

Article

Spatial and Temporal Characterization of Near Space Temperature and Humidity and Their Driving Influences

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Abstract: Near space refers to the atmospheric region 20–100 km above Earth’s surface, encompassing the stratosphere, mesosphere, and part of the thermosphere. This region is susceptible to surface and upper atmospheric disturbances, and the atmospheric temperature and humidity profiles can finely characterize its complex environment. To analyze the relationship between changes in temperature and humidity profiles and natural activities, this study utilizes 18 years of temperature and water vapor data from the TIMED/SABER and AURA/MLS instruments to investigate the variations in temperature and humidity with altitude, time, and spatial distribution. In addition, multiple linear regression analysis is used to examine the impact mechanisms of solar activity, the El Niño–Southern Oscillation (ENSO), and the Quasi-Biennial Oscillation (QBO) on temperature and humidity. The results show that in the mid- and low-latitude regions, temperature and water vapor reach their maxima at an altitude of 50 km, with values of 265 K and $8\text{--}9 \times 10^{-6}$ ppmv, respectively; the variation characteristics differ across latitudes and altitudes, with a clear annual cycle; the feedback effects of solar activity and the ENSO index on temperature and humidity in the 20–40 km atmospheric layer are significantly different. Among these factors, solar activity is the most significant influence on temperature and water vapor, with response coefficients of -0.2 to -0.16 K/sfu and 0.8 to 4×10^{-6} ppmv/sfu, respectively. Secondly, in the low-latitude stratospheric region, the temperature response to ENSO is approximately -1.5 K/MEI, while in the high-latitude region, a positive response of 3 K/MEI is observed. The response of water vapor to ENSO varies between -1×10^{-7} and -4×10^{-7} ppmv/sfu. In the low-latitude stratospheric region, the temperature and humidity responses to the QBO index exhibit significant differences, ranging from -1.8 to -0.6 K/10 m/s. Additionally, there are substantial differences in responses between the polar regions and the low-latitude equatorial region. Finally, a three-dimensional model coefficient was constructed to illustrate the influence of solar activity, ENSO, and QBO on temperature and humidity in the near space. The findings of this study contribute to a deeper understanding of the temperature and humidity variation characteristics in near space and provide valuable data and model references for predicting three-dimensional parameters of temperature and humidity in this region.

Keywords: atmospheric remote sensing; near space; TIMED/SABER; AURA/MLS; temperature; water vapor



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1. Introduction

Near space is specifically defined as the vertical distance above Earth’s surface, ranging from approximately 20 km to 100 km [1]. It encompasses the stratosphere, mesosphere, and part of the thermosphere, forming a transitional zone that spans multiple atmospheric layers. This region has become a hotspot for scientific research and exploration due to its

unique physical, chemical, and environmental characteristics. With increasing altitude, atmospheric pressure decreases sharply, resulting in extremely thin and dry air, which leads to a significant reduction in temperature and water vapor content. Due to its unique environmental conditions, near space has become an ideal venue for testing cutting-edge technologies such as new propulsion systems, materials science, space exploration technologies, and hypersonic vehicles [2,3]. Therefore, in-depth exploration and research on temperature and humidity in near space not only enhance our scientific understanding of Earth's atmosphere and space environment but also lay a solid foundation for the future integrated development of aerospace systems.

Currently, a large amount of satellite observation data are widely used for atmospheric research within the near space region [4]. Raschke et al. analyzed the interannual variations in temperature at 12 pressure levels over 9.5 years using data collected by the Halogen Occultation Experiment (HALOE) satellite [5]. Burrage et al. [6] analyzed the variations in water vapor in the tropical tropopause layer (TTL) and the stratospheric atmosphere using satellite data. Launched in July 2001, the Thermosphere, Ionosphere, Mesosphere, Energetics, and Dynamics (TIMED) satellite aims to study the influences within the mesosphere and lower thermosphere/ionosphere. Analysis of long-term observations from the TIMED satellite over 10 years has revealed a persistent cooling trend in temperature as the years progress [7,8]. Zhao et al. [9] analyzed the long-term temperature trends based on atmospheric detection data from the Sounding of the Atmosphere using a Broadband Emission Radiometry (SABER) instrument. Li et al. [10] integrated nearly 30 years of SABER data to study the long-term trends of middle atmospheric temperature and its relationship with the solar cycle. Liu et al. [11] utilized TIMED/SABER satellite data to extract zonal mean temperatures, discussing temperature characteristics and providing an overview of the global temperature structure. Launched successfully in July 2004, the Microwave Limb Sounder (MLS) has been providing global temperature and water vapor observation data since August of the same year.

As complex physical quantities, temperature and humidity in near space are primarily influenced by solar activity [12–14]. Variations in solar activity, particularly changes in ultraviolet radiation, have a significant impact on the temperature and water vapor distribution in near space through complex radiative, chemical, and dynamic processes. Research indicates that changes in the cold point mesopause temperature (CPM) are closely related to solar activity [15]. Many researchers have utilized long-term satellite observation data to further reveal that the direct effects of solar activity cycles significantly influence the variations in temperature and humidity in near space [16]. Secondly, the anomalous changes in sea surface temperature in the North Pacific are primarily influenced by the El Niño–Southern Oscillation (ENSO) [17–22]. During winter, ENSO-related tropical convection anomalies can trigger remote atmospheric circulation responses over the North Pacific through the Pacific–North American (PNA) teleconnection [23]. Additionally, the Quasi-Biennial Oscillation (QBO) is an important factor influencing temperature and humidity in near space. Its influence is quite extensive; it not only affects the climate of the stratosphere [24–26] but can also impact the troposphere by modulating atmospheric circulation and, through teleconnection effects, influencing surface weather and climate [27].

These studies have not only deepened the understanding of long-term variations in temperature and humidity in near space and their influencing factors but also provided important validation data for climate models [28], enabling more accurate predictions of future climate change [10,29,30]. Given the limited availability of independently accumulated atmospheric parameter data for near space, this study primarily explores the following scientific issues: (1) the spatiotemporal evolution characteristics of temperature and humidity in near space, and (2) how solar activity, the El Niño phenomenon, and the QBO influence the changes in temperature and humidity in near space. This study utilizes temperature and humidity data from the MLS and SABER satellites as the foundational dataset, integrating them to generate three-dimensional global data for the 20–100 km altitude range, and conducting a detailed analysis of their spatiotemporal evolution characteristics.

