific and relative humidity over India for annual and four seasons is prepared based upon 215 surface stations for 1971-2000. Spatial distribution of mean SPH and RH over the country is shown in Figs. 1 and 2 respectively. Annual mean SPH is generally low over the country except over coastal regions. Seasonally, winter has the lowest mean SPH and monsoon season has the highest. While annual mean RH is high in regions along Indian coastline, north and northeast India, the north and westward spread of the region of high humidity in monsoon season is noteworthy.

3.1.1. Specific humidity

Annual mean SPH is highest (> 14 g/kg) along Indian coastline and northeast India and lowest (< 11 g/kg) over Rajasthan and north Jammu and Kashmir as shown in Fig. 1(a). Winter season mean SPH patterns [Fig. 1(b)] are almost similar to annual mean SPH patterns but the values range between 5.0 g/kg and 15.0 g/kg. Fig. 1(c) shows summer season mean SPH patterns where coastal regions are having highest values (> 17 g/kg) and central India, Rajasthan and north Jammu and Kashmir are having lowest (< 9 g/kg). It is clear from Fig. 1(d) that mean SPH becomes higher all over the country during monsoon season and the highest values (> 20 g/kg) are over coastal Andhra Pradesh, Orissa, sub-Himalayan West Bengal and northeast India and lowest (< 14 g/kg) over north Jammu and Kashmir. Fig. 1(e) shows post monsoon season distribution of mean SPH which is highest over coastal areas (>16 g/kg).

3.1.2. Relative humidity

Fig. 2(a) shows distribution of annual mean RH over India which is highest (> 70 %) over coastal areas and northeast and lowest (< 50 %) over Rajasthan. Winter season mean RH is highest (> 70 %) over north and northeast India and along the Indian coastline [Fig. 2(b)]. Large regions over Rajasthan, Gujarat and North Maharashtra are having lowest mean RH (< 45 %). Summer season mean RH is highest (> 70 %) along coastal areas and northeast India while a large region over central India is having lowest mean RH (< 35 %) as shown in Fig. 2(c). Monsoon season mean RH patterns [Fig. 2(d)] indicate increase in moisture over India where coastal regions are having mean RH > 80 %. Only extreme west Rajasthan is having lowest mean RH (< 55 %). Post monsoon season mean RH patterns indicate regions of highest humidity (> 70 %) along coastal areas, south peninsula and northeast India as shown in Fig. 2(e). Regions of lowest mean RH (< 45 %) are over Rajasthan and adjoining Gujarat.

3.2. All India averaged annual and seasonal trends

Table 1 shows all India averaged annual and seasonal means and trends of SPH, RH and DBT. Annual mean SPH, DBT and RH for the country as a whole are 14.1 g/kg, 63.9% and 26.3° C respectively. Seasonal mean SPH is highest in monsoon season (18.3 g/kg) and lowest in winter season (9.8 g/kg). Seasonal mean RH is highest in monsoon season (74.7%) and lowest in summer season (51.4%) while DBT is highest in summer (29.7° C) and lowest in winter (21.1° C). All India trends in SPH are significantly increasing for annual and four seasons. While trends in RH are significantly increasing for annual, winter, summer and post monsoon, trends in DBT are significantly increasing for monsoon season only. The highest increase in SPH, RH and DBT over India is in summer (0.30 g/kg per decade), winter (+1.49% per decade) and monsoon (+0.11° C per decade) seasons respectively.

3.3. Temporal variations

Annual and seasonal temporal variations in SPH and RH for 1969-2007 as anomalies from 1971-2000 averages are shown in Figs. 3(a-e). As given in Table 1, both SPH and RH trends are increasing significantly for annual and four seasons except for RH in monsoon. It is clear from Fig. 3 that both SPH and RH variations are in phase during 1969-2007 and anomalies have become positive since 1990s for most of the years. The highest positive anomaly in annual mean SPH (+1.0 g/kg) and RH (+3.2%) is noticed for the year 1998 which has been one of the warmest years. The highest negative anomaly in annual mean SPH (-0.9 g/kg) and RH (-4.5%) during drought year 1972 is noteworthy. It is evident from Fig. 3(d) that bad monsoon years have largest negative anomalies in humidity.

3.4. Spatial patterns of annual and seasonal trends in humidity and temperature

Warm air can possess more water vapour (moisture) than cold air, so with the same amount of specific humidity, air will have a higher relative humidity if the air is cooler and a lower relative humidity if the air is warmer. Given stable conditions with little advection, the expected correlation between air temperature and relative humidity at any location is negative. While dew point gives a quick idea of moisture content in the air, relative humidity does not since the humidity is relative to the air temperature.

