Response to Reviewer 3 comments
Manuscript Number: EGUsphere-2024-1144
Manuscript title: Spatial and temporal variation in long-term temperature and water vapor in the mesopause Region, by Chaman Gul et al.,

30th July 2024

Dear anonymous reviewer,

Thanks for the comments, suggestions, and recommendations for the EGUspher-2024-1144 manuscript. Comments are constructive and we quite improved the manuscript after addressing all the comments. We have thoroughly considered and carefully addressed all issues mentioned in the comments and have properly outlined every single change made in response to reviewer comments as suggested. We have made the required corrections in the revised manuscript (visible in tracked change mode) and prepared a list of point-by-point responses as given below starting from page #2 of this document. We have attached two copies of the revised manuscript, one with track change mode having all edits/corrections and the other is a fair copy of the manuscript where we have accepted all the mentioned edits/corrections. The reviewer’s comments are in **black** text, the author's responses are in **blue** text, the modified/corrected text from the revised manuscript is in bold **brown** text, and references are in green text. Modified line numbers are in **yellow highlighted** text.

Response to reviewer 3 (R3) comments (Cs):

Review of "Spatial and temporal variation in long-term temperature and water vapor in the mesopause Region" (egusphere-2024-1144) by Gul et al.

General Comments

(R3-C1) This paper presents an analysis of SABER temperature and water vapor profiles in the mesopause region (80-100 km). Selected months (solstices, equinoxes) and geographic regions (Equator, North and South polar) are examined throughout the 22-year data record covering 2002-2023. Extreme values are determined on annual and monthly basis for geographic and seasonal comparisons.

This paper provides relatively little new information. Numerous studies have examined the SABER data set previously. It is not clear that the authors have adequately addressed the changes in SABER sampling over its long data record. The trend analysis is too simplistic, and does not consider multiple periodic forcing functions that also affect the long-term variations of temperature and water vapor.

Definite need for grammar to be polished. Not trying to address all such items in this review.

Response to (R3-C1):

Thank you very much for your precious time and constructive comments. This article investigates long-term changes in temperature and WV and its long-term comparison within a unique selection of time and space domains. We think selected narrow latitude bins from each selected geographical location, excluding transitional months, and inclusion of high latitude regions (beyond ~53ºN or ~53ºS) from both hemispheres make this article different from other previous works. The majority of previously published articles focused on temperature or water vapor. Multiple studies (e.g; Forbes et al., 2021; Liu et al., 2017; Mlynczak et al., 2022; Das et al., 2021) are limited to latitude band ~50°S to ~50°N, mainly due to TIMED ~60 days yaw cycle. In the present study, we have included high-latitude regions from both hemispheres along with some missing data.

Very few researchers (e.g: Hervig et al., 2015) focused on both temperature and water vapor for relatively short periods. Therefore, our temperature and water vapor results, obtained from 22-year SABER observations, are expected to be a robust measure of the mesopause temperature and water vapor variability.