2. Materials and Methods

2.1. Data Sources

2.1.1. TIMED/SABER Satellite Data

The TIMED satellite, launched in 2001, operates in a near-sun-synchronous orbit with an inclination of 74.1° at an altitude of 625 km, moving along latitude circles. The local time of observation changes by approximately 12 min each day. The latitude coverage of the TIMED satellite ranges from 52°S to 83°N , and it achieves complete 24-h local time coverage globally approximately every 60 days. SABER, the scientific payload aboard the TIMED satellite, includes a 10-channel broadband radiometer [31], measuring in the spectral range of 1.27 to $17\ \mu\text{m}$. Vertical profiles of atmospheric temperature, pressure, and the volume mixing ratio of trace gases such as H_2O are obtained through limb scanning at various altitudes [32–34]. TIMED/SABER has provided continuous observations of atmospheric temperature for over 20 years, and the measurement data have been widely utilized in research and practical applications related to the middle and upper atmosphere [34]. The latest version of the SABER V2.0 dataset includes data from January 2002 to the present, making it the only satellite observation dataset that continuously covers the entire near space and has the longest observation period for the middle and upper atmosphere. This study utilizes the temperature and H_2O products from the SABER v2.0 Level 2A dataset, covering the period from January 2005 to December 2022. Figure 1 shows the TIMED/SABER temperature data on 1 January 2022.

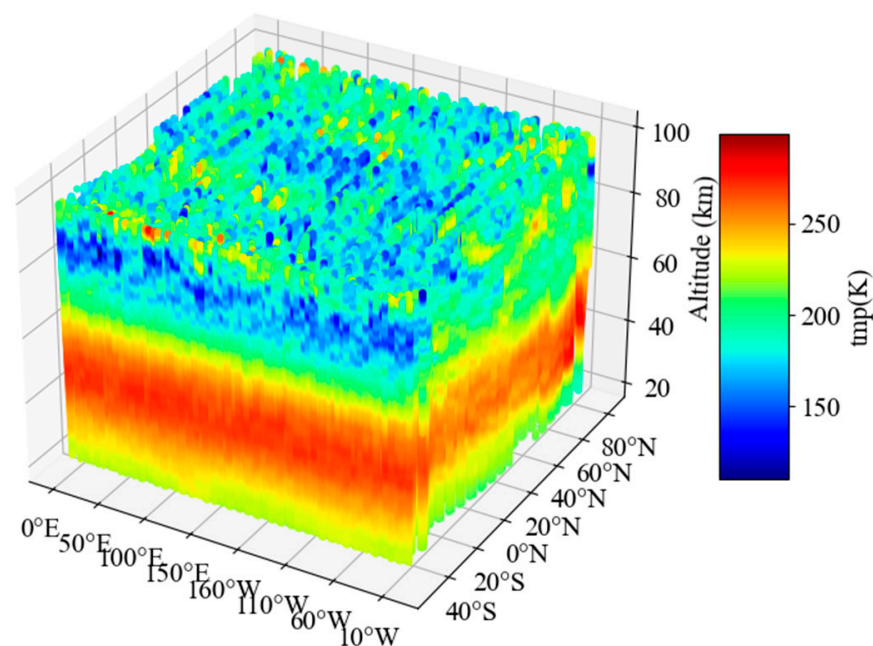


Figure 1. TIMED/SABER temperature data.

2.1.2. AURA/MLS Satellite Data

The Microwave Limb Sounder (MLS) is one of four instruments onboard the Aura satellite. The Aura satellite operates in a near-polar quasi-sun-synchronous orbit at an altitude of approximately 705 km, allowing it to cover global observations of about 15 orbits per day [35]. Aura/MLS employs microwave limb-sounding technology to measure the physical and chemical parameters of Earth's upper troposphere, stratosphere, mesosphere, and lower thermosphere [36]. Aura/MLS takes approximately 24.7 s to vertically scan from the ground to the lower thermosphere during each pass, conducting about 240 scans per orbit and approximately 3500 scans per day. The latitude coverage of the Aura satellite ranges from 82°S to 82°N , allowing the observational data to consistently cover the polar regions. The Aura/MLS data products include a total of 21 geophysical and chemical parameters, with the primary data used in this study being temperature and water vapor

mixing ratio. The data version is v4.2x Level 2, covering an altitude range of 20–100 km and spanning the period from January 2011 to December 2022. Figure 2 shows the Aura/MLS temperature data on 1 January 2022.

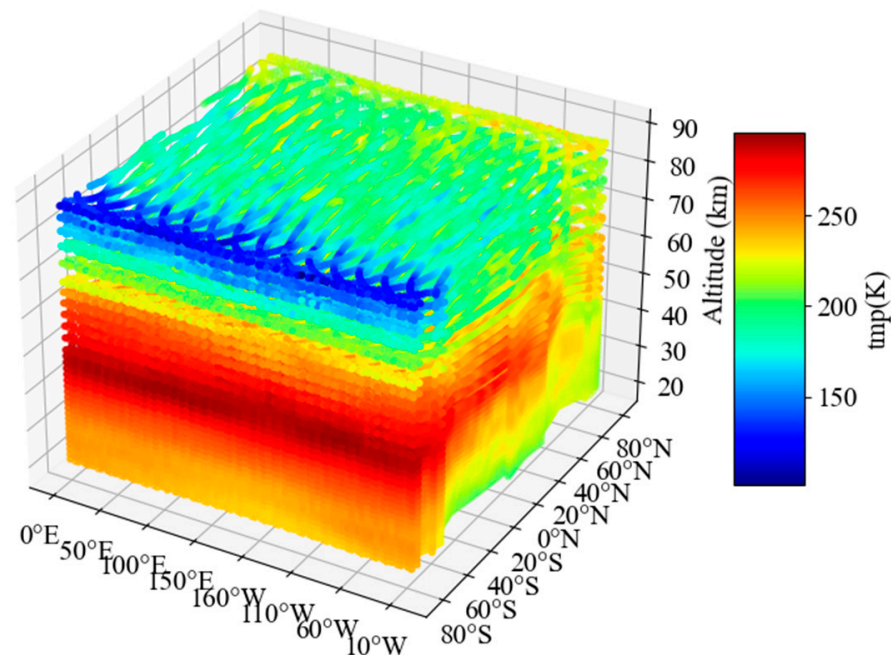


Figure 2. Aura/MLS temperature data.

2.1.3. Auxiliary Data

Additionally, this study utilizes atmospheric-related datasets to investigate the influencing factors of temperature and water vapor changes in near space, primarily including the F10.7 index, ENSO, and QBO indices. The F10.7 index represents the solar radio flux at 10.7 cm (2800 MHz) and is commonly used to describe the intensity of solar activity, with units measured in solar flux units (sfu). The F10.7 index data are sourced from the Solar Influences Data Analysis Center at <https://www.sidc.be/SILSO/infosndhem> (accessed on 15 November 2024).