3.4.1. Specific humidity trends

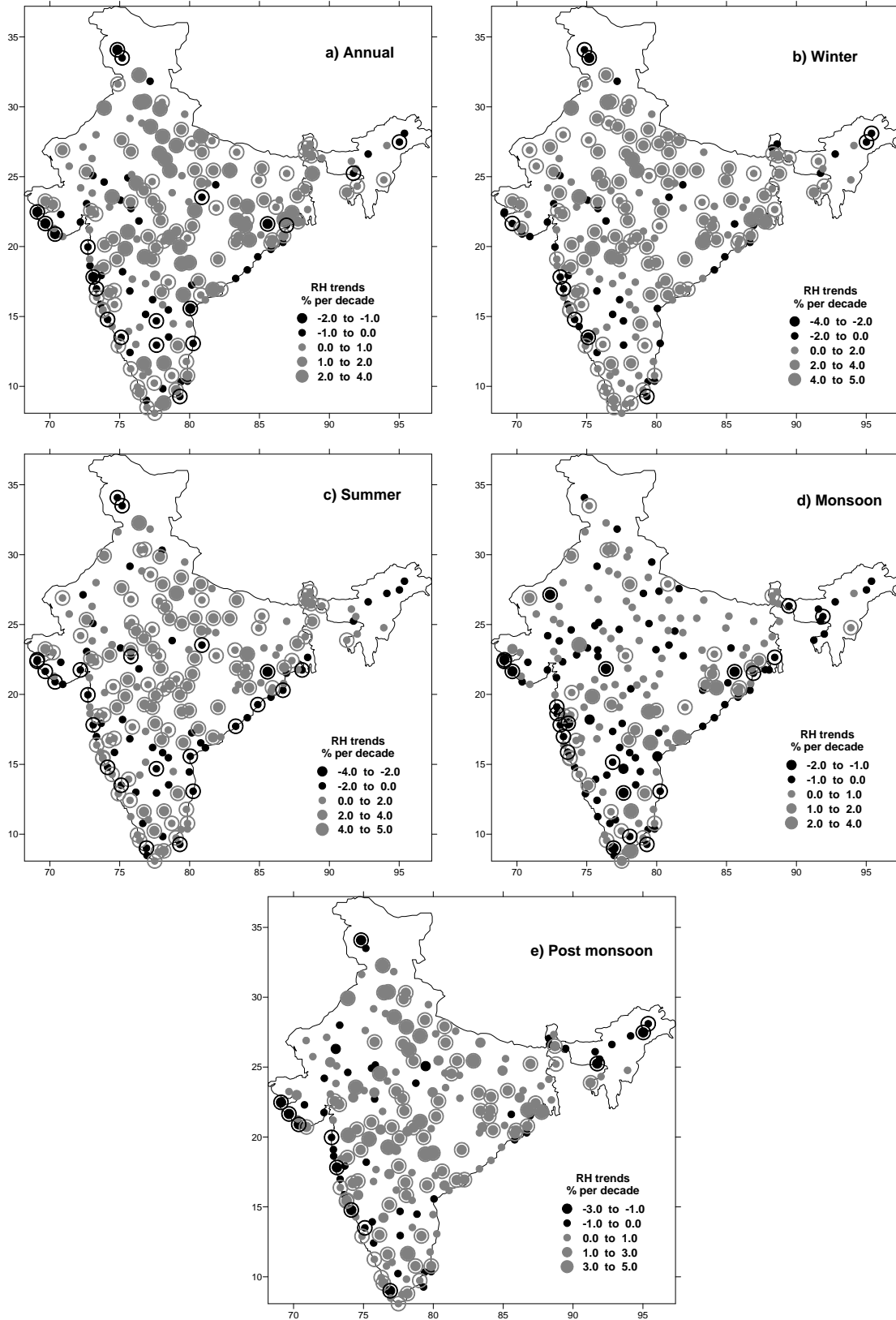
Out of 215 stations considered for this study, 191 stations (89%) are showing increasing trends in annual SPH out of which trends are significant for 145 stations as given in Table 2. Similarly, trends are increasing at 90%, 79%, 86% and 86% stations for winter, summer, monsoon and post monsoon seasons respectively. Seasonally, winter has highest number of stations (65%) showing significant increasing trend in SPH. It is clear from Figs. 4(a-e) that trends in SPH are significantly increasing over the country during 1969-2007 which are consistent with reported trends over India (Dai 2006 and Willett *et al.* 2007) and in other parts of the world such as western Europe (Dai 2006), Canada (Vincent *et al.* 2007), United States (Gaffen and Ross 1999 and Dai 2006) and China (Wang and Gaffen 2001).

