

# Variability in surface inversion characteristics over India in winter during the recent decades

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The variation in surface inversions during the recent decades over 20 stations in the Indian region is documented. Radiosonde data at 00UTC for the period 1971–2000 has been used to compute the inversion frequency. The depth and strength of the inversions as well as the wind speed through the inversion layer have also been computed. The frequency of inversions at stations north of 20°N is ~20–60% higher than stations located south of 20°N. Moreover, all the stations show frequencies increasing from the 1st to the 3rd decade. Most of the stations show decreasing depth and increasing strength significant at 99% level. With the exception of Nagpur and Hyderabad which show high frequency of very deep inversions increasing from the 1st to the 3rd decade, the decadal variations of inversion depth at most of the other stations show that shallow and moderate inversions occur more frequently than deep or very deep inversions. Decadal variations in inversion strength show weak inversion frequencies decreasing from the 1st to the 3rd decade while moderate/strong inversions occur more frequently at most stations. Frequencies of very strong inversions are low or absent. Wind speeds are either weak or moderate with frequencies increasing from the 1st to the 3rd decade. Low frequency of strong winds and negligible frequency of very strong winds are observed.

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## 1. Introduction

Long wave radiation emitted by the earth's surface at night cools the land much faster than the air above it thus trapping cold air at the surface and making the boundary layer stable. Additionally, when the nights are clear and winds are calm or light, occurrence of surface inversions in winter is a common feature. These inversion layers are destroyed in the day time due to insolation. By inhibiting vertical mixing, inversions play a significant role in the trapping and dispersal of pollutants. In the presence of ground inversions along with the surface concentration of pollutants, fog formation is a possibility if some moisture becomes available. Pollutants trapped at the surface pose a serious threat to the health of the public while reduced visibility due to fog is hazardous for aviation and surface transport. Therefore, knowledge of

inversions may help in understanding the dispersal of pollutants and fog, both of which will immensely benefit the public at large, especially in the cities, which has expanded due to rapid growth in urban population and industrialization.

Several researchers have studied ground inversions/low level inversions over different regions of the world based on the analysis of radiosonde data. Hosler (1961) has reported areas with high frequency of inversions being characterized by a higher frequency of clear nights with light winds and *vice-versa*. The study by Baker *et al* (1969) showed that a decrease in frequency and intensity indicated an increased urban influence on the temperature of the region. Wendler and Nicpon (1975) found inversion strength increasing with decreasing cloudiness, wind speed and net radiation. Myrick *et al* (1994) noted that median depths of ground-based early morning inversions

**Keywords.** Surface inversion; frequency of inversion; inversion depth; inversion strength.

Table 1. Data availability (total days) in winter for stations north of 20°N.

Year	AGT	AHM	BWN	CAL	DBH	DLH	GHT	GWL	JDP	LKN	NGP	PTL
1971	–	79	27	90	–	88	86	–	84	81	90	–
1972	–	86	73	90	–	89	88	–	80	86	88	–
1973	–	84	84	90	–	86	65	–	88	84	89	–
1974	–	72	73	88	–	89	81	–	89	88	89	–
1975	–	82	87	89	–	90	89	–	88	88	90	–
1976	–	85	88	83	–	91	85	–	85	87	91	–
1977	–	85	86	83	–	89	90	–	71	82	90	23
1978	27	82	89	88	28	89	90	15	84	88	86	84
1979	85	78	86	58	84	89	84	66	69	83	78	86
1980	88	84	80	89	78	91	79	78	67	86	82	82
1981	90	80	85	80	90	90	75	82	78	84	87	88
1982	87	79	89	72	86	89	89	67	55	90	85	88
1983	88	74	86	88	46	90	63	74	59	82	83	89
1984	52	83	89	85	14	90	53	60	84	86	60	90
1985	54	75	90	86	56	90	87	75	88	83	88	89
1986	69	81	88	89	86	89	83	56	87	88	90	86
1987	68	76	80	90	76	86	88	76	87	88	90	88
1988	84	78	88	91	71	87	90	84	88	90	91	91
1989	74	80	86	89	84	88	88	77	90	86	90	87
1990	86	74	89	89	54	88	87	83	86	83	87	80
1991	73	80	89	90	75	90	85	58	69	70	90	64
1992	82	86	91	91	71	89	89	81	85	91	90	67
1993	84	84	89	90	89	90	85	82	86	88	89	89
1994	75	78	88	90	85	90	86	80	85	89	90	85
1995	85	87	88	89	55	89	86	80	86	86	89	85
1996	84	74	80	90	88	91	91	85	85	82	89	78
1997	81	85	90	90	85	90	88	85	85	75	90	85
1998	72	85	90	90	85	90	89	76	89	88	88	87
1999	59	79	59	89	63	90	90	81	86	90	82	89
2000	30	82	70	90	43	91	90	60	85	90	91	90

were typically 414 m irrespective of season with spring slightly lower at 315 m, while Janhall *et al* (2006) reported that morning temperature inversions resulted in high concentrations of traffic related pollutants including CO, NO, and NO<sub>2</sub>. Bourne *et al* (2009) examined the trends and variability in surface inversion parameters and found an increasing trend in inversion depth and strength with both parameters showing a distinct shift from positive to negative anomalies in late 1970's. Studies of inversion characteristics are available over the Indian region too, e.g., Ananthkrishnan and Rangarajan (1963), Sivaramkrishnan *et al* (1972), Chaudhary (1982, 1983), Viswanadham and Pinaka Pani (1994), Suresh (2000), etc. They found that stable layer occurred on 75% of the occasions and frequencies of inversions were much higher for stations located north of 20°N as compared to the stations south of 20°N. They also reported maximum frequencies of inversion over eastern and southwestern regions of north India while minimum frequencies were observed in the

western parts. A significant increasing trend in the frequencies of nocturnal inversions over Chennai was attributed to rapid urbanization. Studies of surface inversions over India are few and have been done for limited stations and short periods of time, mostly prior to the 1970's. To document the changes that have taken place since then, we have studied the annual and decadal variations in surface inversions over twenty stations in India for the period 1971–2000 during winter.

