Detection of solar cycle signal in the tropospheric temperature using COSMIC data

V. Kumar[1], S. K. Dhaka[1,*], V. Panwar[1], Narendra Singh[2], A. S. Rao[3], Shristy Malik[3] and S. Yoden[4]

[1]Radio and Atmospheric Physics Lab, Rajdhani College, University of Delhi, Delhi 110 015, India
[2]Aryabhatta Research Institute of Observational Sciences (ARIES), Nainital 263 002, India
[3]Department of Applied Physics, Delhi Technical University, Delhi 110 042, India
[4]Department of Geophysics, Kyoto University, Kyoto 606850, Japan

Influence of the solar cycle on temperature structure is examined using radio occultation measurements by COSMIC/FORMASAT-3 satellite. Observations from January 2007 to December 2015 comprising 3,764,728 occultations, which are uniformly spread over land and sea, have been used to study temperature changes mainly in the troposphere along with the solar cycle over 60°N–60°S geographic latitudes. It was a challenging task to identify the height at which the solar cycle signal could be observed in temperature perturbations as different atmospheric processes contribute towards temperature variability. Using a high spatial resolution dataset from COSMIC we are able to detect solar cycle signal in the zonal mean temperature profiles near surface at 2 km and upward. A consistent rise in the interannual variation of temperature was observed along with the solar cycle. The change in the temperature structure showed a latitudinal variation from southern to northern hemisphere over the period 2007–2015 with a significant positive influence of sunspot numbers in the solar cycle. It can be concluded that the solar cycle induces changes in temperature by as much as 1.5°C. However, solar cycle signal in the stratospheric region could not be identified as the region is dominated by large-scale dynamical motions like quasi-biennial oscillation which suppress the influence of solar signal on temperature perturbations due to its quasi-periodic nature.

Keywords: Radio occultation, solar cycle, sunspot number, tropospheric temperature.

TEMPERATURE of the earth's atmosphere is the most important property controlling its structure. In recent years there has been growing interest to understand variability in the temperature structure due to increase in greenhouse gases (GHGs). Solar radiations are the primary forcing of earth's climate. To understand the climate system one needs to have a better understanding of the climate response to this unique solar forcing. Efforts have been made to reconstruct historical spectral solar irradiance to model the climate response to solar variations[1–3]. Studies using independent space-based solar radio meters universally agree that solar irradiance is higher when the Sun is more active, as indicated by an elevated number of sunspots on its surface. Total solar irradiance increased by 0.1% from solar minima to solar maxima[4]. There is also a more substantial change in the ultraviolet (UV) portion of the solar spectrum from minima to maxima, with direct impact primarily observed above ~10 km (ref. 4).

An overall warming trend is observed in the climate of the last two decades. Confounding expectations of a monotonically warming globe, the average warming rate from 2000 to 2008 subsided by almost an order of magnitude and temperatures in 2008 were cooler than those in 2002. These varying trends in global temperature arise in part from the influences of solar irradiance and other natural processes. Difference in solar heating rate between minima and maxima of solar cycle is responsible for the natural change in temperature[5].

In the past there have been several studies on the variation of temperature from solar minimum to maximum. Keckhut *et al.*[6] reported variation in temperature from solar maxima to minima. They showed that at tropical and subtropical latitudes temperature increased by 2°C just below the stratopause region at ~40 km height, whereas at mid-latitudes the signal showed negative response over the region at height 25–50 km with a maximum of 3°C. Hood[7] showed some interesting differences from the results of the Keckhut *et al.*[6]. He found that maximum positive signal over the tropics had greater amplitude (>2°C) and was situated higher in the atmosphere (~50 km), while at mid-latitudes the signal was reduced but still positive, in contrast to the results of Keckhut *et al.*[6]. However, other studies compared the results from different models during the 11-year solar cycle[8,9]. Randel *et al.*[10] reported a statistically significant signal in the tropics (~30°N–30°S), with an amplitude (solar maximum minus solar minimum) of ~0.5°C (lower stratosphere) to ~1°C (upper stratosphere).

The above-mentioned studies were based on the observation of temperature difference from solar minima to maxima and were mainly confined to the stratospheric

*For correspondence. (e-mail: skdhaka@rajdhani.du.ac.in)

region. Also, the studies did not show continuous variation of temperature structure from solar minima to maxima period; only the differences between these two periods have been shown in the past. The present study shows variations in each year and consistent temperature changes from solar minima to maxima during 24-solar cycle (covering the period from 2008 to 2015) over a large latitudinal range (60°N–60°S) in the troposphere.

Also the related studies in the past used various models, i.e. NCEP re-analysis data, ground-based measurement techniques, rocketsonde, radiosonde data and different satellite (SSU/MSU) data. Rocketsonde data are available for the period 1960 to mid-1990, and depend on the station site. The most suitable sites for 11-year solar cycle analysis are mostly concentrated in the tropics and subtropics, covering few northern middle latitudes[6,11,12]. Radiosonde measurements cover almost five decades, but are concentrated over the continental regions in the northern hemisphere. Unlike radiosonde, satellite measurements provide information over land and over sea at a fine spatial–temporal resolution. MSU satellite data are influenced by instrument and orbit changes, calibration problems, instrument drifts and insufficient vertical resolution[13]. On a fine temporal and spatial scale, Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC)/Formosa Satellite Mission (COSMIC/FORMOSAT-3, hereafter COSMIC) satellite provides an excellent data which are used in this study. We selected the 24-solar cycle as data from COSMIC is available only from 2007 onwards.

