MAUSAM, **66**, 2 (April 2015), 187-200

551.524.7 (540)

Temperature variations and trends in the lower atmosphere over Indian longitudes, 1948-2011

R. ASOKAN and B. AMUDHA

Regional Meteorological Centre, India Meteorological Department, Chennai – 600 006, India

(*Received 8 January 2014, Modified 17 April 2014*)

e mail : asokan.ramasamy@gmail.com

सार - प्राकृतिक एवं मानवीय कारणों से निचले वायुमंडल में तापमान-वृद्धि की प्रवृत्ति की जानकारी मिली है। वर्ष 2011-1948की अवधि के एन सी ई पी /एन सी ए आर पुनर्विश्लेषित डेटा सेट का उपयोग करते हुए भारतीय देशांतर 40° पूर्व और 120° पूर्व मध्य उत्तरी और दक्षिणी गोलार्द्धों में ऋतुनिष्ठ और वार्षिक तापमान में भिन्नताओं का विश्लेषण किया गया है। तापमान में परिवर्तन की प्रवृत्ति में होने वाले किसी भी विश्वसनीय बदलाव का विश्लेषण करने के लिए उपग्रह युग के वर्ष 2011-1979तक की और संपूर्ण अवधि के आँकड़ों को लिया गया है। ऐसा पाया गया है कि वार्षिक प्रवृतियाँ दोनों ही गोलार्द्धों के क्षोभमंडल में उष्णता की प्रवृति को दर्शाती हैं जबकि ऋतुनिष्ठ प्रवृतियाँ मिश्रित प्रवृतियों को दर्शाती हैं। इसका प्रत्यक्ष कारण जलवायविक बदलाव और स्थान-महासागर के तापमान में विरोधाभास का होना है। क्षोभमंडल की ऊँचाई में भिन्नता दक्षिणी गोलार्द्ध से उत्तरी गोलार्द्ध के उष्णकटिबंधों में कम होती है। उपग्रह युग में क्षोभमंडलीय सीमा का औसत तापमान अधिक रहा है।

ABSTRACT. Temperature trends in the lower atmosphere are reported to be increasing due to natural and anthropogenic causes. The seasonal and annual variations in temperature in the northern and southern hemispheres over the Indian longitudes between 40° E and 120° E have been analysed using NCEP/NCAR reanalysis data set for the period 1948-2011. The analysis has been carried out for the satellite era 1979-2011 and for the whole period to bring out any plausible change in trends in temperature. It is observed that the annual trends indicate warming of the troposphere in both hemispheres whereas seasonal trends show mixed response obviously due to climatic forcing and land-ocean temperature contrasts. The variation in tropopause height is lesser over tropics of northern hemisphere than the southern hemisphere. The mean tropopause temperature is more in the satellite era.

Key words – Temperature, Troposphere, Stratosphere, Tropopause height, NCEP/NCAR reanalysis data, Trends.

1. Introduction

Researchers all over the world have been curious to understand the long term trends in temperature variability in the atmosphere especially in the climate change and global warming scenario. Radiation input from the Sun is the source of energy for the Earth's climate system. Surface temperatures are at their warmest in the tropics, where the largest amount of solar radiation is received during the course of the year and decrease towards the poles where the annual mean solar radiation received is minimum (Oort and Peixoto, 1992). Dynamical motions arising due to the equator-to-pole gradient, combined with convective processes and the influence due to the rotation of the Earth result in heat transfer from the low to middle and high latitudes, leading to the climatological horizontal and vertical thermal structure (Hartmann, 1994; Salby, 1996).

The vertical thermal profile in the troposphere is the result of a balance of radiative processes involving greenhouse gases, aerosols and clouds, along with the strong role of moist convection and dynamical motions (Stephens and Webster, 1981; Goody and Yung, 1989; Holton, 1979; Held, 1982; Kiehl, 1992). In the tropical upper troposphere, moisture and cloud-related features associated with convection (*e.g.*, upper tropospheric relative humidity, cirrus cloud microphysics and mesoscale circulations in anvil clouds) are important factors in shaping the thermal profile (Ramaswamy and Ramanathan, 1989; Donner *et al.*, 2001; Sherwood and Dessler, 2003). From a global, annual average point of view, the thermal profile of the stratosphere is the consequence of a balance between radiative heating and cooling rates due to greenhouse gases, principally carbon dioxide (CO_2), ozone (O_3) and water vapour (H_2O).

Temperature trends at the surface can be expected to be different from temperature trends higher in the atmosphere because of the nature of the type of surface (sea, snow, ice and different vegetative covers of land) which differ considerably due to the varied physical properties. Near the surface, these differing conditions can produce strong horizontal variations in temperature. Above the surface layer, these contrasts are quickly smoothed out by the atmospheric motions, contributing to varying temperature trends with height at different locations. Changes in atmospheric circulation or modes of atmospheric variability [*e.g.*, El Niño-Southern Oscillation (ENSO)] can produce different temperature trends at the surface and aloft).

Many data sets are used by researchers for temperature trend analysis. Microwave sounding unit (MSU) satellite series data was used by Spencer and Christy, 1990; Christy *et al.*, 1995, 2000, 2003; Mears *et al.*, 2003; Fu and Johnson, 2005. Such investigations have also been undertaken using data of model reanalysis (Pielke, 1998, Chase *et al*., 2000, Pielke Sr., 2001, Santer *et al.*, 2003 and radiosonde data (Angell, 1988 & 2000, Oort and Liu 1993, Parker *et al.*, 1997 and Gaffen *et al.*, 2000). Comparative analysis of the tropospheric temperature trends has been done between satellite and radiosonde data (Christy *et al.*, 2000; Hurrell *et al.*, 2000; Lanzante *et al.*, 2003b; Agudelo and Curry 2004) and between satellite and reanalysis data (Pielke, 1998; Chase *et al.*, 2000; Chelliah and Ropelewski, 2000; Sturaro, 2003; Agudelo and Curry, 2004). Most of the studies are on global mean surface and tropospheric temperature trends and few have studied the stratospheric temperature trends.

At surface, it is observed that globally the temperature increased at a rate of about 0.12 °C per decade and about 0.18 °C since 1979. In the tropics, the temperature has increased at a rate of 0.11 °C per decade since 1958 and by 0.13 °C per decade since 1979. Globally, the temperature increase per decade in the troposphere since 1958 is at the rate of 0.14 °C and 0.10- 0.20 °C since 1979. In the tropics, the temperature is found to increase at a rate of about 0.13 °C since 1958 and by 0.02-0.19 °C per decade. In the lower stratosphere, globally the cooling is about 0.37 °C per decade since 1958 and about 0.65 °C per decade since 1979. (Lanzante, 2006). The above observed temperature changes are related to full longitudes (0° E to 360° E).

With this background, it is proposed to study the temperature changes in Indian longitudes and how it is related to global temperature variations. The objective is to describe the trends in temperature of the lower atmosphere from surface to 10 hPa over the Indian longitudes between 40° E and 120° E utilising NCEP/NCAR reanalysis data sets for the period January 1948 to December 2011. Reanalyses and other multi-system products that synthesise observational data with model results to ensure spatial and inter-variable consistency have the potential of addressing issues on trends in temperature of the surface level and vertical atmosphere. Better use is made of available information and analysis of a more comprehensive, internally consistent and spatially and temporally complete set of climate variables is possible.