The ENSO index MEI (Multivariate ENSO Index) serves as a signal to describe ENSO activity, with data sourced from the Physical Sciences Laboratory of the National Oceanic and Atmospheric Administration (NOAA) at <https://www.psl.noaa.gov/enso/mei> (accessed on 15 November 2024). The MEI index integrates five types of atmospheric and oceanic observational data from the tropical Pacific region (30°S to 30°N, 100°E to 70°W): sea level pressure (SLP), sea surface temperature (SST), the zonal and meridional components of surface wind, and outgoing longwave radiation (OLR). This integration effectively characterizes the strength of ENSO activity.

The Quasi-Biennial Oscillation (QBO) data for the equatorial stratospheric zonal wind is sourced from the National Oceanic and Atmospheric Administration (NOAA) at <https://psl.noaa.gov/data/correlation/qbo.data> (accessed on 15 November 2024). The QBO index dataset provides monthly averaged zonal wind components from 1987 to the present. Finally, the obtained QBO index is normalized. Figure 3 shows the data of the three parameters F10.7, ENSO, and QBO from 2005 to 2022.

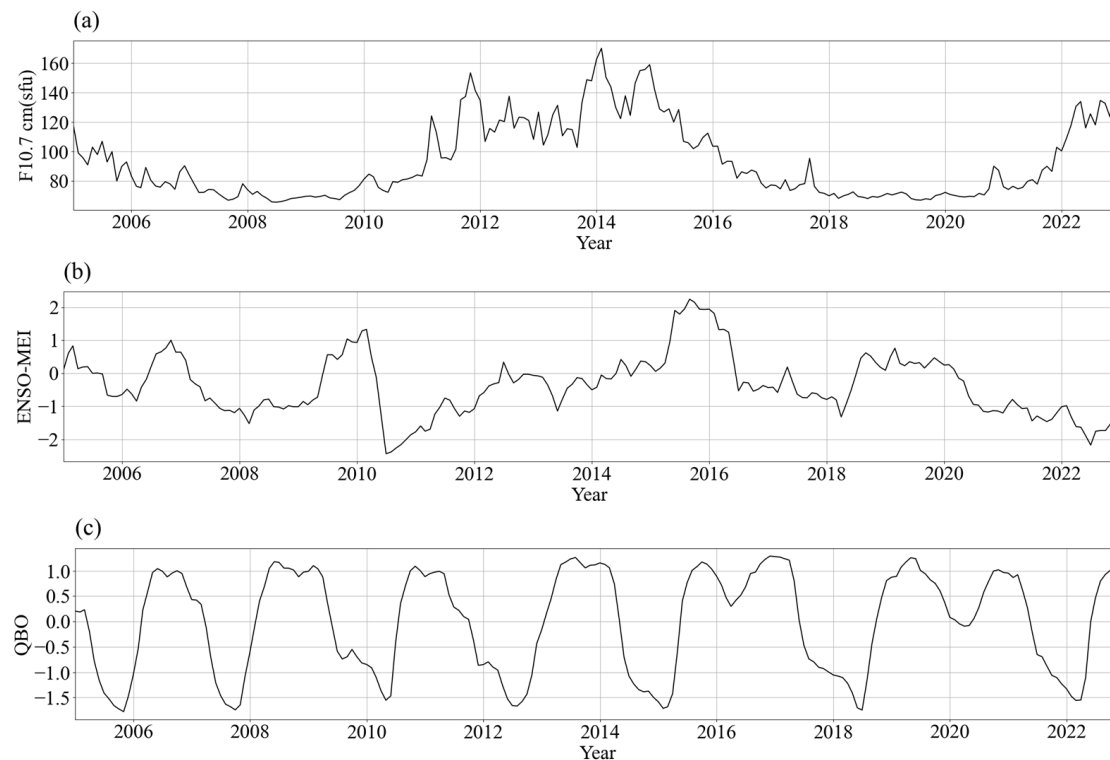


Figure 3. Time series of solar, ENSO, and QBO activity data from January 2005 to December 2022. (a) Time series of solar activity data from January 2005 to December 2022; (b) Time series of ENSO-MEI data from January 2005 to December 2022; (c) Time series of QBO data from January 2005 to December 2022.

2.2. Research Methods

2.2.1. Satellite Data Integration

First, the temperature and water vapor datasets are screened by removing outliers. Since the temperature follows a normal distribution, the monthly averages are calculated within a range of ± 3 °C (standard deviation) to eliminate the outliers. The water vapor data obtained is for the water vapor volume mixing ratio (VMR). Due to the more scattered distribution of the water vapor data, only the data within the 25th to 75th percentiles are selected, and values outside this range are removed. In terms of spatial scale, the N32 reduced Gaussian grid provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) is utilized.

The preprocessed and filtered data are then processed for analysis. For each measurement profile, Kriging interpolation is used to complete the temperature and humidity data within the altitude range of 20–100 km. Kriging interpolation, also known as spatial local interpolation, is a spatial interpolation method based on regionalized variables. It achieves optimal unbiased estimation of unknown points by selecting an appropriate variogram to fit the model. The method used in this study is Ordinary Kriging, which assumes that the property values are spatially stationary. Thus, the regionalized variable must satisfy the second-order stationarity assumption:

The expected value of the regionalized variable $E[z(x)]$ exists and is a constant:

$$E[Z(x)] = m \quad (1)$$

The spatial covariance function of the regionalized variable $E[z(x)]$ exists and is stationary:

$$\text{Cov}[Z(x), Z(x+h)] = E[Z(x)Z(x+h)] - m^2 \quad (2)$$

The basic expression for Ordinary Kriging interpolation is given by:

$$\hat{Z}(x_0) = \sum_{i=1}^N \lambda_i Z(X_i) \quad (3)$$

in the above question, $\hat{Z}(x_0)$ is the estimated value at the location to be estimated; $Z(X_i)$ is the actual observation value at the i -th point; λ_i is the weight assigned to the observation value at the i -th point, and N is the number of given observation values.

For Kriging interpolation calculations, the most crucial step is determining the weights for each location, which are derived from the variogram. Therefore, selecting an appropriate variogram for fitting is key in the process of performing Kriging interpolation. The variogram refers to half the variance of the difference between the observed values $Z(x)$ and $Z(x+h)$ of the regionalized variable at the sample points x and $x+h$:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(x_i) - Z(x_i+h)]^2 \quad (4)$$

in the above equation, $\gamma(h)$ represents the value of the variogram at a spatial distance h , $N(h)$ denotes the number of sample pairs at that distance h , $Z(x_i)$ is the observed value of the regionalized variable $Z(x)$ at point x , and $Z(x_i+h)$ is the observed value of $Z(x)$ at point $x+h$. Finally, the monthly averages are calculated from the continuous grid data obtained through Kriging interpolation of the sensor measurements.

