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In Search of Greenhouse Signals in the Equatorial Middle Atmosphere

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Abstract. A series of Rocketsonde and Radiosonde data (balloon) were collected over the equatorial station Thumba (8°N, 76°E), India extended for about two solar cycle period (1971-1993). This is one of a few longest sets of rare records available from equatorial stations. These data were now analyzed using two independent and upto date new regression models, which are based on multiple function regression theory and also takes account of successive instrumental modifications and tidal effects. These experimental results are complemented with 2-D interactive model results simulated for the same duration and found to agree well. The model accounts for the actual measured growth rate of several greenhouse gases including CO_2, CH_4, N_2O and CFCs for this period. Results of both balloon and rocket data analysis indicate a cooling of the order of 1°K /decade in the lower stratosphere which agrees well with low latitude data by other workers. A negative trend of 2 to 3°K/decade in the lower mesosphere and a rise in cooling up to 5.6°K/decade in the upper mesosphere has been observed. A loss of trend near the stratopause is noticed in annual trend analysis. However, on seasonal scales, trend structure gets modified and shows slightly stronger cooling in winter as compared to summer in the mesosphere.

1. Introduction

The temperature measurements in the middle atmosphere have been done for several decades for variety of reasons including meteorological and climatological requirements, radiative balance estimates, for dynamical study including QBO and so on. However, until recently not much efforts were made to study the long-term trends in the thermal structure of this region due to many constraints like non-availability of near-continuous observations in some cases, difficulty in separating out the natural variation from that of linear anthropogenic trends and most importantly the lack of suitable statistical model to take care of several newly emerging factors of uncertainties like tidal effects, modulation due to instrumental modification, episodic events signals etc. Nevertheless, temperature trends have been reported mainly for mid and high latitudes but a few for low latitudes in search of evaluating the global change signals in the middle atmosphere. The review in stratospheric temperature trend can be found in recent literature (*Ramaswamy et al.*, 2001, *WMO*, 1999). However, the limitation in observational data from a low latitude especially from equatorial station is quite evident from these publications. The analysis of systematic changes in mesospheric and thermospheric temperature is not as comprehensive as the above (for stratosphere) as evident from the brief review included by *Beig* (2000). Several authors have reported a possible greenhouse effect with a moderate cooling in the ionosphere based on long term data base of ionospheric observations (*Bremer*, 1997; *Gadsden*, 1998; *Danilov*, 1997). Recently *Keckhut et al.* (1999) have reported the middle atmospheric cooling trend results for low latitude stations using one of the sophisticated statistical model taking into account all natural, episodic and instrumental factors. They have calculated a negative trend in the stratosphere which becomes stronger in the mesosphere. The high to moderate cooling trend for stratosphere and mesosphere is also reported for low latitudes earlier (*Dunkerton et al.*, 1998; *Clemesha et al.*, 1997; *Kokin and Lysenko*, 1994). In contrast to these findings, a few groups reported no evidence for systematic temporal variations near the mesopause (*Luebken*, 2000; *Burns et al.*, 2001) but their results pertain to high and mid-latitudes. Long-term observations coupled with interactive model study are the key to enhance our understanding of global change impacts. The model results, which accounts for the growth rate of several greenhouse gases including CO_2, CH_4, N_2O, CFCs, have also shown a cooling trend in the middle atmosphere (*Roble and Dickinson*, 1989; *Beig*, 2000; *Beig and Mitra*, 1997). In this work, we report the linear trend results from a revisited rare temperature records of more than two decades from an equatorial station using a very sophisticated regression model which accounts for several new functions that were not considered in earlier analysis on this data series. Analysis is cross-examined by using another statistical approach. Results are also compared with 2-D interactive model simulated results obtained in this work for the similar duration.

2. Data and Statistical Regression Analysis

The rocketsonde temperature sensors were flown on board M-100 rocket from an equatorial station, Thumba (8°N32°N, 76.5°E) during the period from 1971-1993 on almost every Wednesday. The details about the techniques and data corrections are given elsewhere (*Chakravarty et al.*, 1992). The time series of data used here are subjected to a correction, which compensates for aerodynamic heating effect, lag, emissivity, self-heating, conduction and long and short wave radiative heating. The corrected data set available after *Kokin and Lysenko* (1994) and *Chakravary et al.* (1992) are used here for regression analysis along with the additional three more years of records. The altitude range covered was 20-80 km. The number of missing values of data increases above 70 km and so the relative statistical error and the uncertainty associated with the flight termination level. Hence rocket results for 23-70 km are presented here which are statistically significant. The radiosonde data used in this work covered the