2. Data and methodology

The monthly grid point temperature data for the period from January 1948 to December 2011 for the area bounded by 40° E to 120° E and 90° S to 90° N for the pressure levels 1000 hPa, 925, 850,700, 600, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 20 and 10 hPa (Kalnay *et al.*, 1996) has been downloaded from the web site *http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.derived.pressure.html* of the Physical Sciences Division, Data Management NOAA/ ESRL/ PSD, USA. A frozen state-of-the-art global data assimilation system is used in the reanalysis to produce analyses of the global temperature fields at 17 vertical levels in the atmosphere on a 2.5° × 2.5° lat-long grid. These data have a rating 'A' which means that the data is in the most reliable class strongly influenced by the observed data and the influence of the model used to derive the grid point values is minimal. The surface gridded temperatures, tropopause height and temperature data have also been downloaded from the same web site.

The northern and southern hemispheres are divided into six climatic sub-regions with areas between (*i*) 0° N and 30° N as Northern Tropics (NT), (*ii*) 30° N and 60° N as Northern Mid-latitudes (NM), (*iii*) 60° N and 90° N as Northern Polar (NP), (*iv*) 0° S and 30° S as Southern Tropics (ST), (*v*) 30° S and 60° S as Southern Mid-latitudes (SM) and (*vi*) 60° S and 90° S as Southern Polar (SP) regions. India being in the Northern Hemisphere (NH), the standard seasonal classification of months used in the Indian context is taken for the analysis, *viz*., winter (January-February), pre-monsoon (March-May), monsoon (June-September) and post-monsoon (October-December). A comparison of annual and seasonal temperatures in the six sub-regions as mentioned above for the periods 1948-2011 and 1979-2011, hereinafter mentioned as whole period and satellite era respectively, has been done by computing the difference between the zonally averaged temperatures at the surface and for all the 17 vertical levels.

The analysis comprises of five parts. In the first part, the mean annual and seasonal temperature variations at the surface level and in the second, the vertical profile of temperature variations over the six climatic sub-regions

TABLE 1(a)

Mean surface temperature (°C) over tropics, mid-latitudes and Polar Regions in northern hemisphere

	Temperature (°C)								
	Tropics			Mid-latitudes			Polar		
	1979-2011	1948-2011	Diff	1979-2011	1948-2011	Diff	1979-2011	1948-2011	Diff.
Winter	20.96	20.85	0.11	-9.27	-9.62	0.35	-24.20	-25.12	0.92
Pre-monsoon	25.56	25.39	0.17	5.20	4.83	0.37	-12.31	-12.99	0.68
Monsoon	26.85	26.59	0.26	17.68	17.53	0.15	3.91	3.71	0.20
Post-monsoon	22.92	22.68	0.24	-2.07	-2.43	0.36	-17.16	-18.05	0.89
Annual	24.56	24.36	0.2	5.13	4.84	0.29	-10.10	-10.71	0.61

Diff : Difference in temperatures between 1979-2011 and 1948-2011

TABLE 1(b)

Mean surface temperature (°C) over tropics, mid-latitude and Polar Regions in southern hemisphere

	Temperature (°C)								
	Tropics			Mid-latitudes			Polar		
	1979-2011	1948-2011	Diff	1979-2011	1948-2011	Diff	1979-2011	1948-2011	Diff.
Winter	25.70	25.52	0.18	10.85	10.66	0.19	-19.11	-18.44	-0.67
Pre-monsoon	25.28	25.04	0.24	9.83	9.56	0.27	-36.98	-37.79	0.81
Monsoon	22.70	22.51	0.19	6.85	6.66	0.19	-41.35	-42.65	1.30
Post-monsoon	24.15	24.01	0.14	8.28	8.17	0.11	-23.62	-23.26	-0.36
Annual	24.21	24.02	0.19	8.62	8.43	0.19	-32.12	-32.55	0.43

Diff : Difference in temperatures between 1979-2011 and 1948-2011

have been discussed. Monthwise mean temperature variability in surface, four layers, *viz*., three representative layers of the troposphere (850, 500 and 200 hPa) and the lower stratospheric layer (50 hPa) has been discussed in the third part. On both seasonal and annual scales, temperature trends and variability in tropopause height over the six climatic regions have been analysed in the fourth and fifth parts of the study.

3. Results and discussion

3.1. *Surface level variations in mean temperature*

The annual and seasonal mean temperatures at surface level over the six climatic sub-regions for the whole period and satellite era have been computed and presented in Tables 1(a&b).

3.1.1. *Annual mean temperature variability*

The mean temperature (MT) of the tropics in both the hemispheres is nearly equal (approximately 24 °C) and that of the satellite era is about 0.2 °C more than that for the whole period. The MT of the region SM is about 3.5 °C more than that of NM. The mean observed temperature of satellite era is about 0.3 °C more than that during the whole period over NM. SP is about 22 °C colder than that of NP. The observed mean temperature during satellite era is about 0.6 °C more than that during the whole period of study.

3.1.2. *Winter season*

The MT of sub-regions in the NH is colder than that of the southern hemisphere (SH). Temperatures in the NH are colder than SH in this season in tropics by about 5 °C, mid-latitudes by 19 °C and polar region by about 6 °C mainly because climatologically in the Indian context, the winter season of NH is the summer season of SH. The mean temperature in the satellite era is warmer by 0.11 to 0.92 °C in all the climatic sub-regions except over SP where it is colder during satellite era as compared to the whole period.