2.2.2. Multiple Linear Regression Analysis (MLR)

Since the variations in temperature and humidity in the near space are primarily influenced by natural factors, a multiple linear regression model is used to extract the information on these changes. Calculate the monthly mean temperature (T_t) and monthly mean humidity (H_t). The calculation method for T_t is to subtract the average value for that specific month over 18 years from the monthly average value for a particular year. For example, the T_t for January 2022 is obtained by subtracting the average of all January values from 2005 to 2022 from the monthly average value for January 2022. Then, perform multiple linear regression analysis on the monthly mean anomalies T_t and H_t of temperature and water vapor, respectively [12]. The fitting equation for T_t as follows (using T_t as an example):

$$T_t = A \times t + B \times Solar + C \times ENSO + D \times QBO + E \quad (5)$$

In the equation, t represents the 216 months over 18 years, and A is the linear coefficient representing the base value of the temperature anomaly. The coefficients B , C , and D are the linear coefficients representing the influence of Solar activity (F10.7), ENSO (MEI), and QBO indices on the temperature anomaly, respectively. In this study, we present results with a 95% confidence level. The coefficients of the parameters in Equation (5) are used to analyze the relationships between temperature, water vapor, and the influencing variables. E is a constant in the equations.

3. Results

3.1. Time Series Data for Temperature and Water Vapor Concentration

Figure 4a and 4b, respectively, show the monthly variation of temperature and water vapor from 2005 to 2022 in the mid-latitude region of the Northern Hemisphere ($31.5 \pm 1^\circ\text{N}$), representing the mean values generated by merging data from two sensors. From Figure 4a, it can be observed that a high-temperature region exists at an altitude of 40–60 km in the mid-latitude region of the Northern Hemisphere throughout the study period, with temperature values ranging from 245 to 265 K. At an altitude of 50 km, there is a region of extreme values where the temperature exceeds 265 K. In addition, the temperature shows a continuous decreasing trend as the altitude increases or decreases. At altitudes between 20 and 40 km, the temperature ranges from 205 to 235 K; at altitudes between 60 and 100 km, the temperature ranges from 175 to 235 K. At the same time, periodic

temperature variations can be observed at different altitude ranges. The temperature has a significant maximum and periodic variation at 50 km, while it shows very low values and low periodic variation between 70 and 95 km.

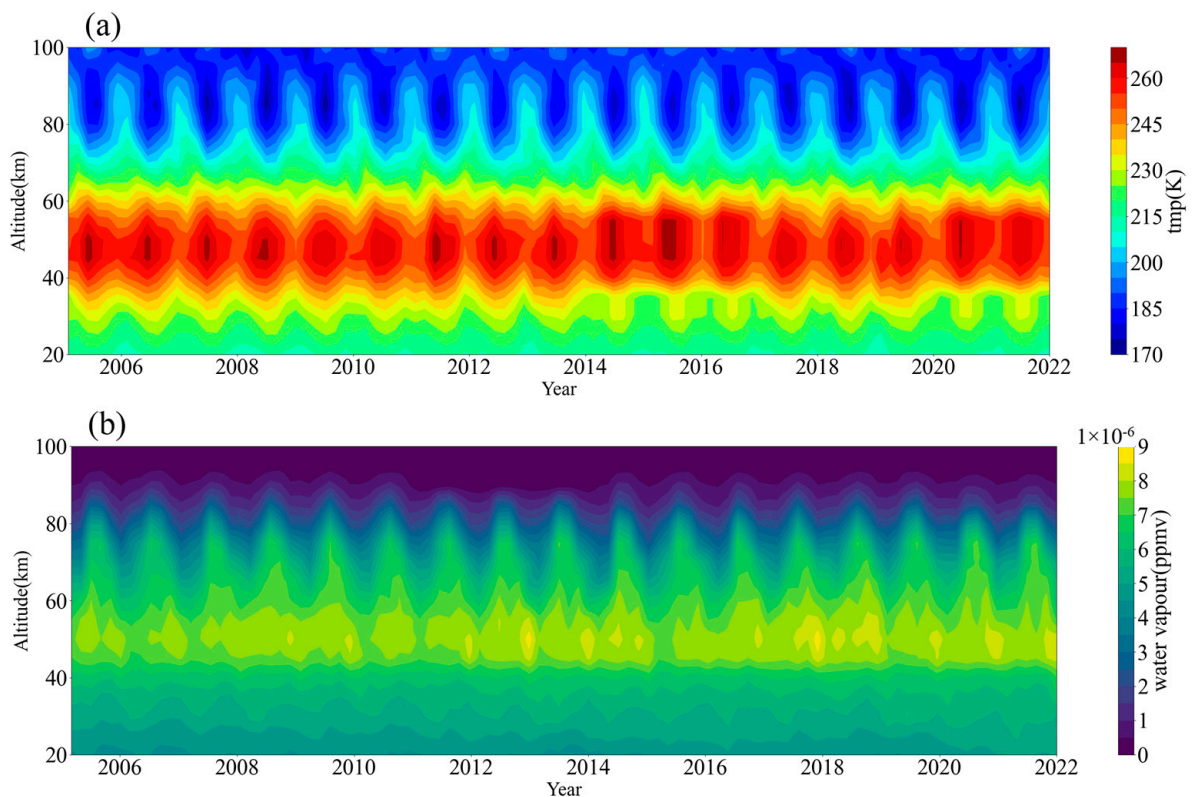


Figure 4. Monthly data for temperature and water vapor concentration. (a) Monthly data of temperature data in the mid-latitude region of the Northern Hemisphere from 2005 to 2022; (b) Monthly data of water vapor data in the mid-latitude region of the Northern Hemisphere from 2005 to 2022.

3.2. The Temperature and Water Vapor Profiles Show Variations in Altitude Characteristics

Figure 5a,b display the range of temperature and humidity profiles, with temperature exhibiting significant characteristics as it varies with altitude. These results are based on global data. At an altitude of 35 km, there is a noticeable temperature trough with an average value of 225 K. In the altitude range of 35 to 50 km, the temperature increases rapidly, rising by approximately 13 K for every 5 km ascent. In the altitude range of 50 to 80 km, the temperature decreases rapidly with increasing height, dropping by 15 K for every 10 km ascent.

Figure 5b shows a significant trend in water vapor concentration with changes in height. At an altitude of 30 km, there is a significant increase in water vapor concentration, forming a peak. In contrast, at altitudes of 50 km and 80 km, there are notable decreases in water vapor concentration, with another peak observed at 80 km. The variation trends of temperature and water vapor exhibit a certain correspondence. To gain a deeper understanding of the reasons behind these significant variations with height, a multiple linear regression analysis will be conducted using temperature, water vapor data, and atmospheric activity data. This will help reveal the influence mechanisms of atmospheric activity on the variations of water vapor and temperature at these heights, providing more detailed data support for atmospheric science research.