## 2. Data and methodology

Daily radiosonde data from India Meteorological Department (IMD) at 00 UTC for 20 stations well distributed over India for the period 1971–2000 in the winter months (December, January and February) are analysed to study the annual as well as decadal variations in surface inversion parameters. As surface inversions are to be studied, we have considered data up to 800 hPa only (~2 km).

Table 2. Data availability (total days) in winter for stations south of 20°N.

Year	BMB	CHN	HYD	MDS	MNC	PBL	PJM	TRV
1971	89	89	30	85	81	87	28	84
1972	83	89	79	89	88	85	82	89
1973	81	84	78	85	87	82	76	79
1974	85	79	64	85	74	86	84	82
1975	79	86	86	83	87	74	57	88
1976	89	77	77	85	85	66	79	89
1977	84	79	82	87	87	86	79	89
1978	84	83	86	90	76	84	82	84
1979	69	77	84	88	80	87	82	88
1980	84	87	90	81	74	87	79	91
1981	81	87	83	90	77	90	85	90
1982	88	86	88	90	64	90	87	88
1983	73	89	87	88	82	89	87	86
1984	82	88	87	84	88	46	87	89
1985	72	86	86	88	86	85	84	90
1986	88	87	87	90	79	74	88	89
1987	85	63	90	88	82	89	84	90
1988	91	74	90	88	70	87	86	91
1989	90	68	75	89	87	65	83	90
1990	88	77	90	87	89	23	80	88
1991	86	74	88	87	79	74	62	86
1992	89	87	87	87	72	86	90	89
1993	90	81	86	88	90	79	84	89
1994	89	86	89	87	89	85	88	90
1995	88	84	86	88	81	79	74	88
1996	91	88	83	90	86	77	83	91
1997	88	90	85	87	82	86	83	89
1998	87	89	83	90	90	66	88	87
1999	90	90	89	89	90	87	88	88
2000	91	90	91	90	89	89	86	77

The Chronometric (C) and Fan (F) type radiosondes which were used in India in the 1950's and 1960's were replaced by Audio Modulated (AM) type in the late 1960's. To avoid inconsistencies in data caused by instrument change, we have used data from 1971 onwards when uniform data was available as the C and F type sondes were replaced by AM type sondes (Kothawale and Rupa Kumar 2002). Before permanent archival, the data is processed and several checks were applied to ensure homogeneity (Srivastava *et al* 1992). Inconsistencies do occur despite these checks, thus, before analyzing we have discarded data whenever abnormal values were found. The observations at standard levels are available at a resolution of  $\sim 500$  m. We have incorporated data at significant levels in the standard levels, so we could get a resolution of  $\sim 200$ – $250$  m. As per WMO convention, pressure is accurate to  $\sim \pm 1$ – $2$  hPa and temperatures are accurate to  $\pm 0.5^\circ\text{C}$  up to 20 km. Wind accuracy is  $\sim 1$  m/s and  $5^\circ$  for speed and direction, respectively. Tables 1 and 2 give the number of days for

which data is available for each station, yearwise, in the winter months. A maximum of 90 days is possible for each year with leap years having 91 days.

The stations have been divided into two regions according to their location as shown in figure 1. The region north of  $20^\circ\text{N}$  is designated as R1 and there are 12 stations in this region, viz., Agartala (AGT), Ahmedabad (AHM), Bhubaneswar (BWN), Kolkata (CAL), Dibrugarh (DBH), Delhi (DLH), Guwahati (GHT), Gwalior (GWL), Jodhpur (JDP), Lucknow (LKN), Nagpur (NGP) and Patiala (PTL). R2 which is south of  $20^\circ\text{N}$  has eight stations, viz., Mumbai (BMB), Cochin (CHN), Hyderabad (HYD), Chennai (MDS), Minicoy (MNC), Port Blair (PBL), Panjim (PJM) and Trivandrum (TRV). The reason for the demarcation is that most of R1 is under the influence of western disturbances in winter while R2 is a peninsular region. The stations' latitude and longitude are shown in table 3.

Ground-based or surface inversion (hereafter simply inversions) is defined as the layer from