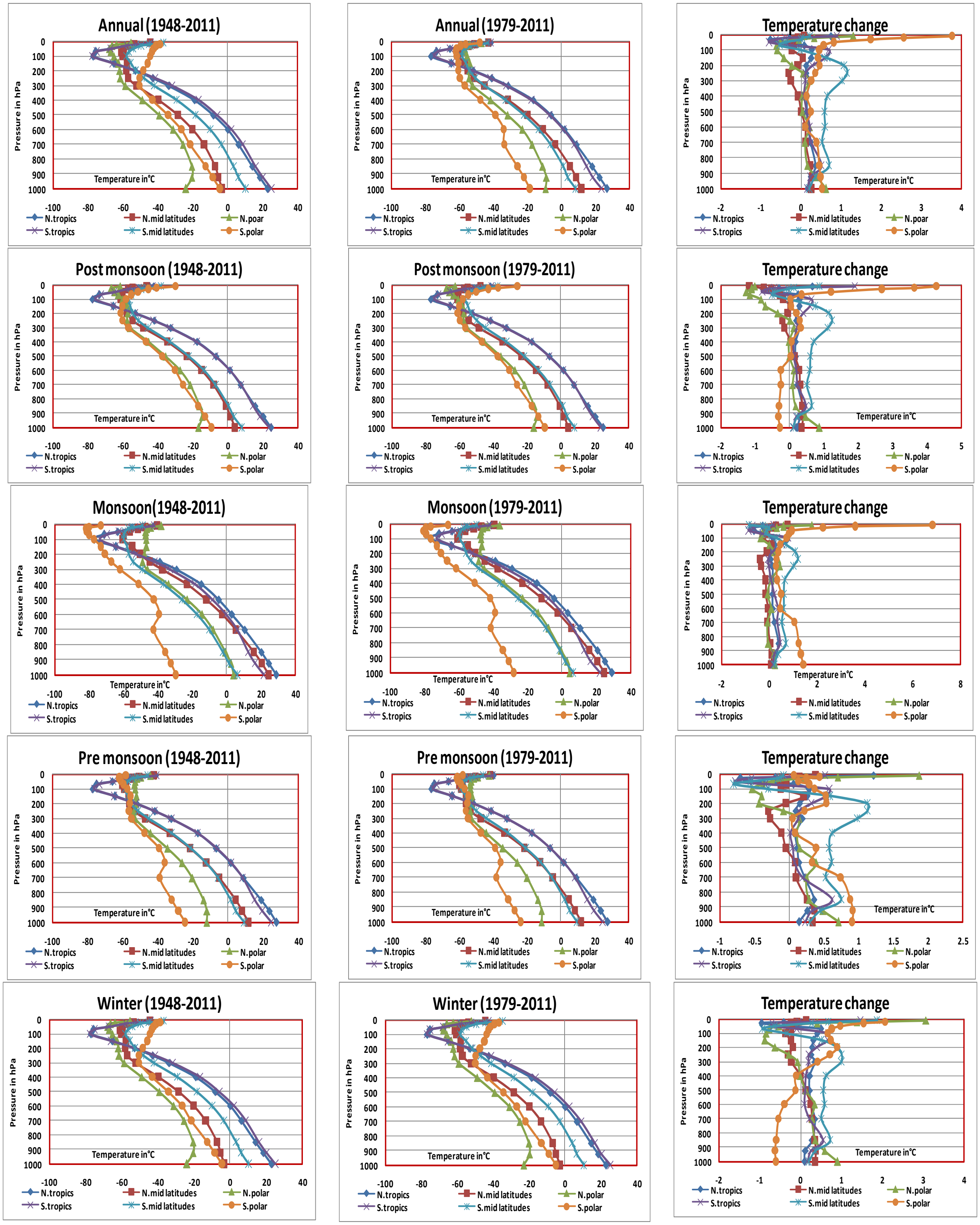

Fig. 1. Zonal mean temperature variability at different pressure levels over the tropics, mid-latitudes and polar regions of northern and southern hemispheres (40° E - 120° E)

3.1.3. *Pre-monsoon season*

Generally, the sub-regions in NH are warmer than that of SH except that the NM is colder than the SM by 4.8 °C. The sub-regions in both NH and SH are warmer during satellite era by about 0.17 °C to 0.81 °C as compared to whole period.

3.1.4. *Monsoon season*

During monsoon season, the MT of the sub-regions in the NH is warmer than their counterparts in the SH. The warming is more in the NP by about 44 °C than that of SP. The MT of SP is 1.3 °C more in the satellite era than that of whole period.

3.1.5. *Post-monsoon season*

During post-monsoon season, the MT of NT and NM is less than that of ST and SM while it is more in NP than in SP. The MT of the satellite era in all the six climatic sub- regions is higher by about 0.11 °C to 0.89 °C except that of SP where it is colder by 0.36°C as compared to the whole period.

3.2. *Profile of vertical temperature variations*

The vertical profile of zonally averaged temperatures over NT, NM, NP, ST, SM and SP at the 17 pressure levels for the four seasons (winter, pre-monsoon, monsoon and post- monsoon) is displayed in Fig. 1 wherein the left side panels correspond to averages for the period 1948-2011 (whole period) and the middle ones are of the averages for the period 1979-2011 (satellite era). The right panel graphs of Fig. 1 indicate the temperature differences between the averages of the satellite era and the whole period under study.

3.2.1. *Winter season*

In winter, the mean temperature (MT) profiles of the whole period for NT and ST are almost equal above 300 hPa and below this level ST is warmer than NT in lower and middle troposphere. ST is warmer than that of NT due to the sun's position over SH during NH winter. The regions SM and SP are warmer than the NM and NP regions at all levels. The patterns in the MT profile of the satellite era are nearly the same as in the whole period. Lowest temperatures of -60 °C and -50 °C respectively in NP and SP are observed at 300 hPa whereas a colder temperature of -77 °C is observed in the NT and ST around 100 hPa. The lowest temperatures over NM and SM are observed at 300 hPa and 200 hPa respectively.

Considering the temperature changes (right panel of Fig. 1) during satellite era and the whole period, it is clear that the atmosphere below 400 hPa is warmer by 0.1 °C to 1.0 °C in the satellite era in all the climatic regions except over SP where the atmosphere is cooler in the last three decades (1979-2011) as compared to the whole period. Above 400 hPa, SP region is warmer for the same decades. At 10 hPa level, the MTs of all six climatic regions are warmer in the satellite era. The mean temperature profile of the satellite era is more by 3 °C over NP region than the MT of the whole period.

3.2.2. *Pre-monsoon season*

The MT profile of the whole period of NT, NM, ST and SM regions are almost equal during pre-monsoon season. The ST is cooler below 700 hPa and NP region is warmer as compared to SP regions at all levels. The patterns in the MT profile of the satellite era are nearly same as that of the whole period. The lowest temperatures of NP and SP are observed at 300 and 200 hPa respectively with SP warmer at -50 °C. Similarly, the lowest temperatures of NT and ST are seen around 100 hPa with colder temperature of -78 °C. The temperature changes (Right panel of Fig.1) in this season show that the atmosphere below 600 hPa is warmer by 0.1 °C-1.0 °C in the satellite era in all the climatic regions. The maximum warming of 2 °C is seen in NP in the satellite era at 10 hPa and maximum cooling is at 70 hPa.

3.2.3. *Monsoon season*

During the monsoon season, the MT profiles of the whole period for NT and ST are almost equal in the upper troposphere. NT is warmer than ST due to the sun's position over NT. The lowest mean temperature of -80 °C is seen in 100 hPa. The MT profile at all vertical levels shows that NM and NP are warmer than that in SM and SP regions. Below 700 hPa, the MT of NM is warmer than ST. The MT decreases up to 100 hPa in both NM and SM. Up to and below 250 hPa the MT profile of SM is slightly lower than that of NP whereas the NP region is warmer than SM by about 3 °C to 12 °C above 250 hPa. An inversion is observed at 600 hPa in the SP and above which the MT decreases up to 20 hPa and the lowest temperatures are seen at 20 hPa over SP. The MT profiles are nearly same for both the satellite era and the whole period under study. Analysis of the temperature change in the two periods points to the fact that the atmosphere below 400 hPa is warmer by 0.1 °C-1.5 °C in the satellite era in all the climatic regions except over NP and NM regions. Satellite era is warmer than the whole period by 0.5 to 3.6 °C over SP at all vertical levels.