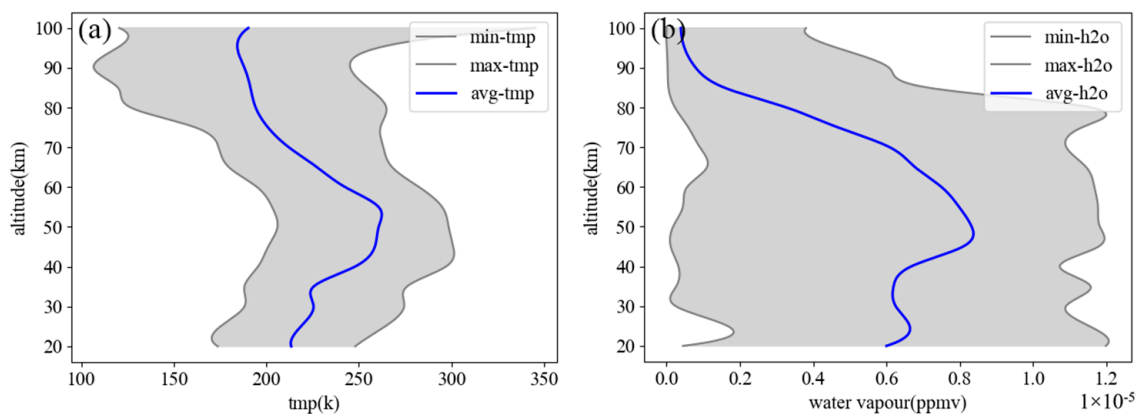


Figure 5. Range of temperature and humidity profile extrema. (a) Range of temperature profile extrema; (b) Range of humidity profile extrema.

3.3. Monthly Mean Temperature and Water Vapor Responses to Solar, ENSO, and QBO Indices

3.3.1. Temperature and Humidity Response to Solar

Figure 6a,b show the responses of the global average (80°S–80°N) near space atmospheric temperature and water vapor to solar activity from 2005 to 2022. The figures represent data from the 180°E longitude band. The solar response coefficients within the altitude range of 20–100 km range from -0.2 K/sfu to 0.16 K/sfu. Among them, in the stratospheric range of 30–40 km, solar activity shows a negative impact on temperature. In the high-latitude regions of both the Northern and Southern Hemispheres, the negative impact reaches between -0.1 K/sfu and -0.2 K/sfu. In other altitude regions, the temperature shows a positive response to solar activity. At an altitude of 50 km, the response coefficient is higher than 0.1 K/sfu. In addition, the temperature response to solar activity exhibits a clear symmetry along the equator. This is mainly due to the regular solar activity between the Tropic of Cancer and the Tropic of Capricorn, resulting in a similarity in the temperature response to solar activity at different altitudes in the Northern and Southern Hemispheres. The negative response in the stratosphere may be due to temperature decreases caused by radiation changes induced by solar activity, while the upper atmosphere may exhibit a positive response due to enhanced radiative heating effects. Additionally, the equatorial symmetry may reflect the uniformity of atmospheric circulation and the global impact of solar activity. This similarity between the Northern and Southern Hemispheres becomes more pronounced, especially in climate responses triggered by variations in solar radiation. Water vapor in the 20–30 km range from 52°S to 20°N exhibits a strong response to solar activity, with a response amplitude ranging from 0.8 to 4×10^{-6} ppmv/sfu. At the same time, the response of water vapor in the Southern Hemisphere is stronger than that in the Northern Hemisphere. This asymmetry may be due to the different indirect effects of solar activity on atmospheric fluctuations between the Southern and Northern Hemispheres. This is because the relatively enclosed oceanic environment in the Southern Hemisphere allows for more stable moisture transport and circulation, while the Northern Hemisphere has more land and more complex climate patterns. These factors may contribute to the Southern Hemisphere being more sensitive to solar activity [37]. At altitudes of 70–90 km, the water vapor concentration decreases with solar activity, with a response value as low as -1.6×10^{-6} ppmv/sfu. The high-latitude regions of both the Northern and Southern Hemispheres also exhibit a negative response, but the degree of response is significantly weaker.

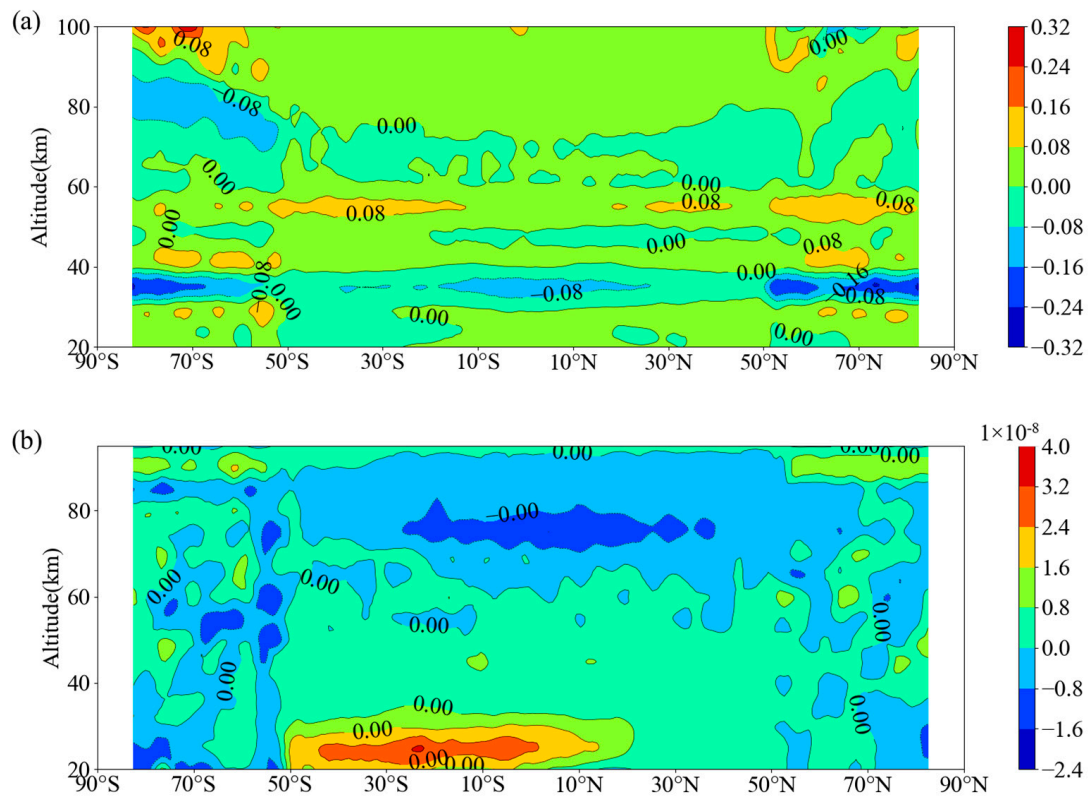


Figure 6. Temperature and water vapor response to solar activity at 180°E. (a) temperature response to solar activity at 180°E; (b) water vapor response to solar activity at 180°E.

