Response of Cold-Point Mesopause Temperature to Solar Activity Based on SABER Dataset

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Abstract

The thermal structure and energy balance of upper atmosphere are dominated by solar activity. The response of Cold-Point-Mesopause(CPM) to solar activity is an important form. This article presents the response of Temperature-of-CPM(T-CPM) to solar activity using fourteen-year SABER data series over 80°S–80°N regions. These regions are divided into 16 latitude zones with 10° interval, and the spatial areas of 80°S—80°N,180°W—180°E are divided into 96 lattices with 10°(latitude)×60°(longitude) grid. The annual-mean values of T-CPM and F10.7 are calculated. The least squares regression method and correlation analysis are applied to these annual-mean series. First, the results show that the global T-CPM is significantly correlated to solar activity at the 0.05 level of significance with correlation coefficient of 0.90. The global solar response of T-CPM is 4.89±0.67K/100 Solar-Flux-Units(SFU). Then, for each latitude zone, the solar response of T-CPM and its fluctuation are obtained. The solar response of T-CPM becomes stronger with increasing latitude. The fluctuation ranges of solar response at middle latitude regions are smaller than those of equator and high latitude regions, and the global distribution takes on W-shape. The co-relationship analysis shows that the T-CPM is significantly correlated to solar activity at the 0.05 level of significance for each latitude zone. The correlation coefficients at middle latitude regions are higher than those of equator and high latitude regions, and the global distribution takes on M-shape. At last, for each grid cell, the response of T-CPM to solar activity and their correlation coefficient are presented.

Full Text

Preamble

Response of the Temperature of Cold-Point-Mesopause to Solar Activity Based on SABER Dataset

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Key Points

- The global response of temperature of cold-point-mesopause to solar activity is 4.89±0.67 K/100SFU
- Temperature of cold-point-mesopause and its solar response increase gradually with increasing latitude
- Latitudinal distribution of correlation coefficients of annual-mean series between solar flux and temperature of mesopause takes on M-shape

Abstract

The thermal structure and energy balance of the upper atmosphere are dominated by solar activity, and the response of the Cold-Point-Mesopause (CPM) to solar variations represents an important manifestation of this influence. This article presents the response of Temperature-of-CPM (T-CPM) to solar activity using fourteen-year SABER data series covering 80°S–80°N regions. These regions are divided into 16 latitude zones with 10° intervals, and the spatial areas of 80°S−80°N, 180°W−180°E are divided into 96 lattices with a 10°(latitude)×60°(longitude) grid. Annual-mean values of T-CPM and F10.7 are calculated, and least squares regression method and correlation analysis are applied to these annual-mean series. First, the results show that the global T-CPM is significantly correlated to solar activity at the 0.05 level of significance with a correlation coefficient of 0.90. The global solar response of T-CPM is 4.89±0.67 K/100 Solar-Flux-Units (SFU). Then, for each latitude zone, the solar response of T-CPM and its fluctuation are obtained. The solar response of T-CPM becomes stronger with increasing latitude. The fluctuation ranges of solar response at middle latitude regions are smaller than those of equatorial and high latitude regions, and the global distribution takes on a W-shape. The correlation analysis shows that the T-CPM is significantly correlated to solar activity at the 0.05 level of significance for each latitude zone. The correlation coefficients at middle latitude regions are higher than those of equatorial and high latitude regions, and the global distribution takes on an M-shape. Finally, for each grid cell, the response of T-CPM to solar activity and their correlation coefficient are presented.

Index Terms and Keywords: Cold-point mesopause, Solar activity, Solar cycle, Solar response, TIMED/SABER

1 Introduction

The energy balance of Earth' s upper atmosphere is greatly affected by solar radiation. The most energetic solar photons at ultraviolet (UV) and shorter wavelengths are absorbed at various levels in the atmosphere, while Earth' s surface re-emits the absorbed energy at long wavelengths. Consequently, numerous energy source and sink processes occur in the upper atmosphere, and its thermal structure is profoundly impacted by the abundance of solar energy striking Earth from a constantly changing Sun. Variations arising on decadal and even longer timescales may play a significant role in long-term trend estimates. One major source of decadal variability in the upper atmosphere is the 11-year solar activity cycle. Electromagnetic radiation from the Sun is not constant and varies mainly at shorter ultraviolet wavelengths on different timescales. Incoming solar radiation provides the external forcing for the Earth-atmosphere system. While the total solar flux is quite constant, the UV spectral irradiance on the timescale of the 27-day and 11-year solar cycles exhibits the largest changes, up to a factor of 2 over a solar cycle for the solar Lyman-alpha flux [**?**]. The thermal structure and energy balance of the upper atmosphere are dominated by the solar activity cycle, and the response of the cold-point-mesopause to solar activity variations constitutes an important form of this influence.

