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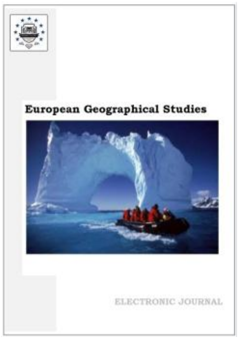

Variations in the Tropopause Temperature and Height over the Vu Gia-Thu Bon River Basin in Vietnam: Insights from GNSS Radio Occultation Observations

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Abstract

This study presents a comprehensive analysis of the tropopause height and temperature over the Vu Gia-Thu Bon river basin using multi GNSS-RO (Global Navigation Satellite System Radio Occultation) data. The findings reveal an average tropopause temperature and height are 195.341K (±0.166K) and 16.467 km (±0.079 km), respectively. Monthly fluctuations in tropopause altitude range from 15.898 km (min) in July 2008 to 17.208 km (max) in February 2010. The highest temperatures and lowest altitudes occur from May to September, while the lowest temperatures and highest altitudes are observed from October to April. Tropopause height varies from 15.848 km to 17.208 km, with deviations from the mean ranging from -0.079 km to 0.232 km. Tropopause temperature ranges from 192.647K to 197.797K, with deviations from the mean ranging from -0.166K to 1.893K. The multi-regression analysis shows a significant upward trend in both tropopause temperature and height from 2002 to 2017. The Tropopause temperature increases approximately by +0.2K with an average yearly increase of 0.013K, while the tropopause height shows an upward trend of about +0.1km with an average yearly increase of 0.008km. The annual and semi-annual periods display sinusoidal variations in both temperature and height, with the annual cycle showing a larger amplitude. These findings highlight the impact of global temperature change on troposphere dynamics, emphasizing the importance of monitoring and understanding these changes for climate forecasting in the Vu Gia-Thu Bon river basin.

Keywords: GNSS-RO, tropopause temperature, tropopause height, trend, Vu Gia-Thu Bon.

1. Introduction

The tropopause, which separates the troposphere and stratosphere, plays a crucial role in atmospheric dynamics. Variations in tropopause temperature and height have important implications. Deep convection in the troposphere plays a key role in transporting mass, heat, and moisture vertically, impacting the temperature and humidity profiles of the tropopause (Reilinger et al., 2006). Changes in convective activity can affect the exchange of water vapor, trace chemicals, and energy between these atmospheric layers. The tropopause acts as a gateway for this exchange, and its height and structure influence the Brewer-Dobson circulation, which affects the distribution of chemical components in the stratosphere (Fueglistaler et al., 2009; Reilinger et al., 2006). Alterations in the tropopause characteristics, such as its height and temperature, are associated with climate change. Human activities, including carbon dioxide emissions and stratospheric ozone depletion, contribute to changes in troposphere and stratosphere dynamics, thereby affecting tropopause features (Lorenz, DeWeaver, 2007; Santer et al., 2004). Given the tropopause's

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significance in climate dynamics and its response to external factors, continuous monitoring and evaluation of its temperature and height are necessary.

Traditionally, atmospheric profiling has relied on radiosonde observations and reanalysis data. Reanalysis data provides consistent and global coverage but lacks real-time observation capability (Sterl, 2004). Radiosonde observations, on the other hand, offer precise in-situ measurements of temperature, wind, and air pressure with excellent vertical resolution (Wang et al., 2012). However, in regions like Vietnam, specifically in the Vu Gia-Thu Bon River basin, there are challenges regarding the availability and distribution of radiosonde observations in terms of space and time. To overcome these limitations, it is necessary to explore the potential of the Global Navigation Satellite System – Radio Occultation (GNSS-RO) technique. This technique provides improved spatial and temporal resolution, addressing the need for more detailed and frequent observations in the area.