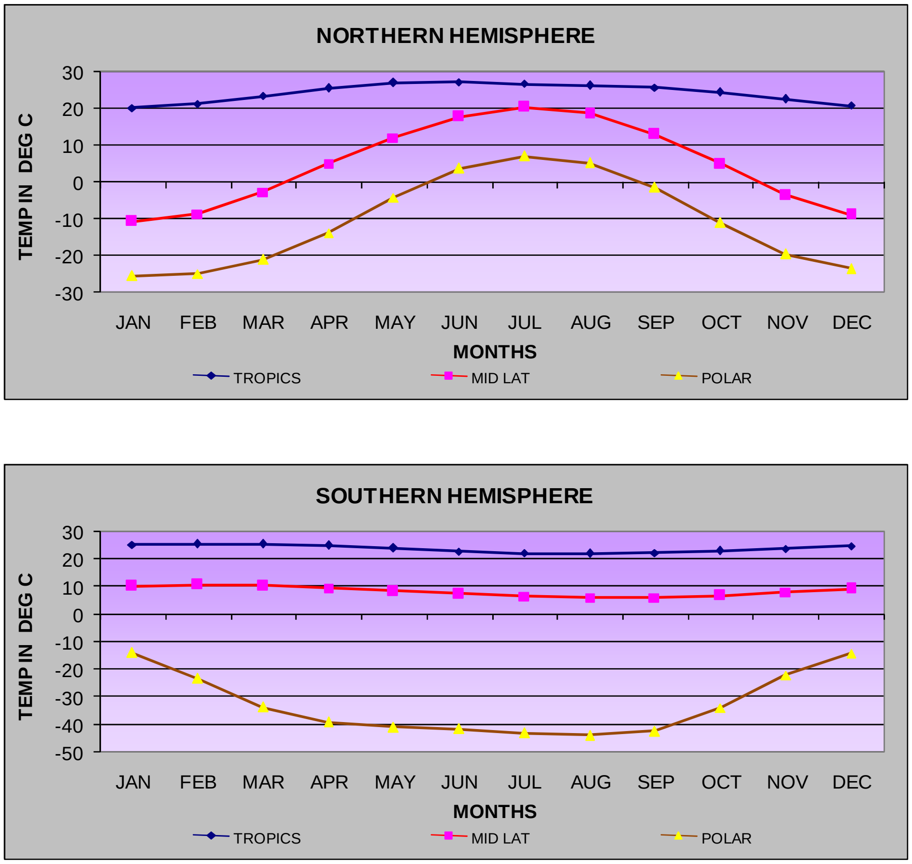

Fig. 2(a). Monthly variation of surface mean temperature of different climatic sub-regions in northern and southern hemispheres

3.2.4. *Post-monsoon season*

The MT profiles of both the periods show no major change in all the six climatic sub- regions at all vertical levels considered. The lowest MT of -80 °C is over NT and ST at 100 hPa. The NP is cooler than SP below 925 hPa. The same pattern prevails in MT profile of satellite era as well. Considering the change in temperature, it is found that the atmosphere below 500 hPa over all the climatic regions is warmer in the satellite era than the whole period except in the SP region which is cooler though above 100 hPa, the warming is evident with a maximum of 4.5 °C over SP at 10 hPa.

3.2.5. *Annual*

As far as the annual mean temperature profile is concerned, the regions NT, NM and NP are warmer than the ST, SM and SP at all levels. The temperature difference is more over NP and SP varying between 3 °C-15 °C. The vertical profile of MT is the same for satellite era and whole period though a warming trend in atmosphere below 500 hPa over all six climatic sub-regions is discernible in the satellite era. The MT of SP region in the satellite era is warmer than the whole period at all levels with a maximum warming at 10 hPa.

3.3. *Monthwise mean temperature variation*

The monthwise variability of MT of six climatic sub-regions is analysed for the surface level, the lower (850 hPa), middle (500 hPa), upper (200 hPa) tropospheric levels and lower stratosphere (50 hPa) and are depicted in Figs. 2(a-c).

3.3.1. Surface

Fig. 2(a) displays the monthly variation of surface mean temperature of the six climatic sub-regions. It can be inferred from the figure that the MT of NT and ST is higher than that of NM, SM, NP and SP regions. The temperature variations are least in tropics and are highest in polar regions in both the hemispheres. In the northern

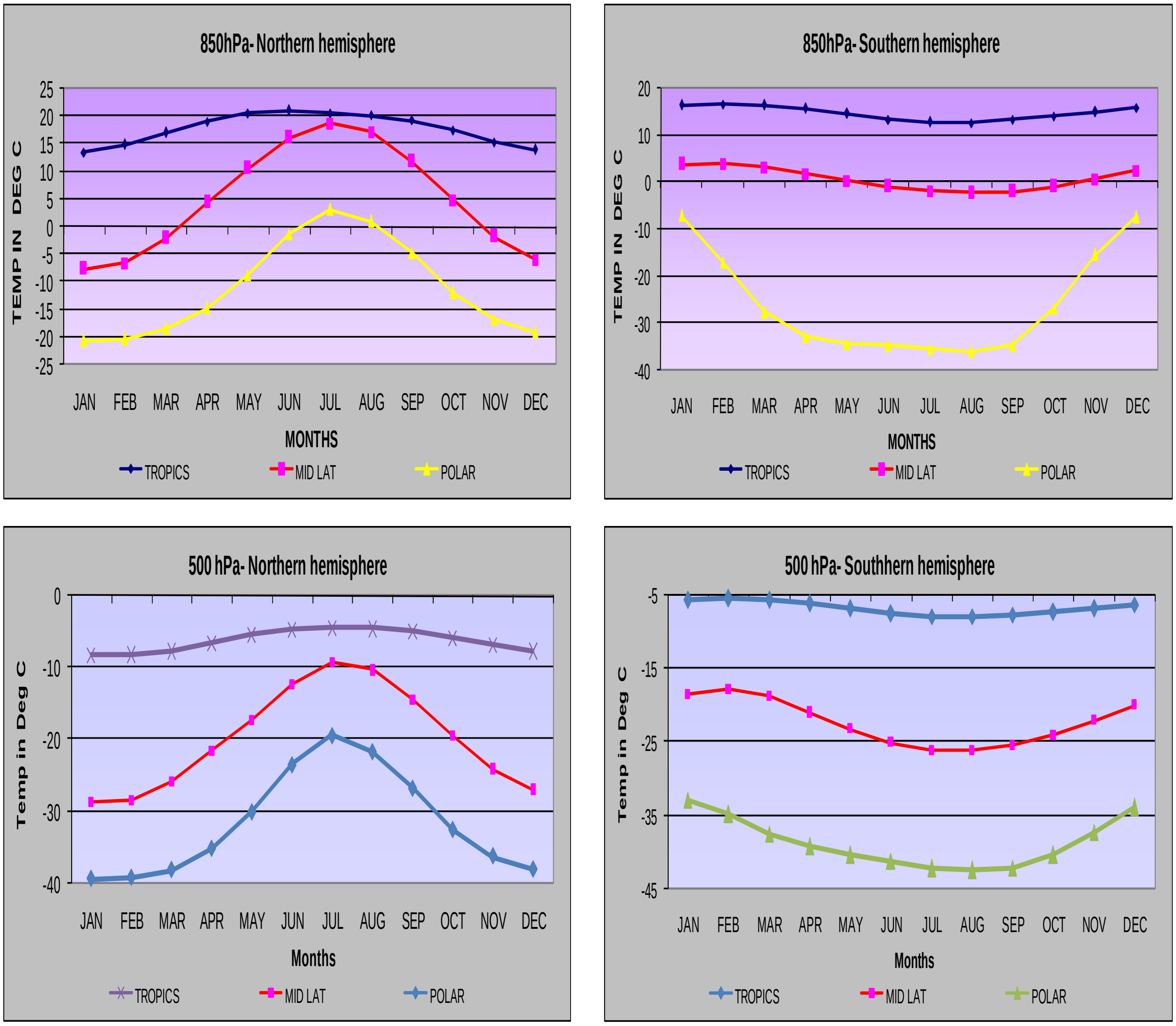

Fig. 2(b). Monthly variation of temperature in lower and middle troposphere

(southern) hemisphere, the MT is highest (lowest) in the months June-July (January) and is lowest in the months of December-January (July-August).