The Cold-Point-Mesopause (CPM), defined as the region where kinetic temperature is minimum, separates the mesosphere from the thermosphere, where transport and exchange of energy occur through subtle and complex processes [**?**]. Temperature is the most important parameter for characterizing this transition from the mesosphere to the thermosphere, and temperature variations may be related to solar activities. Temperature-of-CPM (T-CPM) and Height-of-CPM (H-CPM) are established by radiative, chemical, and dynamical processes, and also display large variability due to internal gravity waves and tides [**?**, **?**].

Solar energy is the original source of all these complex atmospheric processes. Hence, investigations of changes in solar UV spectral irradiance on timescales of the 27-day and 11-year solar cycles have been conducted by many researchers. [**?**] investigated solar cycle effects and temperature trends in the mesopause region based on 894 nights of Na lidar observations obtained during 1990–2007 over Fort Collins (41°N, 105°W). [**?**] analyzed the response of temperature to solar activity at ~87 km based on OH airglow measurements obtained during 1988–2008 over Wuppertal station (51°N, 7°E). [**?**] investigated temperature data based on spectral observations of mesopause emissions at Maymaga station (63°N, 129°E) during 2000-2011, examining the seasonal dependence of the response of received radiation temperatures of OH (6,2) (radiation height 87 km) to solar activity. [**?**] studied the sensitivity of equatorial mesopause temperatures to 27-day solar forcing using nighttime observations of OH(3–1) rotational temperatures with SCIAMACHY (SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY) on Envisat. [?] analyzed measurements of rotational temperature of the hydroxyl near the mesopause region at Maimaga station (63.04°N, 129.51°E) for the period from August 1999 to March 2013 in search of solar activity effects and temperature trends. However, the above literature mainly reported results for separate local mesopause regions through analyzing temperature data obtained by ground-based remote sensing.

Ground-based remote sensing, such as lidar measurements or OH airglow measurements, can only observe a small portion of the upper atmosphere located over an observation site. Consequently, ground-based remote sensing was limited to separate local sites with a restricted number of observation days and failed to provide continuous observations on a global scale.

Satellite remote sensing, such as HALOE or SABER observations, is the most efficient method for obtaining atmospheric parameters to investigate global-scale effects of solar variability on temperature in the upper atmosphere. [?] reported solar cycle effects in temperature versus altitude from the Halogen Occultation Experiment (HALOE) for the mesosphere. [?] investigated long-term variabilities and trends of middle atmospheric temperature and their responses to quasi-biennial oscillation (QBO), solar cycle, and El Niño-southern oscillation (ENSO), extending 20–100 km altitude and 10–15°N latitude using SABER observations for 2002-2012. [?] investigated the response of the middle atmosphere at various heights to changes in solar activity using SABER temperature data during 2002-2013 and covering 20-110 km altitude. [?] studied solar cycle variabilities of tropical (10°N–15°N) mesopause temperature structure through analyzing SABER observations during 2002–2012. Detailed reviews of this subject were provided by [?] and [?]. However, the global distribution of the response of T-CPM (at the mesopause actually) to solar activity, obtained using the same data source with coverage of at least one complete solar cycle, was not reported. In our work, the close connection of T-CPM with the level of solar activity is statistically presented based on a large volume of data, and the nonuniform latitudinal and longitudinal distribution of the response of T-CPM to solar activity is shown.

The Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) is one of four instruments on NASA' s TIMED (Thermosphere Ionosphere Mesosphere Energetics Dynamics) satellite launched in December 2001. The primary goal of the SABER experiment is to provide data needed to advance our understanding of the fundamental processes governing energetics, chemistry, dynamics, and transport in the mesosphere and lower thermosphere. The latitudinal coverage of SABER observations is either 83°N to 52°S or 83°S to 52°N depending on the yaw cycles, and it makes ~15 orbits per day with a period of ~1.6 hours. SABER scans the atmosphere from the troposphere up to the lower thermosphere once every ~58 seconds and obtains vertical profiles of kinetic temperature, geopotential height, and other parameters [?, ?, ?, ?]. SABER observations offer a sufficiently high-quality dataset with larger scope and much longer records than OH airglow measurements and lidar measurements. Thus, SABER observations represent an optimal data source for investigating global-scale long-term temperature responses to solar activity. According to the characteristics of SABER observations, for convenience in dividing latitude zones and conducting analysis, we present the response of T-CPM to solar activity and their correlation coefficient globally from 80°S to 80°N based on 2002-2015 SABER temperature products in this paper. Solar activities are represented by the 10.7 cm solar radio flux (F10.7) dataset. The results are restricted to nighttime situations to minimize the impact of fluctuations caused by the propagation of internal gravity waves and tides. In Section 2, the data and methodologies used in the investigation are introduced. The results of the response of T-CPM to solar activity are shown in Section 3, and a brief discussion and conclusions are provided in the final section.

2.1 Data Source

The atmospheric temperature profiles used in this investigation are SABER version 2.0 (V2.0) Level 2A dataset, which extends from January 25, 2002 to the present. The V2.0 products were made available to the public in November 2012. Compared to prior versions, the V2.0 production retrieval algorithm has many substantial improvements that significantly impact all parameters. More details on the retrieval algorithm and data quality assessment can be obtained from [**?**], [**?**, **?**], and the website: http://saber.gats-inc.com/V107vsV2.php.

The 10.7 cm solar radio flux (F10.7), which varies with the solar cycle, is often taken as an index of solar activity [**?**, **?**, **?**, **?**, **?**]. The daily data of F10.7 adjusted to an arbitrary unit (1 A.U.) is used to analyze the response of T-CPM to solar activity.

2.2 The Methodology for CPM Data Quality Control Processing

Through processing 14 years (14 yr) of temperature profile data from SABER observations from 2002 to 2015, the T-CPM is first identified for each temperature profile based on the definition of CPM. The H-CPM is the corresponding height for the T-CPM. Owing to some incorrect CPMs in the temperature profiles, it is necessary to preprocess the profiles by carrying out quality control for T-CPM. For all 4,495,286 temperature profiles with any valid nighttime event reports in the Level 2A dataset of SABER version 2.0 during 2002-2015, the following three steps are carried out for each temperature profile. First, temperature profiles with maximum height lower than 90 km, which cannot provide an effective determination of T-CPM and H-CPM, are ignored. Second, temperature profiles are ignored when the height of the temperature profile does not rise above the H-CPM, as these are ineffective records, as shown by the circle symbol in Fig. 1a. Finally, the circle symbol shown in Fig. 1b is considered an effective CPM, and the corresponding effective temperature, height, date, latitude, and longitude are saved for subsequent analysis.

[Figure 1: see original paper]

Fig. 2a shows the distribution of the amount of global available temperature profiles for each year from 2002 to 2015 in the Level 2A dataset of SABER version 2.0. The original data are shown as hollow hexagons, and the effective data after CPM quality control are shown as solid circles. After quality control of CPM, the total amount of global available temperature profiles of T-CPM decreases from the original 4,495,286 to 4,492,664. A total of 2,622 temperature profiles are removed outside the CPM quality control for T-CPM, and approximately 99.94 percent of the 4,495,286 profiles are effective values. As also found in Fig. 2a, due to SABER observations lacking data from January 1, 2002 to January 24, 2002, the amount of temperature profiles of T-CPM in 2002 is about 1/14 less than that of other years. To match the satellite data series, the daily data of F10.7 during January 1-24, 2002 are also removed.

