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Seasonal variations, trend in the tropopause height/temperature over Indian stations and its modulations by SST anomalies of east Pacific Ocean

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सार – ग्रीन हाउस गैसों में वृद्धि के परिणामस्वरूप पूरे भूमंडल का गर्म होना अब भली भाँति जाना जाने लगा है। इस विषय पर हुए अनेक अध्ययन पर क्षेत्रीय पैमानों के साथ-साथ भूमंडलीय पैमानों से भी वर्षा की घटनाओं, उष्णकटिबंधीय चक्रवातों/तूफानों की आवृत्ति एवं तीव्रता, अधिकतम/न्यूनतम तापमान, महासागरों के समुद्र सतह तापमान आदि जैसे मौसम विज्ञान से संबंधित प्राचलों के संबंध में वर्षों में देखे गए परिवर्तनों का पता भी चलता है। अधिक डाटा सेटों पर आधारित भारत में प्रत्येक 5° अक्षांश पर मौसम संबंधी परिवर्तनों में क्षोभसीमा ऊँचाई और तापमान का पता लगाने के अलावा इस अध्ययन में स्थान चित्रित किए गए जहाँ इस प्रवृत्ति के संभावित कारणों के पता लगाने के अतिरिक्त वार्षिक पैमाने पर भारतीय क्षेत्र पर देखी गई तापमान और उँचाई के संबंध में महत्वपूर्ण संबंध होते है। इस अध्ययन में भारतीय स्थानों में क्षोभसीमा तापमान उँचाई के मध्य महत्वपूर्ण रैखिक संबंध और समुद्र सतह तापमान वाले एक वर्ष के बीच संबंध की भी पुष्टि होती है।

ABSTRACT. Global warming due to increase in the Green House Gases is now well known. There are several studies, also, suggesting discernible changes over the years in respect of meteorological parameters like, rainfall events, frequency and intensity of tropical cyclones/hurricanes, maximum/minimum temperature, SST of oceans etc, on regional as well as global scale. The present study besides finding out seasonal variations in tropopause height and temperature across each 5° latitude over India based on a longer data set, has demarcated the locations where significant trend in respect of temperature and height was observed over Indian region on annual scale besides investigating the possible causes of this trend. The study has also confirmed significant linear associationship between tropopause temperature/height over Indian stations and SST anomalies of east Pacific Ocean with SST leading by one year.

Key words – Tropopause height/temperature, Sea surface temperature, Trend, Mann-Kendall test.

1. Introduction

After remaining a burning topic for the debate/study for a considerable long time, the phenomenon of global warming due to enhancement of greenhouse gases, has conclusively been proved. In that context, it has become inevitable to study the climatic changes, if any, in respect of other meteorological parameters/elements, also. Trend in meteorological parameters has been reported by several research workers. Sen Roy and Prasad (1991), Srivastava and Sinha Ray (1994), discussed the global and regional aspects of climate change. Srivastava *et al*. (1992, 1994) and Subramaniam *et al.* (1992) studied trends in southwest monsoon and annual rainfall subdivisionwise, districtwise and country as a whole. Sinha Ray *et al*. (1997) discussed the trends in maximum and minimum temperature over India. De and Rajeevan (1997) reviewed anthropogenic climate changes. Srivastava *et al*. (2000) reported that there was decreasing trend in the frequency of cyclonic storms over Indian seas. Sinha Ray and Srivastava (2000) studied the trend in frequency of heavy rainfall events to find that there is significant decreasing trend over almost all stations.

There are several studies examining various characteristic features such as monthly, seasonal variations in temperature and height of tropopause over Indian stations *viz*., by Shastry and Narasimham (1966), Sharma (1966), Sivaramakrishnan (1986). However, data involved in above studies are of very limited period (data of four years only have been used). Further, Ramamurthy (1976) studied the possible relationship between water vapour in troposphere and tropopause height, over India to conclude that no uniform or unique relationship exists between two. Desikan *et al*. (1994) found that tropopause generally loses energy throughout the year except during monsoon season.