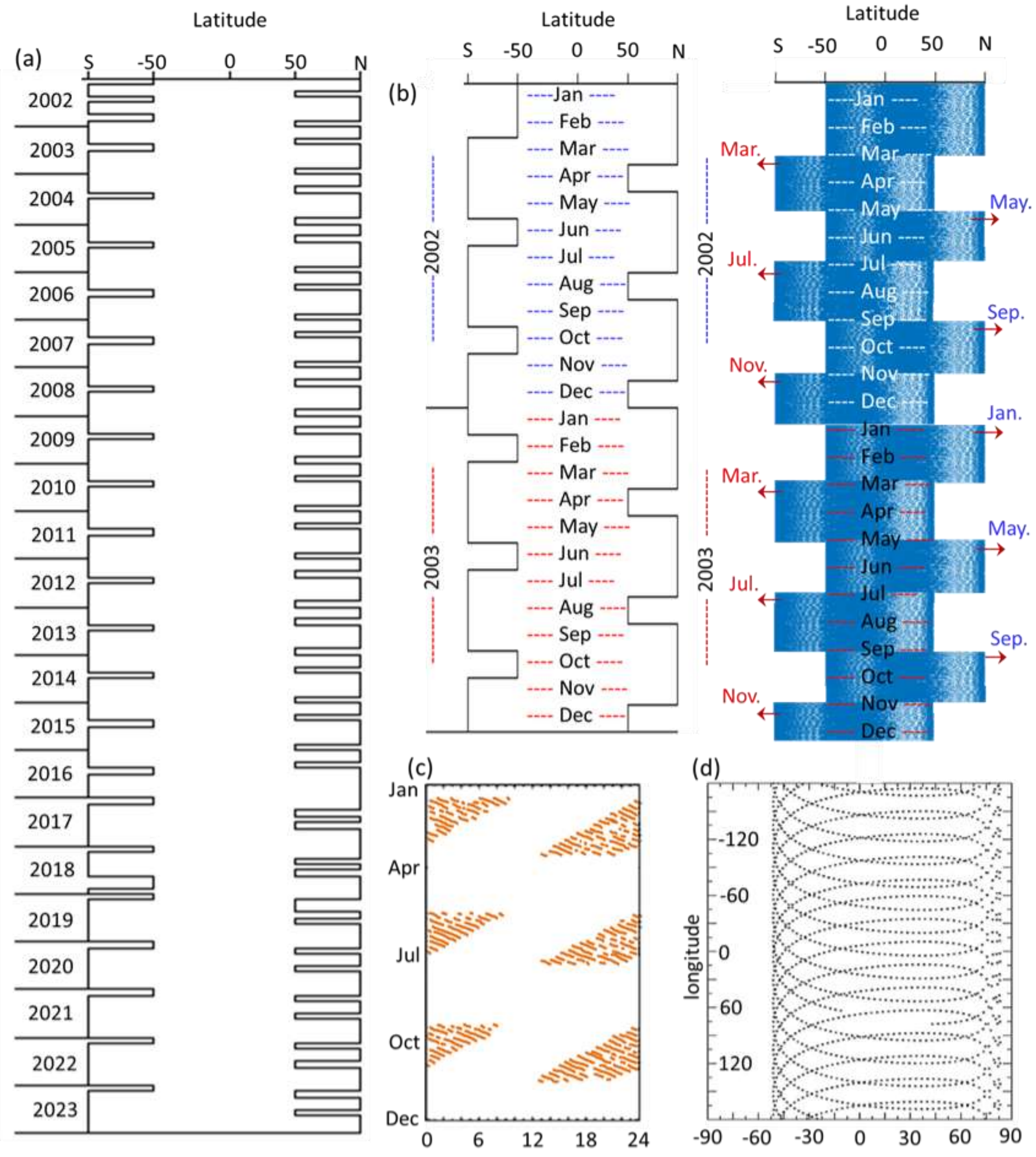
We have added information related to SABER instrument latitude coverage vs time (lines 126-175 of the revised manuscript) and the same is given below

"2.2. TIMED-SABER instrument

The TIMED-SABER satellite views 90° to the right of the velocity vector of the TIMED spacecraft, and completes a full 24-hour local time coverage in 60-63 days (Russell III et al., 1999; Mlynczak et al., 2003; Figure 1). The SABER instrument scans the

atmosphere from the troposphere up to the lower thermosphere and obtains vertical profiles kinetic temperature and volume mixing ratio of WV (Russell et al., 1999). The instrument performs near-global measurements and provides an excellent quality of the measured infrared limb radiances (Esplin et al., 2023). Technical description of the SABER instrument and further relevant information are discussed by Mlynczak, (1997) and Russell III et al. (1999). TIMED satellite rotates 180° about its yaw axis and provides latitude coverage continuously in the range of 53°S to 83°N and then switching to 83°S to 53°N every ~60 days (Russell III et al., 1999). Due to the asymmetrical latitudinal coverage of the SABER instrument, there are some missing measurement months at high latitudes (52°N-83°N or 52°S-83°S). Multiple studies (e.g; Forbes et al., 2021; Liu et al., 2017; Das, 2021) are limited to the latitude band ~50°S to ~50°N, mainly due to the TIMED ~60 days yaw cycle. In the present study, we have included high-latitude regions from both hemispheres along with some missing data. For example, coverage of high northern latitudes included July in the early years, but not during the recent several years (2017-2023)………" Please have a look at this section in the revised manuscript for full details.

Revised Figure 1: (page #7)



Revised Figure 1. SABER instrument latitude coverage versus time for observation. a) Monthly data coverage in selected months versus latitude ranges from January 2002 to December 2023, excluding transitional months. b) Comparison of SABER latitude coverage and monthly data versus time during years (2002-2003). c) Typical temporal coverage of TIMED-SABER instrument measurements. d) Latitude versus longitude tangent point locations for one day of observations in its north viewing phase (83°N to 52°S) – a north viewing yaw mode.

Uncertainties related to high latitude regions: (line numbers 713 and onward)

"Section 6. Associated uncertainties and limitations

The possible sources of uncertainties during the analysis of long-term temperature and WV are mentioned below.