3.3.2. *Lower troposphere (850 hPa)*

In the lower troposphere, as depicted in Fig. 2(b), the MT of NT and ST is more than that in NM, SM and NP, SP regions in the corresponding months. Generally the maximum MT occurs during monsoon months in the NH while it occurs during winter months of the SH in all the three sub-regions. The minimum occurs during December-January in the NH while it occurs during June-July in the SH.

The monthly mean temperature of NT varies from 13.5 °C (January) to 21.0 °C (June) while that of ST is from 12.4 °C (August) to 16.8 °C (February). The temperature variation is higher in NH than that in SH since the major part of SH is oceanic and NH has a majority of land mass. The NM shows higher temperature variations than NT. The lowest mean temperature of -7.7 °C in January and the highest MT of 18.7 °C in July are observed in NM while in the SM, the lowest MT of -2.5 °C (August) and the highest MT of 3.7 °C (February) are seen. In the SP, the MT varies from -36.3 °C (August) to -7.5 °C (January) while in the NP, the lowest temperature is in January (-20.6 °C) and the highest in July (3.2 °C).

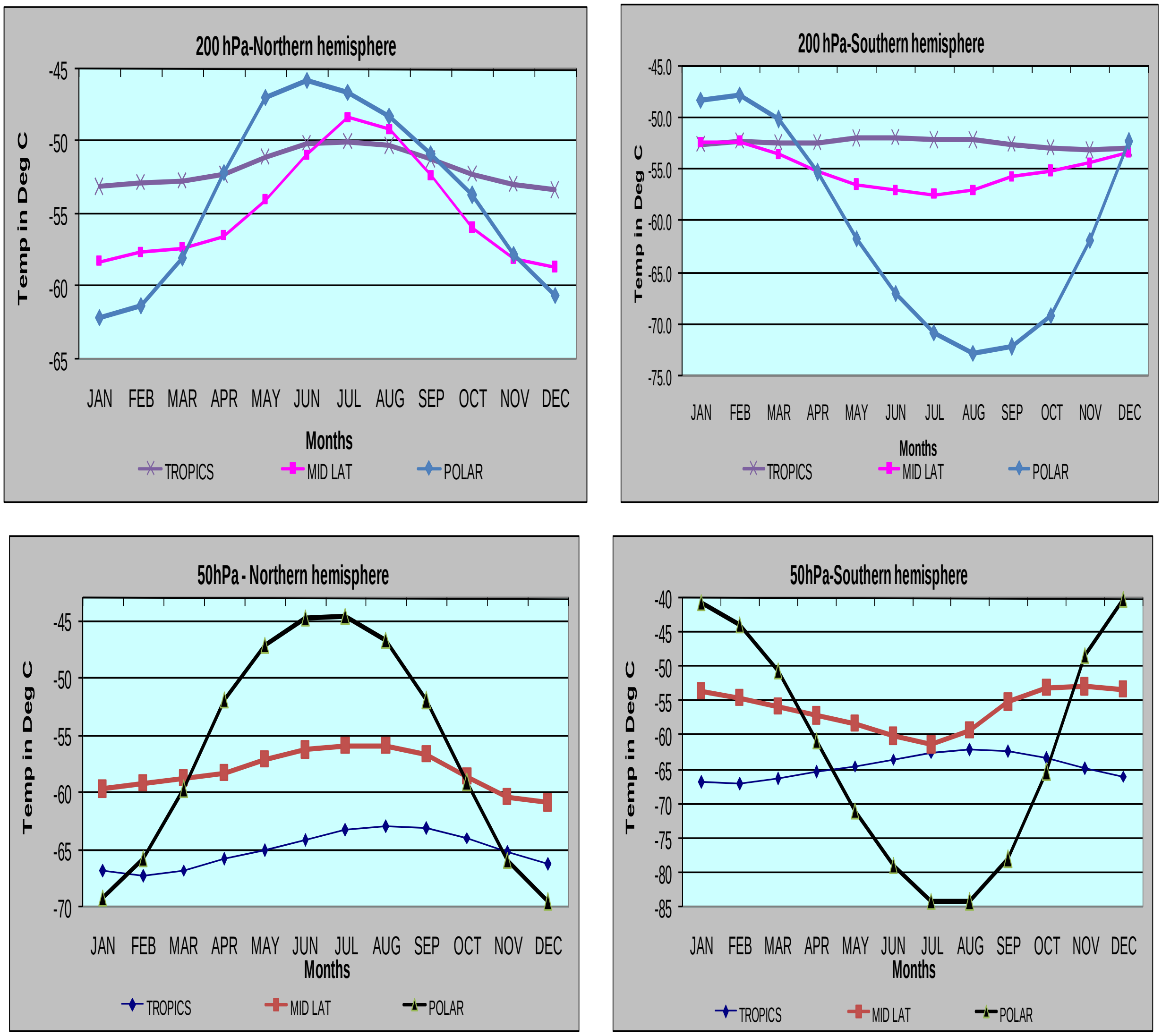

Fig. 2(c). Monthly variation of temperature in upper troposphere and lower stratosphere

3.3.3. *Middle troposphere (500 hPa)*

In the middle troposphere, the MT is higher in tropics than that in the mid-latitude and polar regions of both NH and SH [Fig. 2(b)]. The range of temperatures is lower in NT and ST than in NM, SM, NP and SP regions. The MT in the NT is maximum during July-August and is minimum during January-February whereas the MT is maximum during January- February and minimum during July-August.

The monthly MT of NT varies from -8.3 °C (January) to -4.5 °C (July) while that of SHT is from 8.0 °C (July) to -3.9 °C (January). The temperature variation is higher in NH than SH since the response of SH is mostly oceanic and for the NH it is from the land mass. The NM also shows higher temperature variation than NT with the lowest MT of -28.5 °C (January) and highest MT of -9.3 °C (July) while in the SM, the lowest MT is of -26.4 °C (August) and the highest MT is -18.0 °C (February). In the SP, the MT varies from -42.6 °C (August) to -33.0 °C (January) while in the NP, the lowest temperature is -39.3 °C (January) and the highest being -19.4 °C (July).

3.3.4. *Upper troposphere (200 hPa)*

Fig.2 (c) (top) represents the monthly variation in MT of the upper troposphere. The warmest temperature is observed over NP during July while the lowest is in January. During January-March and October-December, the MT of NT is higher than that of NM and NP regions.