However, none of the above studies concerning tropopause deals with trend if any in the characteristics of tropopause.

TABLE 1

Name of Station	Latitudinal Belt	Plotted against Latitude
Srinagar (SRG), Patiala (PTL)	30° N and north	35° N
Jodhpur (JDP), Delhi (DLH), Lucknow (LKN), Gauhati (GHT)	25° N – 30° N	30° N
Ahmedabad (AHM), Nagpur (NGP) Bhubaneshwar (BWN), Calcutta (CAL)	20° N – 25° N	25° N
Panjim (PJM), Bombay (BMB), Hyderabad (HYD), Visakhapatnam (VSK)	15° N – 20° N	20° N
Madras (MDS), Bangalore (BNG),Mangalore (MNG)	10° N – 15° N	15° N
Trivandrum (TRV), Minicoy (MNC), Cochin (CHN)	10° N and south	10° N

Stations used for computing mean of seasonal averages for different latitudinal belt

In the present study, besides studying seasonal variations of tropopause height and temperature based on long series of data, authors have tried to find out whether there is any trend in the tropopause height and temperature over different Indian stations. They have also examined its link with SST anomalies of east Pacific Ocean. It is to be mentioned that besides reporting tropical tropopause throughout the year, some northern stations (Srinagar, Delhi etc.) also report extratropical tropopause at lower height [Sastry and Narsimham (1966), Sivaramakrishnan *et al*. (1972)] during the months November to April. Same was found in this study too. It was observed that extratropical tropopause was reported under first tropopause while data of tropical tropopause over all stations were reported under second tropopause. Hence, data of second tropopause, hereafter referred as tropopause, were used in the study.

2. Data and methodology

Monthly data of tropopause height and temperature over different Indian stations from the year 1968 onwards and upto the year 1991 were considered for the study. Verma (1980) has reported that upper air temperatures recorded over Indian stations prior to 1968 were 2° to 3° C higher than those of later period. A recent study by Gaffin *et al*. (2000) has also indicated the influence of radiosonde data quality on trends in temperature. Hence, the data prior to the year 1968 were not considered for the study. Data were subjected to quality test as suggested by Sellers and Liu (1988). Values deviating from the mean for a given month by more than (1.76 + 0.08N)S where N is sample size ($N \geq 5$) and S is standard deviation of the sample, were rejected. Thereafter, seasonal and annual values were computed from the monthly values to see the seasonal variations and those values were subjected to Mann-Kendall analysis to determine the trend. SST anomalies values of east Pacific Ocean received from National Centres for Environmental Prediction (NCEP) were used to calculate correlation coefficients between SST anomalies of east Pacific Ocean and temperatures/heights of the tropopause over different stations.

3. Results and discussions

(*i*) *Seasonal variations of tropopause height and temperature*

Twenty stations having more than 20 years (except station Patiala, which has 15 years of data) of data were considered for calculating mean of seasonal averages of tropopause height and temperature for different 5° latitudinal belts. These are shown in Table 1. These were calculated for stations lying within each 5° latitudinal belt and plotted against northern latitude of the belt. Thus, the mean of seasonal averages of tropopause height and temperature of the stations, south of 10° N *viz*., Trivandrum (TRV), Minicoy (MNC) and Cochin (CHN) was plotted against 10° N. Similarly, same for the stations lying between 10° N and 15° N *viz*., Mangalore (MNG), Bangalore (BNG) and Madras (MDS) was plotted against 15° N and so on and are shown in Fig. 1. The fluctuations of tropopause north and south are associated with the seasonal migration of subtropical high which has its northernmost position in the monsoon season and southernmost in winter. This is clearly revealed in following discussion.