The GNSS-RO technique operates by capturing signals from Global Navigation Satellite Systems (GNSS) in low-Earth orbit (LEO) as they traverse the Earth's atmosphere. Occultation events occur when the LEO satellite receiver becomes obscured or emerges from behind the Earth's surface from the perspective of a GNSS satellite. These events cause the GNSS signal to undergo bending as it propagates through the atmosphere, with its trajectory influenced by atmospheric properties such as pressure, temperature, and water vapor content. The degree of bending is directly linked to the atmospheric parameters. Through the analysis of GNSS signal characteristics during occultation, valuable information regarding atmospheric conditions, including temperature, humidity, and pressure profiles, can be derived using the GNSS-RO technique (Awange, Grafarend, 2005).

The GNSS-RO method offers several advantages that address the limitations associated with conventional observation techniques. It facilitates global coverage, enabling observations to be conducted in remote and inaccessible areas. With its high vertical resolution, the technique enables detailed profiling of the atmosphere. Moreover, GNSS-RO data exhibits long-term stability, making it well-suited for monitoring gradual changes in atmospheric conditions. Notably, the GNSS-RO approach focuses on the critical region of the atmosphere spanning from 7 to 25 kilometers, which corresponds closely to the troposphere's height range. Therefore, GNSS-RO emerges as a valuable tool for monitoring convection processes and obtaining precise measurements of tropopause height and temperature. There have been several studies that have utilized GNSS-RO data to determine tropopause temperature and height at different scales, ranging from global to regional analyses (Awange et al., 2011; Khandu et al., 2016; Nascimento et al., 2020; Schmidt et al., 2005; Schmidt et al., 2008). However, it appears that no specific studies have been conducted for the Vu Gia-Thu Bon river basin using GNSS-RO data.

To obtain tropopause temperature and height information for the Vu Gia Thu Bon river basin using GNSS-RO data, it is crucial to conduct further research or specific studies focusing on this region. The primary objective of this study is to provide valuable insights into the tropopause characteristics and dynamics specific to the Vu Gia-Thu Bon river basin using GNSS-RO data. By analyzing the GNSS-RO data in this particular area, the study aims to enhance our understanding of the local atmospheric processes, including the behavior of the tropopause.

This research endeavor will contribute to filling the existing knowledge gap and facilitating a more comprehensive understanding of the atmospheric conditions in the Vu Gia-Thu Bon river basin from 2002–2017. The findings and insights gained from this study will be instrumental in improving the modeling and prediction of local climate dynamics. Ultimately, the research outcomes will aid in better understanding the interactions between the troposphere and stratosphere, the exchange of mass and energy, and the impact of these processes on the local climate system.

2. Research area and data

Vu Gia-Thu Bon is one of the nine largest basins in Vietnam, located at 14°57'10" to 16°16'50" North latitude, 107°53'50" to 108°12'20" East longitude. In this study, data from multiple occultation missions have been utilized for analysis of the tropopause height and temperature over the Vu Gia-Thu Bon river basin from January 2008 to December 2017. These missions include Challenging Minisatellite Payload (CHAMP), NASA's Gravity Recovery and Climate Experiment (GRACE), the European Meteorological Satellite Organization's Meteorological Operational

Satellite Program (MetOp), and the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC).

The CHAMP mission, which was active from 2001 to 2008, provided valuable data for this analysis. NASA's GRACE mission, which operated from 2007 to 2016, primarily focused on monitoring Earth's gravity field but also contributed to atmospheric research through GNSS-RO measurements. The MetOp satellites, part of the European Meteorological Satellite Organization's Meteorological Operational Satellite Program, have been in operation since 2006 and were specifically designed for weather and climate-related observations. The COSMIC mission, a joint effort between the United States and Taiwan, has been providing high-quality atmospheric, ionospheric, and climate observations since its launch in 2006. By leveraging data from these missions, this study conducts a comprehensive analysis of the tropopause dynamics in the Vu Gia-Thu Bon river basin and investigates its relationship to regional warming patterns.

By combining data from these different occultation missions, the study aims to maximize the availability of observations and enhance the coverage and accuracy of the derived tropopause parameters in the study area.

The dry temperature and tropopause height in this region was extracted from ROM SAF (Radio Occultation Meteorology Satellite Application Facility) central via the link: https://www.romsaf.org/ (EUMETSAT).