Fig. 2b shows the distribution of 4,492,664 temperature profiles of T-CPM for each integer latitude interval between approximately 83°S and 83°N. From the solid circle symbols shown in Fig. 2b, we can find that between 52°S and 52°N, the number of T-CPM profiles exceeds 25,000 for each integer latitude interval, and the number of T-CPM profiles exceeds 10,000 between 52°N and 83°N or between 52°S and 83°S. The uneven distribution of temperature profiles accords with the latitudinal coverage of SABER observations, which is either 83°N to 52°S or 83°S to 52°N depending on the yaw cycles. Latitudinal coverage varies with time because SABER performs a yaw maneuver approximately every 60 days, so only the latitude range from 52°S to 52°N is continuously covered by SABER observations. Based on the above analysis, to avoid the impact of yaw cycles on the solar response of T-CPM, we only analyze the annual-mean response of T-CPM to solar activity and their correlation coefficient, and the global annual-mean of T-CPM is calculated by averaging latitude zone mean values in this study.

[Figure 2: see original paper]

Finally, during the period from 2002 to 2015, a total of 4,302,764 temperature profiles are adopted in the following investigations over the 80°S–80°N latitude region, which is about 45 times the amount of HALOE temperature profiles reported in the literature [**?**].

2.3 The Methodologies for CPM Data Analyzing

We divide the latitude regions from 80°S to 80°N into 16 latitude zones with an interval of 10°. The annual-mean of T-CPM for each latitude zone is calculated from the T-CPM of all temperature profiles within the latitude zone. For investigations of the spatial (latitude-longitude) distribution of the response of T-CPM to solar activity and their correlation coefficient, we divide the areas of 80°S−80°N, 180°W−180°E into 96 lattices using a 10°(latitude)×60°(longitude) grid to ensure each grid cell contains a sufficient number of CPM samples. The annual-mean of T-CPM for each grid cell is calculated from the T-CPM of all temperature profiles within the cell.

In this study, the global annual-mean of T-CPM is calculated from the corresponding average of 16 latitude zones, and the annual-mean of F10.7 is calculated from the daily data of F10.7. Using the least squares method and linear regression analysis, we obtain the global solar response of T-CPM and the fluctuation range of solar response. Through correlation analysis, we obtain the global correlation coefficient of annual-mean series values between F10.7 and T-CPM, and the global significance of the correlation coefficient is tested with a 12 degrees of freedom T-test. Then, for each latitude zone and each grid cell, the solar response of T-CPM and its fluctuation are analyzed by the least squares regression method, and the corresponding significance of the correlation coefficient is also tested with a 12 degrees of freedom T-test. The spatial distribution characteristics of the solar response of T-CPM and their solar cycle dependence are obtained.

3.1 Global Response of T-CPM to Solar Activity and Their Correlation Coefficient

To reduce noise and increase statistical significance, the global annual-mean of T-CPM is calculated from the corresponding average of 16 latitude zones. Using the least squares method and linear regression analysis, the scatter plot of T-CPM and F10.7 is shown in Fig. 3a, and the global solar response of T-CPM and the fluctuation range of solar response are obtained. From Fig. 3a, we can find that T-CPM varies almost linearly with the solar flux F10.7. The global solar response of T-CPM is 4.89±0.67 K/100SFU.

Through calculation of the correlation coefficient, we analyze the dependence relation of the fourteen-year time series average between T-CPM and F10.7, as shown in Fig. 3b, and the correlation coefficient is 0.90. Since the probability density function of the sample correlation coefficient obeys the T-distribution [?], the significance of the correlation coefficient is tested with a 12 degrees of freedom T-test in this paper. By calculation, the critical value of the correlation coefficient is 0.53 at the 0.05 level of significance. The correlation analysis shows that the global annual-mean of T-CPM is significantly correlated to solar activity at the 0.05 level of significance during 2002-2015. Solar variations are the dominant influence on the upper atmospheric temperature structure.

[Figure 3: see original paper]

Fig. 3b clearly shows a strong dependence of T-CPM on changes in solar activity. T-CPM decreases from 2002 to a bottom in 2008, then gradually increases to a peak. The changes in T-CPM closely follow the changes in solar activity. It is well known that solar activity has 11-year solar activity cycles. The annual-mean of T-CPM coincides with the solar 11-year-cycle changes.

One important mechanism for this dependency is that CO cooling is dominant during solar minimum, while NO cooling becomes more important during solar maximum [?]. The solar cycle dependence is due to the relative importance of CO infrared cooling and NO infrared cooling. NO density at solar maximum is about three times that at solar minimum. Consequently, CO cooling is relatively less important at solar maximum [?]. SABER measurements revealed a decrease of the global NO cooling rate from 2002 to 2009 by nearly an order of magnitude, while the global CO cooling rate decreased only by 35% [?].