It can be seen that on annual scale, minima in tropopause height (16.41 km) and maxima in tropopause temperature (−67.5° C) occurs in the northernmost latitudinal belt *i.e.* north of 30° N and height (temperature) increases (falls) to the southward upto the latitudinal belt 10° N - 15° N where tropopause height (temperature) is maximum (minimum) to 16.71 km (−80.3° C). However, further southward there is slight fall (increase) in tropopause height (temperature) in the southernmost latitude. Thus, the range of variation in tropopause height is about 0.3 km while it is 12.8° C for tropical temperature.

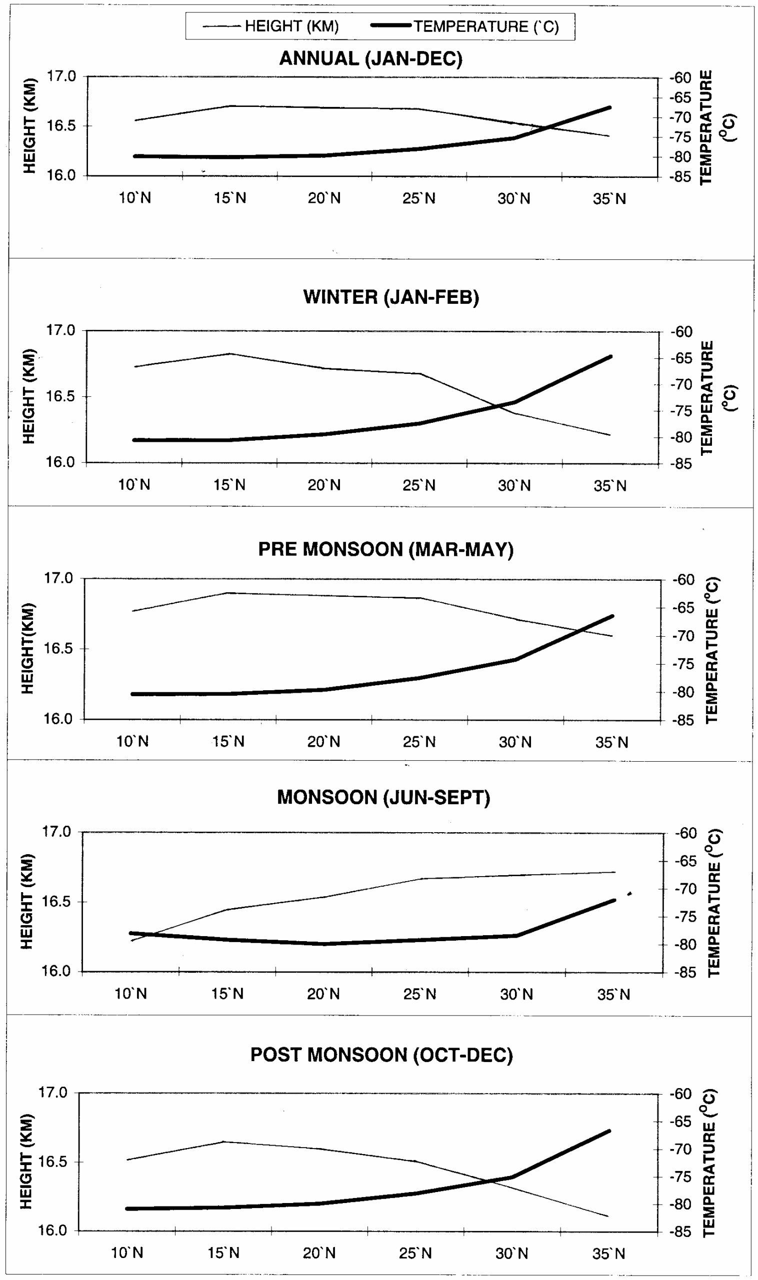

Fig. 1. Seasonal variations in tropopause height and temperature across different latitudinal belts

