

Letters to the Editor

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LONG TERM TRENDS IN THE THERMAL STRUCTURE OF THE MIDDLE ATMOSPHERE OBTAINED FROM SATELLITE OBSERVATIONS OVER INDIA

1. The concentration of several greenhouse gases, in particular CO₂, CH₄, N₂O and CFCs (Chlorofluorocarbons) are increasing due to anthropogenic activities. This is likely to warm the troposphere and cool the atmosphere above the tropopause (Roble, 1995). The issue of global change in the stratosphere and mesosphere has attracted the attention of scientific community only recently. To study the long term changes and trends in the stratosphere, SPARC (Stratospheric Process And their Role in Climate) has constituted STTA (Stratospheric Temperature Trend Assessment) Panel. This panel has made the detailed assessment of stratospheric temperature trends and reported a moderate cooling in the stratosphere (Ramaswamy *et al.*, 2001). However for the mesospheric altitudes, study related to the detection of temperature trend is in the initial stage. During the past one decade, efforts to quantify the temperature trend in the mesospheric region have been accelerated and number of results are published (Golitsyn *et al.*, 1996; Luebken, 2000; Keckhut *et al.*, 1999). The results reported for mesospheric temperature trends are diverse. Some authors have reported a very high cooling (Golitsyn *et al.*, 1996) and some have reported no trend at all (Lubeken, 2000). Such discrepancies need to be resolved. Moreover studies related to temperature trend over the low latitudes are relatively sparse. A few authors have reported moderate to high cooling trend (Dunkerton *et al.*, 1998; Beig and Fadnavis, 2001) based on Rocketsonde data. The aim of this paper is to study the long term trend in temperature of the middle atmosphere using the satellite based HALOE (version -19) data over the Indian tropical region and to compare these results with available results for this region.

2. HALOE experiment is basically designed to monitor vertical distribution of several minor constituents and temperature (Marsh and Russell, 2000; Russell *et al.*, 1993). It is a satellite solar occultation experiment instrument launched aboard the Upper Atmospheric Research Satellite (UARS). Here the attenuation of the Sun's radiation by the limb of the atmosphere is measured as the sunrise and sunset relative to the satellite. The

attenuated sunlight is measured in several infrared wavebands using wide band and gas cell correlation radiometry techniques. The UARS orbit has an inclination of 57° and a period of about 96 minutes. This results in HALOE viewing on average 15 sunrises and 15 sunsets each day. It sweeps from 80° S to 80° N in Latitude approximately every 30 days.

Temperature vertical profile data (HALOE version 19, Level-3AT) for the period October 1991 to September 2001 has been used for this study. The HALOE temperature data available during this period for the altitude range from 33 km to 86 km (vertical resolution of about 2.5 km) for the Indian tropical region (0-30° N, 60-100° E) has been decoded and retrieved for the analysis. For the altitudes 20 km to 34 km time series has been extended down using National Centers for Environmental Prediction reanalyzed data for this region. Sunrise and sunset measurements are combined and averaged for a day. Thus 339 days for sunrise events and 327 days for sunset events are obtained in the region considered. On each those days when satellite is passing through the selected latitude bin, 5-16 profiles are obtained. Days having less than 5 profiles are not taken into consideration due to statistical considerations. The monthly means have been calculated for statistical analysis.

The Regression model used here is an extended and modified version of the model originally described by Stolarsky *et al.*, (1991) and Ziemke *et al.*, (1997). The extended model version is described in detail recently by us (Beig and Fadnavis 2001). The regression equation can be written as follows

$$\theta(t,m) = \alpha(m) + \beta(m).t + \gamma(m).QBO(t) + \delta(m).Solar(t) + Residual(t) \quad (1)$$

$$m = 1,2,... 12; \quad t = 1,2,3,... N$$

Where θ is the time series of monthly mean temperature data points N . $\alpha(m)$, $\beta(m)$, $\gamma(m)$, $\delta(m)$ represent 12 month seasonal, trend, quasi-biennial oscillation (QBO) and solar coefficients respectively and residual (t) is the noise time series. Model uses the

harmonic expansion to calculate coefficients α , β , γ , and δ .