T-CPM is determined by many factors under radiative, chemical, and dynamical processes. Because the Sun is the original source of all these complex atmospheric processes, it is not surprising that changes in solar energy result in variations of these processes and cause changes in T-CPM. We find that changes in T-CPM depend closely on changes in solar activity from SABER observations over the global region.

With increasing solar flux index F10.7, solar UV photons increase, the production of ion pairs by photoionization (N , O) and the production of atoms by molecular (O) photodissociation increase, thus the abundance of O atoms varies with solar activity and in turn induces changes in the thermal structure of the middle atmosphere, thereby affecting temperature-dependent reaction rates and long- and short-wave radiative heating. In the lower thermosphere, thermal collisions with O atoms provide the principal excitation process, so temperature varies with solar activity. These mechanisms may explain why T-CPM varies with solar activity.

The global annual-mean of H-CPM is also calculated from the corresponding average of 16 latitude zones, as shown in Fig. 4. The annual-mean of H-CPM serves as the location reference for the solar response of T-CPM. The variation of the annual-mean of H-CPM is small, around 95.4±0.4 km, and it has a negative dependence on the solar cycle with a correlation coefficient of the annual-mean of H-CPM.

[Figure 4: see original paper]

3.2 Latitudinal Distribution of the Response of T-CPM to Solar Activity and Their Correlation Coefficient

To study the latitudinal distribution of the response of T-CPM to solar activity and their correlation coefficient, the annual-mean of T-CPM for each latitude zone is calculated from the T-CPM of all temperature profiles within the latitude zone. Using the least squares method and linear regression analysis, the latitudinal distribution of the solar response of T-CPM and the fluctuation range of solar response are obtained. Fig. 5a shows the solar response of T-CPM and the fluctuation range of solar response for every 10° interval. From Fig. 5a, we can see that the latitudinal distribution characteristics of the solar response of T-CPM are remarkable.

[Figure 5: see original paper]

In the northern hemisphere, the solar response of T-CPM increases gradually from low latitude zones to high latitude zones, with solar response values varying from a minimum of 2.78±0.69 K/100SFU in the 0°N−10°N latitude zone to a maximum of 7.21±1.85 K/100SFU in the 70°N−80°N latitude zone. The fluctuation range of solar response increases gradually from the 20°N−30°N latitude zone to high latitude zones, with fluctuation values varying from ±0.35 K/100SFU in the 20°N−30°N latitude zone to ±1.85 K/100SFU in the 70°N −80°N latitude zone. In the equatorial region, the fluctuation range of solar response decreases gradually from the 0°N−10°N latitude zone with ±0.69 K/100SFU to the 20°N−30°N latitude zone with ±0.35 K/100SFU. The smallest fluctuation of solar response with ±0.35 K/100SFU occurs in the 20°N−30°N latitude zone, and the largest fluctuation of solar response with ±1.85 K/100SFU occurs in the 70°N−80°N latitude zone.

In the southern hemisphere, except for the 70°S−80°S latitude zone with 6.13±1.21 K/100SFU, the solar response of T-CPM increases gradually from low latitude zones to high latitude zones, with solar response values varying from 2.82±0.73 K/100SFU in the 0°S−10°S latitude zone to 6.35±1.16 K/100SFU in the 60°S−70°S latitude zone. The minimum solar response of 2.82±0.73 K/100SFU occurs in the equatorial latitude region (0°S−10°S), and the maximum solar response of 6.35±1.16 K/100SFU occurs in the 60°S−70°S latitude zone. Except for the 0°S−10°S latitude zone with ±0.73 K/100SFU, the fluctuation range of solar response increases gradually from low latitude zones to high latitude zones, with fluctuation values varying from ±0.42 K/100SFU in the 10°S−20°S latitude zone to ±1.21 K/100SFU in the 70°S −80°S latitude zone. The smallest fluctuation of solar response with ±0.42 K/100SFU occurs in the 10°S−20°S latitude zone, and the largest fluctuation of solar response with ±1.21 K/100SFU occurs in the 70°S−80°S latitude zone. Based on the above analysis and combined with Fig. 5a, it can be concluded that the fluctuation ranges of the solar response at middle latitude regions are remarkably smaller than those of equatorial and high latitude regions, and the solar response fluctuation with latitude at the global scale takes on a W-shape. This phenomenon has not been reported before.