3.3.2. Temperature and Humidity Response to ENSO

Figure 7a,b illustrate the responses of temperature and water vapor to ENSO activity. In the lower stratosphere (30–40 km) of the equatorial region, temperature exhibits a negative response to ENSO activity, with a cooling response of approximately -1.5 K/MEI. This is because ENSO events typically lead to increased convective activity in the equatorial region, which can result in lower stratospheric temperatures by altering the energy balance of the climate system. In the high-latitude regions, the temperature shows a positive response to ENSO activity of 3 K/MEI. In other altitude regions, the temperature shows an opposite response trend to ENSO activity. In low-latitude regions, the temperature shows a positive response to ENSO activity, while in high-latitude areas, the temperature exhibits a negative response to ENSO activity. Additionally, the response of temperature to ENSO activity is relatively mild, with coefficients ranging from -1.5 K/MEI to 1.5 K/MEI. The influence of ENSO on atmospheric circulation patterns exhibits different characteristics at varying altitudes and latitudes. For example, the Walker circulation in the equatorial region and the Hadley circulation in the high-latitude regions are affected to varying degrees during ENSO events, leading to differences in temperature responses. Water vapor in the range of 20–30 km from 52°S to 20°N shows a strong negative response to ENSO activity, with a response magnitude ranging from -1×10^{-7} ppmv/sfu to -4×10^{-7} ppmv/sfu. This negative response also exhibits spatial asymmetry between the Northern and Southern Hemispheres, similar to the influence of the sun on water vapor. ENSO influences global atmospheric circulation patterns, particularly the transport of water vapor in tropical and subtropical regions. During El Niño events, enhanced convective activity in the equatorial region leads to a reduction in water vapor in the stratosphere. This negative response may be more pronounced in the tropical and subtropical regions, and it can propagate to higher latitude regions through atmospheric circulation. This is related to changes in the Walker and Hadley circulations during ENSO, while water vapor concentrations in other regions show a weak response.

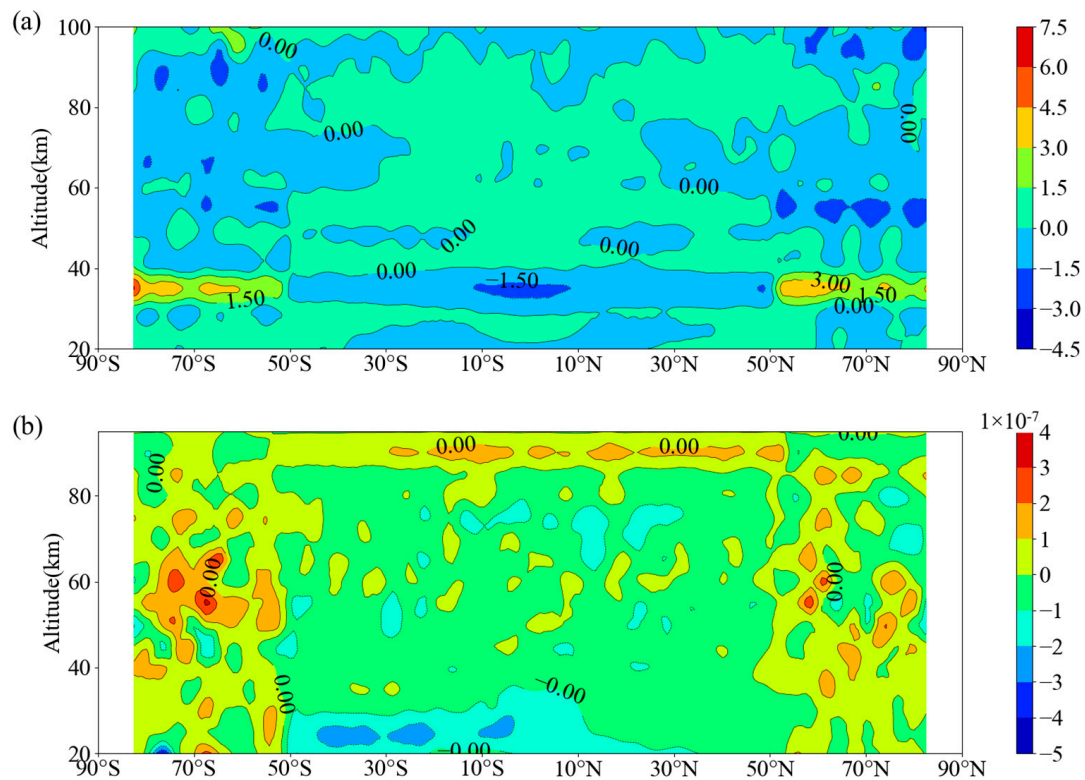


Figure 7. Temperature and water vapor response to ENSO at 180°E. (a) temperature response to ENSO at 180°E; (b) water vapor response to ENSO at 180°E.

3.3.3. Temperature and Humidity Response to QBO

Figure 8a,b illustrate the responses of temperature and water vapor to QBO activity. In the low-latitude stratosphere (20–40 km), the response of temperature to QBO activity shows significant variations. At an altitude of 30–40 km, the temperature response to QBO activity reaches -1.8 K/10 m/s, while at an altitude of 20–25 km, it is 0.6 K/10 m/s. This indicates that the impact of QBO activity on temperature is primarily concentrated in the low-latitude stratospheric region [29]. However, the impact of QBO activity on water vapor shows a significant difference compared to its effect on temperature. In the low-latitude stratospheric region, the QBO activity at an altitude of 30–40 km shows a positive impact on temperature, reaching over 0.5×10^{-7} ppmv/sfu. In the height range of 20–25 km, the QBO activity shows a significant negative correlation, with values below -0.5 ppmv/sfu. In addition, in other regions, there was a clear opposite trend in the response of temperature and water vapor to QBO activity.

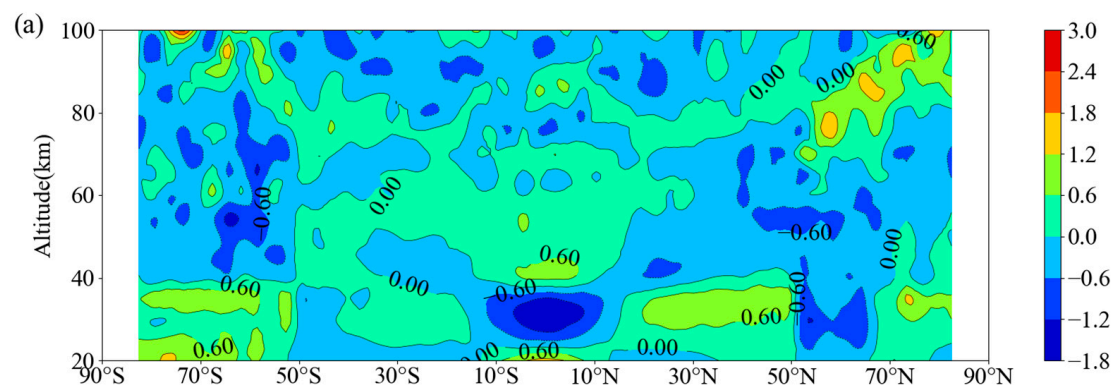


Figure 8. Cont.

