Long term variability in temperature in the upper troposphere and lower stratosphere over Indian and Indonesian region using Atmospheric Infrared Sounder (AIRS) observations

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The spatio-temporal patterns and vertical structure of the temperature anomalies, obtained from Atmospheric Infrared Sounder (AIRS), spanning over 9 years (2003-2011) over Indian and Indonesian regions in the upper troposphere and lower stratosphere (UTLS) region, have been examined. An equatorial biennial oscillation with amplitude ranging ~4-6 K and having a period of ~24 months was observed in lower stratosphere (LS) from 100 to 50 hPa, whereas it was not seen in the upper troposphere (UT) from 150 to 200 hPa over both the Indian and Indonesian regions. At 50, 70 and 100 hPa, the annual oscillations (AO) with amplitude ~1-3.5 K were observed near equator in the UT region (at 150 and 200 hPa). However, near subtropics, the nature and amplitude of AO over Indian and Indonesian region was found to be different at different pressure levels. The amplitude of AO at 50 and 70 hPa was larger by ~1.0-1.5 K over Indonesian region as compared to Indian region. But at 100 and 200 hPa, the amplitude of AO over Indian region was larger by ~2-3 K, as observed over Indonesian region. It was also observed that the subtropical AO over both the regions was found to be out of phase with the equatorial AO. The subtropical warm temperature anomalies at 100 hPa were found to be typically collocated with subtropical higher values of ozone (using AIRS data) present in the LS. It was also noted that the temperature anomalies at 100 hPa were also found to be anti-correlated with those at 200 hPa.

Keywords: Upper troposphere and lower stratosphere (UTLS) region, Temperature anomaly, Subtropical temperature anomaly, Total column ozone

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1 Introduction

Temperature in the troposphere and lower stratosphere in the Earth’s atmosphere plays an important role in the radiation budget and in understanding the variation of various chemical species. The important aspect of studying the tropospheric and lower stratospheric temperature and its trends would help in better understanding of the exchange of the trace constituents between troposphere and stratosphere. Tropopause marks the transition between the troposphere and the stratosphere and plays an important role in stratosphere-troposphere exchange (STE) and wave propagation between the regions. Therefore, study of dynamical features near and above the tropopause is important.

Temperature controls the rates of chemical reactions and thus the ozone (O3) abundance, and it is one of the most important parameters in terms of its influence on dynamical and radiative processes in the terrestrial atmosphere, particularly, in the upper troposphere – lower stratosphere (UTLS) region. Observational studies of the UTLS thermal structure have traditionally been based on the global radiosonde network with large data sparse regions or model-dependent analysis and reanalysis products with relatively low vertical resolution and attendant biases. A significant advancement in the understanding of the UTLS thermal structures has recently come from the satellite observations. The thermal structure of tropical tropopause based on the GPS/MET data have been studied. Observations of the global tropopause became possible with the launch of the Challenging Mini-satellite Payload (CHAMP) and Satellite de Aplicaciones Cientificas-C (SAC-C) missions that increased the
spatial and temporal sampling of the Global Positioning System Radio Occultation (GPS RO) data. Some of the studies have characterized the global tropopause parameters using the CHAMP and SAC-C data\textsuperscript{16-20}. These have focused mainly on the time-mean thermal structure of the UTLS instead of its variability.

The main purpose of this work is to characterize and quantify on long term basis, the spatio-temporal patterns and vertical structure of the temperature variability in the UTLS and also to examine the role of ozone in influencing this temperature variability using Atmospheric Infrared Sounder (AIRS) observations. The advantage of AIRS data is that it provides very high spatial and temporal resolution (1° × 1°) and the number of profiles, available in each day is of the order of 324,000, which gives high confidence in using such a high resolution data. Gupta \textit{et al.}\textsuperscript{21} have shown the details of AIRS data in their recent study on meridional temperature gradient over Indian region.

In this paper, long term variability in temperature anomalies in the lower stratosphere and upper troposphere region at equator and subtropics has been analysed, i.e. from 40°N to 40°S over Indian and Indonesian region. In addition, the role of total column ozone has also been analysed in influencing the variation in temperature at equator and near subtropics in the UTLS region.