Using correlation analysis, we obtain the correlation coefficients of annual-mean series between F10.7 and T-CPM for 16 latitude zones, as shown in Fig. 5b. The correlation coefficients also show obvious latitudinal distribution characteristics. The correlation coefficients at middle latitude regions are higher than those of equatorial and high latitude regions, and the correlation coefficients with latitude at the global scale take on an M-shape. This phenomenon was also not reported previously. Due to the correlation coefficient of each latitude zone being greater than 0.53, the correlation analysis shows that the annual-mean of T-CPM is significantly correlated to solar activity at the 0.05 level of significance for each latitude zone.

Based on the above analysis and combined with Fig. 5, it can be concluded that the correlation coefficient depends on the corresponding fluctuation range of solar response. The lower the correlation coefficient, the larger the fluctuation amplitude. The phenomenon of larger fluctuation and lower correlation coefficient at equatorial and high latitude zones might indicate that temperature variation in the mesopause atmosphere is more active at equatorial and high latitude zones.

To verify the reliability of these results, we count the number of CPM samples at each latitude zone. Fig. 6 shows the distribution of global available CPM samples for each latitude zone. From Fig. 6, we can see that each latitude zone contains a sufficient number of CPM samples, with more than 10 samples for each latitude zone. Thus, the number of CPM samples is large enough to ensure statistical credibility for the solar response of T-CPM over global zones.

[Figure 6: see original paper]

Fig. 7a shows the latitudinal distribution of the 14-year average of T-CPM for each latitude zone, calculated from the T-CPM of all temperature profiles within the latitude zone during 2002-2015, and the corresponding H-CPM is shown in Fig. 7b. The 14-year average of H-CPM serves as the location reference for the solar response of T-CPM for each latitude zone. From Fig. 7a, we can see that the latitudinal distribution characteristics of T-CPM are obvious, and T-CPM increases gradually from the equator to both sides toward high latitude zones. It is known that the behavior of a seasonal mesopause at high latitudes has a two-level structure: the mesopause drops to ~85 km and cools down to 130-140 K in summer. Due to latitude zones containing uneven amounts of CPM samples as shown in Fig. 6, and there being no CPM samples for some nights at polar latitude zones in summer, the 14-year average of T-CPM and H-CPM may be lower for high latitude zones above 60 degrees.

[Figure 7: see original paper]

3.3 Spatial Distribution of the Response of T-CPM to Solar Activity and Their Correlation Coefficient

In this section, we focus on the spatial (latitude-longitude) distribution of the response of T-CPM to solar activity and their correlation coefficient for each grid cell. The annual-mean of T-CPM for each grid cell is calculated from the T-CPM of all temperature profiles within the grid cell. Using the least squares regression method, the solar response of T-CPM is obtained for each grid cell. Through correlation analysis, we obtain the correlation coefficient of annual-mean series between F10.7 and T-CPM, and then the significance of the correlation coefficient is tested with a 12 degrees of freedom T-test for each grid cell. Fig. 8a shows the spatial distribution of the solar response of T-CPM, and Fig. 8b shows the spatial distribution of correlation coefficients of annual-mean series between T-CPM and F10.7 during 2002-2015.

[Figure 8: see original paper]

As shown in Fig. 8a, the solar response of T-CPM shows obvious spatial distribution characteristics, and the variation amplitude of the solar response of T-CPM varies from 2.12 K/100SFU to 8.18 K/100SFU. The minimum solar response of T-CPM with 2.12 K/100SFU occurs in the grid cell located in the 0°N –10°N, 0°E–60°E region, as shown by the black star symbol. The maximum solar response of T-CPM with 8.18 K/100SFU occurs in the grid cell located in the 70°N–80°N, 60°W–120°W region, as shown by the black triangle symbol.

Under the same longitude zone with every 60° interval, on the whole, the change gradient of the solar response of T-CPM increases gradually from the equator to both sides toward high latitude regions, except for some individual grid cells.