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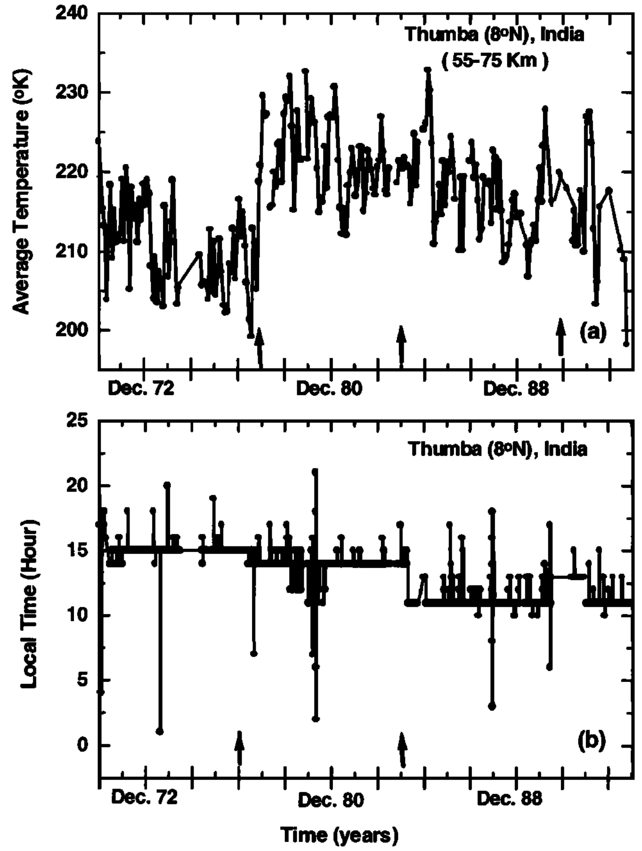

Figure 1. (a) The time series plot of temperature averaged over the altitude range 55-75 km as obtained by rocketsonde in this work, (b) The time series (actual date of measurement of raw data) plot with local time of measurements for the rocketsonde data.

period 1983-1993 for the altitude range from 10-33 km. The sampling interval was 1 km in both rocket and balloon data.

The present data sets have been analyzed by two different statistical approaches. The similarities in the output of both the models have given the confidence about the quality control. In the framework of the joint working group II.F of IAGA (International Association of Geomagnetism and Aeronomy), a mesospheric temperature trend assessment (MTTA) group has been formulated. The MTTA has proposed to re-analyze some data sets to update trend detection, taking into account all already known and newly emerged factors like tidal effects, seasonal changes, instrumental changes, volcanic effects, solar changes etc. The present analysis method is in line with this new multi functional regression analysis process and done at each 1 km altitude resolution. The final linear trend detection is accomplished using the least square fitting technique. Regression model used by us is an extended and modified version of the model originally described by *Stolarsky et al.* (1991) and *Ziemke et al.* (1997) for ozone. It considers the following functions-

$$\theta(t,z) = \alpha(z) + A(z).\ \mathrm{Trend}(t) + B(z).\ \mathrm{Solar}\ F_{10.7}(t) + C(z).\ \mathrm{QBO}(t) + D_i(z).\ \mathrm{Step1}(t_i) + E_j(z).\ \mathrm{Step2}(t_j) + F_k(z).\ \mathrm{Step3}(t_k) + \mathrm{Residual}\ (t,z).$$

Where θ is the time series of monthly (z) mean of total temperature data points t. In this work, three additional step function terms (step1, step2 and step3) are included. The coefficients α, A, B and C involves the known sine and cosine functions and consider upto two harmonics to fit the seasonal variability. The coefficients A, B and C are multiplied with respective proxies. The α is total seasonal coefficient hence involves no proxy. The first step function (step1) is included at November 1977 where first major data discontinuity is found as shown in Figure 1a. The time series in Figure 1a is a perfect illustration of the sensor correction and possible tidal effect, where averages of 55-75 km temperature minimize the noise and average out the inhomogeneities. Although tides are not perfectly known but the first inhomogenity due to time of measurement (December, 1977) coincides with the sensor correction time as clear from Figure 1b where local time of measurement of raw data is plotted against the time series. The correction factor due to these factors varies with altitude. In regression model, a step function (which takes care of both sensor correction and possible tidal effect) with one before the change (November 1977) and 0 after the change is considered. The model computes the shift in D statistically at each altitude level. The amplitude of the shift in D is found to be roughly the same as calculated manually in another simplified approach by taking the correcting factor as difference of 3 years mean before and after the transition period (November 1977) at each altitude level. The sensor and the carrier were also changed at the end of 1990 and accordingly another step function (step2) with a coefficient F is added. At lower heights, the shift calculated by the fitting procedure was found to be close to 0. The other major shift in the time of measurement was noticed at December 1983 as shown in Figure 1b (and it is reflected in Figure 1a at the same period), which is attributed purely due to tides for which a step function (step3) having shift in E is included for correction. The amplitude of the shift in E is found to be highly significant especially for lower stratosphere indicating that tidal interference is stronger in this region. In addition to this, data have been selected according to the measurement time with ± 2.5 hours of mean. The residual temperature deviations have been calculated by taking tidal characteristics from numerical simulations (*Hagan et al.*, 1995) and local time of measurements. Two related phenomena, El-Nino and Southern Oscillation (ENSO) have a major impact on lower stratospheric temperature in tropics (*Ramaswamy et al.*, 2001) were also not considered by *Kokin and Lysenko* (1994), probably due to the fact that it was poorly known at that time. We have considered a harmonics with its proxy coefficient for this correction in our radiosonde and rocketsonde data, only for the stratosphere. Residual consists of spurious signals possibly due to volcano and the other unknown noises. The Mt. Pinatubo volcanic perturbation was noticed in this series around September 1991 but El Chichon volcanic signal of 1982 was found to be probably mixed with noise.