Data used

Global Positioning System Radio Occultation (GPS-RO) provides global atmospheric profiling under all weather conditions. This technique is not affected by clouds, aerosols or precipitation. RO data are superior to traditional data sources (NCEP and ECMWF) in high southern latitude, tropical tropopause region[14]. In RO technique, satellite moves in the low-earth orbit (LEO) to collect the GPS signal. During occultation, receivers in LEO set or rise behind the earth's limb; hence the signal has to pass through the earth's atmosphere, which induces extra delay from GPS to LEO receiver. The vertical profiles of bending angle α and refractivity are reconstructed from this delay in signal from which neutral atmospheric density, pressure, temperature, moisture profiles and ionospheric electron density can be retrieved. The atmospheric refractivity N is a function of pressure P (hPa), temperature T (K) and water vapour pressure P_w (hPa) in the netural atmosphere through the relationship[15]

$$N = 77.6\frac{P}{T} + 3.73 \times 10^5 \frac{P_W}{T^2},$$

Hajj *et al.*[16] have presented a more detailed description on atmospheric sounding by GPS occultation.

The quality of RO soundings is very high in the upper troposphere and lower stratosphere. RO technology offers great potential for numerical weather forecasts, space weather monitoring and climate change detection[13,15,17,18]. COSMIC RO mission is a collaborative project of the National Space Organization (NSPO) in Taiwan and the University Corporation for Atmospheric Research (UCAR) in the United States. The six micro satellites were launched into a circular, 72° inclination orbit, at an altitude of 800 km to form a constellation of satellites providing over 2500 occultation events per day covering the entire globe. Therefore, much-improved spatial coverage is now available from the COSMIC mission compared to the CHAMP and SAC-C missions (as ~150–200 occultations/per day, only on receiver), where the spatial coverage is still relatively coarse[19]. The vertical resolution of COSMIC-RO profiles varies from ~100–200 m (lower troposphere) to ~1.4 km (stratosphere), having a wide spatial coverage with high accuracy (average accuracy ~0.1 K)[20–22]. COSMIC data have been validated with tradition data sources such as NCEP, JRA-25 and UK Met Office[23].

Figure 1 represents the COSMIC zonal mean occultation feature for the year 2007 over 60°N–60°S. COSMIC level-2 wet profiles of temperature are used in this study from January 2007 to December 2015 (available at www.cosmic.ucar.edu). These data profiles are interpolated at 100 m height interval. Table 1 shows the number of occultations derived from COSMIC between 60°N and 60°S over the period 2007–2015.

Results and discussion

Figure 2 shows altitude profiles of temperature difference from solar maxima year (2015) to solar minima year (2008), which are zonally averaged over different latitudes from equatorial (5°N–5°S) to tropical region (30°N–30°S). The left panel in Figure 2 highlights the

Table 1. Number of occultations observed during 2007–2015 from COSMIC

Year	Number of occultations over 60°N–60°S
2007	507,709
2008	523,209
2009	520,242
2010	399,829
2011	332,576
2012	308,760
2013	549,285
2014	244,914
2015	378,204
Total	3,764,728

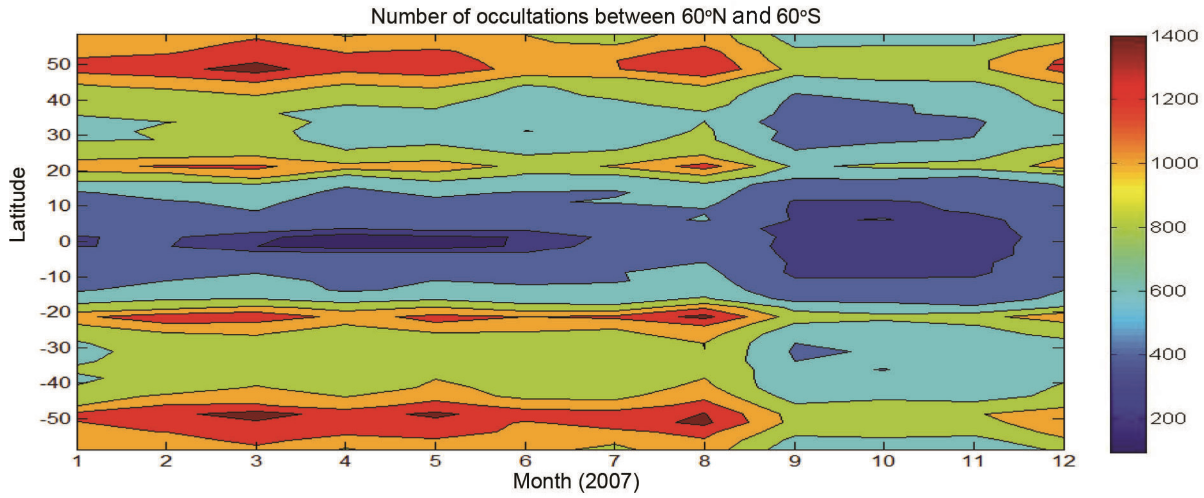


Figure 1. Zonally averaged number of occultations during 2007 measured by COSMIC over 60°N–60°S. Occultations are counted on 2.5° lat. grid and shown by a colour bar.