2 Data analysis

The AIRS/Advanced Microwave Sounding Unit (AMSU) sounding system\textsuperscript{22,23} on the NASA Aqua platform has been operational since 01 September 2002. The AIRS and AMSU instruments are each cross-track scanning nadir sounders that are co-aligned and have a swath roughly 1650 km wide. The AIRS instrument is a 2378-channel grating spectrometer measuring infrared radiance at wavelengths in the range 3.7–15.4 μm with a horizontal resolution of about 13.5 km at nadir\textsuperscript{22}. The AMSU instrument is a 15-channel microwave radiometer with a horizontal resolution of about 45 km at nadir\textsuperscript{24}. Nine AIRS fields of view are contained within each AMSU field of view. The AIRS/AMSU geophysical retrieval method uses an iterative, least-square physical inversion of cloud-cleared infrared radiances, obtained from a combination of infrared and microwave observations. The algorithm is referred to as the AIRS/AMSU combined retrieval\textsuperscript{25}. Following common practice, any discussion of AIRS in this work implicitly refers to the AIRS/AMSU system. The AIRS sounding system produces about 324,000 temperature profiles every day, separately by ascending and descending orbits. The horizontal resolution is about 45 km and the vertical resolution is about 1 km for AIRS temperature profile retrievals, referred to as Level-2 (L2) products\textsuperscript{26}.

AIRS (AIRX3STM) temperature data (http://airs.jpl.nasa.gov/) has been used for the present analysis. The AIRS Level-3 (L3) temperature profile product is the gridded averages of the AIRS L2 temperature profiles on horizontal 1°× 1° grids and 24 pressure levels from 1000 hPa to 1 hPa. It may also be noted that only high quality measurements from the level 2 products are used to derive the level 3 products to avoid the fallback cases\textsuperscript{26,27}. Monthly averaged temperature data at 5 different pressure levels 200, 150, 100, 70, and 50 hPa over Indian and Indonesian region for 9 years (over 2003-2011) have been used. Hereafter, levels 200 hPa and 150 hPa will be referred to as tropospheric and levels with pressure less than 100 hPa as stratospheric. According to a study\textsuperscript{11} based on European Centre for Medium Range Forecast (ECMWF), United Kingdom Meteorological Office (UKMO) and National Centre for Environmental Prediction (NCEP) data, the 100 hPa height tracks nearly identically the tropopause height. Hence, the 100 hPa level will be referred to as the tropopause level. Validation of AIRS temperature retrievals over various regions of high latitudes have already been performed\textsuperscript{28-30}.

To find the influence of ozone on temperature in UTLS region, AIRS (L3) version 5, monthly averaged, total column ozone data have been used. An evaluation of the Atmospheric Infrared Sounder (AIRS) version 5 (V5) retrieved ozone profiles with total column ozone has already been performed using collocated ozonesonde (O3SND) profiles and total ozone measurements from the World Ozone and Ultraviolet Radiation Data Centre (WUDC) archives\textsuperscript{31}. The V5 retrieval biases with global O3SNDs are less than 5% for both the stratosphere and the troposphere. The root mean square (RMS) differences are less than 20% for the upper stratosphere and are close to 20% for the lower stratosphere and the troposphere. Total ozone amounts from V5 versions agree well with the global Brewer Dobson (BD) station measurements with a bias of less than 4% and an RMS difference of approximately 8%. Analysis of V5 total ozone...
monthly maps reveals that the V5 ozone retrievals depict seasonal trends and patterns in concurrence with ozone monitoring instrument (OMI) and Solar Backscatter Ultra-Violet Experiment (SBUV/2) observations.

3 Results and Discussion

3.1 Latitudinal and vertical variability in the annual and biennial oscillations over Indian region

The temperature anomalies of AIRS data spanned over 2003-2011 ranging 40°N-40°S are analysed at five different pressure levels, i.e. at 200, 150, 100, 70 and 50 hPa over Indian and Indonesian region. Figures (1 and 2) represent the latitude-time sections of temperature anomalies for 9 years at 50, 70 and 100 hPa and at 100, 150 and 200 hPa, respectively over Indian region. The temperature anomalies contour in Fig. 1 shows the presence of equatorial biennial oscillations (BO) of amplitude ranging 4-6 K with period ~ 2 years in the LS (50, 70 hPa) and at 100 hPa. These BO (of period ~ 2 years) are similar to as observed by Pillai32,33 over tropical Indian region. They named these oscillations as tropospheric biennial oscillations (TBO) and extensive work has been done in associating these oscillations with the Indian monsoon, Indian dipole moment, El Nino southern oscillations (ENSO), etc. They have highlighted the role of ocean system in maintaining the TBO. In the present study, similar oscillations have also been observed with a period of ~ 2 years in the lower stratosphere (LS). The BO observed in LS appears to be influenced by the changes in temperature occurring in the troposphere.