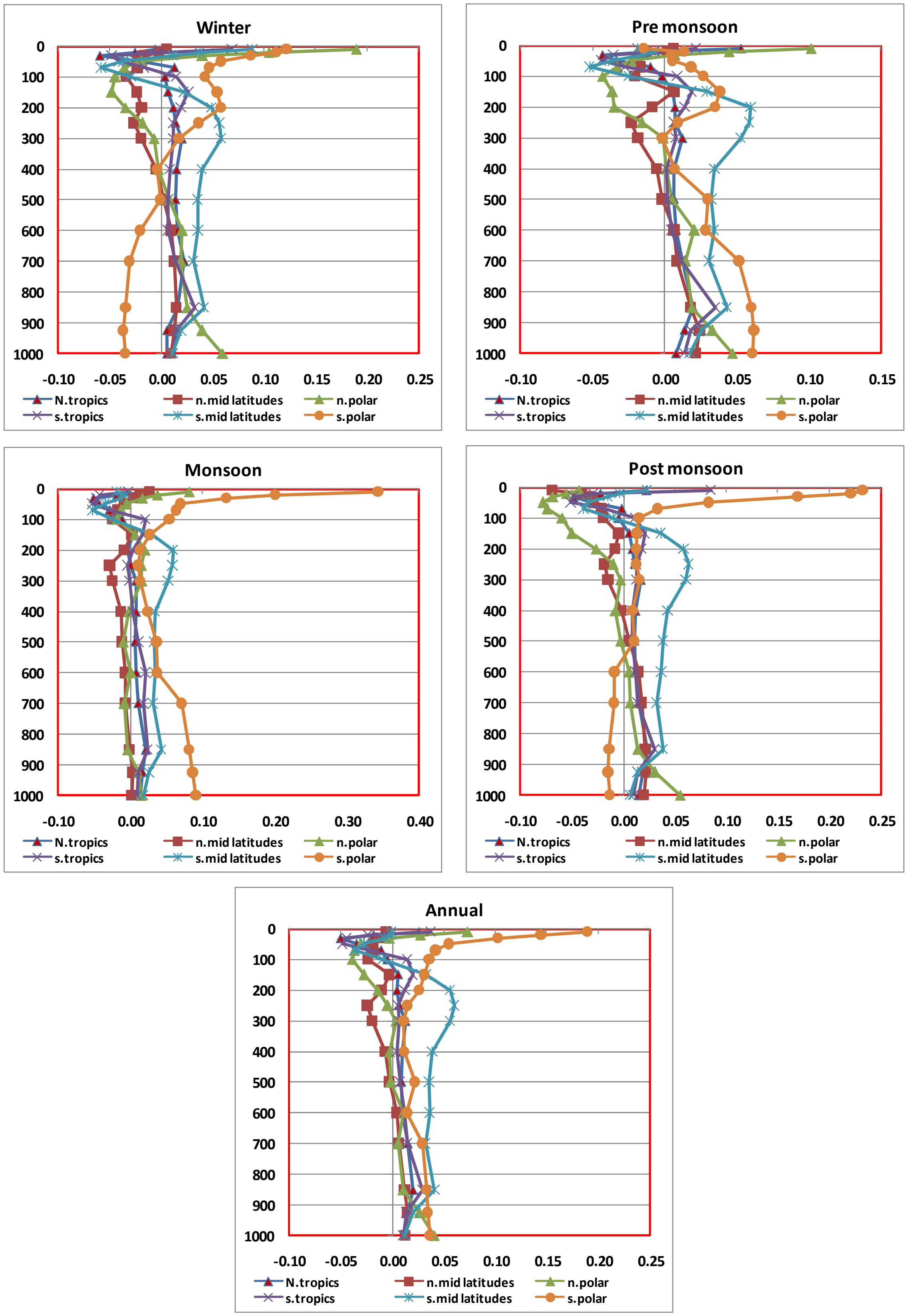

Fig. 3. Seasonal and annual temperature trends (°C/year) in the lower atmosphere over six climatic sub-regions

TABLE 2

Seasonal and annual trends in surface level mean temperatures (°C per year) of six climatic sub-regions

Season	Period	NT	NM	NP	ST	SM	SP	Whole region
Winter	1948-2011	0.006	0.008	0.058	0.011	0.010	-0.040	0.009
	1979-2011	0.019	0.042	0.065	0.010	0.006	-0.026	0.020
Pre-monsoon	1948-2011	0.008	0.023	0.044	0.014	0.015	0.055	0.027
	1979-2011	0.013	0.031	0.078	0.012	0.016	0.031	0.040
Monsoon	1948-2011	0.015	0.005	0.012	0.010	0.010	0.084	0.024
	1979-2011	0.014	0.031	0.035	0.006	0.011	0.095	0.031
Post-monsoon	1948-2011	0.015	0.020	0.056	0.010	0.006	-0.017	0.015
	1979-2011	0.020	0.027	0.091	0.006	0.001	-0.001	0.025
Annual	1948-2011	0.012	0.014	0.039	0.011	0.011	0.030	0.020
	1979-2011	0.016	0.032	0.065	0.008	0.009	0.047	0.030

TABLE 3

Seasonal and annual trend (°C per year) in mean tropopause height over six climatic sub-regions

Season	Period	NT	NM	NP	ST	SM	SP	Whole region
Winter	1948-2011	0.093	0.098	-0.249	-0.079	-0.318	0.257	-0.039
	1979-2011	0.047	0.065	-0.065	-0.160	-0.446	-0.116	-0.120
Pre-monsoon	1948-2011	0.019	0.181	-0.140	-0.097	-0.184	-0.010	0.043
	1979-2011	-0.015	0.095	-0.227	-0.161	-0.267	-0.201	-0.134
Monsoon	1948-2011	-0.046	0.240	0.213	-0.077	-0.129	0.415	0.109
	1979-2011	-0.060	-0.057	-0.055	-0.104	-0.230	-0.228	-0.118
Post-monsoon	1948-2011	0.016	0.129	-0.078	-0.075	-0.217	0.114	-0.017
	1979-2011	-0.000	0.010	-0.201	-0.121	-0.451	-0.675	-0.242
Annual	1948-2011	0.009	0.174	-0.025	-0.082	-0.196	0.207	0.014
	1979-2011	-0.016	0.018	-0.136	-0.132	-0.330	-0.314	-0.153

During April, the MT of NT and NP regions is nearly equal and higher than that of NM. During May-September, the MT of NP is higher than that of other regions. The MT of SP is higher than that of ST and SM during January-March while the MT of ST is higher than that of SM and SP during April to November. The MT of SP is about 15 °C less than that of SM.

The monthly MT of NT varies from -53.3 °C (December) to -50 °C (July) while that of ST is from -53.1 °C (July) to -52.0 °C (January). The monthly MT variations in upper troposphere are low when compared to lower and middle tropospheres. The NM shows higher temperature variation than NT. The lowest MT is -58.6 °C (December) while the highest MT is -48.3 °C (July). In the SM, the lowest and highest MTs are -57.5 °C (July) and -52.4 °C (February) respectively. In the SP, the MT varies from -72.9 °C (August) to -47.9 °C (January) while in the NP, the lowest and highest temperatures are 62.1 °C (January) and -45.8 °C (July) respectively.

3.3.5. *Lower stratosphere (50 hPa)*

In the lower stratosphere (50 hPa), the mean temperature of NP is higher than NT and NM while it is lower in the SP region [Fig. 2(c)-bottom]. The monthly variation of MT is nearly same in both the NT and ST with variation from -67.3 °C (February) to -63.0 °C (August) in NT while that of ST is from -67.0 °C (February) to -62.1 °C (August). In NM, the lowest MT is -60.9 °C (December) and the highest MT being -55.9 °C (August). While in the SM, the lowest MT is -61.3 °C (July) and the highest is -52.9 °C (November). The SP shows higher monthly temperature variations as compared to other climatic sub-regions with variation from -84.3 °C (August) to -46.1 °C (December) while in the NP, the lowest and highest temperatures are -69.6 °C (December) and -44.5 °C (July) respectively.