$$\alpha(t) = A_0 + A_1 \cos(1.2\pi \cdot dt/365.25) + A_2 \sin(1.2\pi \cdot dt/365.25) \quad (12 \text{ months})$$

$$+ A_3 \cos(2.2\pi \cdot dt/365.25) + A_4 \sin(2.2\pi \cdot dt/365.25) \quad (6 \text{ months})$$

$$+ A_5 \cos(3.2\pi \cdot dt/365.25) + A_6 \sin(3.2\pi \cdot dt/365.25) \quad (4 \text{ months})$$

$$+ A_7 \cos(4.2\pi \cdot dt/365.25) + A_8 \sin(4.2\pi \cdot dt/365.25) \quad (3 \text{ months}) \quad (2)$$

Where A_0, A_1, A_2, \dots are constants. While calculating coefficients α, β, γ , and δ , 12 months, 6 months, 4 months and 3 months variations are considered respectively.

QBO (t) is the time series for Singapore zonal winds and Solar (t) is the time series of F10.7 solar index (The Ottawa 10.7 cm microwave flux) used as Solar proxies (Ziemke *et al.*, 1997). It is assumed that the temperature would change linearly with increasing abundance of several greenhouse gases. To account for this a linear trend coefficient β (m) is considered in Eqn. (1).

3. Fig. 1 shows the vertical distribution of annual mean temperature values as obtained from HALOE measurements over the Indian region and Rocketsonde data over Thumba (8°N , 76.5°E) averaged for the period from 1971 to 1993. Both the data sets are found to agree well quantitatively and validate each other. A slight difference in magnitudes (not exceeding 5°K) may be attributed due to some factors like that of (i) Period of time series considered and (ii) Limited geographical coverage in Rocketsonde data as compared to satellite data, etc. However, this difference seems to be consistent in vertical profile and does not affect the trend detection. The maximum near stratopause is very well noticed in both the profiles of Fig. 1 which occurs near 50 km. Fig. 2 shows the time series of trend fit (in $^\circ\text{K}/\text{decade}$) $\beta(m)$ of temperature at two selected altitudes (*viz.* 32 km, 75 km) as obtained from HALOE measurements. $\beta(m)$ is a linear coefficient and its value is representative of the product of monthly trends value and linearly varying numbers of time series which artificially create a wave like structure. It can be noticed from the Fig. 2. That a monotonic decrease in temperature is evident during the last 10 years in both the cases. The fluctuation in this figure also represents the seasonal variability. A least square fit in this time series provide the temperature trend in a given time series. For example the trend calculated for two different heights in

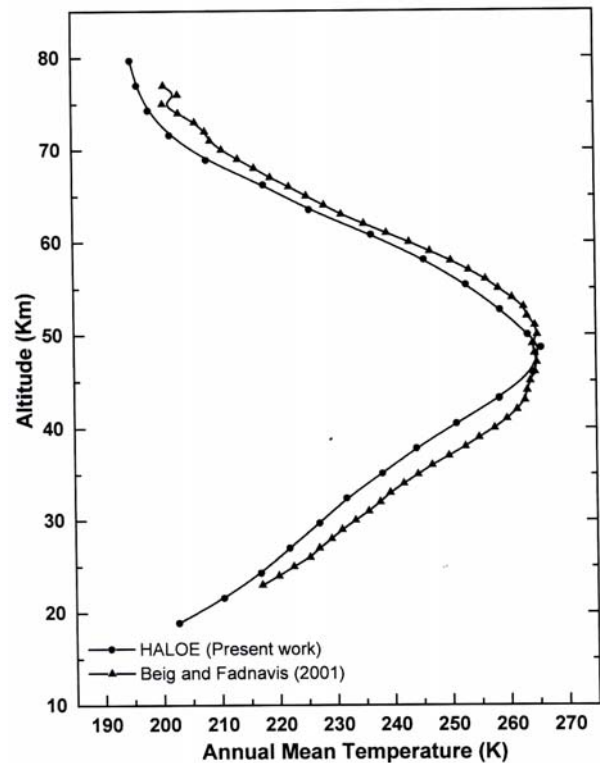


Fig. 1. Vertical profiles of Annual Mean temperatures (K) obtained from HALOE and Rocketsonde measurements over the Indian tropical region by averaging the complete time series considered in this work