Besides observing BO near equator, annual oscillations (AO) (indicating seasonal variability) have also been observed in the temperature anomalies as shown in Fig. 1 at 50, 70, 100 hPa and the amplitude of the oscillations is of the order of ~1.0-3.5 K. As one moves below in the upper troposphere (UT) region (at 150 and 200 hPa shown in Fig. 2), the AO turns weak with amplitude of ~1.0-1.5 K [Fig. 3(a)]. From Figs (1 and 2), it can also be noticed that AO presents different nature near equator and in subtropics in the UTLS region. At 50 hPa, the equatorial temperature anomalies show AO with amplitude of the order ~1.0-2.0 K; while at
Fig. 2 — Latitude time section of temperature anomalies for 9 years (represented as 108 months) over Indian region at 100, 150 and 200 hPa

Fig. 3 (a) — Time series of temperature anomalies at different pressure levels (200, 150, 100, 70, 50 hPa) for 9 years (2003-2011) at equator over Indian region
70 and 100 hPa, the amplitude rises to ~2.0-3.5 K. However, in the UT region (at 150 and 200 hPa), the amplitude of AO reduces (~1.0-1.5 K) and are not very prominent as well [Fig. 3(a)]. In the subtropics, at 50 and 70 hPa, AO of amplitude ~1-2 K is found similar to equatorial region. But at 100 and 200 hPa (pronounced over northern hemisphere), the amplitude of AO becomes stronger (~5.0-6.0 K) as shown in Fig. 2 and Fig. 3(b). Thus, analysis suggests that in subtropics, AO prevails with large amplitude than in equatorial region.

It was, further, noticed that at 100, 150 and 200 hPa, the equatorial AO were found to be out of phase with the AO observed near subtropics, i.e. the warm anomalies in subtropics are found adjacent to the cold anomalies of equatorial region [Fig. 2 and Fig. 3(a,b)]. It is known that in subtropics 100 and 150 hPa lie in the stratosphere and ozone is the key component for radiative balance in stratosphere. To observe any influence of ozone on subtropical temperature anomalies, total column ozone data from AIRS has been analysed. Since the ozone data are also taken from AIRS, having the same resolution and retrieval procedure as temperature data, therefore, the association between temperature and ozone can be easily made.

About nine years of monthly averaged total column ozone data has been analysed from 40°N to 40°S over Indian region (Fig. 4), which represents the variation in ozone near equator (20°N-20°S) and subtropics. A very strong annual oscillation in ozone is observed in subtropics, which is not seen in the equator. The higher values [~350-400 Dobson unit (DU)] of ozone during winter months (in northern hemisphere (NH)) are observed to be collocated with the subtropical warm anomalies in temperature for the same latitude.
range [Figs (2 and 4)]. Increased ozone (in the subtropics) could have possibly caused the enhancement in temperature and hence, the warm anomalies appear over these latitudes. The other possibility of this difference is coming from the fact that pressure levels of 100 and 150 hPa are the representative of stratosphere, while these levels are the part of troposphere in the equatorial region.

From Fig. 2, it is also noticed that the subtropical temperature anomalies (in NH) at 100 hPa are anti-correlated with anomalies at 200 hPa. The results reported here are found similar to the observations made by Bencherif et al. over Durban, South Africa (30°S, 30.9°E), a subtropical site in southern hemisphere (SH). The authors have analysed 22 years of temperature data in the UTLS region and found that the seasonal cycle in temperature at 250 hPa is anti-correlated with the seasonal cycle at 100 hPa. Similar behaviour has also been observed between 100 and 200 hPa in subtropical temperature anomalies, which is more pronounced in NH.

It is apparent from the above observations that the temperature changes, which take place at 200 hPa, are reflected at 100 hPa level, but with a time delay and could be the possible reason for the anti-correlation. Observations of delayed response above 200 hPa level in temperature indicate that strong horizontal transport could have a role in controlling the temperature. Panwar et al. have shown that the transport of water vapour from 215 hPa to 68 hPa takes about 3-4 months.

3.2 Latitudinal and vertical variability in the annual and biennial oscillations over Indonesian region

Figures (5 and 6) show the latitude - time plots for the temperature anomalies observed over Indonesian region at 50, 70 and 100 hPa, and at 100, 150 and 200 hPa, respectively. Figure 5 shows the presence of equatorial BO of amplitude ~4.0-6.0 K of period ~2 years in temperature anomalies at 50, 70 and 100 hPa. Besides, observing BO near equator, AO has also been observed with amplitude of ~1.0-3.5 K, as observed over Indian region. As one moves down to 150 and 200 hPa, the amplitude of AO becomes less ~1.0-1.5 K [Fig. 6 and Fig. 7(a)]. It can be noticed from the above observations that the nature and variations in BO and AO near equator have similar behaviour as observed over Indian region. However, near subtropics, the behaviour of AO over Indonesian region is different from Indian region. At 50 and 70 hPa, over Indonesian region, amplitude of AO is found larger (~2.0-3.0 K at 50 hPa and ~3.5-4.5 K at 70 hPa), as compared to the Indian region [Fig. 7(b)]. The variation in amplitude of AO over Indonesian region is more, as it is highly convective region as compared to Indian region, and partly it may be due to the effect of walker circulation in this region, which is not examined here.