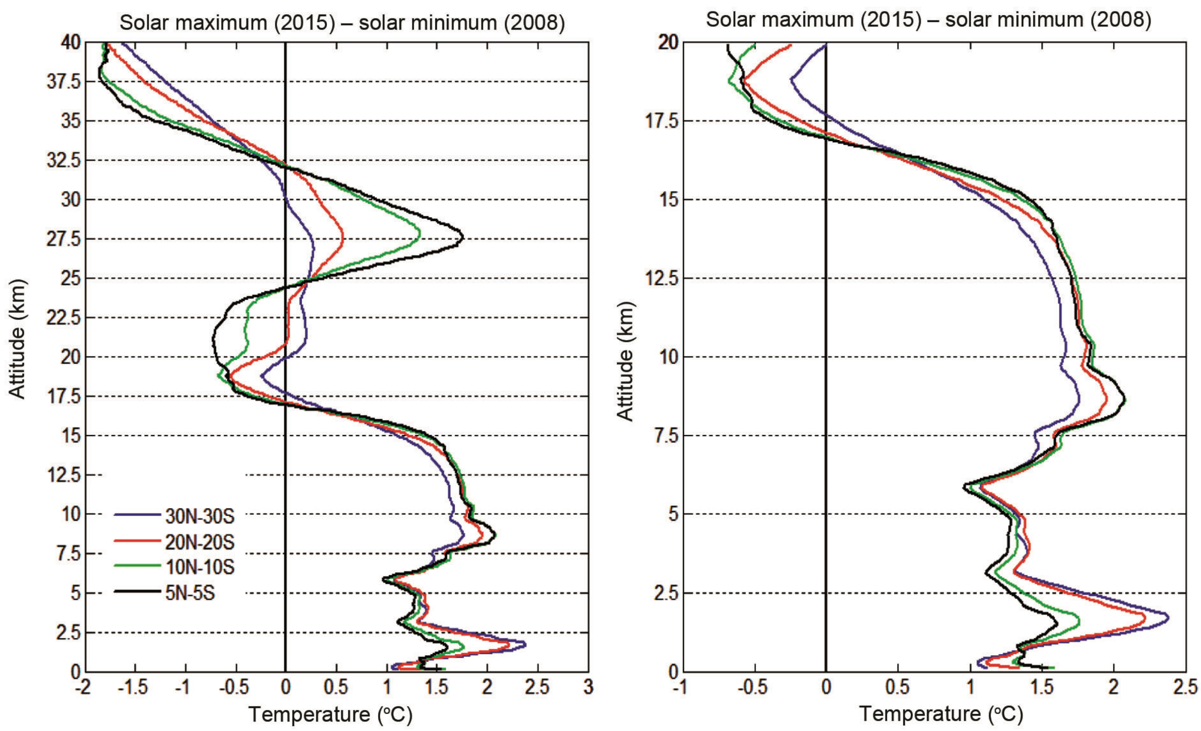


Figure 2. Altitude profiles of temperature difference from solar maxima (averaged over the entire year of 2015) to solar minima (averaged over the entire year of 2007); profiles are zonally averaged over 5°N–5°S, 10°N–10°S, 20°N–20°S and 30°N–30°S. Different colours shown in the figure denote different latitude ranges. (Left panel) Altitude variation up to 40 km height. (Right panel) Troposphere and lower stratosphere up to 20 km altitude.

effective changes in temperature during solar maxima year in comparison to solar minima year from lower troposphere to 40 km altitude. Positive values show effective rise in temperature, whereas negative values represent a cooling region especially between altitudes 18 and 25 km as well as above 30 km. In the entire troposphere, there is a warming signal during solar maxima. The right panel in Figure 2 highlights the troposphere and lower stratosphere (1–20 km), with expanded *x*-axis to show clearly the rise in temperature during the solar maxima period.

All profiles in the broad latitude range showed similar vertical behaviour. Maximum rise of ~2.0°C in temperature was noted near 2 km in the lower troposphere (~ atmospheric boundary layer) and near 8 km altitude regions. In the lower troposphere below 5 km, latitude range of 5°N–5°S experienced slight rise in temperature in comparison to other latitude ranges and a continuous increase in the temperature was observed from equatorial (5°N–5°S) to tropical region (30°N–30°S). Reverse scenario was observed in the upper tropospheric region (7.5–17.5 km). Vertical temperature profiles in the latitude range 5°N–5°S experienced the largest influence of solar maxima period, and the magnitude of difference in temperature vertically was greater than the temperature profile shown over 30°N–30°S. Hence in the lower troposphere (below 5 km), warming due to solar signal seems to dominate as we cover profiles from equatorial to tropical region, whereas in the upper troposphere (above 7.5 km) the equatorial region is influenced to a greater extent by the solar signal. The 5–7.5 km tropospheric region is identified as a transition zone above which warming dominates in the equatorial region and below it dominates in the tropical region. Thus, we have observed that the influence of solar maximum over solar minimum is reflected by the rise in temperature vertically in the entire troposphere. In the lower tropospheric region below 5 km, minimum influence is seen over 5°N–5°S latitude range, which is considered a relatively cloud-free zone.