Fig. 2. indicates a cooling of $1.63^\circ\text{K}/\text{decade}$ and $4.99^\circ\text{K}/\text{decade}$ for 32 and 75 km altitudes respectively. Similar analysis is carried out for each altitude for HALOE data and vertical distribution of temperature trend ($^\circ\text{K}/\text{decade}$) is calculated which is shown in Fig. 3. (profile 1). For the comparison, results obtained by Beig and Fadnavis (2001) and Keckhut *et al.* (1999) for tropical latitudes are also shown in Fig. 3 as profiles 2 and 3 respectively. Vertical trends (profile 2) obtained by Beig and Fadnavis (2001) are from Rocketsonde measurements over the equatorial station, Thumba (8.32°N , 76.5°E) for the 23 years period (1971-93). The vertical trend profile obtained by Keckhut *et al.* (1999) is also from Rocketsonde measurements (reported a mean annual trend averaged over the six sites from 8°S to 34°N) for the period 1969-91. The horizontal bars in this figure represent 2σ standard deviation. Broadly, present results for stratosphere are found to be in good agreement, within the 2σ error limit with that of other profiles (2 and 3) shown in Fig. 3. In general, present results indicate a cooling of the order of 1-2 $^\circ\text{K}/\text{decade}$ in the stratosphere and 2-5 $^\circ\text{K}/\text{decade}$ in the mesosphere. In the lower stratosphere, HALOE results indicate ($\sim 2^\circ\text{K}/\text{decade}$) a

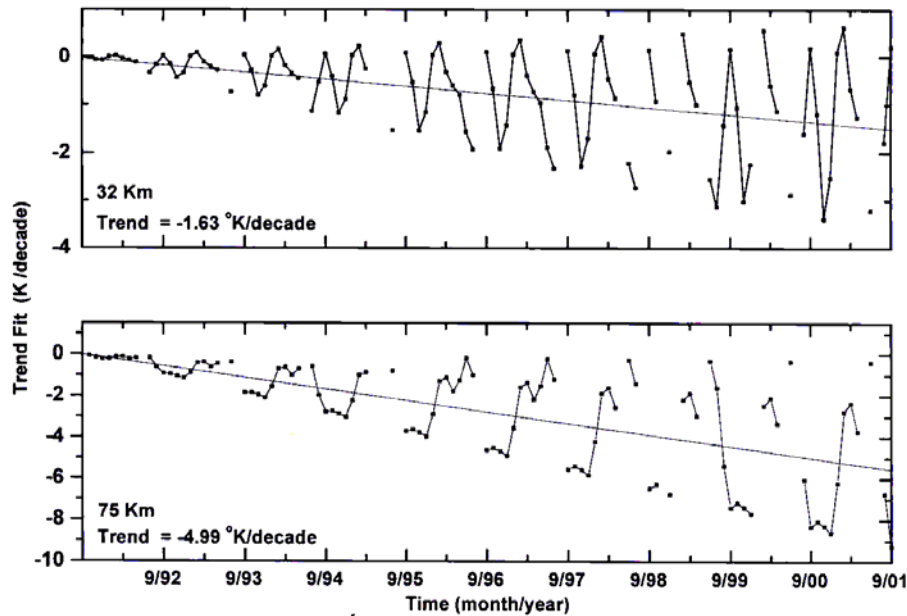


Fig. 2. Time series of trend fit function $[\beta(m)]$ as obtained from HALOE data at 32 km and 75 km