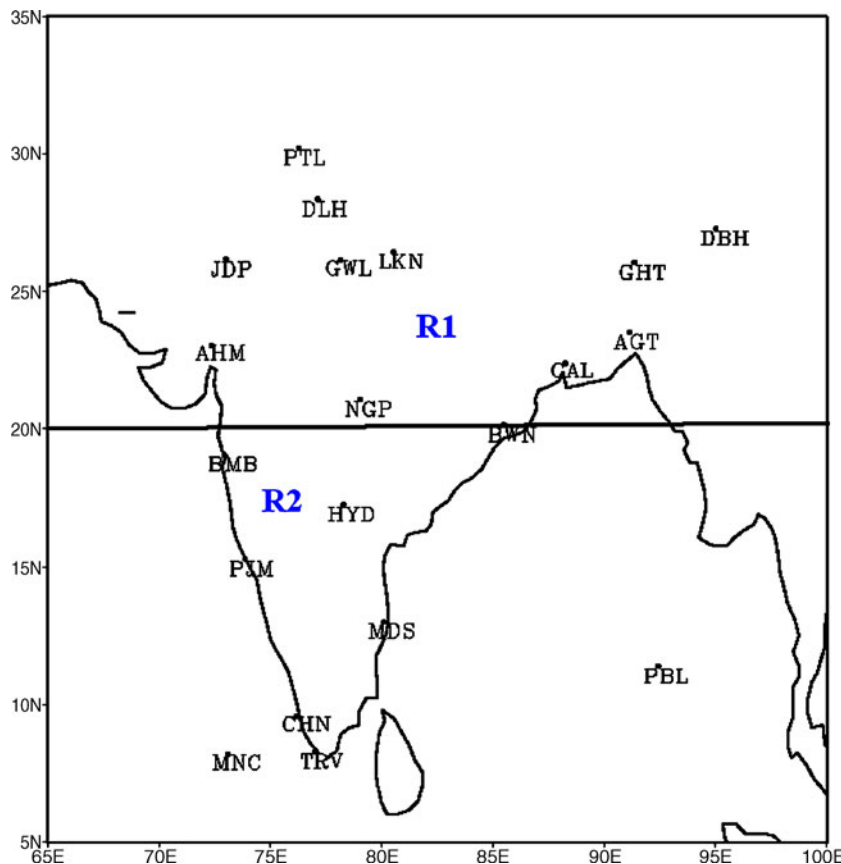


Figure 1. Map showing location of the stations.

the surface in which an increase in air temperature is observed. The top of the inversion is the height above which temperature first decreased with elevation. The frequency distribution of the inversion layers during the winter months are obtained for the three decades, viz., 1971–1980 (1st decade), 1981–1990 (2nd decade) and 1991–2000 (3rd decade) to understand their secular variations. The annual and the decadal variations in inversion depth and strength as well as the changes in the wind speed through the inversion layer are also studied.

The basic characteristics of inversion are: (a) depth ( $\Delta h$  meter) which is the height of the top of the inversion from the ground and (b) strength ( $\Delta T$  °C) which is the temperature difference between the top of the inversion and the ground. Based on its depth the inversion is classified as shallow, moderate, deep and very deep as:

Shallow :  $\Delta h = 0\text{--}200$  m  
 Moderate :  $\Delta h = 201\text{--}400$  m  
 Deep :  $\Delta h = 401\text{--}600$  m  
 Very deep :  $\Delta h > 600$  m.

Similarly, the inversion is classified as weak, moderate, strong and very strong based on its strength as:

Weak :  $\Delta T = 0\text{--}2^\circ\text{C}$   
 Moderate :  $\Delta T = 2\text{--}6^\circ\text{C}$   
 Strong :  $\Delta T = 6\text{--}10^\circ\text{C}$   
 Very strong :  $\Delta T > 10^\circ\text{C}$ .

### 3. Results and discussion

#### 3.1 Frequency distribution of inversions

Table 3 gives the frequency distribution of the inversions for all stations in R1 and R2. It is clear from the table that the inversion frequencies are  $\sim 20\text{--}60\%$  higher in R1 as compared to R2 in all the decades. Further, the frequency of inversions increased from the 1st to the 3rd decade for all stations in R1 except GWL, NGP and PTL. Though these three stations show frequencies of  $\sim 90\%$  in all the decades, a slight decrease of  $\sim 3\%$  is observed from the 1st to the 3rd decade. Comparatively,

Table 3. Frequency distribution (%) of surface inversions.

Stations	Latitude (°N)		Longitude (°E)		1971–1980	1981–1990	1991–2000
Agartala (AGT)	23	53	91	15	88	89	92
Ahmedabad (AHM)	23	04	72	38	84	86	91
Bhubaneshwar (BWN)	20	15	85	50	41	65	79
Kolkata (CAL)	22	39	88	27	71	76	88
Dibrugarh (DBH)	27	29	95	01	67	77	73
New Delhi (DLH)	28	35	77	12	88	88	92
Guwahati (GHT)	26	06	91	35	64	80	79
Gwalior (GWL)	26	14	78	15	92	94	89
Jodhpur (JDP)	26	18	73	01	87	79	91
Lucknow (LKN)	26	45	80	53	77	73	77
Nagpur (NGP)	21	06	79	03	93	84	90
Patiala (PTL)	30	20	76	28	95	93	91
Mumbai (BMB)	19	07	72	51	77	84	92
Cochin (CHN)	10	09	76	24	11	16	25
Hyderabad (HYD)	17	27	78	28	23	46	56
Chennai (MDS)	13	00	80	11	31	50	58
Minicoy (MNC)	08	18	73	09	8	16	23
Port Blair (PBL)	11	40	92	43	6	11	11
Panjim (PJM)	15	29	73	49	50	70	74
Trivandrum (TRV)	08	28	76	57	4	8	35

lower frequencies ( $\sim 4$ – $31\%$  in the 1st decade to  $\sim 11$ – $58\%$  in the 3rd decade) are observed in R2 at all stations except BMB and PJM where it ranges from  $\sim 50$ – $77\%$  in the 1st decade to  $74$ – $92\%$  in the 3rd decade. Though the frequencies are lower, all stations in R2 show an increase in the frequency of inversions from the 1st to the 3rd decade.

### 3.2 Annual variations in inversion depth and strength

The annual variations in the inversion depth (figure 2) show that all stations in R1 except DLH, GWL, JDP and NGP (where trends are not significant) show a decline in the inversion depth significant at 99% level. The maximum decline of 12.3 m/year is observed at AGT and the minimum decline is observed at CAL (3.3 m/year). In R2, a decreasing trend in inversion depth ( $\sim 4$  m/year) is seen at BMB, HYD and PJM significant at 99% level. While an increasing trend in inversion depth is not observed at any of the stations in R1, three stations located in R2 show an increase in inversion depth ranging from 3–8.5 m/year significant at 99% level for CHN and MNC and at 95% level for MDS. No significant trend is observed at PBL and TRV.