3. Method

3.1 From bending angle dry temperature

GNSS-RO is a satellite remote sensing technology that utilizes GNSS data collected by LEO satellites to profile the Earth's atmosphere. The signals transmitted by the GNSS satellites experience delays in phase and amplitude as they pass through the atmosphere, which can be observed and measured by the LEO satellite.

The phase delay of the GNSS signal is particularly important in GNSS-RO. It is inverted using a mathematical technique called the Abel transformation to derive the refractivity of the air along the signal path. Refractivity is a measure of how much the path of the signal is bent by the atmosphere due to variations in temperature, pressure, and humidity.

During an occultation event, which takes place when a low-Earth orbit (LEO) satellite passes behind or emerges from the Earth's limb from the perspective of a GNSS satellite, the paths of GNSS signals undergo bending as a result of refractivity gradients in the atmosphere. The bending of these signals is depicted in Figure 1, which illustrates the geometry of the GNSS-RO technique. Through the analysis of this signal bending, valuable data pertaining to atmospheric properties along the signal path, including temperature and humidity, can be retrieved.

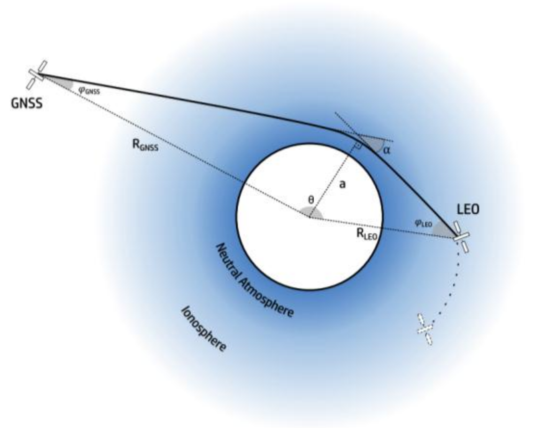

Fig. 1. Geometry of GNSS – LEO satellite occultation
Source: Sievert, 2019

The relationship between the bending angle α, the impact parameter a, and the refractive index n can be described as follows (Awange, Grafarend, 2005):

$$\alpha(a) = -2a \int_{r=r_o}^{r=\infty} \frac{1}{\sqrt{n^2r^2 - a^2}} \frac{d\{\ln(n)\}}{dr} dr \tag{1}$$

where α represents the bending angle of the signal, a is the impact parameter (the radial distance at the beginning and end of the signal's bending), n is the refractive index, and r the signal's path length.

The inverse Abel transformation is applied to the right-hand side of equation (1) to describe and analyze the associated parameter. This transformation allows for the retrieval of the bending angle, which is obtained from GNSS and LEO satellite location and velocity data, as a function of parameter a. Subsequently, the refractive index n can be calculated based on this relationship, as demonstrated by (Awange, Grafarend, 2005).

$$n(r_o) = \exp\left[\frac{1}{\pi} \int_{a=a_o}^{a=\infty} \frac{\alpha(a)}{\sqrt{a^2 - a_o^{\ 2}}} da\right] \tag{2}$$

where r_o represents the radius measured from the center of the Earth to the specific height being considered.

In the context of atmospheric science, the relationship between refractivity (N) and refractive index (n) can be expressed:

$$N = (n - 1) * 10^6 \tag{3}$$

This equation relates the refractivity (N) to the refractive index (n) by subtracting 1 from the refractive index and multiplying the result by 10^6. The refractivity is typically measured in N-units.

The temperature, pressure, and air density can be calculated using the refractivity N through equation 4 (Awange, Grafarend, 2005).

$$N = 77.6\frac{P}{T} + \left(3.73\times10^5 \frac{P_w}{T^2}\right) - \left(40.3\times10^6 \frac{n_e}{f^2}\right) + 1.4w \tag{4}$$

where P is the air pressure in mbar, T is the air temperature in K, P_w is the water vapour partial pressure in mbar, n_e is the electron density per cubic meter in number of electrons/m^3, f is the transmitter frequency in Hz, and w is the liquid water content in g/m^3.