slightly stronger cooling as compared to profiles 2 and 3. However in the upper stratosphere HALOE shows a decline in cooling as compared to lower stratosphere. A few authors have also attempted to deduce the temperature trend over the globe. Ramaswamy *et al.* (2001) made a detailed assessment of temperature trend in the stratosphere and reported an average cooling trend of around ~ 0.75 °K/decade (20-30 km) in the Northern Hemisphere based on number of data sets. A Valley like feature where temperature trends are minimum or absent is observed in HALOE data in the upper stratospheric altitudes that is around 38-45 km. Beig and Fadnavis (2001) have reported this feature around 42-50 km. This feature is not found by Keckhut *et al.* (1999), but they reported a cooling of 1.7 ± 0.7 °K/decade in 35-50 km region. In the valley like region, (*i.e.* in the altitude range of 38-45) HALOE shows cooling of ~ 0.7 °K/decade and Beig and Fadnavis (2001) reported cooling trend of ~ 0.5 °K/decade (in altitude range of 42-50 km). In altitude range of 35-42 km Beig and Fadnavis (2001) reported cooling of ~ 2 °K/decade. Ramaswamy *et al.* (2001) reported cooling trend of ~ 2.5 °K/decade around 30-50 km. In the lower mesosphere the HALOE data shows relatively less cooling trends (~ 2 °K/decade) as compared to the trends obtained by Beig and Fadnavis (2001) and Keckhut *et al.* (1999). However, Keckhut *et al.* (1999) reported cooling trend of 3.3 ± 0.9 °K/decade near 60 km which agrees well with our results. Earlier Kokin and Lysenko (1994) have reported a cooling of

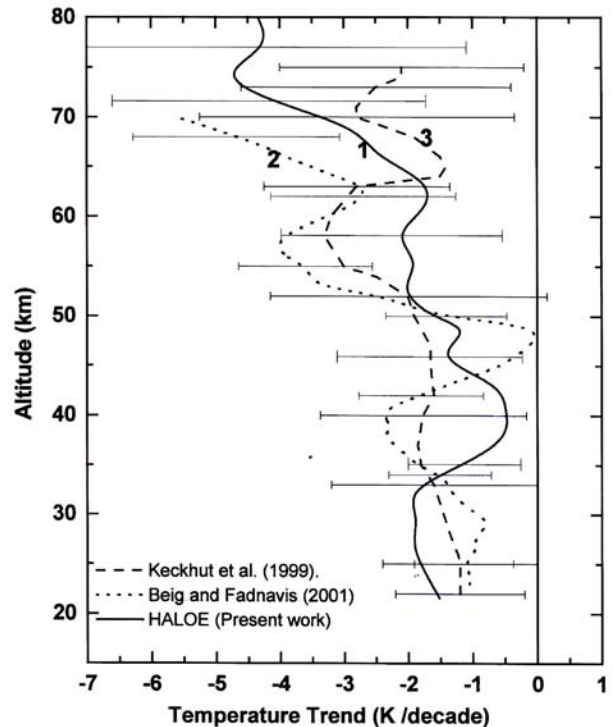


Fig. 3. The vertical profile temperature trends (°K/decade) as obtained in this work using HALOE data. Results obtained by Beig and Fadnavis (2001) [profile 2] and Keckhut *et al.* (1999) [profile 3] for the tropical regions are also shown