For the other seasons, except monsoon season *i.e.* for winter, pre-monsoon and post monsoon seasons, variation in tropopause height across different latitudinal belts is similar to the annual pattern from lowest (16.22, 16.60 and 16.11 km respectively), in northernmost latitudinal belt and increasing southward to attain peak values (16.83, 16.90 and 16.65 km respectively) in the belt 10° - 15° N before falling slightly further southward. But variation in tropopause temperature for these seasons are rather uniform from maximum in northernmost latitudinal belt (–64.6°, –66.4° and –66.6° C respectively) and decreasing southward to attain minimum values (–80.7°, –80.5° and –81.0° C respectively) in the southernmost latitudinal belt. The ranges of variation in tropopause height (temperature) are 0.61, 0.30 and 0.54 km (16.1°, 14.1° and 13.4° C) respectively for winter, pre and post monsoon seasons.

For the monsoon season, pattern in the variation of tropopause height and tropopause temperature is remarkably different. Maxima in height (16.72 km) occurs in the northernmost latitudinal belt (actually, it is

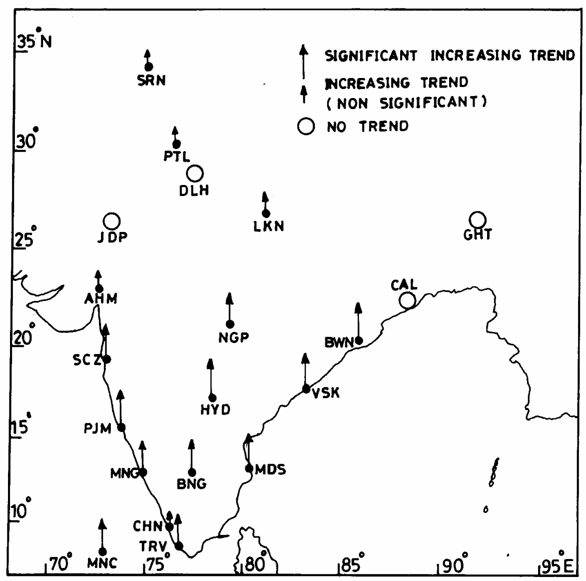

Fig. 2. Annual tropopause height trend

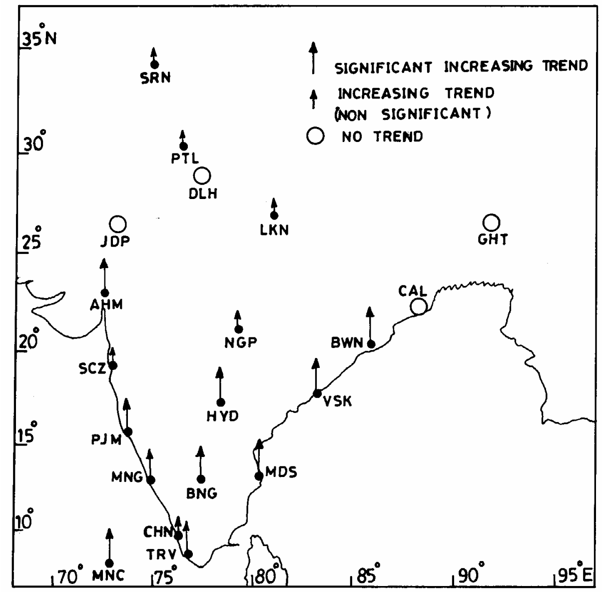

Fig. 4. Annual 500 hPa temperature trend

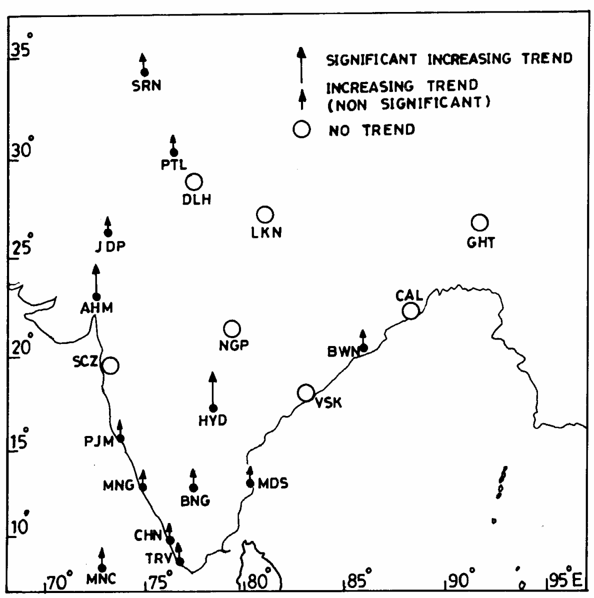

Fig. 3. Annual tropopause temperature trend

almost equal for first two northernmost latitudinal belt) and decreases steadily southward to attain the minima (16.22 km) in the southernmost latitude. However, temperature like annual pattern decreases southward from the maxima (–72.0° C) in the northernmost latitude (temperature rapidly falls from first (–72.0° C) to second latitudinal (–78.4° C) and there after it does not practically change) to the minima (–79.2° C) in the 10° N-15° N latitude belt and again slightly rises in the southernmost latitude. Thus, for monsoon season the range for tropopause height is 0.5 km while it is 8.0° C for tropopause temperature.

Thus, tropopause height on annual as well as on seasonal scales except for monsoon season (where maxima occurs in the northernmost latitude) is maximum in the 10° N - 15° N belt and maxima in tropopause temperature (in all season) occurs in northernmost belt. Minima in tropopause height on annual as well as on seasonal scales occurs in the northernmost latitudinal belt except for monsoon season (where minima occurs in the southernmost latitudinal belt) and same for tropopause temperature occurs in southernmost latitude for winter, premonsoon and post monsoon season and in 10° N - 15° N belt for annual and monsoon season. We can also notice the variation in tropopause height (0.61 km) as well in tropopause temperature (16.1° C) is maximum in winter season while minima in variation for tropopause height occurs in pre monsoon months (0.3 km) and same for tropopause temperature occurs during monsoon months (8.0° C). It can also be noticed that minima (16.11 km) in tropopause height occurs in post monsoon season in the northernmost latitude and maxima (16.90 km) occurs in 10° N - 15° N belt in pre monsoon season. Similarly, minima (–80.9° C) in tropopause temperature occurs in post monsoon season in southernmost latitude and maxima (–64.6° C) occurs in winter season in the northernmost latitude.

On examining different latitudinal belts, it is found that for the 15° N -20° N belt variation in tropopause