We have shown in a recent study that there is a strong connection of seasonal solar influence over wide tropical region through diabatic heating, which eventually controls the lower troposphere to upper tropospheric region[22]. Though this connection has large longitudinal difference, zonally averaged features do reflect stronger solar influence a little away from the equator. As it is well known that solar influence (flux) increases from solar minima to solar maxima period, there is a 11-year solar cycle in which the Sun passes via minima to maxima at this time interval. During solar maxima, deep convective heating in the troposphere is larger in comparison to solar minima; hence the atmosphere shows a response through variation in temperature. Studies have clearly shown that there is a strong convective heating near 10–15° in both the hemispheres[22,24]. Latitudinal spread of temperature with time also reflects that rise in temperature and strong connection between lower and upper troposphere are more confined over the wider tropical belt in comparison to the equatorial region. Therefore, during solar maxima atmosphere temperature is slightly larger in the troposphere in comparison to solar minima period.

Interestingly, a clear wave fluctuation in temperature pattern can be seen above the tropopause region from 17 to 40 km (Figure 2). There is a warming signal of the order 1°C in altitude range 17–25 km and 32–40 km, and cooling can be seen in the region of height 25–30 km. If these patterns are related with the solar cycle then there should be a continuous rise in the magnitudes of these patterns as we move from minima to maxima period (2008–2015). To identify whether this signal is related to the solar signal or not, we separated the mean temperature profiles in 2008 from other years such as 2013 and 2014 and Annexure 1 shows the difference. The left panel in Annexure 1 highlights the temperature changes from 2013 to 2008, the middle panel from 2014 to 2008 and the right panel from 2015 to 2008. Hence Annexure 1 illustrates systematically the difference in mean temperature profiles of solar minima year (2008) from the maxima period. It is noteworthy that warming can be seen in the entire troposphere and the magnitude continuously increases (1–2.5°C) as we move from solar minima to solar maxima year (i.e. 2013–2015). These results suggest that the systematic rise in temperature in the lower tropospheric region is related with the solar cycle. Interestedly, peaks dominate at ~2.0 and 8.2 km altitude in all panels of Annexure 1 as in Figure 2.

In the stratospheric region the wave fluctuation pattern in the mean temperature profiles is not consistent with the solar cycle. Tendency of temperature difference between 2013 and 2008 is opposite in comparison with difference of 2014 and 2008 in the stratosphere, especially from 20 km to 30 km altitudes. The warming and cooling patterns in the stratospheric region dominate in the equatorial profiles (5°N–10°N and 10°N–10°S) almost by a factor of 2 in comparison to the tropical region (30°N–30°S). These periodic features of temperature deviation in the stratospheric region highlight the role of dynamical characteristics that can suppress the effect of solar signal. Temperature in the equatorial region (10°N–10°S) starting from the middle stratosphere to the tropopause region is strongly influenced by quasi-biennial oscillation (QBO). QBO can produce warming (cooling) of the order of 3–4°C corresponding to westerly (easterly) phase[25,26]. Temperature of the stratospheric region at some specific heights may be altered by 6–8°C from westerly to easterly phase. The impact of QBO can be seen in the entire tropical belt (30°N–30°S); however, it dominates at the equatorial region (see figure 3 of Kumar *et al.*[25]). Strong QBO signal can suppress features of the solar cycle from tropopause to stratospheric region. Thus QBO is a key which is responsible for non-consistency in mean temperature profiles in the stratospheric region.

Marsh and Svensmark[27] have argued that low cloud properties are changed due to solar cycle irradiance through varying galactic cosmic rays. They have also mentioned that surprisingly, the influence of solar variability was strongest in low clouds (≤3 km), which points to a microphysical mechanism involving aerosol formation that is enhanced by ionization due to cosmic rays. Peak rise in temperature near 2 km altitude in Figure 2 appears to be correlated with their findings of maximum influence of solar irradiance on low clouds. However, wave pattern in mean temperature profiles just above the tropical tropopause seems to be related with QBO. The rise in temperature is in accord with the radiative balance in the presence of maximum solar variability near the top of the tropopause layer. In the middle stratosphere, warming signals in the specific regions (40 to 50 km altitudes) as a consequence of solar maxima period were reported in the