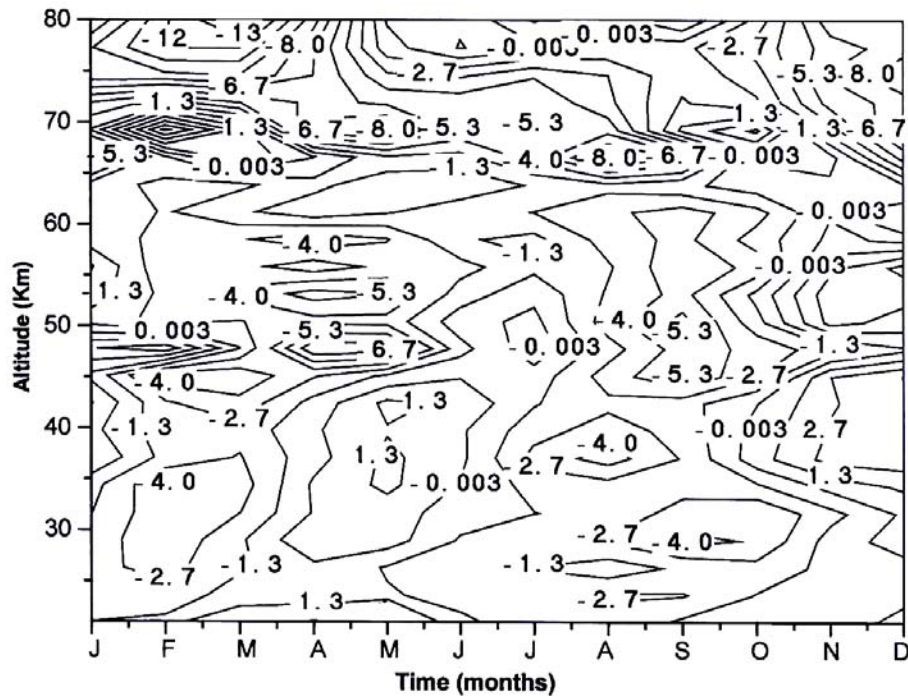


Fig. 4. Vertical structure of seasonal variations (monthly mean) of temperature trend ($^{\circ}\text{K}/\text{decade}$) for the entire altitude range (20-80 km) as obtained from HALOE data

3-10 $^{\circ}\text{K}/\text{decade}$ in mesosphere for low and mid latitudes, which is higher than that obtained in the present analysis. The reason for this discrepancies are reported earlier (Beig and Fadnavis, 2001). In the altitude range 65-75 km cooling trend increases steeply in HALOE, it reaches to ~ 5 $^{\circ}\text{K}/\text{decade}$ at 75 km. Beig and Fadnavis (2001) have also reported steep increase in cooling from 65 km onward and reported cooling trend ~ 5.5 $^{\circ}\text{K}/\text{decade}$ at 70 km. However, Keckhut *et al.* (1999) did not find steep gradient and have reported a cooling trend of $\sim 2-3$ $^{\circ}\text{K}/\text{decade}$ in the altitude range 65-75 km.

Thus the above study shows that the vertical profiles of temperature trends obtained from satellite compare reasonably well with the profiles obtained by other workers (Beig and Fadnavis, 2001) and Keckhut *et al.*, 1999). However, some differences in the results, (profiles 1-3 in Fig. 3) can be seen which are attributed mainly due to the fact that HALOE data is considered for complete Indian region from $0-3^{\circ}\text{N}$, $60-100^{\circ}\text{E}$, whereas analysis of (Beig and Fadnavis, 2001) pertains to single equatorial station. In Keckhut *et al.*, 1999) trends are obtained from an average of six tropical and subtropical Rocketsonde ($8^{\circ}\text{S}-34^{\circ}\text{N}$) observations. In addition to this, length of data series and duration is different in all the three cases, which could perhaps be another reason for some of the discrepancies obtained in the vertical profile of temperature trends from the different data sets of Fig. 3. However the range of vertical profiles of temperature

trends in Fig. 3 lie well within the 2σ standard deviation limit of each other.

HALOE measurements are further analyzed to study the seasonal variations in the vertical structure of temperature trends. Fig. 4 shows the monthly mean temperature trends obtained for the 10 years period of HALOE data, over the altitude range of 20-80 km. In the lower stratosphere, cooling trends are observed during the months of January to March and then small warming trend till June and then again cooling trends are found for rest of the months. Maximum cooling is observed around 28 km during the months of September and October. Similar seasonal variations are found in the upper stratosphere but intensity of warming (positive trend) is more in May. Maximum cooling trends ($\sim 6-7$ $^{\circ}\text{K}/\text{decade}$) are observed around 50 km in the months of April and May. Around 70 km altitude (mesospheric heights) there is maximum cooling in April and May (~ 8 $^{\circ}\text{K}/\text{decade}$) and small warming trend around September. This is opposite to the nature of trends observed at stratosphere altitudes. Thus long term temperature trends are not constant through out the year but have strong seasonal variations.