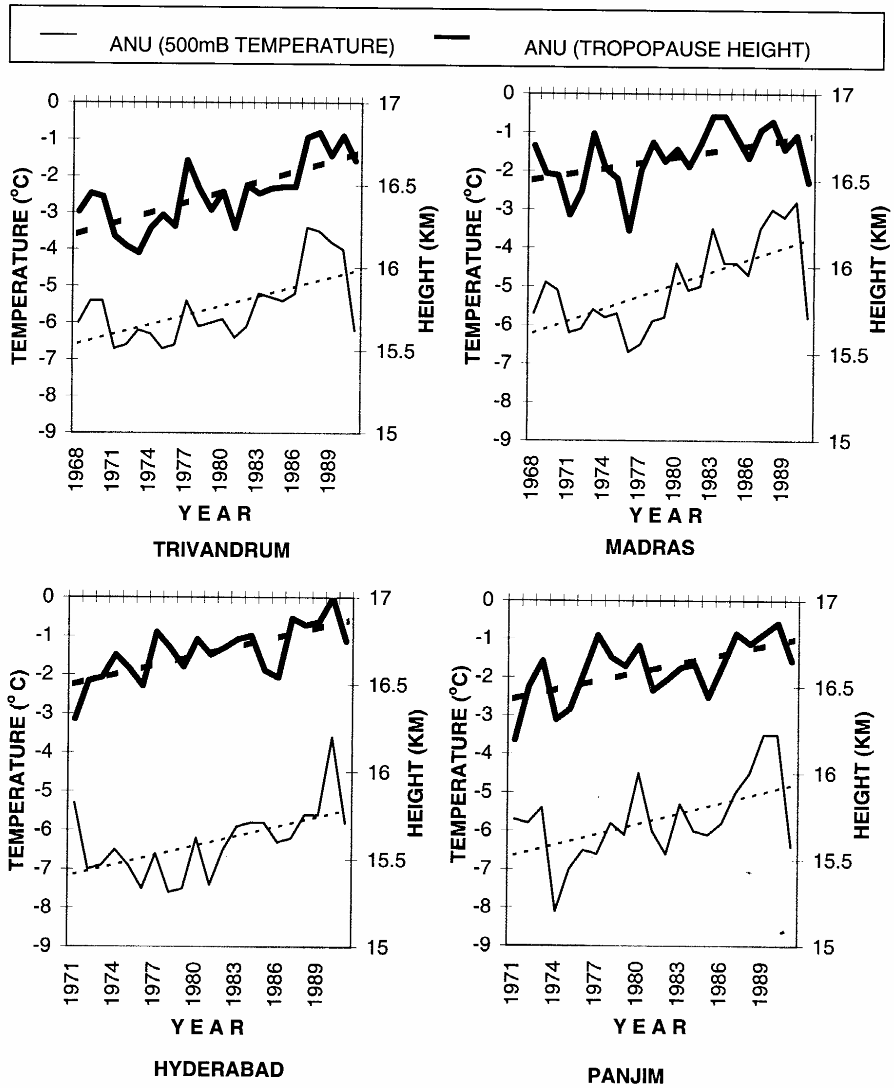

Fig. 5. Trend in annual tropopause height *vis-à-vis* trend in annual temperature of 500 hPa, over various stations

height (0.34 km) and tropopause temperature (less than 1° C) is least while for the northernmost belt variation in tropopause height (0.61 km) and tropopause temperature (7.4° C) is maximum.

As usually jet streams are associated with a steep horizontal gradient in the tropopause height (Namias and Clapp, 1951), it may be noticed that the minima in tropopause height during winter, post-monsoon and monsoon seasons occur around the normal position of westerly (for winter and post monsoon seasons) and easterly (for monsoon season) jet streams and are of almost same order.

(*ii*) *Annual trend in tropopause height and tropopause temperature*

Figs. 2&3 show the annual trend in tropopause height and temperature respectively. It can be noticed that most of the stations show an increasing trend in height and this is statistically significant over a number of central and almost all southern stations. On seasonal scales similar trend is observed for monsoon season while it is mostly non-significant for other seasons. As far as trend in annual tropopause temperature is concerned, although most of stations show increasing trend but it is statistically significant only for Ahmedabad (AHM) and Hyderabad

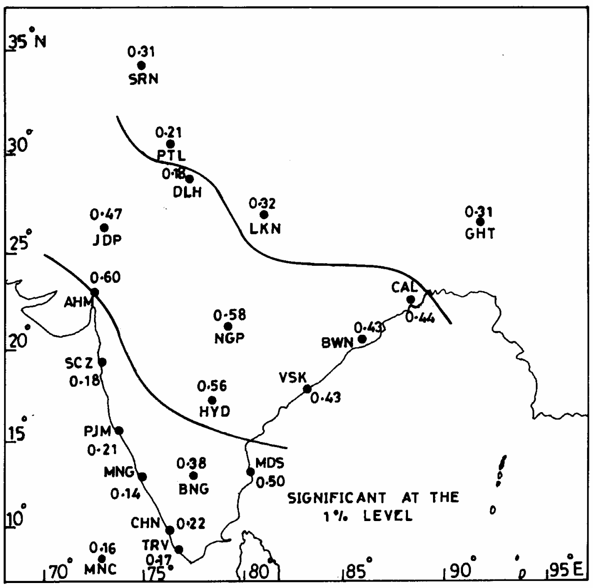

Fig. 6. Correlation coefficient between pre-monsoon SST anomalies of nino 3 region and pre-monsoon tropopause height with SST leading by one year