3.2. From dry temperature to tropopause height

The determination of the tropopause position can vary depending on the definition used. The lapse rate tropopause is commonly employed for assessing climatological variability. In this study, the tropopause heights and temperatures were extracted from GNSS RO profiles based on the thermal definition provided by the World Meteorological Organization (WMO) in 1957.

According to the WMO, the tropopause is defined as the lowest level at which the lapse rate (the rate of temperature decrease with height) decreases to 2 degrees Celsius per kilometer (2°C/km) or less. Additionally, it is required that the average lapse rate between this level (referred to as "z") and all higher levels within 2 kilometers above (z + 2) does not exceed 2°C/km. It is important to note that only the first occurrence of the lapse rate tropopause is considered in this study.

The lapse rate (z_i) is determined using expression 5 (Schmidt et al., 2005):

$$\Gamma_{(z_i)} = -\frac{\partial T}{\partial z} = \frac{T_{i+1} - T_i}{z_{i+1} - z_i} \tag{5}$$

where T and z are the temperatures and heights above mean sea level, respectively.

According to WMO definition, when the lapse rate is greater than -2K/km, the following conditions are considered:

- Mean Lapse Rate Condition: The mean lapse rate between the height level zi and the level zi + 2 km should be larger than -2K/km.

- Layer Comparison Condition: If the mean lapse rate between the layers (z_{i+1}, z_i), (z_{i+2}, z_{i+1}) and (z_{i+3}, z_{i+2}) is greater than -2K/km, and the mean lapse rate between the (z_{i+1}, z_i), (z_{i+2}, z_{i+1}) and (z_{i+3}, z_{i+2}) is less than -2K/km, then it satisfies the condition.

If both of the conditions mentioned earlier are fulfilled, indicating that the lapse rate meets the specified criteria, the lapse rate (z_i) corresponding to that specific lapse rate can be chosen as the lapse rate tropopause.

3.3. From dry temperature and tropopause height to tropopause temperature

In addition to determining the lapse rate tropopause, the temperature at the tropopause can be estimated using linear regression analysis with the dry temperature data corresponding to the selected lapse rate tropopause height. The linear regression model allows for the estimation of temperature values at the tropopause level based on the relationship between the lapse rate tropopause height and the corresponding dry temperature observations. This provides a means to obtain an estimate of the temperature at the tropopause, which is an important parameter for understanding the characteristics and dynamics of the atmosphere in that region.

4. Results and discussion

4.1. Monthly and annual tropopause heights and temperatures

In this study, the tropopause heights and temperatures over the Vu Gia – Thu Bon region have been analyzed on a monthly and annual basis to investigate any variations between these periods. Figure 2 illustrates the monthly mean tropopause heights, while Figure 3 displays the corresponding monthly mean tropopause temperatures. The data used for these analyses were obtained from CHAMP, GRACE, MetOp, and COSMIC missions.

Based on the data analysis, the study reveals that the mean tropopause height over Vu Gia – Thu Bon is estimated to be 16.467 km. Concurrently, the corresponding mean tropopause temperature is found to be 195.341K.