3.4. *Decadal temperature trends*

The season wise and annual trends in variability in MT are shown in Fig. 3 with the discussions hereunder.

3.4.1. *Surface level*

The trends in the seasonal and annual mean surface temperatures over the six climatic sub-regions during the whole period and satellite era are calculated and presented in Table 2. From the Table 2, it is seen that the trend values vary from 0.009 °C/year to 0.040 °C/year and are positive over the area of study during all the four seasons and whole year period. The annual and seasonal trend values are more during the satellite era as compared to the whole period (1948-2011).

In the NH, all the six climatic sub-regions show increasing trend in temperature which is more during satellite era as compared to that of whole period. The temperature trends range from 0.005 °C per year to 0.091 °C per year. The trends are more over Polar Regions than others. In the SH, all the climatic sub-regions show increasing trends whereas Polar Regions show decreasing trend during winter and post-monsoon seasons. During winter and post-monsoon season, the trend values are lesser during satellite era than that during the whole period in all the climatic sub-regions in the SH.

3.4.2. *Winter season*

The temperature trends in winter season as seen from Fig. 3 of six climatic sub-regions over 17 vertical levels vary from -0.04 to 0.19 °C per decade. Below 500 hPa, an increasing trend in temperature is observed in ST, NT, NM, SM and NP except over SP which shows a decreasing trend from -0.04 to 0.0 °C up to 500 hPa per decade; the lowest layer of atmosphere up to around 925 hPa shows large decreasing trend which however decreases with height. Between 500 and 200 hPa, all regions show increasing trends except over the NP and NM where the temperature trends are negative. The increasing trends over SM are generally higher at all levels between 500 and 200 hPa. The trends in all six climatic regions decrease with height above 200 hPa, up to the levels between 100 and 30 hPa and then increase up to 10 hPa. The NP shows highest increasing trend at 10 hPa.

3.4.3. *Pre-monsoon season*

The temperature trends during pre-monsoon season vary from -0.05 to 0.10 °C per decade. Below 500 hPa, the increasing temperature trends are observed while the SP at surface level shows a large increasing trend. Between 500 and 300 hPa, all regions show increasing trend except over NM where the temperature trends are negative. The increasing trend over SM is generally higher at all levels between 500 to 200 hPa. Above 300 hPa, the trends in all six sub-regions decrease with height up to the levels between 250 hPa and 30 hPa and then increase up to 10 hPa. The NP shows highest increasing trend at 10 hPa.

3.4.4. *Monsoon season*

The decadal temperature trends in monsoon season vary from -0.05 to 0.35 °C. A highest increasing trend of 0.35 °C per decade is evident in SP. The NP and NM show slight increasing trend whereas NT and ST have a decadal decreasing trend.

3.4.5. *Post-monsoon season*

During the post-monsoon season, decadal trends vary from -0.08 to 0.23 °C. Below 600 hPa, increasing trend in all five regions except SP which shows a decreasing trend from -0.02 to 0.0 °C per decade. At 925 hPa large decreasing trend which decreases with height is observed. Between 400 hPa to 250 hPa, all regions show increasing trend except over the NP and NM regions where the temperature trends are negative. The increasing trend over SM is higher at all levels between 850 hPa to 150 hPa. Above 100 hPa, the trends of all six climatic regions except SP decrease with height up to the levels between 70 and 20 hPa and then increase up to 10 hPa. The SP shows increasing trend from 100 hPa reaching the highest value at 10 hPa.

3.4.6. *Annual trends*

The annual decadal temperature trends of six climatic sub-regions in 17 levels vary from -0.04 to

TABLE 4

Seasonal and annual trend in mean temperatures (°C per year) of tropopause level

Season	Period	NT	NM	NP	ST	SM	SP	Whole region
Winter	1948-2011	0.017	-0.017	-0.031	0.008	0.026	0.023	0.003
	1979-2011	-0.018	0.003	0.040	-0.014	-0.005	-0.032	-0.005
Pre-monsoon	1948-2011	0.001	-0.009	-0.012	0.003	0.044	0.003	0.004
	1979-2011	-0.036	0.007	0.030	-0.033	0.019	-0.008	-0.003
Monsoon	1948-2011	-0.014	-0.007	0.028	0.017	0.051	0.057	0.023
	1979-2011	-0.045	-0.015	0.056	-0.020	0.027	0.011	0.000
Post-monsoon	1948-2011	-0.002	-0.002	0.020	0.008	0.045	0.016	0.009
	1979-2011	-0.041	-0.001	0.038	-0.035	0.035	0.000	0.017
Annual	1948-2011	-0.002	-0.008	-0.001	0.010	0.043	0.028	0.011
	1979-2011	-0.037	-0.003	0.042	-0.029	0.012	-0.024	-0.006

NT, NM, NP, ST, SM, SP are as defined in Para 2 of the ‘Data and methodology’ section.

0.19 °C. Below 500 hPa the temperature trends are increasing. SM has a higher increasing trend between 850 hPa and 200 hPa whereas from 400 hPa to 200 hPa, all regions show an increasing trend except over NM where the trends are negative. Above 50 hPa, the trends of all six climatic sub-regions increase with height.

3.5. *Variability in tropopause*

Tables 3 & 4 give the seasonal and annual trends in mean tropopause height and temperature over different climatic sub-regions.

3.5.1. *Tropopause height (hPa)*

The seasonal and annual trend in mean tropopause height (Table 3) varies from -0.242 to 0.109 hPa/year. The negative (positive) trend values mean that the troposphere is having a tendency to expand (shrink). During the satellite era, the trend values become more negative / change from positive to negative values as compared to whole period (1948-2011).

The trends in ST and SM mean tropopause heights are negative during all the four seasons. The values are more negative during satellite era which means that the troposphere over ST and SM has an expanding tendency. In NT and NM the tropopause mean height trend values are positive (troposphere is having shrinking tendency) except in monsoon season, when the trend value is negative (the troposphere is showing expanding tendency). During the satellite era, the trend values become more negative / less positive as compared to the whole period in the NH and over SP.

3.5.2. *Tropopause mean temperature*

The mean tropopause temperature trends show increasing trend during the whole period while it shows decreasing trend during the last four decades (Table 4). Seasonal trend values are positive during all the four seasons and change sign during winter and pre-monsoon period during recent 40 years of the study period.

The mean tropopause temperature shows decreasing (increasing) trends over the three climatic sub-regions in the northern (southern) hemisphere. This rate of increase (decrease) in trend indicates a tendency which is less positive/negative (more negative) during satellite era. Over the region between latitudes 90° S to 30° N, the mean temperatures show an increasing trend while a decreasing tendency is observed during all the four seasons.

4. Conclusions

The analysis indicates an annual increasing trend in temperatures in the troposphere of both NH and SH though seasonwise there is a mixed trend. It can be inferred that the troposphere is indeed warming in the recent years due to natural climate forcing as well as anthropogenic causes, though seasonal trends do not depict increasing trends alone.

(*i*) During winter, the atmosphere below 400 hPa is warmer by 0.1 °C to 1.0 °C in the satellite era in all the climatic regions except over SP where the atmosphere is cooler in the last three decades.

(*ii*) In the pre-monsoon season, the atmosphere below 600 hPa is warmer by 0.1 °C-1.0 °C in the satellite era in all the climatic regions.