(HYD). On seasonal scales also this trend is non-significant over most of the stations. In view of above, authors tried to examine the possible causes of the significant increasing trend in annual tropopause height over central and southern stations of India.

It may be mentioned that although, globally no significant trend in tropopause height and temperature was noticed (Hoinka, 1999), significant trend in the same on the regional scale has been reported by several studies. Studies by Hoinka *et al.* (1996), Degorska *et al.* (1996), Wege and Claude (1997), Bojkov and Fioletov (1997), Hoinka (1998) have found the increasing trend in tropopause height over a number of European stations. They have attributed this trend due to ozone depletion in stratosphere. But a study by Steinbrecht *et al.* (1998) has shown that ozone depletion is only partially responsible for increasing trend in tropopause height. The study has further found that tropospheric warming is well correlated with this trend and may be one of the reasons. Moreover, it has been reported by Schubert and Mounteanu (1988) that the correlation between amount of total ozone and tropopause height for tropics is not significant and therefore depletion of ozone may not be reason for the increasing trend in tropopause height particularly for the tropics. Therefore, it is imperative that relationship between tropopause height and tropospheric temperature and trend if any should be investigated.

It is worthy to mention that Srivastava *et. al.*, (2000) had already reported increasing trend in upper air tropospheric annual temperature along a number of coastal stations. Therefore, authors again examined the trend in upper air tropospheric annual temperature over remaining stations of India and incidently most of the stations reporting increasing trend in tropopause height reported increasing trend in tropospheric upper air temperature too. It may also be mentioned that this increasing trend in temperatures of 500, 300 and 200 hPa levels was almost identical and result for 500 hPa is shown in Fig. 4. Similar trend in annual temperatures of 850 and 700 hPa level was also found. We have made time series of 500 hPa temperature and tropopause height for a number of stations and are shown in Fig. 5. The similarity between two quantities are striking and they appear to be highly correlated. Finally, we have calculated correlation coefficients between annual tropopause height and annual 500 hPa temperature for different stations. The correlation coefficient between two was found to be of the order of 0.70 (significant at the 0.01% level) for almost all stations. For other tropospheric levels *viz*., for 300 and 200 hPa levels also, almost similar relationship exists and these results are in coherence with the results of Steinbrecht *et al.* (1998).

Therefore, tropospheric warming may be the one of the possible causes for the increasing trend in tropopause height. This increase in tropopause height is approximately 0.17 km/decade over most stations while increase in 500 hPa temperature is approximately 0.8° C/decade.

(*iii*) *Modulation of tropopause height and temperature by SST anomalies of east Pacific Ocean*

Angell (1981), Sellers and Liu (1988) have shown that there exists a significant 2-3 season lag linear relationship between Sea Surface Temperature (SST) of the equatorial east Pacific Ocean and global temperature from surface to 100 hPa layer, with SST leading. Authors have verified these results for the tropopause data of Indian stations (where tropoapuse occurs approximately around 100 hPa) by calculating correlation coefficients between annual height/temperature and SST anomalies of east Pacific Ocean (Nino 3 region) with SST leading by one year. It was found that annual tropopause height over major parts of the country have positive correlation with annual SST anomaly. Similarly, annual tropopause temperature over northern, central and eastern stations has negative correlation with same. Further, it was found that this association is stronger for tropopause height/ tropopause temperature of winter and premonsoon seasons and premonsoon SST anomalies with one year lead and correlation coefficients significant at the 1% level were found between premonsoon tropopause height and premonsoon SST (leading by one year) and between