As shown in Fig. 8b, the correlation coefficients also show obvious spatial distribution characteristics, and the variation amplitude of correlation coefficients between T-CPM and F10.7 varies from 0.51 to 0.95. The minimum solar cycle dependence with a correlation coefficient of 0.51 occurs in the grid cell located in the 0°N–10°N, 0°E–60°E region, as shown by the black star symbol. The maximum solar cycle dependence with a correlation coefficient of 0.95 occurs in the grid cell located in the 30°N–40°N, 0°E–60°E region, as shown by the black triangle symbol. For each grid, the significance of the correlation coefficient is tested with a 12 degrees of freedom T-test. Only one grid cell region, shown in blue on the map, is not significantly correlated to solar activity at the 0.05 level of significance. The remaining ninety-five grid cells are significantly correlated to solar activity at the 0.05 level of significance.

Additionally, both the solar response of T-CPM and their correlation coefficient show slight longitudinal dependence, as can be seen in Fig. 8.

Fig. 9a shows the spatial distribution of the 14-year average of T-CPM for each grid cell, calculated from the T-CPM of all temperature profiles within the grid cell during 2002-2015, and the corresponding H-CPM is shown in Fig. 9b. The 14-year average of H-CPM serves as the location reference for the solar response of T-CPM for each grid cell. As in Fig. 7a, T-CPM shows remarkable latitudinal dependence and little longitudinal dependence.

[Figure 9: see original paper]

4.1 Discussion

A wide range of literature has investigated the influence of solar activity on upper atmosphere temperature [?, ?, ?, ?, ?, ?, ?, ?, ?]. [?] and [?] provided a compilation of existing studies quantifying the sensitivity of middle atmospheric temperatures to solar activity in terms of the 11-year solar activity cycle, with most estimations lying in the range from 0 to 10 K/100 SFU in the mesopause region. We process a large array of data, and the results show a strong dependence of the temperature of cold-point-mesopause and its latitudinal distribution on changes in solar activity. Our results for the northern and southern hemispheres, referring to heights around 95 km, coincide with most conclusions obtained by different observations separated by several decades. However, the magnitude of solar response reported by different authors is found to differ slightly compared to our results. Some of these differences in temperature response to solar activity in the mesopause region are understandable.

The differences may be attributed to the fact that ground-based remote sensing (such as lidar measurements and OH airglow measurements) results were averages of measurements obtained over several nighttime hours, whereas HALOE results were strictly based on data obtained only at sunrise and sunset times, and HALOE observations were intermittent, as shown on the website: http://haloe.gats-inc.com/coverage/index.php. The differences in the magnitude of solar response of T-CPM reported by other researchers compared to our results may also be due to height differences since the solar temperature response increases with altitude from the middle mesosphere into the lower thermosphere [?]. The differences may also be due to decadal or solar cycle effects in tidal forcing at the tropics, where tidal amplitudes are large [?].

Due to the lack of previous literature results obtained using the same data source with long-term data series for the global-scale mesopause region, the major challenge lies in interpreting the latitudinal or longitudinal variability of the response of T-CPM to solar activity. Our results show that the spatial distribution characteristics of the solar response are obvious. The spatial changes in the response of T-CPM to solar activity may be mainly caused by changes in the spatial distribution of chemically active gases (such as ozone, NO, CO , and O) and by changes in solar UV irradiation. The spatial changes may also be related to solar radiation intensity or solar incidence angle in different mesopause regions, though other reasons for these spatial changes warrant further investigation.

4.2 Conclusions

The first global distribution of the response of T-CPM to solar activity and their correlation coefficient is presented through analyzing temperature profiles from the Level 2A dataset in SABER version 2.0 from 2002 to 2015. The analyses include latitudinal distribution, spatial distribution, the solar response of T-CPM and its fluctuation, and solar cycle dependence and significance of correlation coefficient. The results show a close connection between T-CPM (at the mesopause actually) and the level of solar activity, and there exists a nonuniform latitudinal and longitudinal distribution of the response of T-CPM to solar activity based on a large volume of data.

A total of 4,302,764 temperature profiles are applied for this period. Using the least squares method and linear regression analysis, the solar response of T-CPM and its fluctuation range are presented. The global solar response of T-CPM is 4.89±0.67 K/100SFU. The global T-CPM clearly follows the solar cycle, and the corresponding significant correlation coefficient is 0.90.