However, at 100, 150 and 200 hPa (over Indonesian region), besides observing AO of amplitude ~3.0-4.0 K, ~1.0-2.0 K and ~2.0-3.0 K, respectively, semi-annual oscillations (SAO) of weak amplitude (~1.0-2.0 K) are also observed [Fig. 6 and
Fig. 5 — Latitude time section of temperature anomalies for 9 years (represented as 108 months) over Indonesian region at 50, 70 and 100 hPa.

Fig. 6 — Latitude time section of temperature anomalies for 9 years (represented as 108 months) over Indonesian region at 100, 150 and 200 hPa.
Fig. 7 (a) — Time series of temperature anomalies at different pressure levels (200, 150, 100, 70, 50 hPa) for 9 years (2003-2011) at equator over Indonesian region.

Fig. 7 (b) — Time series of temperature anomalies at different pressure levels (200, 150, 100, 70, 50 hPa) for 9 years (2003-2011) at subtropics over Indonesian region.
Fig. 7(b). Bencherif et al.\textsuperscript{34} have shown similar observations for SAO in their study over Durban which is also a subtropical site.

Over Indonesian region too, the equatorial AO are found to be out of phase with the subtropical AO. Similar analysis, as conducted over Indian region, is being performed in Indonesian region. It has been found that total column ozone from AIRS (Fig. 8) is higher near subtropics (20°-40°) as compared to the equator in both the hemisphere. The high value (~350-400 DU) of ozone, during winter months, observed to be collocated with the subtropical warm anomalies in temperature, which is evident from Figs (6 and 8). High values of ozone (in the subtropics) could have possibly caused the increase in temperature (and hence the warm anomalies appear) over these latitudes.

4 Summary and Conclusions

The temperature anomalies over a period 2003-2011 from AIRS are analysed at different pressure levels at 200, 150, 100, 70 and 50 hPa in the range of 40°N-40°S over Indian and Indonesian region to observe long term latitudinal and vertical structure of temperature variability in the UTLS region. The salient features are:

(i) Biennial oscillations (BO) of period ~2 years with amplitude ~4.0-6.0 K were observed in the equatorial temperature anomalies at 50, 70 and 100 hPa both over Indian and Indonesian region.

(ii) Besides observing BO near equator, annual oscillations (AO) in the temperature anomalies were also observed at 50, 70, 100 hPa with amplitude ~1.0-3.5 K, which reduces to ~1.0 K in the UT region (at 150 and 200 hPa) both over Indian and Indonesian region.

(iii) In the subtropics, the behaviour of AO over Indian and Indonesian region is found to be different. At 50 and 70 hPa, over Indian region, the amplitude is ~1.0-2.0 K but over Indonesian region, the amplitude increases to 2.0-3.0 K at 50 hPa and 3.5-4.5 K at 70 hPa. At 100 and 200 hPa, over Indian region, the amplitude of AO is large (~5.0-6.0 K) as compared to Indonesian region (~2.0-3.0 K). The variation in amplitude over Indonesian region in LS is more as it is highly convective region and the upward flux may be more intense that reaches in LS as compared to Indian region.

(iv) Over Indonesian region at 100, 150 and 200 hPa, besides observing AO, SAO of weak amplitude (~1.0-2.0 K) is also observed (Fig. 6).

(v) It was, further, noted that at 100 hPa and in UT, the equatorial AO were found to be out of phase with the AO observed near subtropics, i.e. the warm anomalies in subtropics are found to lie adjacent to the cold anomalies of the equatorial region (both over Indian and Indonesian region). Large values (~350-400 DU) of ozone during winter months (in NH) were found to be collocated with the subtropical warm anomalies in temperature. Therefore, it appears that seasonal variations in ozone (in the subtropics) have caused the warm anomalies in temperature.

(vi) In addition, temperature anomalies at 100 hPa are also found to be anti-correlated with temperature.
anomalies at 200 hPa, suggesting slow upwelling due to strong horizontal wind in the UT region.

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