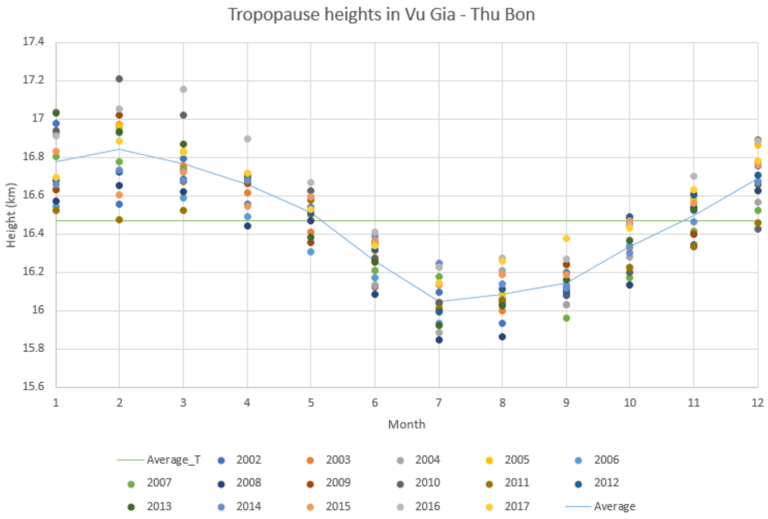

Fig. 2. Tropopause heights in Vu Gia – Thu Bon

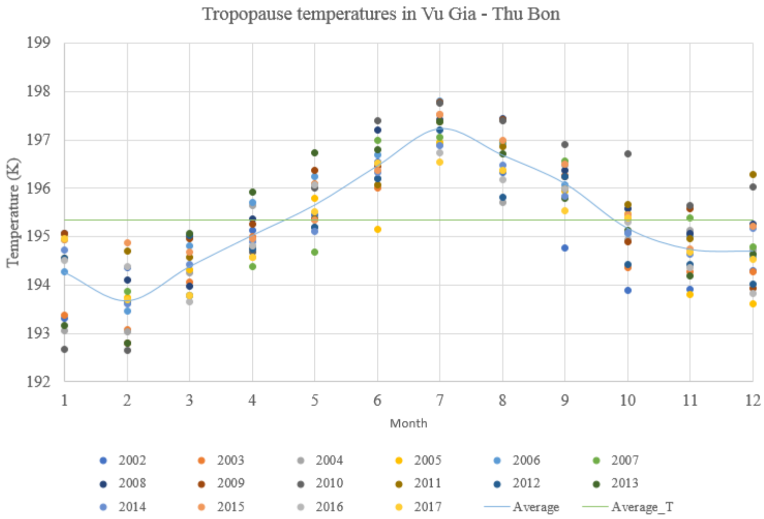

Fig. 3. Tropopause temperatures in Vu Gia – Thu Bon basin

Based on the data presented in Figure 2 and Figure 3, the tropopause altitude in the Vu Gia – Thu Bon region reached its lowest value of 15.898 km in July 2008, while the highest altitude of 17.208 km was recorded in February 2010, coinciding with the highest temperature of 197.797K observed in July 2006 and the lowest temperature of 192.647K in February 2010. These findings demonstrate that the tropopause elevation fluctuates on a monthly basis, with certain months surpassing the average value of 16.467 km. Specifically, in January, February, March, May, November, and December, the altitude exceeds the mean, while in June, July, August, September, and October, the values are lower than the average. Contrasting with the altitude pattern, the tropopause temperature exhibits different trends. Months such as May, June, August, September, and October experience temperatures above the average of 195.341K, while January, February, April, and the months of October, November, and December exhibit temperatures below the mean.

4.2. Seasonal variations

The convective zone in the averaged region exhibits the following patterns: (1) The season with the highest temperature and lowest altitude occurs from May to September, which corresponds to the months when the monitoring station records the highest air temperatures; (2) The season with the lowest temperature and highest altitude is observed from October of the previous year to April of the following year, aligning with the months when the monitoring stations measure lower temperatures; and (3) The tropopause height varies between 15.848 km and 17.208 km across different seasons, with differences from the mean ranging from -0.079 km to 0.232 km. Similarly, the tropopause temperature ranges from 192.647K to 197.797K, depending on the season, with differences from the mean ranging from -0.166K to 1,893K.

4.3. Trend, annual and semianual amptitude analysis

To assess the trend of tropospause temperature and altitude in the Vu Gia-Thu Bon River basin, an analysis is conducted. This analysis includes the examination of level, trends, annual and semiannual cycles of tropopause temperature and altitude, as depicted in Figure 4, 5, and Table 1.