Half of the stations located in R1 show an increasing trend in inversion strength (figure 3) ranging from 0.03–0.06°C/year significant at 99%

level for BWN, DLH and JDP and at 95% level for AGT, AHM and CAL. The remaining six, viz., DBH, GHT, GWL, LKN, NGP and PTL are among the stations that do not show any significant trend. In R2, all stations except BMB, MNC and TRV show an increase in the strength of the inversions from 0.02–0.05°C/year significant at 99% level for PBL and PJM and at 95% level for CHN, HYD and MDS.

### 3.3 Decadal variations in inversion depth

Figure 4 shows the decadal variations in inversion depth. It is observed that shallow inversions are absent for all stations in R1 except CAL and BWN where frequency of  $\sim 20\%$  in the 1st decade decreases to  $< 5\%$  in the 3rd decade. Moderate inversions are absent in the 1st decade for all stations. The frequency generally increases by  $\sim 20\%$  from the 2nd to the 3rd decade for AHM, BWN, AGT, CAL, DBH and GHT. For the other stations, low frequency ( $< 15\%$ ) is observed in the 2nd and 3rd decades. Frequency of deep inversions decreases from 80% in the 1st to  $\sim 50\%$  in the 2nd decade and to  $\sim 20$ – $30\%$  in the 3rd decade for all stations. Very deep inversions with low frequencies in all the decades are observed at all stations except PTL, JDP, GWL, NGP and DLH. Over these stations, frequency increases from 20% in the 1st decade to 30% in the 3rd decade. NGP shows high

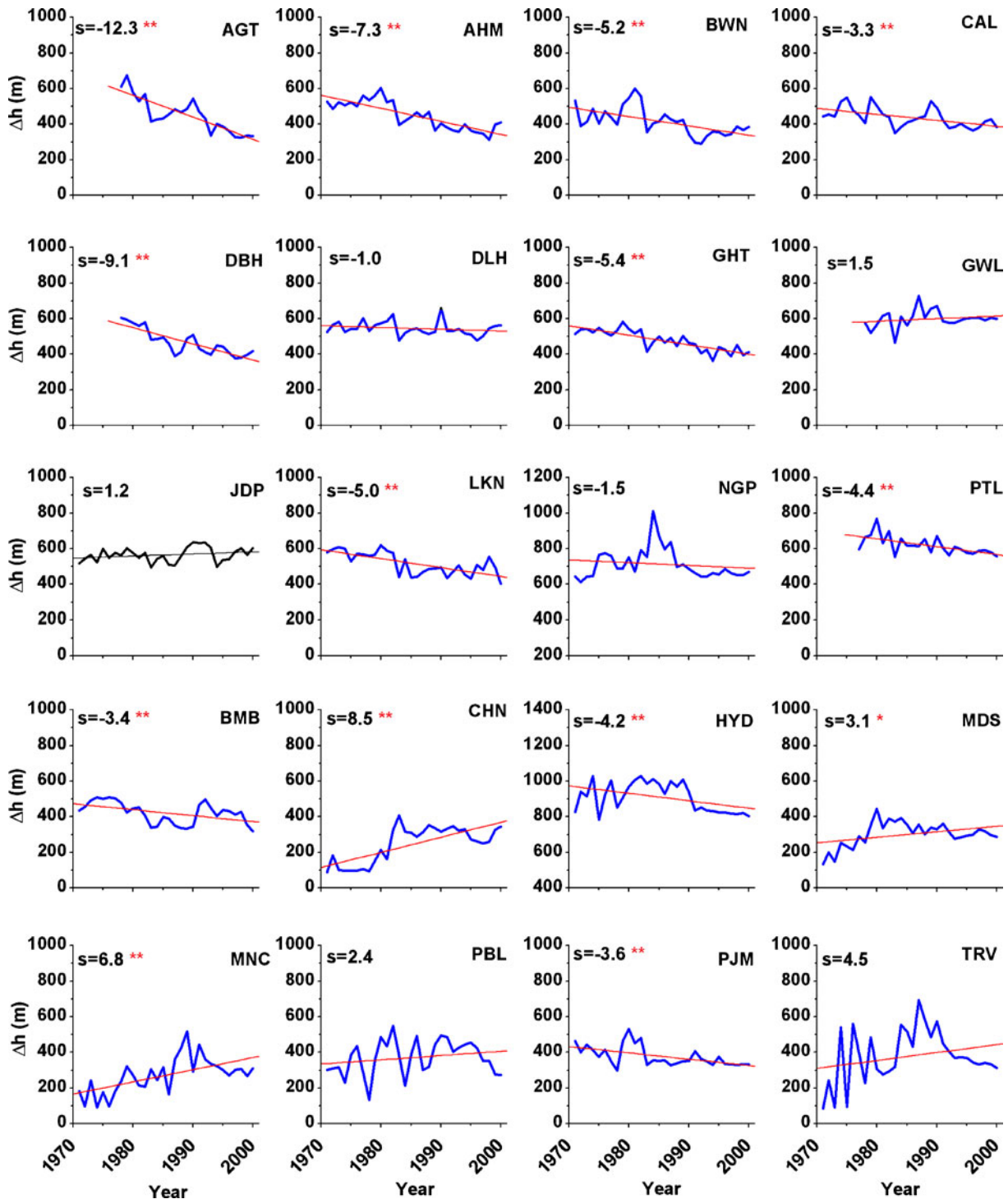


Figure 2. Annual variations in inversion depth (trends significant at 95% (99%) level are marked by \* (\*\*)).

frequency of very deep inversions increasing from  $\sim 50\%$  in the 1st decade to  $\sim 70\%$  in the 2nd and 3rd decades.