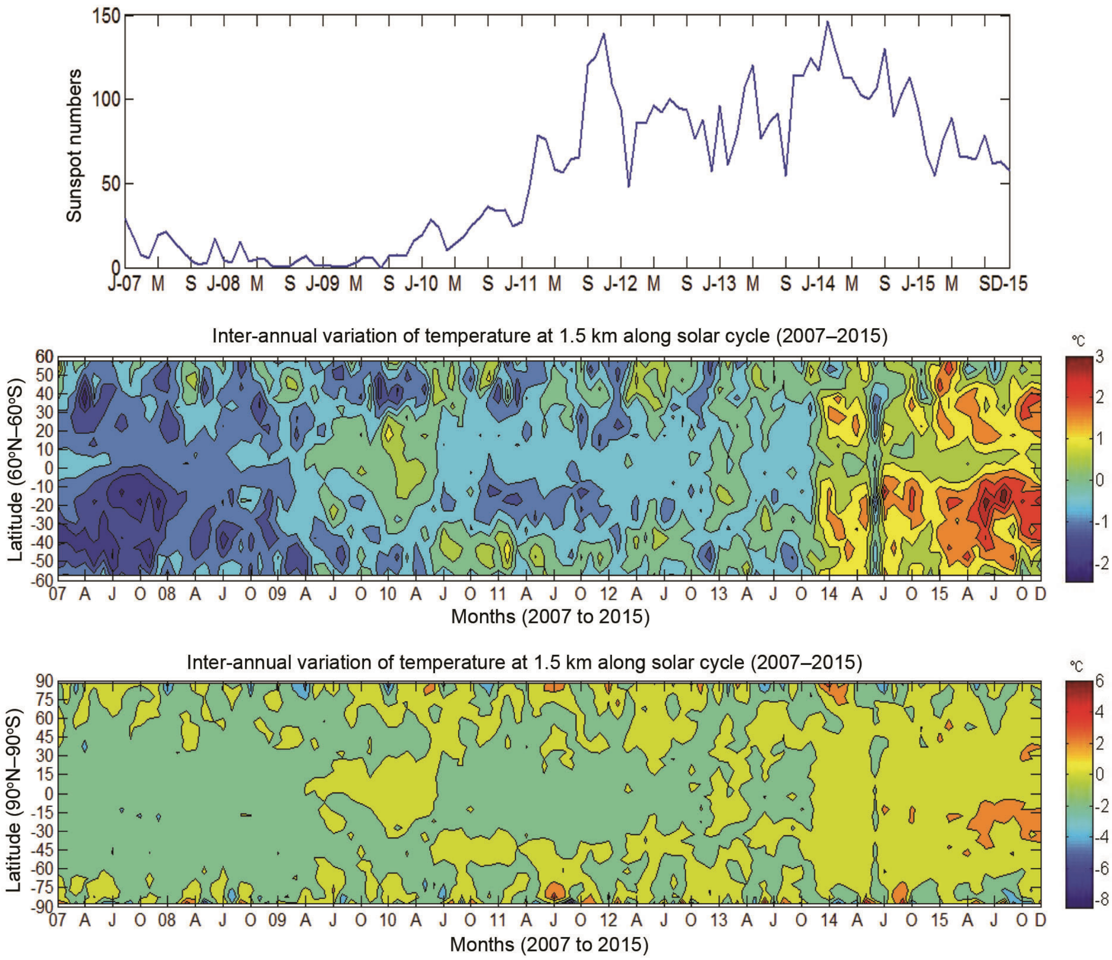


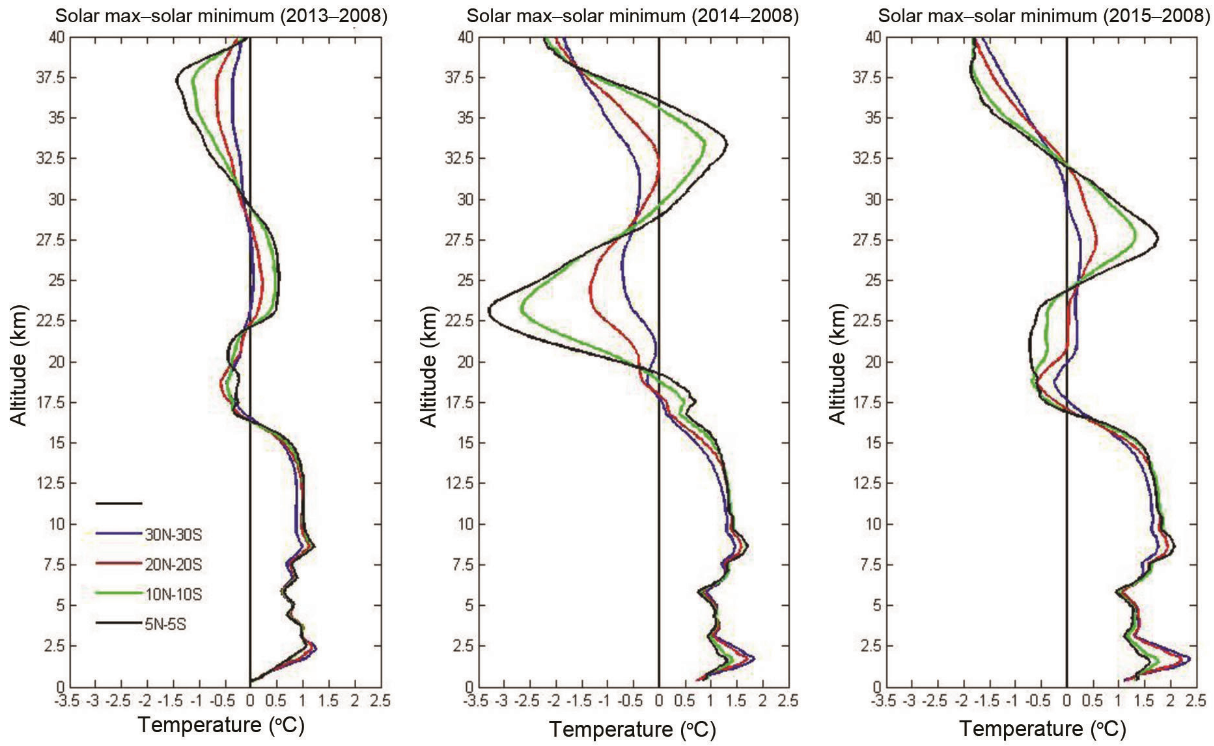
Figure 3. (Top panel) Monthly variation of sunspot numbers from January 2007 to December 2015. (Middle panel) Anomalies in temperature at 1.5 km height from January 2007 to December 2015 in the latitude range 60°N–60°S. (Bottom panel) Same as middle panel but in extended latitudes from 90°N to 90°S over entire globe. Each month anomalies represent the monthly deviation from 9 years mean temperature (2007 to 2015).