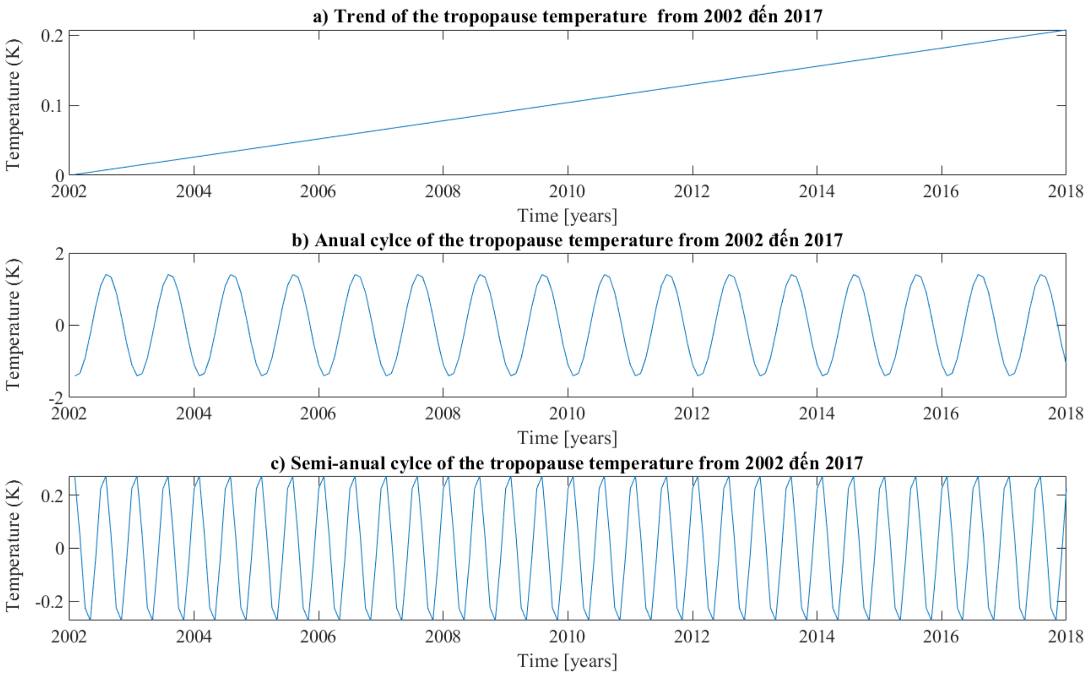

Fig. 4. The trends, annual and semi-annual cycles of the tropopause temperature during the period from 2002 to 2017