Through analysis of the latitudinal distribution of the response of T-CPM to solar activity and its fluctuation, it is found that the latitudinal distribution characteristics of the solar response are obvious. The solar response of T-CPM increases gradually from the equator to both sides toward high latitude zones except for one latitude zone (70°S–80°S), and the fluctuation range of solar response increases gradually from low latitude zones to high latitude zones except for three latitude zones in the tropical region over 10°S–20°N. The correlation analysis shows that the annual-mean of T-CPM is significantly correlated to solar activity at the 0.05 level of significance for each latitude zone.

The following phenomena were not reported in previous literature: the fluctuation ranges of solar response at middle latitude regions are remarkably smaller than those of equatorial and high latitude regions, and the solar response fluctuation with latitude at the global scale takes on a W-shape. The correlation coefficients at middle latitude regions are higher than those of equatorial and high latitude regions, and the correlation coefficients with latitude at the global scale take on an M-shape. The correlation coefficient and the corresponding fluctuation range of solar response are related values, and the lower the correlation coefficient, the larger the amplitude.

Through analysis of the spatial distribution of the response of T-CPM to solar activity and their correlation coefficient for each grid cell, the nonuniform latitudinal and longitudinal distribution of the solar response of T-CPM is shown. The values of solar response of T-CPM vary from 2.12 K/100SFU at the equatorial region to 8.18 K/100SFU at high latitude regions. The minimum solar response of T-CPM with 2.12 K/100SFU occurs in the grid cell located in the 0°N–10°N, 0°E–60°E region. The maximum solar response of T-CPM with 8.18 K/100SFU occurs in the grid cell located in the 70°N–80°N, 60°W–120°W region. For each grid cell, the significance of the correlation coefficient is tested with a 12 degrees of freedom T-test. Only one grid cell region, with a correlation coefficient of 0.51, is not significantly correlated to solar activity at the 0.05 level of significance; the remaining ninety-five grid cells are significantly correlated to solar activity at the 0.05 level of significance.

In summary, the present analysis has demonstrated that T-CPM is significantly sensitive to solar activity based on a large volume of data. Changes in T-CPM due to solar activity changes, taken to bracket the assumed 11-year cycle, are substantial. Our results show a relationship between solar activity and temperature structure in mesopause regions. These results demonstrate a potentially significant physical mechanism that may link the 11-year solar cycle and the dynamic state of the mesopause.

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Figure Captions

Figure 1. Examples of the CPM data quality control process. (a) The temperature profile is the 100th event in orbit 75361 on the night of November 4, 2015; (b) The temperature profile is the 40th event in orbit 76214 on the night of December 31, 2015.

Figure 2. Distribution of global available profiles of T-CPM. (a) Amount of total temperature profiles of T-CPM for each year before CPM quality control (hollow hexagon) and after CPM quality control (solid circle); (b) Distribution of 4,492,664 profiles of T-CPM for each integer latitude interval after CPM quality control.

Figure 3. The scatter plot and annual-mean of T-CPM and solar flux index during 2002-2015. (a) The scatter plot of T-CPM and F10.7; (b) The annual-mean of T-CPM and F10.7.

Figure 4. The annual-mean of H-CPM during 2002-2015.

Figure 5. Latitudinal distribution of solar response and solar cycle dependence with every 10° interval. (a) Latitudinal distribution of solar response of T-CPM, with vertical bars showing the fluctuation range of solar response; (b) Latitudinal distribution of correlation coefficients between T-CPM and F10.7.

Figure 6. Latitudinal distribution of 4,302,764 temperature profiles with every 10° interval.

Figure 7. Latitudinal distribution of 14-year average for T-CPM and H-CPM with every 10° interval. (a) Latitudinal distribution of 14-year average of T-CPM; (b) Latitudinal distribution of 14-year average of H-CPM.

Figure 8. Maps of the solar response and solar cycle dependence. (a) Spatial distribution of the solar response of T-CPM, with contour interval of 1 K/100SFU; (b) Spatial distribution of the correlation coefficients between T-CPM and F10.7, with contour interval of 0.05 above 0.53.

Figure 9. Maps of 14-year average for T-CPM and H-CPM. (a) Spatial distribution of 14-year average of T-CPM, with contour interval of 2K; (b) Spatial distribution of 14-year average of H-CPM, with contour interval of 0.5 km.

Note: Figure translations are in progress. See original paper for figures.