(*iii*) Satellite era is warmer over NP and SP at all vertical levels during the monsoon season.

(*iv*) The MT profile shows no major change during post-monsoon season in all the six climatic regions at all vertical levels considered.

(*v*) An increasing trend in annual temperatures below 500 hPa is evident in the satellite era.

(*vi*) The monthly lower tropospheric and mid-tropospheric temperature variations are higher in NH than SH since the SH is mainly covered with ocean and NH has a majority of land area. For the same areas, upper tropospheric temperature variations are lower than that in the lower and middle troposphere. Lower stratospheric monthly MT is nearly same in the tropics of NH and SH.

(*vii*) Variation in tropopause height is less over NT than ST.

(*viii*) Mean tropopause temperature is more in satellite era.

Acknowledgement

The authors are grateful to Dr. Y. E. A. Raj, Deputy Director General of Meteorology for his support and permission to take up research on this topic.

References

Agudelo, P. A. and Curry, J. A., 2004, "Analysis of spatial distribution in tropospheric temperature trends", *Geophys. Res. Lett.*, **31**, L222207.

Angell, J. K., 1988, "Variation and trends in tropospheric and stratospheric global temperature, 1958-87", *J. Climate*, **1**, 1296-1313.

Angell, J. K., 2000, "Tropospheric temperature variations adjusted for El Niño, 1958-1998", *J. of Geophys. Res.*, **105,** 11841-11849.

Chase, T. N., Pielke Sr, R. A., Knaff, J. A., Kittel, Timethy, G. F. and Eastman, J. L., 2000, "A comparison of regional trends in 1979-1997 depth averaged tropospheric temperature", *Intl. J. Clim.*, **20**, 503-518.

Chellaiah M. and Ropelewski, C. F. 2000, "Reanalysis based tropospheric temperature estimate: uncertainties in the context of global climate change detection", *J. Climate*, **13**, 3187-3205.

Christy, J. R., Spencer, R. W. and McNider, R. T. 1995, "Reducing noise in the MSU daily lower tropospheric global temperature data set", *J. Climate*, **8**, 888-896.

Christy, J. R., Spencer, R. W. and Braswell, W. D. 2000, "MSU Tropospheric temperatures: data set construction and radiosonde comparisons", *J. Atmos. Oceanic Technol.*, **17,** 1153-1170.

Christy, J. R., Spencer, R. W., Norris, W. B., Braswell, W. D. and Parker, D. E., 2003, "Error estimates of Version 5.0 of MSU/AMSU bulk atmospheric temperatures", *J. Atmos. Oceanic Technol.*, **20**, 613-629.

Donner, L., Seman, C. J., Hemler, R. S. and Fan, S., 2001, "A cumulus parameterization including mass fluxes, convective vertical velocities, and mesoscale effects: thermodynamic and hydrological aspects in a general circulation model", *J. Climate*, **14,** 3444-3463.

Fu, Q. and Johnson, C. M., 2005, "Satellite-derived vertical dependence of tropical tropospheric temperature trends", *Geophys. Res. Lett.*, **32**, L10703, doi: 10.1029/2004GL022266.

Gaffen, D. J., Santer, B. D., Boyle, J. S., Christy, J. R., Graham, N. E. and Ross, R. J., 2000, "Multi decadal changes in the vertical structure of the tropical troposphere", *Science*, **287**, 1242-1245.

Goody, R. M. and Yung, Y. L., 1989, "Atmospheric Radiation: A Theoretical Basis", Oxford University Press, New York, 519.

Hartmann, D. L., 1994, "Global Physical Climatology", Academic Press, San Diego, CA, 411.

Held, I. M., 1982, "On the height of the tropopause and the static stability of the troposphere", *J. Atmos. Sci.*, **39**, 412-417.

Holton, J. R., 1979, "An Introduction to Dynamic Meteorology", Academic Press, New York, 391.

Hurrell, J. W., Brown, S. J., Trenberth, K. E. and Christy, J. R., 2000, "Comparison of tropospheric temperature from radiosonde and satellites:1979-98", *Bull. Amer. Meteor. Soc.*, **81**, 2165-2178.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deanen, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Leetma, A. and Reynolds, R., 1996, "The NCEP/NCAR 40-year reanalysis project", *Bull. Amer. Meteor. Soc.*, **77**, 437-471.

Kiehl, J. T., 1992, "Atmospheric general circulation modelling", In: Climate System Monitoring, Ed., K. Trenberth, Cambridge University Press, U. K., 319-369.

Lanzante, J. R., Klein, S. A. and Seidel, D. J., 2003b, "Temporal homogenisation of monthly radiosonde temperature data, Part II: Trends, sensitivities and MSU comparison", *J. Climate*, **16**, 241- 262.

Lanzante, J. R., 2006, "Temperature trends in the lower atmosphere-Understanding and reconciling differences", Chapter-3", p47.

Mears, C. A., Schabel, M. C. and Wentz, F. W., 2003, "A reanalysis of the MSU channel tropospheric temperature record", *J. Climate*, **16,** 3650-3664.

Oort, A. H. and Peixoto, J., 1992, "Physics of Climate", American Institute of Physics, New York, 520.

Oort, A. H. and Liu, H., 1993, "Upper air temperature trends over the globe, 1956-1989", *J. Climate*, **6**, 292 -307.

Parker, D. E., Gerden, M., Cullum, D. P. N., Sexton, D. M. H., Folland, C. K. and Rayner, N., 1997, "A new global gridded radiosonde temperature database and recent temperature trends", *Geophys. Res. Lett.*, **24**, 1499-1502.

Pielke, R. A., 1998, "Climate prediction as an initial value problem", *Bull. Amer. Meteor. Soc*., **79**, 2743-2746.

Pielke, R. A., Sr., 2001, "Influence of the spatial distribution of vegetation and soils on the prediction of cumulus convective rainfall", *Review of Geophysics*, **39**, 151-177.

Ramaswamy, V. and Ramanathan, V., 1989, "Solar absorption by cirrus clouds and the maintenance of the tropical upper troposphere thermal structure", *J. Atmos. Sci.*, **46,** 2293- 2310.

Salby, M. L., 1996, "Fundamentals of Atmospheric Physics", Academic Press, San Diego, CA, 627.

Santer, B. D., Wehner, M. F., Wigley, T. M. L., Sausen, R., Meehl, G. A., Tayler, K. E., Ammann, C., Arblaster, J., Washington, W. M., Boyle, J. S. and Brueggemann, W., 2003, "Contributions of anthropogenic and natural forcings to recent tropopause height changes", *Science*, **301**, 479-483.

Sherwood, S. C. and Dessler, A. E., 2003, "Convective mixing near the tropical tropopause : Insights from seasonal variations", *J. Atmos. Sci.*, **60**, 2674-2685.

Spencer, R. W. and Christy, J. R., 1990, "Precision and radiosonde validation of satellite grid point temperature anomalies, Part II: A tropospheric retrieval and trends during 1979-90", *J. Climate*, **5**, 858-866.

Stephens, G. L. and Webster, P. J., 1981, "Clouds and climate: sensitivity of simple systems", *J. Atmos. Sci.*, **38**, 235-247.

Sturaro, G., 2003, "Patterns of variability in the satellite microwave sounding unit temperature record: comparison with surface and reanalysis data", *Intl. J. Clim.*, **23**, 1799-1820.