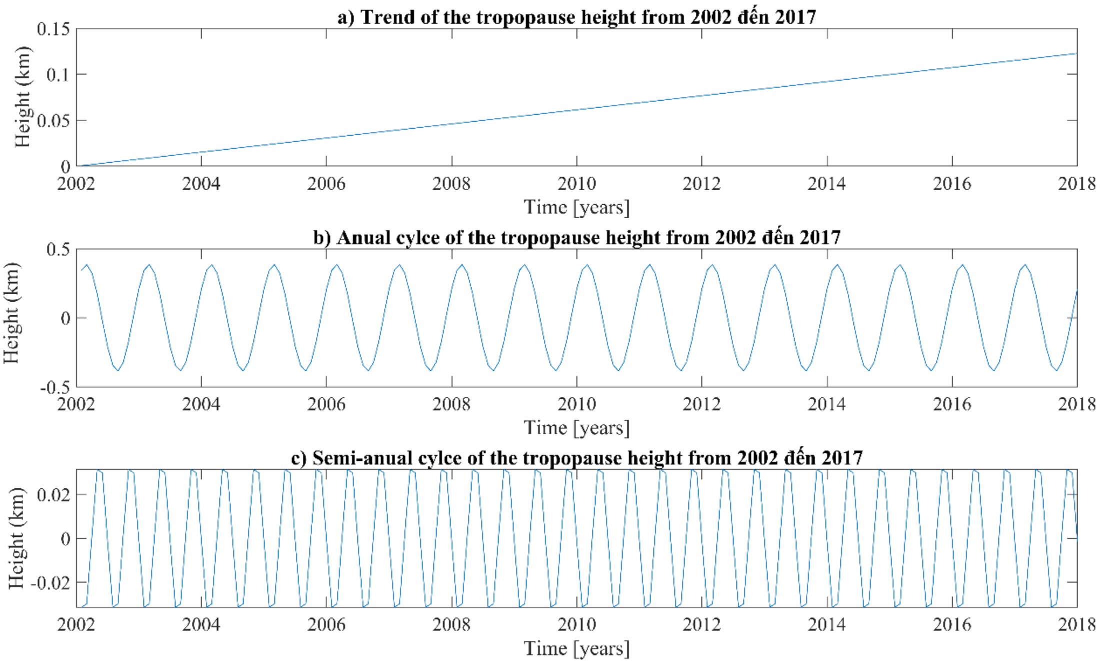

Fig. 5. The trends, annual and semi-annual cycles of the tropopause height during the period from 2002 to 2017

The levels, trends, annual and semi-annual cycles of the tropopause temperature and height were determined using multi-regression analysis. The "level" represents the baseline or average temperature and height of the tropopause during the analyzed period. The "trend" indicates the overall direction and magnitude of the temperature and height change observed over time. The "annual cycle" captures the yearly variations in tropopause temperature and height, reflecting any recurring patterns or seasonal changes. The "semi-annual cycle" highlights the shorter-term variations within each year, displaying the temperature and height fluctuations over a six-month period.

Based on the analysis presented in Figure 4, 5, and Table 1, it can be observed that between 2002 and 2017, both the temperature and height of the tropopause exhibit an upward trend. The tropopause temperature tends to increase by approximately +0.2K during this period, with an average yearly increase of 0.013K. Similarly, the tropopause height shows an upward trend of about +0.1km, with an average yearly increase of 0.008km. These findings provide valuable insights into the long-term changes and variations in tropopause temperature over the specified time frame.

Table 1. The results obtained from determining the levels, trends, and annual and semi-annual cycles for the period 2002–2017

Properties	Temperature (K)	Altitude (km)
Level	195.237	16.405
Trend/year	0.013	0.008
Anual Amplitude	1.423	0.386
Semi-Annual Amplitude	0.291	0.035
Regression mean square error (RMSE)	0.620	0.129
Regression coefficient R^2	0.742	0.820

The tropopause temperature and height exhibit sinusoidal variations in both the annual and semi-annual periods. The annual cycle is the main variation, with a larger amplitude compared with the semi-annual cycle.

5. Conclusion

This study analyzes the tropopause height and temperature over the Vu Gia-Thu Bon River basin using multi GNSS RO (Global Navigation Satellite System Radio Occultation) data in period 2002–2017. The analysis provides valuable insights into the behavior of the tropopause in this region with the following key findings:

1. The average tropopause height was estimated to be 16.467 km, with an average temperature of 195.341K. The tropopause altitude exhibited monthly fluctuations, reaching its lowest point in July 2008 at 15.898 km, and its highest point in February 2010 at 17.208 km.
2. The highest temperatures and lowest altitudes of the tropopause occurred from May to September, while the lowest temperatures and highest altitudes were observed from October to April. The tropopause height ranged from 15.848 km to 17.208 km, with deviations from the mean ranging from -0.079 km to 0.232 km. Similarly, the tropopause temperature ranged from 192.647K to 197.797K, with deviations from the mean ranging from -0.166K to 1.893K.
3. Utilizing multi-regression analysis, the study identified an upward trend in both tropopause temperature and height between 2002 and 2017. The tropopause temperature exhibited an approximate increase of +0.2K with an average yearly increase of 0.013K, while the tropopause height showed an upward trend of about +0.1km with an average yearly increase of 0.008 km. Both tropopause temperature and height displayed sinusoidal variations in the annual and semi-annual periods, with the annual cycle exhibiting a larger amplitude.

The study underscores the impact of global temperature change on tropopause temperature and height. These findings suggest that monitoring changes in tropopause temperature and height can provide valuable insights into regional warming.

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