Spatial patterns of trends in annual mean SPH [Fig. 4(a)] indicate significant increase all over the country but more coherently over central, southeastern and western parts. Annual mean SPH trend values are in the range -0.17 g/kg per decade to +0.88 g/kg per decade. Stations showing decreasing trends in annual SPH are scattered over the country and trends are significant at three coastal (Porbandar, Harnai and Ongole) and one inland (Umaria) station. As given in Table 2, almost 90% stations are showing increasing trends in winter season mean SPH. Spatial variability of trends in winter mean SPH indicates more coherent decreasing trends over north, central, eastern and northeastern India [Fig. 4(b)]. Almost all stations in the Indo-Gangetic plains are having significant increasing trend in winter season mean SPH, which has contributed to increase in fog days over the region resulting in significant decrease in atmospheric horizontal visibility as reported by De *et al.* (2001). The trend values of winter season mean SPH are in the range -0.24 to + 0.93 g/kg per decade. It is clear from Fig. 4(c) that summer season SPH trends are increasing strongly over north, central and eastern parts of India where many stations are having trends greater than +0.8 g/kg per decade. Spatial variability of monsoon season SPH [Fig. 4(d)] indicates increasing trends all over the country except in some pockets over south peninsula and Tamil Nadu where it is decreasing. The increasing trends in monsoon SPH are stronger over northwest and southeast India where most of the stations are having significant increase at ~0.4 g/kg per decade. The calculated trends in monsoon season SPH are between -0.22 and +1.10 g/kg per decade. Post monsoon season trends in SPH are increasing over the country except in small pockets over Western Ghats, south Rajasthan and adjoining Gujarat as shown in Fig. 4(e). Stations showing significantly increasing trends are located over north, east and south

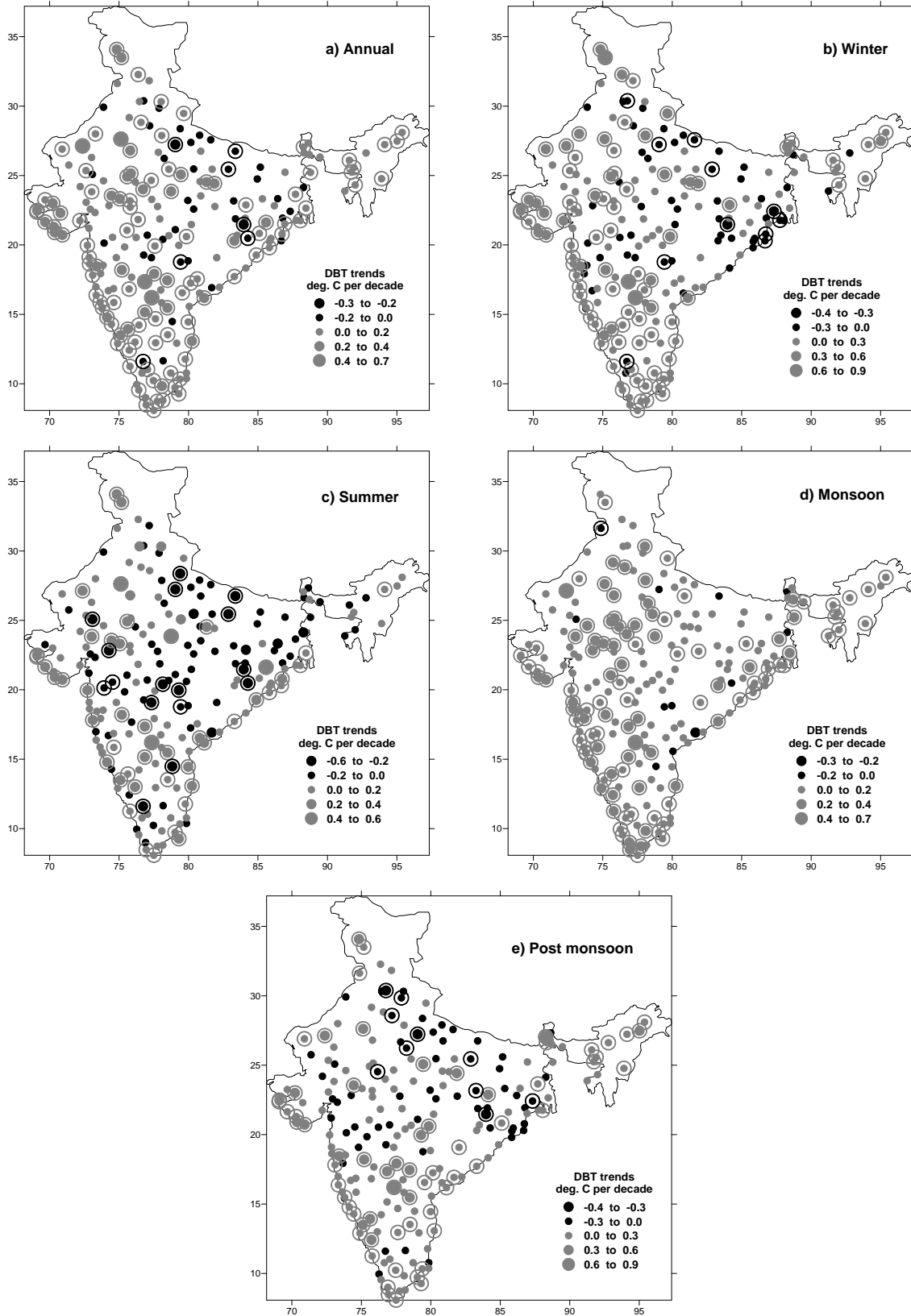
India where large numbers of stations have increasing trends greater than +0.5 g/kg.