earlier studies as well[6,7,10]. However, we have identified specific regions where cooling is more pronounced in the lower stratosphere. It is not clear whether the entire stratosphere shows warming signal. As our data are limited up to 40 km altitude, the present results are not consistent with those of earlier studies using rocket and lidar measurements[6,7].

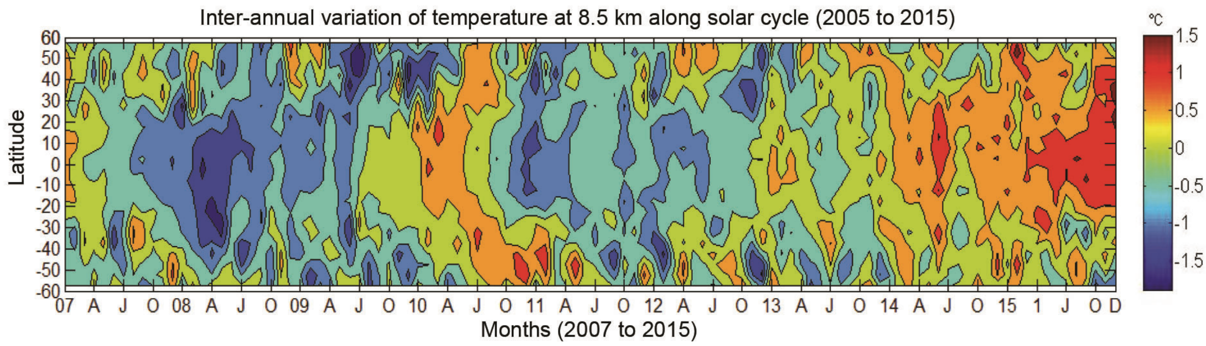
Latitudinal distribution of the differences of solar maxima from solar minima periods requires in depth examination in order to check consistency of warming signals at all the latitudes, specifically from tropics to middle latitudes. It is complex to present latitudinal characteristic changes in the vertical direction; hence we have examined some specific altitudes (1.5 and 8.5 km) at which solar signal dominates in temperature perturbation.

Latitudinal variation in tropospheric temperature along the solar cycle

As discussed above, the solar cycle signal in temperature perturbation dominates at 1.5 and 8.5 km. Therefore, changes in the temperature structure at 1.5 km along with 24-solar cycle are studied at each 5° lat. band in the lat. range 60°N–60°S from 2007 to 2015. The top panel in Figure 3 shows monthly variation of sunspot number from January 2007 to December 2015. To identify the solar cycle effect, the temperature anomalies are computed between 60°N and 60°S, and shown in middle panel of Figure 3. For these temperature anomalies all occultations are averaged each day over 0–5°N, 5–10°N, 10–15°N, 15–20°N, 20–25°N up to 60°N latitude bands. A similar procedure is performed in the southern hemisphere (SH) up to 60°S. Monthly mean is constructed using daily values. To compute the anomalies in the temperature for different months, average temperature of 9 years (January 2007–December 2015) is computed and separated from individual months. The middle panel in Figure 3 demonstrates inter-annual temperature anomalies from 2007 to 2015, which do not include seasonal variation. The bottom panel in Figure 3 represents variation in extended latitudes from 90°N to 90°S covering the entire globe.



Annexure 1. Zonal mean temperature profiles and their differences from solar maxima to solar minima in different latitude ranges. Colour codes denote the following latitude ranges, black (5N–5S), green (10N–10S), red (20N–20S) and blue (30N–30S). Left panel shows difference between 2013 and 2008, middle panel between 2014 and 2008, and right panel between 2015 and 2008.



Annexure 2. Latitudinal distribution of temperature from 2007 to 2015 at 8.5 km height. Colour code shows temperature range from –1.5 to 1.5°C.

It is evident from Figure 3 (top panel) that 2007–08 and 2008–09 are the solar minimum years, as less sunspot number is observed during these years. From mid-2009, the sunspot number increases as we move towards solar maxima. It can also be observed from Figure 3 (middle panel) that temperature during 2007 and 2008 is ~2°C less than the average of 9 years. This feature is observable over all the latitude range from 60°N to 60°S and seems to be dominating in the SH. From mid-2009 when sunspot numbers increase, quick response can be seen in temperature as it starts increasing. However, the increase in temperature is the order of ~2°C and is limited to the tropical region over 30°N–30°S. Note that latitudinal increase in temperature is prominent from June 2009 to mid-2010, that is related with ENSO phenomenon (this feature is shown in figure 3 of Kumar *et al.*[25]). According to NASA updates, 2009 is considered to be one of the warmest years and the period from June 2009 to mid-2010 was strongly influenced by ENSO; hence, temperature in the troposphere increased marginally. Further as we move from mid-2010 to 2014 (along the solar cycle), the magnitude of temperature decreases in comparison to ENSO period, which is obvious. However, continuous increase in temperature can be seen in comparison to 2007 and 2008. Temperature of this period on an average is more by 1.5°C.