4. The present study revealed that trends obtained from HALOE data shows cooling in the middle atmosphere. A cooling trend of about 2 $^{\circ}\text{K}/\text{decade}$ is found in the stratosphere and 2-5 $^{\circ}\text{K}/\text{decade}$ in the mesosphere. Vertical profiles of temperature trends

obtained from HALOE shows similar structure with comparable magnitude with vertical profiles reported by other workers for the tropical regions. Seasonal trend in HALOE measurements shows strong cooling in the months of January, February, September and October in the stratospheric altitudes. The April and May months shows maximum cooling trend in mesosphere.

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References

- Beig, Gufran and Fadnavis, S., 2001, "In search of green house signals in the equatorial middle atmosphere", *Geophys. Res. Lett.*, **28**, 4603-4606.
- Dunkerton, T. J., Delisi, D. P. and Baldwin, M. P., 1998, "Middle atmosphere cooling trend in historical rocketsonde data", *Geophys. Res. Lett.*, **25**, 3371-3374.
- Golitsyn, G. S., Semenov, A. I., Shefov, N. N., Fishkova, L. M., Lysenko, E. V. and Perov, S. P., 1996, "Long term temperature trends in the middle and upper Atmosphere", *Geophys. Res. Lett.*, **23**, 1741-1744.
- Keckhut, P., Schmidlin, F. J., Hauchecorne, A. and Chanin, M. L., 1999, "Stratospheric and mesospheric cooling trend estimates from U.S. rocketsondes at low latitudes stations (8° S - 34° N), taking into account instrumental changes and natural variability", *J. Atmos. Sol. Terr. Phys.*, **61**, 447-459.
- Kokin, G. A. and Lysenko, E. V., 1994, "On temperature trends of the atmosphere from rocket and radiosonde data", *J. Atmos. Terr. Phys.*, **56**, 1035-1040.
- Luebken, F. J., 2000, "Near zero temperature trend in the polar summer mesosphere", *Geophys. Res. Lett.*, **27**, 3603-3606.
- Marsh, D. R. and Russell III, J. M., 2000, "A tidal explanation for the sunrise/sunset in HALOE low-latitude nitric oxide observations", *Geophys. Res. Lett.*, **27**, 3197-3200.
- Ramaswamy, V., Chanin, M. L., Angell, J., Barnett, J., Gaffen, D., Gelman, M., Keckhut, P., Koshelkov, Y., Labitzke, K., Lin, J. J. R., O'Neill, A., Nash, J., Randel, W., Rood, R., Shine, K., Shiotani, M. and Swinbank, R., 2001, "Stratospheric temperature Trends : Observations and model simulations", *Rev. Geophys.*, **39**, 1, 71-122.
- Roble, R. G., 1995, "Major greenhouse cooling (yes, cooling) : The upper atmosphere response to increased CO₂", *Rev. Geophys. Supp.*, 539-546.
- Russell, J. M., Gordley, L. L., Park, J. H., Dragsion, S. R., Hesketh, W. D., Cicerone, R. J., Tuck, A. F., Frederick, J. E., Harries, J. E. and Crutzen, P. J., 1993, "The Halogen occultation Experiment", *J. Geophys. Res.*, **98**, 10777-10797.
- Stolarsky, R. S., Bloomfield, P., McPeters, R. D. and Herman, J. R., 1991, "Total ozone trends deduced from Nimbus 7 TOMS data", *Geophys. Res. Lett.*, **18**, 1015-1018.
- WMO, 1999, "Scientific Assessment of Ozone Depletion : 1998, World Meteorological Organization, Global ozone research and monitoring Project", Report No. 44, Geneva.
- Ziemke, J. R., Chandra, S., McPeters, R. D. and Newman, P. A., 1997, "Dynamical proxies of column ozone with applications to global trend models", *J. Geophys. Res.*, **102**, 6117-6129.

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