Frequencies of shallow inversions in R2 decrease sharply from the 1st to the 2nd decade and are very low or absent in the 3rd decade for all stations except HYD where no frequency in this range is observed. Moderate inversions are not

observed in the 1st decade for any of the stations. An increase in the frequency ( $\sim 20\text{--}40\%$ ) of moderate inversions from the 2nd to the 3rd decade is seen for all stations except BMB where a 20% decrease is observed. The frequency of deep inversion decreases by  $\sim 40\text{--}50\%$  from the 1st to the 3rd decade for nearly all the stations. Very deep inversions are absent for all stations except HYD

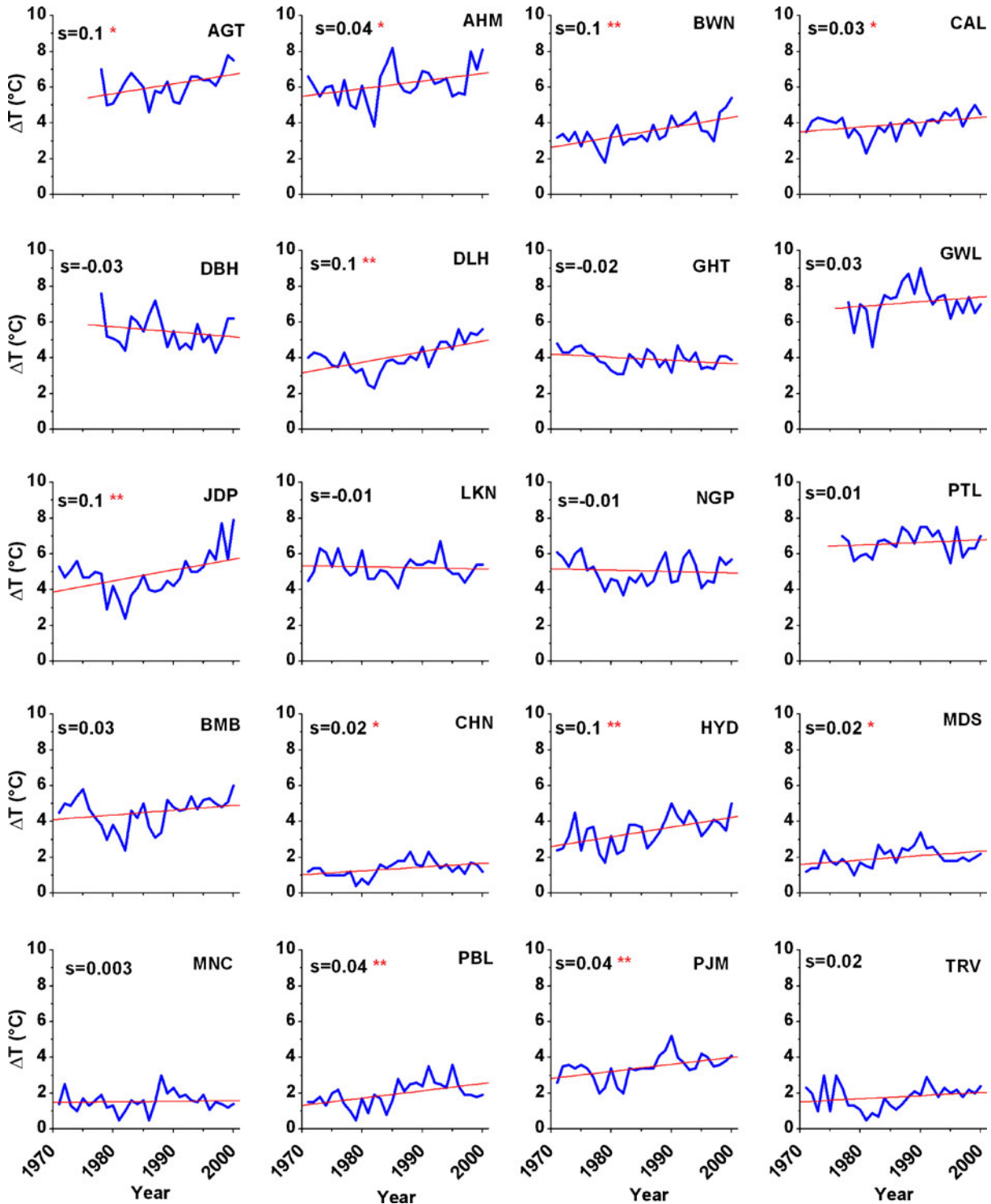


Figure 3. Annual variations in inversion strength (trends significant at 95% (99%) level are marked by \* (\*\*)).

where frequencies increase from the 1st (70%) to the 3rd (~90%) decade.

#### 3.4 Decadal variations in inversion strength

Frequency of weak inversions in R1 (figure 5) decreases from the 1st to the 3rd decade. Most of

the inversions are either moderate or strong for all the stations. For DLH, GHT and CAL, the maximum frequency occurs in moderate inversions for all decades though a slight decrease is observed from the 1st to the 3rd decade. Moderate inversions are found to decrease from ~40–60% in the 1st decade to 30–55% in the 3rd decade for PTL,