3.4.2. Relative humidity trends

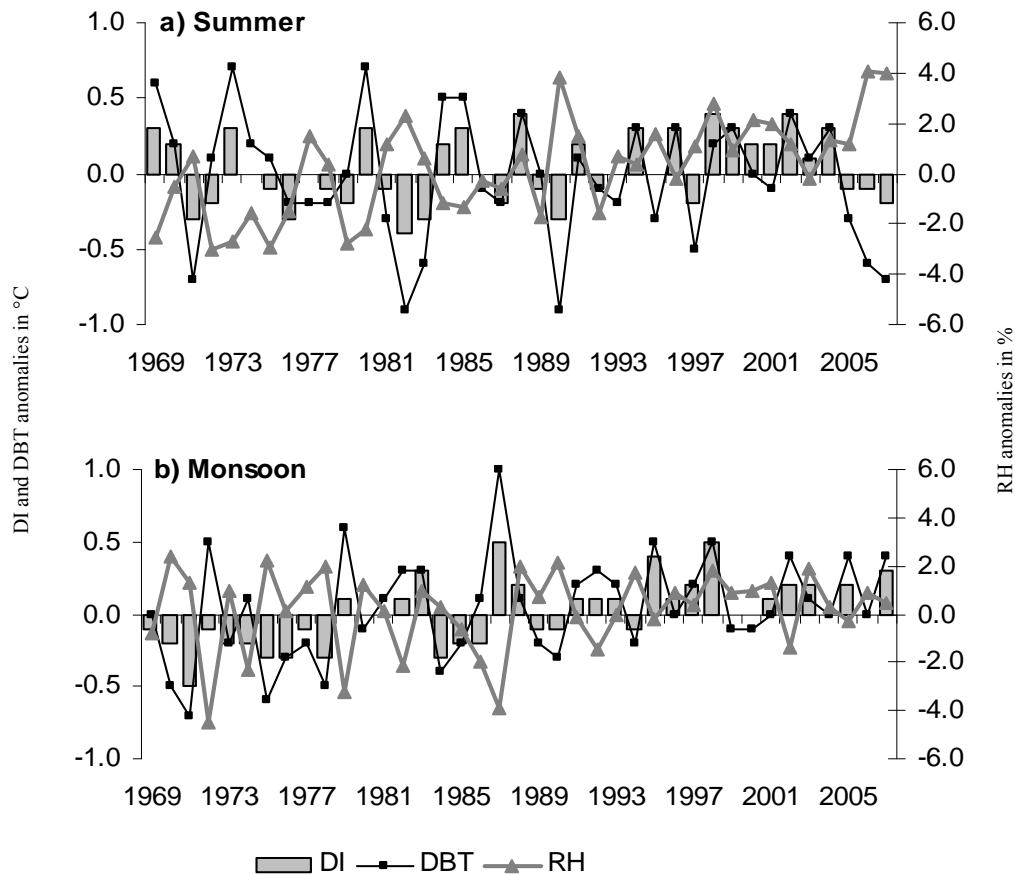
As given in Table 2, RH trends are increasing at 161, 169, 155, 125 and 162 stations for annual, winter, summer, monsoon and post monsoon seasons respectively. The calculated trends in annual mean RH are significantly increasing at 54% stations. Spatial patterns of trends in annual mean RH [Fig. 5(a)] suggest significant increase over north, central and south western parts of the country where trends greater than +2% per decade are obtained at large numbers of stations. However annual RH trends are significantly decreasing over Jammu and Kashmir and some pockets over coastal Gujarat, Western Ghats, Karnataka, Andhra Pradesh, Orissa and northeast India. The decreasing trends over Jammu and Kashmir agree with trends reported by Jaswal (2010b). The range of annual RH trends is from -1.78% to +3.60% per decade. The increasing trends in RH over India are consistent with trends reported by Dai (2006). Winter RH trends are increasing over India except Jammu and Kashmir, northeast and over some pockets along west coast of India as shown in Fig. 5(b). The increasing trends are spatially coherent over Indo-Gangetic plains, north Maharashtra and adjoining Andhra Pradesh where RH is increasing at more than 3% per decade. Significant increase in winter season RH over the Indo-Gangetic plains is consistent with reported significant decrease of horizontal visibility by De *et al.* (2001). Winter trends in RH are in the range between -3.50% and +4.96% per decade. Fig. 5(c) shows spatial variability of summer mean RH trends indicating significant increase over large parts of the country. Stations showing significant increasing trends are spatially more coherent over north, central, east and south peninsula. Stations in Jammu and Kashmir, northeast India and Tamil Nadu are showing decrease in summer season RH trends. Spatial patterns of trends in monsoon season mean RH are mixed over the country as seen in Fig. 5(d). Out of 125 stations showing increase in monsoon season RH, the calculated trends are significant at 21% stations only (Table 2). Even though the trends are weak, spatially these are increasing over large parts of the country except over Jammu and Kashmir, Assam, south Rajasthan, north Maharashtra and interior Karnataka. The trend values are in the range -1.87% and +3.60% per decade. Fig. 5(e) shows spatial distribution of post monsoon mean RH trends which indicates overall increase over the country except Jammu and Kashmir, northeast and some pockets over central Rajasthan, south Gujarat and south peninsula. Stations showing significantly increasing trends in post monsoon RH are spatially more coherent over Indo-Gangetic plains, north Maharashtra and adjoining Andhra Pradesh where