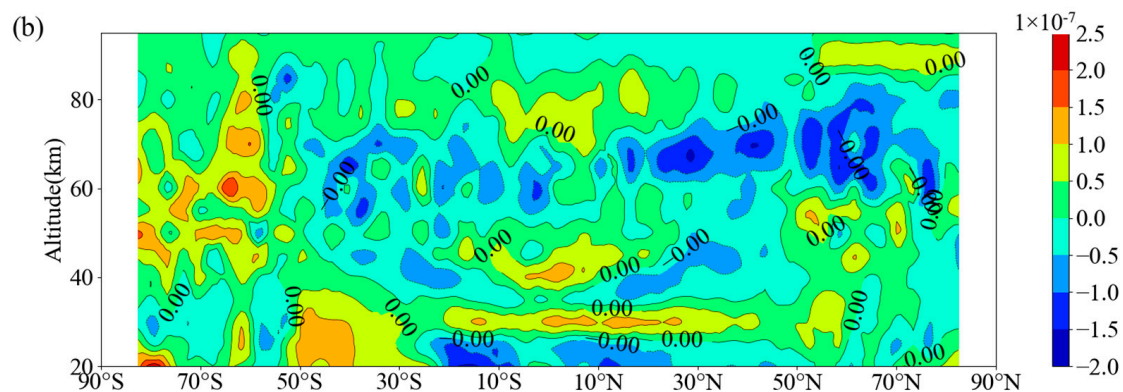


Figure 8. Temperature and water vapor response to QBO at 180° E. (a) temperature response to the QBO; (b) water vapor response to the QBO.

3.3.4. Characterization of Temperature and Humidity Response to Solar Activity, ENSO, and QBO at Altitude

Figure 9 illustrates the boxplots of temperature and water vapor responses to solar, ENSO, and QBO activities across the 20–100 km altitude range. In the 20–40 km stratosphere, solar activity alters radiative transfer, leading to a decrease in temperature in the lower stratosphere at altitudes of 30–40 km. Especially in the high latitudes of both hemispheres (80°S–80°N), the negative response reaches -0.1 K/sfu to -0.2 K/sfu (Figure 9a). In the higher mesosphere, such as at 55 km altitude, solar activity enhances the radiation intensity, with the temperature response coefficient exceeding 0.1 K/sfu. This symmetry in temperature along the equator (around 0° latitude) indicates the uniform impact of solar radiation on the atmosphere in both the Northern and Southern Hemispheres. Compared to solar radiation, the impact of ENSO and QBO on temperature is relatively weaker and more stable, fluctuating around 0 (Figure 9b,c). This is primarily because ENSO and QBO mainly occur in low-latitude regions, with their impacts concentrated at the top of the troposphere and the middle to lower parts of the stratosphere. Therefore, their impact is relatively small at altitudes above 20 km. As for water vapor, its response to solar radiation generally shifts from positive to negative with increasing altitude. In the height range of 20–50 km, water vapor exhibits a positive response to solar radiation, with an average response value of 1 ppmv/sfu. In the height range of 70–90 km, the negative response of water vapor to solar radiation averages 0.8 ppmv/sfu. The influence of ENSO and QBO on water vapor is significant only at heights of 20–30 km, with values reaching -1 ppmv/MEI and 0.5 ppmv/10 m/s, respectively. At heights above 30 km, the influence on water vapor becomes weaker and more stable.

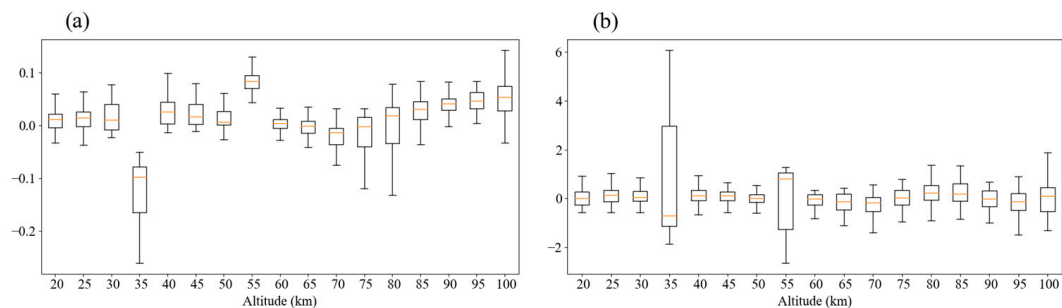


Figure 9. Cont.

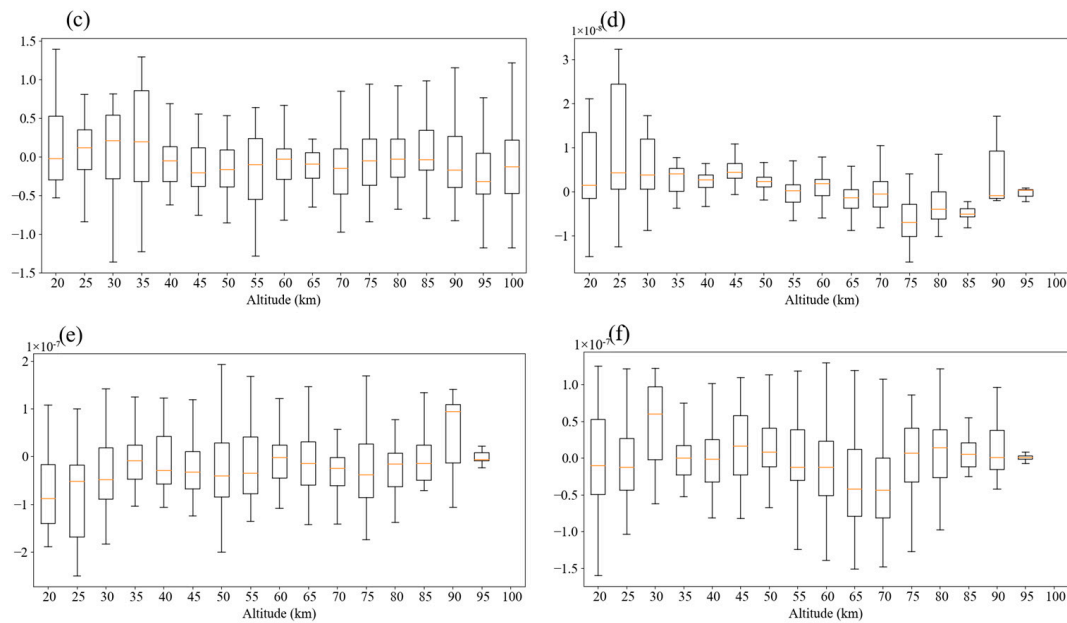


Figure 9. Box plot of coefficients at different altitudes. (a) Box plot of TMP-solar coefficients at different altitudes; (b) Box plot of TMP-ENSO coefficients at different altitudes; (c) Box plot of TMP-QBO coefficients at different altitudes; (d) Box plot of H₂O-solar coefficients at different altitudes; (e) Box plot of H₂O-ENSO coefficients at different altitudes; (f) Box plot of H₂O-QBO coefficients at different altitudes.