3. Results and Discussion

The long-term temperature data series after correcting for the above effects has been subjected to linear trend analysis. Figure 2 shows the vertical distribution of temperature trend per decade as obtained in this work. The experimental results obtained from rocketsonde and radiosonde data series are shown as profile 1 and 2 respectively along with the standard deviation from the mean in both the profiles where the error bar indicates the two sigma standard deviation

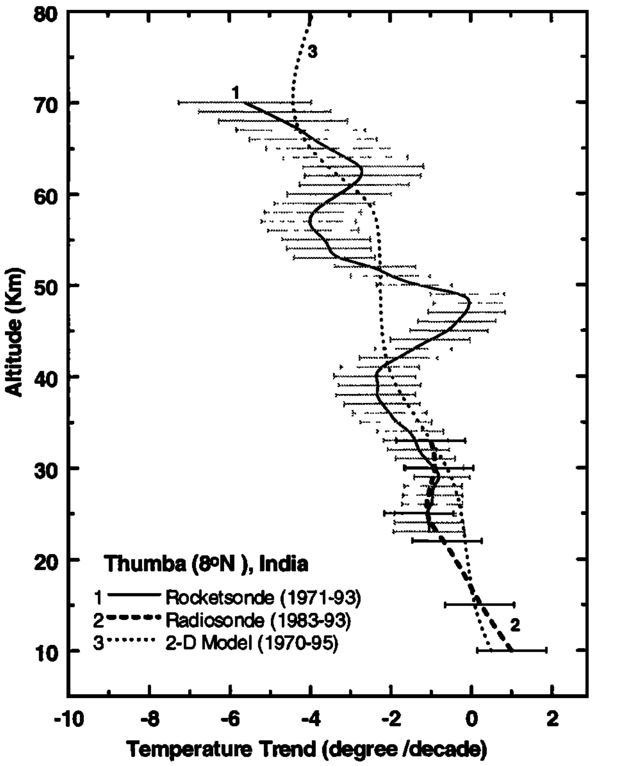

Figure 2. The comparison of the vertical distribution of temperature trend per decade as obtained in this work using radiosonde, rocketsonde and 2-D model for the altitude range from 10 to 80 km.

(estimate of combined instrumental trend error and statistical error for the model fit). Profile 3 is calculated in this work using two dimensional interactive model of radiation, dynamics and chemistry which, considers the actual measured growth rates of major forcing parameters (CO_2, N_2O, CH_4 and CFCs) for the past 2.5 decades 1970-1995 (*WMO,* 1999) for calculating the temperature trend due to anthropogenic activities. The effect of variation in solar activity is filtered in the model simulations. The 2-D model used in this work is same as used by *Beig* (2000) with improved non-LTE algorithm (*Ogibalov et al.,* 2000; *Fomichev et al.,* 1998). It is an extended version of the model described in detail elsewhere (*Brasseur et al.,* 1990; *Beig and Mitra,* 1997). The model extends from surface to 120 km and from South to North pole with a spatial resolution of 1 km is altitude and 5° in latitude. There appears to be a good agreement in experimental and and theoretical results for the lower stratosphere in Figure 2. However, a sudden loss of trend (implying neither cooling nor heating) and a valley-like feature near the stratopause (42-50 km) is noticed in rocketsonde data. To establish the 'repeatability of this dip, rocketsonde data were analyzed on monthly basis and this feature is found in all the months. The physical mechanism for this feature in experimental data is not clear. This might be related to some dynamical phenomenon of stratopause over the equatorial region, details of which, could not be incorporated in the model and hence it could not be reproduced. This feature is not found in the recent results reported by *Keckhut et al.* (1999) for other tropical and sub-tropical latitudes. The negative trend in rocketsonde data increases with altitude in the mesosphere and touches a value of -3.5 °K/decade at 65 km and agrees with model profile 3. However, above 65 km, a steep rise in negative trend is found which shows a stronger cooling of 5.6°K/decade at 70 km. Present results shows stronger cooling in the lower stratosphere in both balloon and rocket data as compared to *Kokin and Lysenko* (1994). This is attributed to the additional filtering terms (like tidal corrections, volcanic) considered in the present analysis. *Semenov* (2000) also noticed the high negative gradient above 65 km for mid-latitude. A sensitive test study has been performed in 2-D model where highly temperature sensitive reaction rates involving CH_4 and H_2O are varied (as their temperature dependence is not yet known properly) and the feedback of nitric oxide variation to temperature is included. This study indicates a steeper gradient (negative) in upper mesosphere (effect of increase in H_2O density) from 1970 to 1995 followed by a sudden drop in cooling trend near the mesopause which may be partially attributed to the decrease in the concentration of NO from 1970 to 1995 (*Beig,* 2000).