Figs. 5(a-e). Spatial distribution of trends in relative humidity (RH) in % per decade for 1969-2007. Trends significant at 95% level are shown by an outer circle



Figs. 6(a-e). Spatial distribution of trends in dry bulb temperature (DBT) in °C per decade for 1969-2007. Trends significant at 95% level are shown by an outer circle



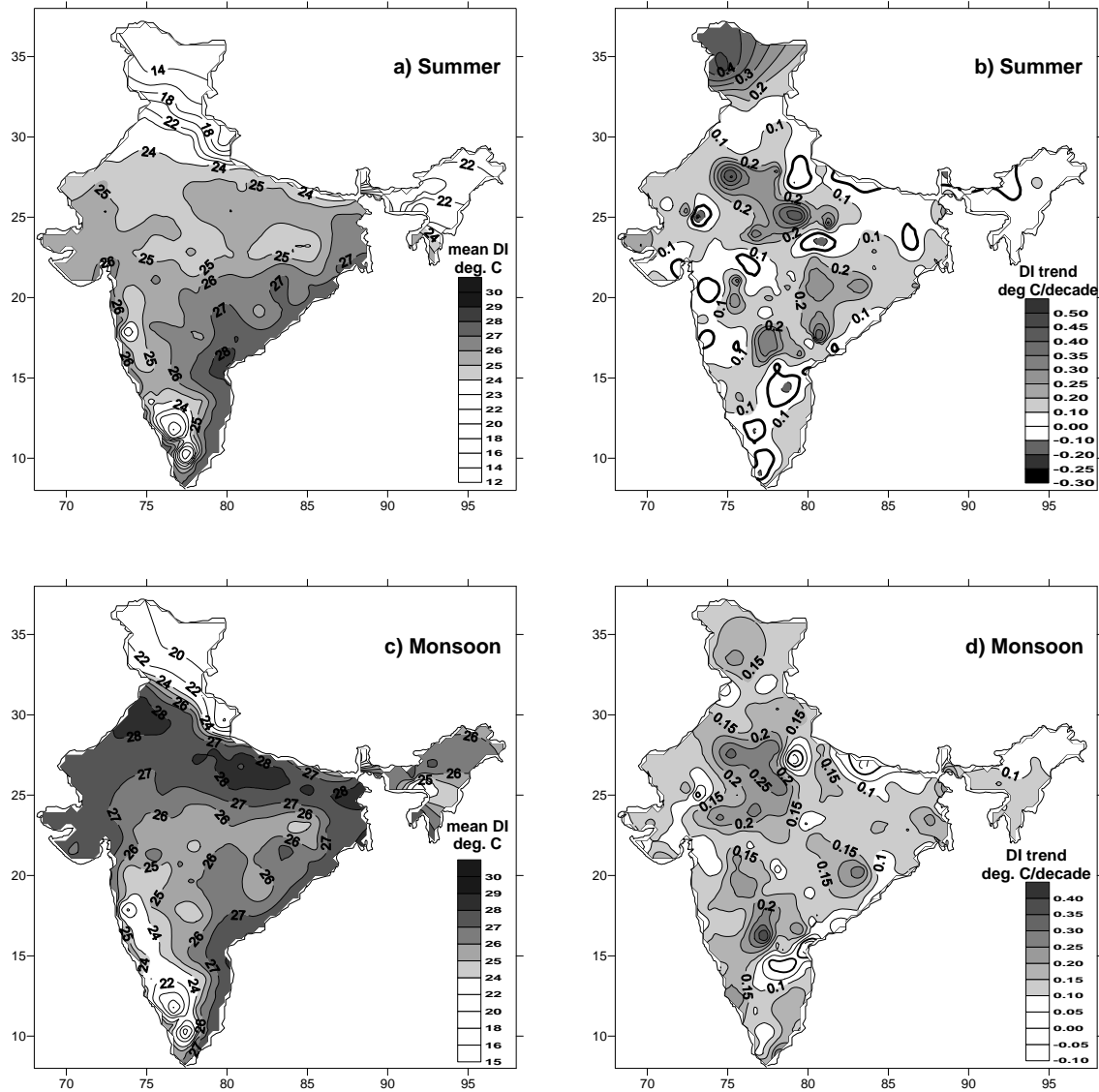
Figs. 7(a&b). Temporal variations of all India averaged discomfort index (DI), dry bulb temperature (DBT) and relative humidity (RH) for (a) summer and (b) monsoon seasons during 1969-2007. Data series are anomalies from 1971-2000 averages