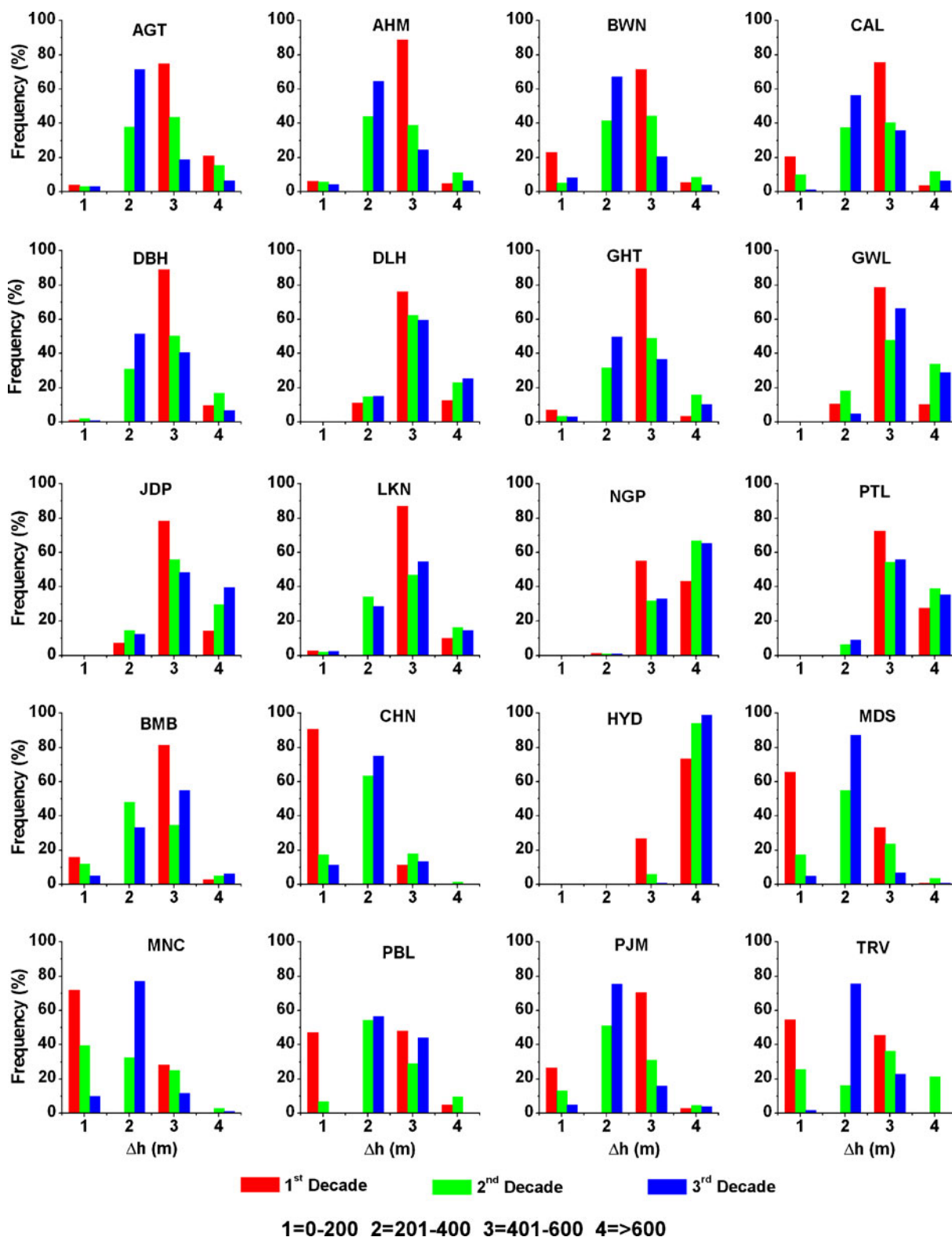


Figure 4. Decadal variations in inversion depth.

JDP, GWL, NGP, AHM, LKN and AGT. A 10% increase in moderate inversions from the 1st to the 3rd decade is observed at BWN. Similarly, slight increase (~5–10%) in strong inversions from the

1st to the 3rd decade is seen at PTL, GWL, NGP, AHM, LKN, JDP and AGT while a decrease from the 1st (42%) to the 3rd decade (38%) is seen at DBH. For DLH, CAL and GHT, frequencies