Figure 3 shows the comparison of present model and experimental trend results for some specific heights with the review of results obtained by other workers for the tropical regions reported till date. In general, all the results clearly indicate mostly negative temperature changes for the tropics during the past three decades throughout the middle atmosphere. In tropics, most of the results reveal quite good agreement unlike in the mid-latitudes. The recent assessment of stratospheric temperature trend (WMO, 1999; Ramaswamy et al., 2001) concludes a global cooling trend of 2.5°K/decade at 50 km, which agrees with present model and experimental results. Keckhut et al. (1999) calculated the annual trend results from six locations in tropical and sub-tropical regions, which gave an estimate of -1.7± 0.7°K/decade at 40-50 km and a maximum of -3.3 ± 0.9°K/decade at 60 km. These results are close to the present model and experimental values. There appears to be a latitudinal effect in the temperature change for the mesosphere as revealed when present data of tropics are compared with the results reviewed by Beig (2000) for other latitudes. This aspect needs to be

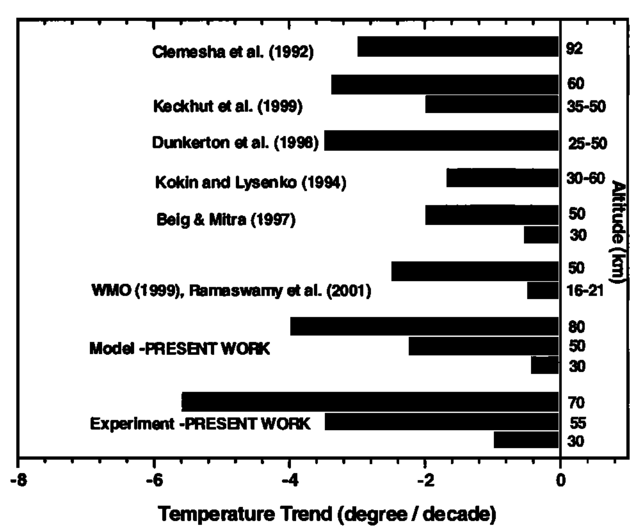

Figure 3. A comparison of the temperature trend per decade obtained in this work (both experimental and model) with the experimental results reported by other workers for the tropical region for specific altitudes in the middle atmosphere.

investigated in detail, which is one of the tasks of the assessment group MTTA.

In recent time, some results in long term trend on the basis of seasons have started to emerge (*Semenov*, 2000). Present result for winter season shows a constant cooling of around 2°k/decade upto about 60 km but shows a slightly stronger cooling as compared to summer above 60 km. Russian data indicate no trend around 82 km in summer and 102 km in winter. This 'altitude of no trend' varies with season as per the variation of mesopause height which is reported to be higher for winter as compared to summer (*She et al.*, 2000).

4. Concluding Remarks

The detection of global change signals in temperature for the middle atmosphere, especially for mesosphere has attracted the attention of scientific community only recently. The identification of human induced temperature perturbations from that of natural variability, episodic factors and more recently the modulations due to tidal effect and instrumental modifications, has always been a complex issue, yet to be resolved adequately. Several past data sets like the one used here were revisited and analyzed in light of new regression models, which are now designed to take care of several spurious signals mentioned above in a more precise manner to reduce the uncertainty that were earlier considered negligible or ignored in absence of adequate statistical treatment. Results reported here are hence claimed to be more robust and accurate then the previous analysis. The cooling trend of the order of 2°K/decade in the stratosphere is clear and in agreement with mid-latitude results. However, a loss of trend around stratopause is noticed in the present study, interpretation of which needs to be worked out that requires further study. A moderate cooling in the mesosphere is calculated which show the high gradient (-5.6 °K/ decade at 70 km) as we move upward. The sensitivity of reaction rates involving CH_4, H_2O and NO and their feedback in the mesosphere is established in evaluating the temperature trend theoretically in this work which might explain some special features if accounted for properly in the model. The 2-D interactive model study reproduces roughly well the observations.

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