many stations are having trends greater than 2% per decade.

3.4.3. Dry bulb temperature trends

Annual mean DBT trends are increasing at 174 stations (Table 2) and trend values lie between -0.30°C and $+0.60^{\circ}\text{C}$ per decade. Spatial patterns of annual trends indicate general increase over the country except over east Uttar Pradesh, Bihar and Chhattisgarh [Fig. 6(a)]. Stations over Jammu and Kashmir, Rajasthan and south peninsula have increasing trends ($\sim 0.2^{\circ}\text{C}$ per decade) which are spatially more coherent. However, annual DBT trends are decreasing ($\sim 0.1^{\circ}\text{C}$ per decade) in Indo-Gangetic plains which agree with trends reported by Singh and Sontakke (2002). Spatial patterns of winter mean DBT trends [Fig. 6(b)] suggest increase over large parts of the country except over Indo-Gangetic plains and Orissa. Many stations in Jammu and Kashmir, Rajasthan, Gujarat and

south peninsula are exhibiting increasing trends ($> 0.2^{\circ}\text{C}$ per decade) in winter DBT. The significant increase in winter DBT over Jammu and Kashmir and western Himalayas ($> 0.1^{\circ}\text{C}$ per decade) is consistent with overall trends reported over the region by Pant *et al.* (1999) and Bhutiyani *et al.* (2007). Summer DBT trends are increasing at 127 stations but spatially large parts of the country over Uttar Pradesh, Bihar, Sikkim, West Bengal, Assam and central India are having decreasing trends ($\sim 0.1^{\circ}\text{C}$ per decade) as shown in Fig. 6(c). Stations showing significant increase in summer DBT are spatially clustered in Jammu and Kashmir, Rajasthan, west Madhya Pradesh and south peninsula. 94% stations are showing increasing trend in monsoon mean DBT and spatial distribution of the trends [Fig. 6(d)] indicates general warming over all parts of the country with trend values in the range -0.23°C and $+0.61^{\circ}\text{C}$ per decade. Stations in Jammu and Kashmir, Rajasthan, west Madhya Pradesh, south Gujarat, Orissa, south peninsula and northeast India



Figs. 8(a-d). Spatial distribution of means ($^{\circ}\text{C}$) and trends ($^{\circ}\text{C}$ per decade) of discomfort index (DI) for summer and monsoon seasons for 1969-2007. Contours of mean DI $> 24^{\circ}\text{C}$ and trends in DI $> 0.1^{\circ}\text{C}$ per decade are shaded

are showing significant increasing trends ($> 0.2^{\circ}\text{C}$ per decade). Spatial patterns of post monsoon mean DBT trends [Fig. 6(e)] indicate increase over Jammu and Kashmir, northwest India, south peninsula and northeast India and decrease over Indo-Gangetic plains, south Rajasthan and west Madhya Pradesh.

3.5. Effects of rising temperature and humidity on human comfort

Human comfort and health are influenced by temperature and humidity variations and in India summer

and monsoon seasons are more prone to human discomfort. Extreme hot and sultry weather results in loss of productivity and increase in energy demand. High humidity compounds the effects by reducing evaporation and thus rendering perspiration a less effective cooling mechanism. According to Thom (1959), above a DI of 20°C the perspiration system becomes effective as a cooling mechanism to prevent body overheating. The higher the DI the more ineffective this mechanism becomes and as per classification of DI values by Giles *et al.* (1990), more than 50% population experience discomfort above 24°C and above 27°C most of the

population suffers discomfort. Some recent studies about discomfort over Indian cities have reported significant increase in discomfort in Mumbai in May and June (Srivastava *et al.* 2001) and in Chandigarh from May to August (Singh *et al.* 2006). Fig. 7(a) depicts temporal variations of summer season anomalies of DI, DBT and RH. The years of highest DI and DBT anomalies have lowest RH anomalies till 1990 when RH anomalies became continuously positive. From 2004 onwards DI and DBT anomalies have become negative while RH anomalies remain positive. It is clear from Fig. 7(b) that weak monsoon years (1972, 1979, 1987, 2002 and 2004) have higher positive DI and DBT anomalies and lower negative RH anomalies.