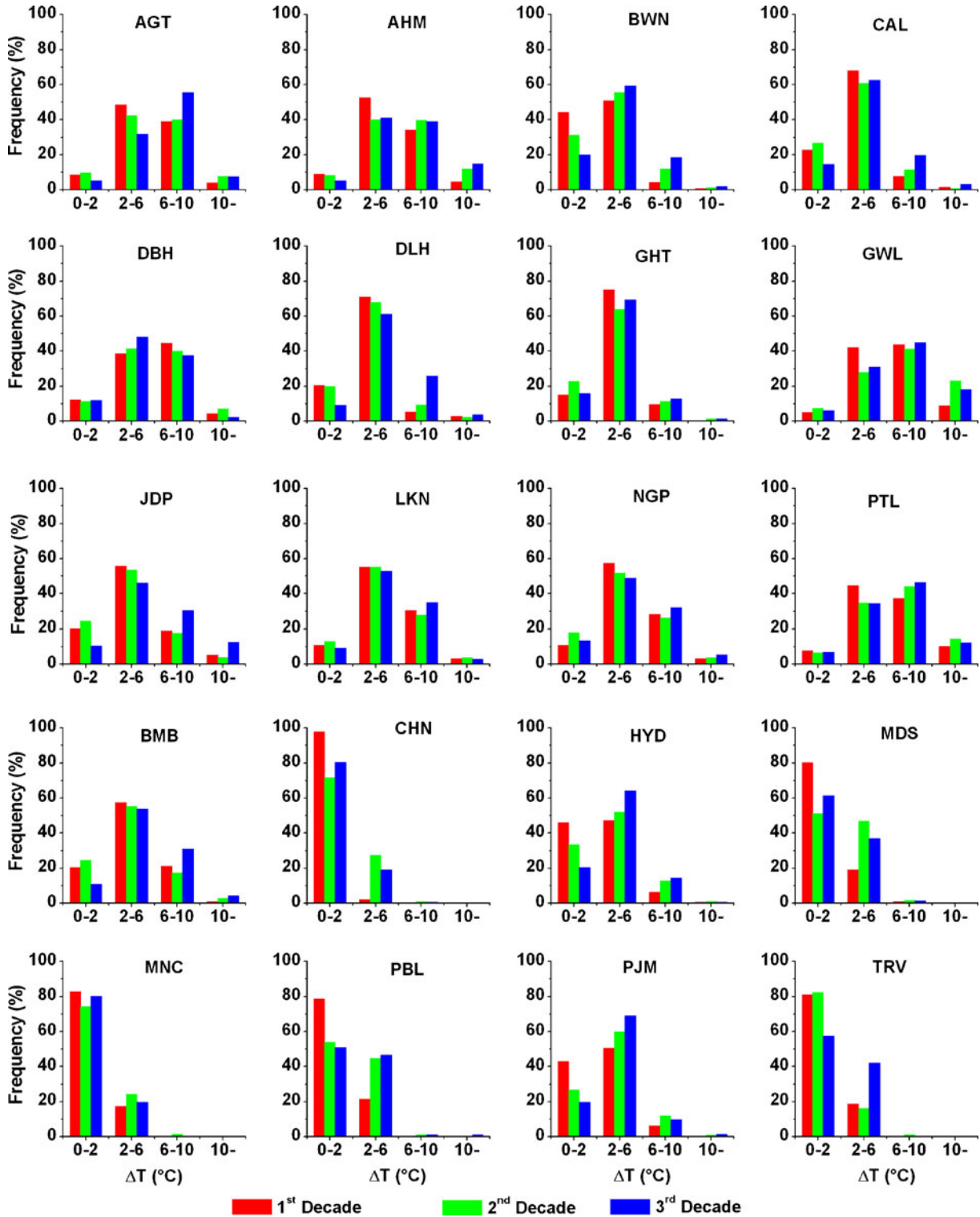


Figure 5. Decadal variations in inversion strength.

of strong inversions are low though an increase is observed from the 1st to the 3rd decade ( $\sim 5\%$ – $\sim 20\%$ ). The frequencies of very strong inversions are either low ( $<20\%$ ) or are absent.

In R2, frequency of weak inversions is 80% in the 1st decade for CHN, MNC, TRV and PBL.

This reduces to  $\sim 50\text{--}70\%$  in the 2nd decade and increases to  $\sim 60\text{--}80\%$  in the 3rd decade for CHN, MNC and MDS. A decrease to 55% from the 2nd to the 3rd decade is observed for TRV and PBL while PJM and BMB show a reduction of 50% from the 1st to 3rd decade. For moderate inversions,

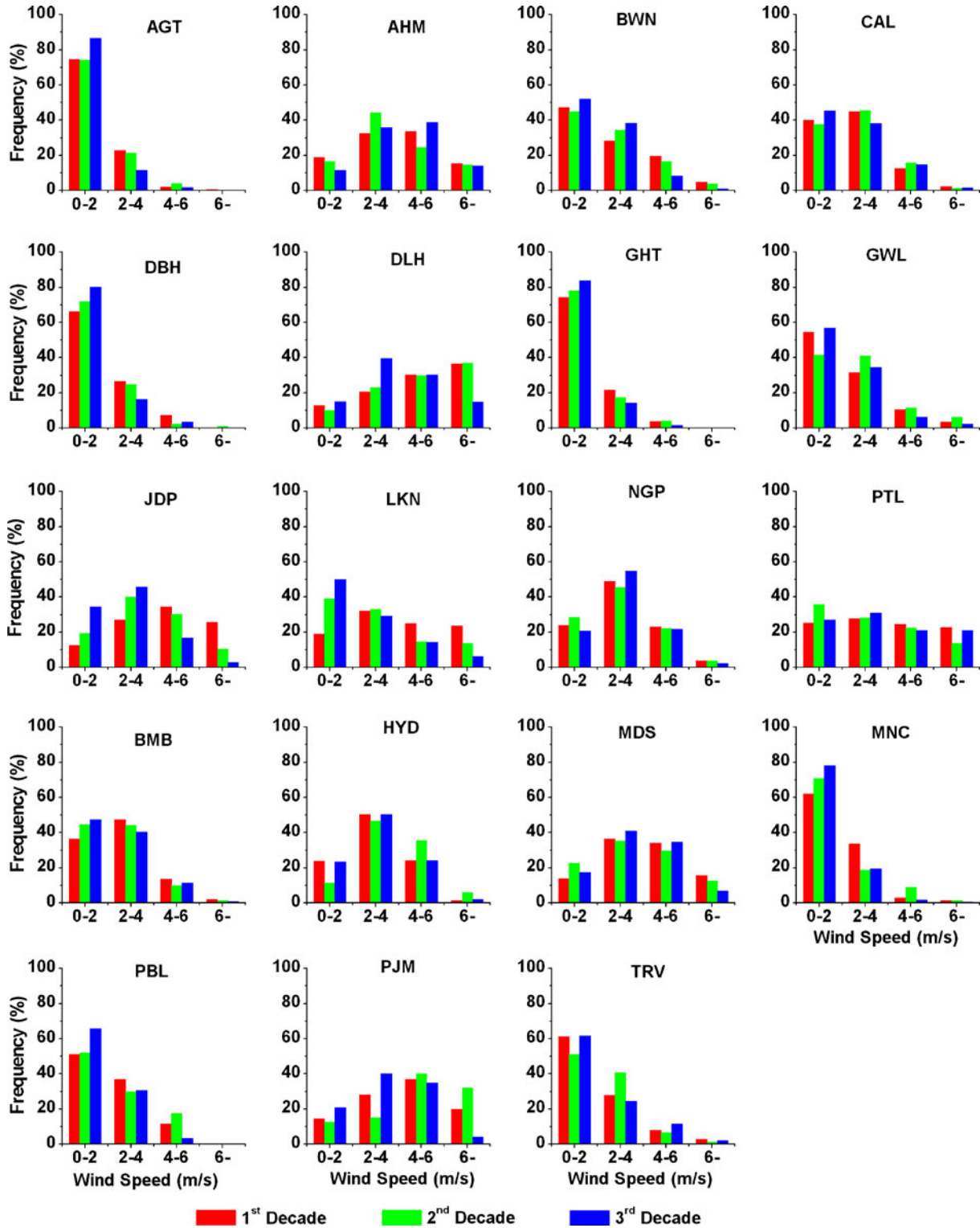


Figure 6. Decadal variations in the wind speed through inversion layer.