Figure 10 shows the computed three-dimensional temperature and water vapor response coefficient set for atmospheric activities in the near space. This study provides a reasonable data reference for simulating and predicting three-dimensional temperature and water vapor in the near space using solar activity, ENSO, and QBO, which is significant for improving climate models and future climate predictions.

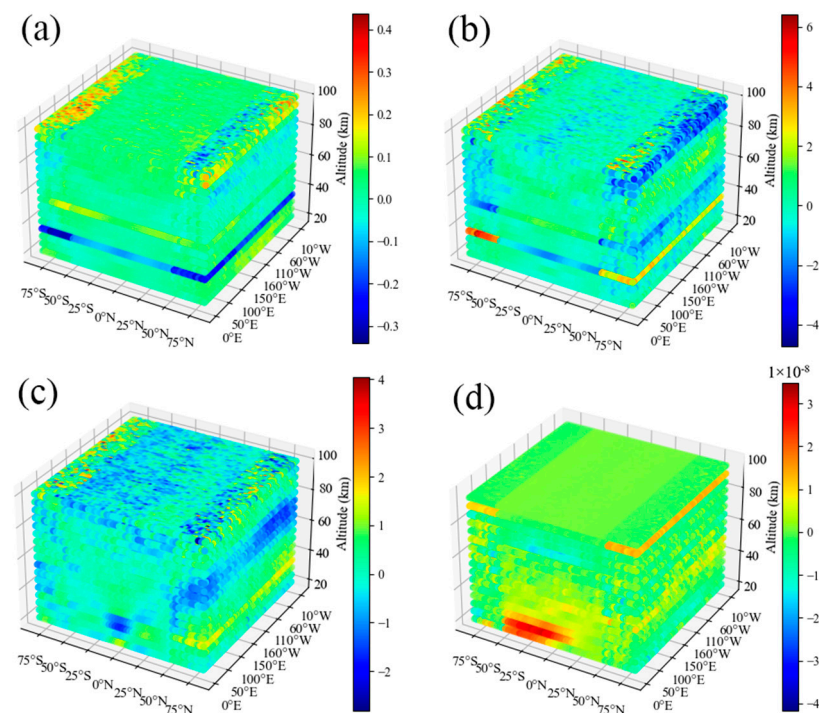


Figure 10. Cont.

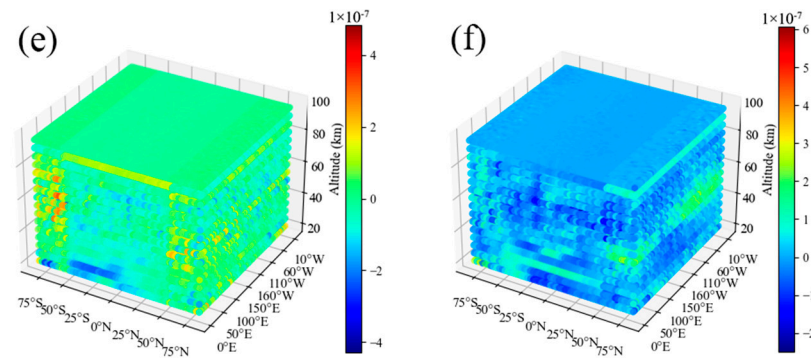


Figure 10. 3D scatter plot of coefficients. (a) 3D scatter plot of temperature response coefficients to solar activity; (b) 3D scatter plot of temperature response coefficients to ENSO; (c) 3D scatter plot of temperature response coefficients to QBO; (d) 3D scatter plot of water vapor response coefficients to solar activity; (e) 3D scatter plot of water vapor response coefficients to ENSO; (f) 3D scatter plot of water vapor response coefficients to QBO.

4. Conclusions

In this study, the distribution of temperature and water vapor concentration over 18 years, provided by TIMED/SABER and AURA/MLS observational data, is presented (Section 3.1). Subsequently, in Section 3.2, the global temperature and humidity profiles were statistically analyzed, revealing the general patterns of their variations. Using multiple linear regression analysis, the monthly average temperature and humidity response were calculated (Section 3.3). The main conclusions are summarized as follows:

- In the atmosphere, there is a region of high temperatures at altitudes of 40–60 km, with values ranging from 245 to 265 K, where the temperature exceeds 265 K at an altitude of 50 km. The temperature gradually decreases in 20–40 km and 60–100 km and exhibits periodic variations. Regarding water vapor, the vertical temporal variation pattern is similar to that of temperature and is primarily influenced by temperature changes. The water vapor concentration reaches high values ($7\text{--}9 \times 10^{-6}$ ppmv) in the height range of 40–70 km, with a peak at 50 km. From the profile range display, a significant temperature trough (225 K) can be observed at an altitude of 35 km, with a rapid increase in temperature between 35–50 km and a rapid decrease in temperature between 50 and 80 km. The water vapor concentration peaks at 30 km, with a significant decrease at 50 km and another peak at 80 km. Overall, the temperature and water vapor trends show a certain correspondence.
- The responses of atmospheric temperature and water vapor to solar activity and ENSO exhibit significant regional differences at different altitudes and latitudes. Solar activity induces a cooling effect on temperature in the lower stratosphere at altitudes of 30–40 km, particularly in the high latitudes (80°S – 80°N), while in the middle layer above 50 km, it results in warming. Water vapor in the range of 20–30 km from 52°S to 20°N exhibits a strong response to solar activity, with the Southern Hemisphere being more sensitive. ENSO leads to a temperature decrease in the equatorial stratosphere (30–40 km) of approximately -1.5 K/MEI, while in the high-latitude regions, the temperature increases by about 3 K/MEI. Water vapor exhibits a strong negative response to ENSO in the 20–30 km range, with a notable north/south asymmetry. QBO activity affects temperature and water vapor in distinct ways in the low-latitude stratosphere, with temperature responses varying by altitude. In contrast, water vapor displays contrasting trends at 30–40 km and 20–25 km.

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