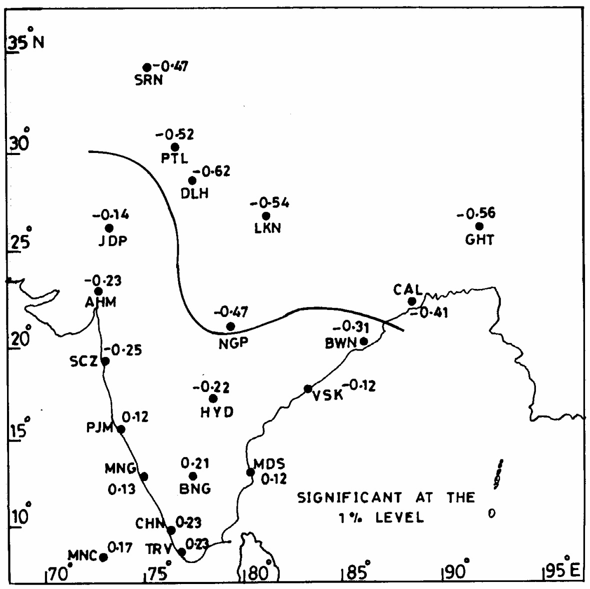

Fig. 7. Correlation coefficient between pre-monsoon SST anomalies of nino 3 region and winter tropopause temperature with SST leading by one year

TABLE 2

Sub-division	(A)	(B)
Rajasthan West	28	9
West Madhya Pradesh	-10	-26
East Madhya Pradesh	-11	-20
Gujarat	-13	-45
Konkan & Goa	-11	-52
Madhya Maharashtra	2	-5
Marathawada	7	-25
Vidarbha	-9	-29
Coastal Andhra Pradesh	10	-10
Telangana	1	-28
Coastal Karnataka	12	-4
Kerala	-6	-14
Lakshadweep	8	-22

Percentage departure of pre-monsoon rainfall during
(A) other years excluding years following the El-Nino years
(B) years following the El-Nino years in the data set of period 1950 – 98

winter tropopause temperature and premonsoon SST (leading by one year). These results are shown in Figs. 6&7. Therefore, it can probably be inferred that tropopause height particularly in premonsoon months following El-Nino years should increase and tropopause temperature for the winter season for north India should decrease.

Therefore, premonsoon rainfall data over subdivisions (to which those stations belong and have significant positive correlation with one year leading SST anomalies) were divided into two parts *viz*., data of years following El-Nino years and data of years excluding these years from the data set of 1950-98. Means of two data sets were calculated and results are shown in Table 2. It was noticed that mean premonsoon rainfall for years following El-Nino events are less compared to the mean during other years. The difference was found to be quite large indicating less premonsoon rainfall in the years following El-Nino events. However, the difference was not found statistically significant when student '*t*' test was applied. This is probably due to large standard deviation in rainfall values.

4. Conclusions

(*i*) Maxima in tropopause height on annual and seasonal scales except for monsoon season occurs in 10° N – 15° N belt while same in tropopause temperature occurs in the northernmost latitudinal belt.

(*ii*) Maximum variation in tropopause height as well as in tropopause temperature is in winter while minimum variation in tropopause height occurs in premonsoon months and same for tropopause temperature occurs during monsoon months.

(*iii*) In the latitudinal belt 15° N - 20° N variation in tropopause height and tropopause temperature during different seasons are least, while variation is maximum in the northernmost latitude for both tropopause height and tropopause temperature.

(*iv*) Significant increasing trend in tropopause height was found over a number of central and almost all southern stations and it is approximately 0.17 km/decade. No significant trend was noticed for tropopause temperature except for one or two stations.

(*v*) Tropospheric warming may be one of the causes for this trend.

(*vi*) Intensity of pre-monsoon showers in years following El-Nino events is likely to be less in comparison to the other years.

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