A substantial increase in sunspot numbers from 50 to 100 can be seen during 2012 to the end of 2015; this variation is not continuous but has had fluctuations. The years 2014 and 2015 show maximum sunspot numbers. A strong warming in the temperature can be observed during these years only, which is larger than other years and is of order ~2–3°C. This warming is observable at all the latitude ranges. Some localized features of warming can be seen from SH to the northern hemisphere. The warming dominated in the mid-latitude range on both sides of the equator. This localized feature may be due to the different locations of sunspot numbers and their influence on the Earth's surface. Period of maximum sunspot numbers has shown strong influence in the mid-latitude regions on the Earth's surface, which is responsible for greater warming in these latitudes during the solar maxima period.

We have extended our results to the entire latitude range (90°N–90°S; bottom panel, Figure 3). In the higher latitude region beyond 60° of both hemispheres, the solar signal is not observable. The low sunspot number influences this part of the globe. In addition, these regions are mainly dominated by several local atmospheric activities like sudden stratospheric warming, which changes the temperature by tens of degrees, thus the solar cycle signal is not observable in high-latitude regions.

We have shown that the solar signal mainly dominates at 1.5 and 8.5 km. Annexure 2 shows the temperature structure over 60°N–60°S latitude range at 8.5 km height. Note that colour bar legends at 8.5 km is different from those at 1.5 km, and maximum variation of temperature is –1.5°C to 1.5°C. The latitudinal structure at 8.5 km height shows similar feature as at 1.5 km, with clear indication of ENSO signal from June 2009 to mid-2010. There is a clear consistency of increase in temperature with the solar cycle.

Concluding remarks

From COSMIC RO measurements we were able to detect solar cycle signal in temperature structure in the entire troposphere, which was maximum at specific altitudes such as 1.5 and 8 km. Maximum rise of 1.5°C in temperature was observed along the solar cycle spanning from solar minima to solar maxima. In this study, we have shown the continuous change in temperature from solar minima to maxima with a clear latitudinal distribution of solar cycle influence on temperature. Larger deep convective heating occurs in the troposphere during the solar maxima period in all seasons in comparison to those in solar minima, which is considered to be one of the causes for this slight rise in temperature. Middle latitudes experience more positive influence of solar sunspot numbers. Previous studies focused on the stratospheric region with limited data[6,10]. COSMIC data have provided a unique opportunity to reveal the most complex signal to be identified in the troposphere, which is full of convective activities and motions on a small scale (few hours) to a larger scale (several months and years), both in time and space. These results demonstrated the potential of the COSMIC mission.

1. Rind, D., Lean, J. and Healy, R., Simulated time-dependent climate response to solar radiative forcing since 1600. *J. Geophys. Res.*, 1999, **104**, 1973–1990.
2. Shindell, D., Rind, D., Balachandran, J., Lean, J. and Lonergran, P., Solar cycle variability ozone and climate, *Science*, 1999, **284**, 305–308.
3. Meehl, G. A., Washington, W. M. and Wigley, T. M. L., Arblaster, J. M. and Dai, A., Solar and green house gas forcing and climate response in the twentieth century. *J. Climate*, 2003, **16**, 426–444.
4. Lean, J., Rottman, G., Harder, J. and Kopp, G., SORCE contributions to new understanding of global change and solar variability. *Sol. Phys.*, 2005, **230**(1–2), 27–53; doi:10.1007/s11207-005-1527-2.
5. Larkin, A., Haigh, J. D. and Djavidnia, S., The effect of solar UV irradiance variations on the Earth's atmosphere. *Space Sci. Rev.*, 2000, **94**, 199–214.
6. Keckhut, P., Cagnazzo, C., Chanin, M. L., Claud, C. and Hauchecorne, A., The 11-year solar-cycle effects on temperature in the upper stratosphere and mesosphere. Part I: Assessment of observations. *J. Atmos. Solar-Terrest. Phys.*, 2004, **67**, 940–947; http://dx.doi.org/10.1016/j.jastp.2005.01.008.
7. Hood, L. L., Effects of solar UV variability on the stratosphere in solar variability and its effects on climate. *Geophys. Monogr. Ser.*, 2004, **141**, 283–304.
8. Austin, J. *et al.*, Coupled chemistry climate model simulations of the solar cycle in ozone and temperature. *J. Geophys. Res.*, 2008, **113**, D11306; doi:10.1029/2007JD009391.
9. Marsh, D. R., Garcia, R. R., Kinnison, D. E., Boville, B. A., Sassi, F., Solomon, S. C. and Matthes, K., Modeling the whole atmosphere response to solar cycle changes in radiative and geomagnetic forcing. *J. Geophys. Res.*, 2007, **112**, D23306; doi:10.1029/2006JD008306.
10. Randel, W. J. *et al.*, An update of observed stratospheric temperature trends. *J. Geophys. Res.*, 2009, **114**, D02107, doi:10.1029/2008JD010421.
11. Dunkerton, T. J., Delisi, D. P. and Baldwin, M. P., Middle atmosphere cooling trend in historical rocketsonde data. *Geophys. Res. Lett.*, 1998, **25**, 3371–3374.
12. Keckhut, P. F., Schmidlin, J., Hauchecorne, A. and Chanin, M.-L., Stratospheric and mesospheric cooling trend estimates from US rocketsondes at low latitude stations (8°S–34°N), taking into account instrumental changes and natural variability. *J. Atmos. Sol. Terr. Phys.*, 1999, **61**, 447–459.
13. Anthes, R., Rocken, C. and Kuo, Y. H., Applications of COSMIC to meteorology and climate. *Terr. Atmos. Ocean Sci.*, 2000, **11**, 115–156.
14. Foelsche, U. *et al.*, Observing upper troposphere–lower stratosphere climate with radio occultation data from the CHAMP satellite. *Climate Dyn.*, 2007, **31**(1), 49–65.
15. Kursinski, E. R., Hajj, G. A., Schofield, J. T., Linfield, R. P. and Hard, R. R., Observing earth's atmosphere with radio occultation measurements using the global positioning system. *J. Geophys. Res.*, 1997, **102**, 23429–23465.
16. Hajj, G. A., Kursinski, E. R., Romans, L. J., Bertiger, W. I. and Leroy, S. S., A technical description of atmospheric sounding by GPS occultation. *J. Atmosph. Solar-Terr. Phys.*, 2002, **64**(4), 451–469; **https://doi.org/10.1016/S1364-236826(01)00114-6.**