Patterns of long-term mean DI for summer [Fig. 8(a)] indicate higher DI values ($> 24^{\circ}\text{C}$) over the country except hilly areas in the north, northeast and small pockets in the south where values are lower. Regions of highest DI lie along both western and eastern coasts of India where mean DI $> 27^{\circ}\text{C}$ is noticed at many places suggesting strong heat stress. Spatial patterns of trends in mean DI for summer [Fig. 8(b)] indicate regions of strong increase in DI ($> +0.2^{\circ}\text{C}$ per decade) over Jammu and Kashmir, east Rajasthan, south Uttar Pradesh, north Madhya Pradesh, Chhattisgarh and Andhra Pradesh. Except for the hilly areas in the north and some pockets in the southwest all regions in the country have mean DI $> 24^{\circ}\text{C}$ for monsoon season as shown in Fig. 8(c). It is clear from the patterns of mean DI for monsoon that large areas along the eastern coast, Indo-Gangetic plains, Rajasthan and Gujarat are in high discomfort zone with mean DI $> 27^{\circ}\text{C}$. Western Maharashtra and southwest peninsula which is under the influence of southwest monsoon have DI values $< 24^{\circ}\text{C}$. Trends in mean DI for monsoon are increasing at the rate greater than $+0.15^{\circ}\text{C}$ per decade over Jammu and Kashmir, Madhya Pradesh, Andhra Pradesh and north Karnataka as shown in Fig. 8(d).

Based upon 215 surface meteorological stations well spread over India, the climatology of humidity for 1971-2000 is first studied followed by the analysis of spatial distribution of patterns of trends in SPH, RH and DBT. Then the effects of rising temperature and humidity on human comfort over the country are studied for summer and monsoon seasons. The climatology of humidity shows both temporal and spatial variations over the country with moist coastal regions and northeast India and driest central, north and northwest regions. While winter season has lowest humidity, it is the monsoon season when almost entire country has highest moisture. Annual means of SPH suggest coastal regions particularly east coast and northeast India as regions of highest ($> 14\text{ g/kg}$) moisture. Rajasthan and hilly areas of Himachal Pradesh, Jammu

and Kashmir and Uttarakhand are regions of lesser moisture ($\sim 11\text{ g/kg}$) in the country. Annual mean RH is highest ($> 60\%$) over Jammu and Kashmir, Himachal Pradesh, Punjab, Haryana, Indo-Gangetic plains, coastal areas, extreme south peninsula and northeast India. Seasonally, there are large variations in SPH with monsoon season having mean SPH $> 14\text{ g/kg}$ almost all over the country except Jammu and Kashmir and some pockets over Tamil Nadu while winter season has the lowest mean SPH ($< 8\text{ g/kg}$) over large parts of the country. Seasonal mean RH values are highest in monsoon when almost all regions of the country except west Rajasthan have RH $> 60\%$. However, summer season has lowest mean RH ($< 35\%$) over major part of the country particularly over Rajasthan and central India.

The trend analysis shows that all India trend in SPH is significantly increasing by $+0.23\text{ g/kg}$ per decade which agrees with regional and global increasing trends reported by Dai (2006) and Willett *et al.* (2007). The reported significant increasing trends in global and North Hemispheric SPH during 1976-2004 are $+0.06\text{ g/kg}$ and $+0.08\text{ g/kg}$ per decade respectively (Dai 2006). Recently, Willett *et al.* (2007) have found significant increase in global specific humidity at $+0.07\text{ g/kg}$ per decade with higher increasing trends over tropics from the homogenized gridded dataset for 1973-2002. The annual mean RH has significantly increased by $+0.85\%$ per decade with corresponding increase in annual mean DBT (non-significant) by $+0.04^{\circ}\text{C}$ per decade. The obtained increasing trends in RH are consistent with upward trends for India, eastern United States and western China reported by Dai 2006. The significantly increasing seasonal trends in SPH and RH (except monsoon) possibly explain significant decrease in pan evaporation over the country reported by Jaswal *et al.* (2008). The seasonal trends in mean SPH and RH indicate that the water content has increased significantly over the country in all four seasons. Even though the warming is more in monsoon ($+0.11^{\circ}\text{C}$ per decade), the highest increase in moisture content over the country is in winter and summer with significant increases in SPH (0.25 g/kg and 0.30 g/kg per decade respectively) and RH (1.49% and 1.10% per decade respectively).