frequencies do not show any decadal variation over BMB while it increases over PJM and HYD from the 1<sup>st</sup> (~45%) to the 3<sup>rd</sup> (~65%) decade. For the other stations, though the frequencies are low, they generally show an increase from the 1<sup>st</sup> to the 3<sup>rd</sup> decade. For strong inversions, BMB shows

an increase from the 1<sup>st</sup> (~20%) to the 3<sup>rd</sup> (30%) decade. HYD too shows an increase in frequency from the 1<sup>st</sup> to the 3<sup>rd</sup> decade though the values are lower (~10%–18%). For the other stations, frequencies are very low or absent. Very strong inversions are almost absent in R2.

Several researchers have attributed the reduction in inversion depth and strength to the increase in warm air advection, aerosols, greenhouse gases, etc. (e.g., Bradley *et al* 1993; Abdul-Wahab 2003; Abdul-Wahab *et al* 2004; Kassomenos and Koletsis 2005). But they have also mentioned that it is difficult to identify a specific reason due to strong interaction between many potential factors. Over India, warm air advection is rare in the winter season and a continuous record of aerosols and greenhouse gases during the study period is not available. Therefore, we believe that urbanization, industrialization and a steady increase in urban population are possibly some of the causes for the observed changes in inversion depth and strength during the study period.

### 3.5 Wind speed through inversion layer

Figure 6 shows the frequency distribution of wind speed through the inversion layer for the three decades. In R1, frequency of weak winds (0–2 m/s) is >65% for AGT, DBH and GHT in the 1st decade increasing to >80% in the 3rd decade. A 10% decrease in the frequency of moderate wind (2–4 m/s) from the 1st to the 3rd decade and very low frequency of strong winds (4–6 m/s) are observed over these stations. Very strong winds (>6 m/s) are absent. For the other stations in R1 except DLH, frequencies are evenly distributed for weak and moderate winds, with an increasing trend observed from the 1st to the 3rd decade for most of the stations. The frequency of strong winds decreases from ~20–30% in the 1st to ~10% in the 3rd decade. Very strong wind frequency generally decreases from the 1st to the 3rd decade (~20% to <10%). DLH also shows increase in weak and moderate winds from the 1st to the 3rd decade. Frequency of strong winds remains unchanged at ~30% for all the three decades while a 50% reduction in the frequency of very strong winds from the 1st to the 3rd decade is observed.

For the R2 region, frequencies of weak winds either increase from the 1st to the 3rd decade or are same for all the stations. Winds for CHN are not plotted due to the unavailability of data. Moderate winds at BMB, MNC, PBL and TRV show a decrease of ~8–10% from the 1st to the 3rd decade, MDS and PJM show a slight increase and for HYD, there is no decadal change. Low frequencies (<10%) of strong winds are observed at BMB, MNC, PBL and TRV while for HYD, MDS and PJM, frequencies are ~35–40% in all decades. BMB, HYD, MNC, PBL and TRV have negligible frequencies of very strong winds whereas it reduces by ~50% from the 1st to the 3rd decade for MDS and PJM.

Wind speed influences the movement and dispersion of emissions and together with wind direction, it influences the distribution of pollutants. A decrease in wind speed helps in sustaining the inversion and increasing its strength. For most of the stations in R1, frequencies of weak and moderate winds are more than that of strong or very strong winds. With the exception of a few stations, when winds are strong or very strong, the frequencies generally decrease from the 1st to the 3rd decade. A similar trend is observed for most stations in R2. The weak and moderate winds sustained the observed inversions in R1 and R2 and a decrease in the frequency of strong and very strong winds from the 1st to the 3rd decade probably increased the frequency of inversions from the 1st to the 3rd decade. These results are in agreement with those obtained by Rao *et al* (2004) and Nandankar (1999) where a significant decreasing trend in wind speed was reported. They also observed calm winds under stable conditions during night time, which led to poor diffusion of the pollutants released in the atmosphere.

## 4. Conclusions

Radiosonde data for the period 1971–2000 for the winter months (December, January, February) has been analyzed to study quantitatively the secular variations in ground-based inversions. Inversion frequency in R1 (stations north of 20°N) was ~20–60% higher in all the decades compared to R2 (stations south of 20°N). Almost all stations in R1 and R2 show increase in the frequency of inversions from the 1st to the 3rd decade. The inversions are characterized according to their depth and strength. Annual variations in depth and strength of inversions show that nearly all stations in R1 and three stations in R2 show a decline in inversion depth significant at 99% level. An increasing trend in inversion depth is not observed in any of the stations in R1 while three stations in R2, viz., CHN, MDS and MNC show significant increasing trend. About half the stations in R1 and R2 show significant increase in inversion strength while in the other half, though increasing trends are observed, they are not significant.

Over the decades at most stations analyzed, inversions are shallower but stronger. With the exception of a few stations, wind speeds are either weak or moderate, the frequencies increasing from the 1st to the 3rd decade. Strong wind frequencies are low and very strong winds are absent; thus facilitating the formation and sustenance of inversions. Since inversions have a detrimental effect on the concentration of pollutants and their dispersal and may cause fog formation, information about

these layers may be used by planners for identifying areas for industrial development and expansion of cities.

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