17. Hajj, G. A., Lee, I. C., Pi, X., Romans, L. J., Schreiner, W. S., Straus, P. R. and Wang, C., COSMIC GPS ionospheric sensing and space weather. *Terr. Atmosp. Ocean. Sci.*, 2000, **11**(1), 235–272.
18. Kuo, Y.-H., Sokolovskiy, S. V., Anthes, R. A. and Vandenberghe, F., Assimilation of GPS radio occultation data for numerical weather prediction. *Terr. Atmosp. Ocean. Sci*., 2000, **11**(1), 157–186.
19. Anthes, R. A. *et al.*, The COSMIC/FORMOSAT-3 mission: early results, *Bull. Am. Meteorol. Soc.*, 2008, **89**, 313–333; doi:10.1175/BAMS-89-3-313.
20. Ho, S. P. *et al.*, Estimating the uncertainty of using GPS radio occultation data for climate monitoring: intercomparison of CHAMP refractivity climate records from 2002 to 2006 from different data centers. *J. Geophys. Res.-Atmosp.*, 2009, **114**, 20; doi:10.1029/2009JD011969.
21. Dhaka, S. K., Kumar, V., Choudhary, R. K., Ho, S. P., Takahashi, M. and Yoden, S., Indications of a strong dynamical coupling between the polar and tropical regions during the sudden stratospheric warming event January 2009: a study based on COSMIC/FORMASAT-3 satellite temperature data, *Atmos. Res*., 2015, **166**, 60–69; doi:10.1016/j.atmosres.2015.06.008.
22. Kumar, V., Dhaka, S. K., Singh, N., Singh, V., Reddy, K. K. and Chun, H. Y., Impact of inter-seasonal solar variability on the association of lower troposphere and cold point tropopause in the tropics: observations using RO data from COSMIC. *Atmos. Res*., 2017, **198,** 216–225; https://doi.org/10.1016/j.atmosres.2017.08.026.
23. Kishore, P., Namboothiri, S. P., Jiang, J. H., Sivakumar, V. and Igarashi, K., Global temperature estimates in the troposphere and stratosphere: a validation study of COSMIC/FORMOSAT-3 measurements. *Atmos. Chem. Phys*., 2009, **9**, 897–908.
24. Chun, H.-Y., Goh, J.-S., Song, I.-S. and Ricciardulli, L., Latitudinal variations of convective source and propagation condition of inertio-gravity waves in the tropics. *J. Atmos. Sci.*, 2007, **64**, 1603–1618.
25. Kumar, V., Dhaka, S. K., Reddy, K. K., Gupta, A., Prasad, S. B., Panwar, V. and Singh, N., Impact of quasi-biennial oscillation on the inter-annual variability of the tropopause height and temperature in the tropics: a study using COSMIC/FORMOSAT-3 observations. *Atmos. Res*., 2014, **139**, 62–70; http://dx.doi.org/10.1016/j.atmosres.2013.12.014.
26. Randel, W. J., Wu, F. and Gaffen, D. J., Interannual variability of the tropical tropopause derived from radiosonde data and NCEP reanalyses. *J. Geophys. Res.*, 2000, **105**(D12). 15509–15523.
27. Marsh, N. D. and Svensmark, H., Low cloud properties influenced by cosmic rays. *Phys. Rev. Lett*., 2000, **85**, 5004–5007.

ACKNOWLEDGEMENTS. Data are obtained from http://cdaac-www.cosmic.ucar.edu/cdaac/login/cosmic/level2/wetPrf/ and we thank all members of the CDAAC team for providing the COSMIC datasets. Sunspot number data were obtained from the NASA, USA website. We also thank the University of Delhi for financial support as part of the work was performed during Innovation project in 2013–14.

Received 20 July 2017; revised accepted 24 September 2018

doi: 10.18520/cs/v115/i12/2232-2239