Annual patterns of trends in SPH are increasing significantly over northwest, central and southeast India. Seasonally, the trends in SPH are increasing all over the country for all seasons but more coherently over northwest, central and southeast India during winter and summer. As given in Table 3, numbers of stations having positive correlation between SPH and DBT are 60%, 82%, 45%, 45% and 67% for annual, winter, summer, monsoon and post monsoon respectively. On the other hand, the numbers of stations having negative correlation between

TABLE 3

Numbers of stations having negative/positive correlation between mean specific humidity (SPH) and mean dry bulb temperature (DBT) for 1969-2007

	Numbers of stations				
	Annual	Winter	Summer	Monsoon	Post Monsoon
Negative	86	38	118	119	71
Positive	129	177	97	96	144

TABLE 4

Numbers of stations having negative/positive correlation between mean relative humidity (RH) and mean dry bulb temperature (DBT) for 1969-2007

	Numbers of stations				
	Annual	Winter	Summer	Monsoon	Post Monsoon
Negative	196	168	211	210	194
Positive	19	47	4	5	21

RH and DBT are 91%, 78%, 98%, 98% and 90% for annual, winter, summer, monsoon and post monsoon respectively (Table 4) suggesting spatially strong negative correlation. Annual DBT and RH trends are generally opposite and regions of strong increase (decrease) in DBT have decrease (increase) in RH. Increase in DBT and decrease in RH over Jammu and Kashmir and decrease in DBT and increase in RH over the Indo-Gangetic plains is noteworthy.

Human comfort is strongly influenced by the increase in DBT and RH over coastal regions and southeast India in summer and over east coast, west and northwest India and entire Indo-Gangetic plains during monsoon season where average DI values are more than 27° C. The increasing trends in DI over Jammu and Kashmir are more influenced by strong increasing trends in DBT since RH trends are decreasing. Summer season increase in DI over Indo-Gangetic plains is more due to increase in RH over the region as there is decrease in DBT. The strong increasing trends in DI over northwest, central, southeast India and southwest peninsula appears to be due to strong increase in both DBT and RH.

There are several possible causes for the increase in moisture content over India but the major factors seem to be urbanization, land-use modification and large increase in irrigation in many parts of the country during last 3-4 decades. Impacts of deforestation and changes in land use

patterns on climate have been the focus of several studies (Kalnay and Cai 2003, Zhou *et al.* 2004 and Zhang *et al.* 2005) which have attributed surface temperature warming to changes in land-use pattern. Therefore further studies are required to validate these findings.

4. Conclusions

In this study, annual and seasonal trends in humidity and temperature are examined for 1969-2007 in order to determine if there are any significant changes in the moisture content of the surface layer over India. The data analysis has shown evidence of significant increase in both atmospheric moisture content and temperature with trends in annual mean specific humidity, relative humidity and air temperature showing increase at 89%, 75% and 81% stations respectively. The main results of this study are summarized below.

(i) Annual mean specific humidity is generally low (~9 g/kg to 12 g/kg) over the country except over coastal regions. Seasonally, the lowest mean specific humidity (~5 g/kg to 9 g/kg) is observed in winter while monsoon season has the highest (~17 g/kg to 21 g/kg) over almost entire country. Mean relative humidity is lowest in summer (~35% to 50%) and highest in monsoon when almost all parts of the country have humidity more than 60%.

(ii) Seasonal mean specific humidity is highest (18.3 g/kg) in monsoon season and lowest (9.8 g/kg) in winter season while relative humidity is highest (74.7%) in monsoon season and lowest in summer season (51.4%).

(iii) All India averaged specific humidity trends are significantly increasing for all periods while relative humidity trends are significantly increasing except for monsoon. Dry bulb temperature trends are weak and increasing significantly for monsoon season only. The rate of change of specific humidity, relative humidity and dry bulb temperature are highest in summer (+0.28 g/kg per decade), winter (+1.49% per decade) and monsoon (+0.11° C per decade) respectively.

(iv) Specific humidity trends are significantly increasing and spatially highly coherent over the country for all periods indicating general increase in moisture content. However, spatial patterns of trends in relative humidity and dry bulb temperature are nearly complementary and regions of strong increase (decrease) in dry bulb temperature have decrease (increase) in relative humidity.

(v) The spatial patterns of discomfort index show that the aerial extent of uncomfortable conditions over India increases both north and westward as season progresses from summer to monsoon. Heat stress is more severe in monsoon season over Indo-Gangetic plains, Rajasthan, Gujarat and east coast where trends are positive.

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