1. **Large uncertainty is related to the analysis of temperature and WV over SH and NH (above ~53^0 latitudes) and has a relatively larger bias in results as compared to the results over the equator. The yaw cycle is ~60 days, and only one polar region (SH or NH) is observed in each yaw cycle, and the selected polar regions are only alternatively observed half of a year owing to the yawing of the TIMED satellite. In other words, the latitudinal coverage is governed by a 60-day yaw cycle that allows observations of latitudes from 83^{0}S to 52^{0}N in the south-viewing phase or from 53^{0}S to 82^{0}N in the North-viewing phase (further details are given in the text). Multiple studies (e.g; Forbes et al., 2021; Liu et al., 2017; Mlynczak et al., 2022; Das, 2021) are limited to the latitude band ~50°S to ~50°N. In the present study, we have included high-latitude regions from both hemispheres along with some missing months. Missing months are usually April, August, or December in the NH and February, June, or October in the SH. As a result, the choice of these months for high latitudes introduces a systematic bias in the time series.**
2. **Temperature and WV trends over NH and SH are calculated for six months because April and December data were insufficient for long-term trends over NH. Similarly, June and October data was limited for SH trend estimation. Therefore, trends over the equator are more accurate than those of NH and SH trends.**

"

So, we present our results along with the above-mentioned uncertainties in the revised text.

We used multiple linear regression analysis to determine temperature and water vapor trends from the observations. We derived trends using multiple linear regression with the inclusion of two terms, 1) the solar cycle (e.g., using Lyman – alpha) and 2) time (i.e., the trend). We have modified the sentences as suggested (lines 198-217 of the revised manuscript) and the same is given below

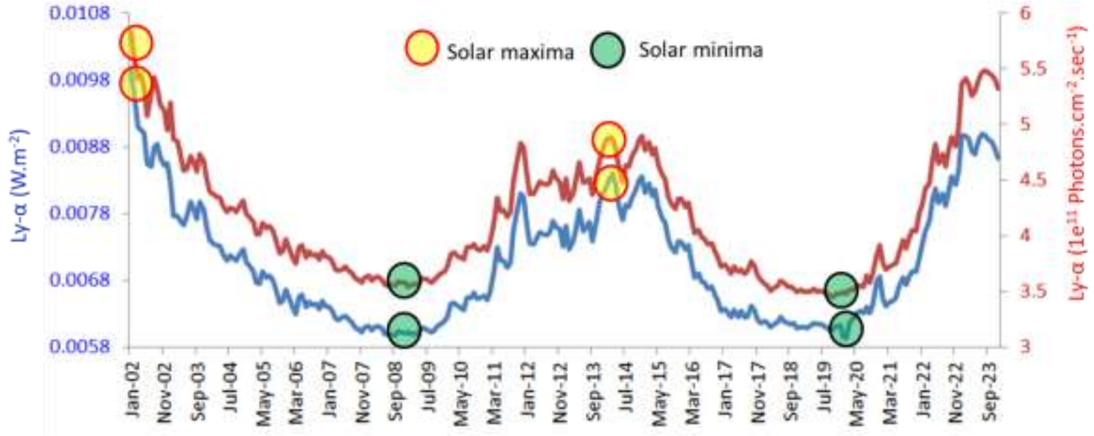
"2.3.1. Multiple linear regression analysis

To investigate the long-term trends (temperature and WV) and the solar response of the mesopause temperature, a three-component harmonic fit is applied to remove the seasonality from the monthly data series. Then a multiple linear regression model is performed to solar activity, linear trend, and residual temperatures versus constant. Applying the regression analysis to latitude-averaged temperature and WV provides a more statistically significant value of their trends. Lyman-α flux is a proxy for solar

activity, so the monthly mean of Lyman-α solar flux is used in multiple linear regression equation (1) as a measure of solar variability. Multiple linear regression analysis technique has been used by multiple authors in the past (e.g., Chandra et al., 1997; Hervig et al., 2015, 2016; Yue et al., 2019). To analyze the temperature and WV trends using multiple linear regression with the inclusion of the solar cycle and time we applied the following multiple regression analysis for trend estimation.

$$\mathbf{Temperature\ or\ WV = C_o + C_1(Lyman.\alpha) + C_2(time) + error} \qquad (1)$$

Where C_0 is constant (intercept), C_1 and C_2 are regression coefficients characterizing the linear long-term trend (temperature and WV per year) and solar activity term. We calculate temperature and WV trends using multiple linear regression involving monthly temperature and WV (SABER) data over time. Before applying the multiple regression model we calculate solar radiation according to monthly data sets. For example, Monthly means of the Lyman-α index are computed for each month, yielding 176 points for both global and equator."



A subpart of Figure 1: Lyman- α index during January 2002-December 2023.

We have modified /revised the whole manuscript (including the language) based on the reviewers' comments.

A few examples of these updates are given below.

1. We revised all figures and tables.
2. We added additional required sections, for example, section 2.3 Solar cycle response, and section 2.3.1 Multiple linear regression analysis.
3. We removed less relevant (or having a repetition of information) sections, for example, section 3.1.3 (relationship between temperature and WV). We already showed an inverse relation between temperature and WV in multiple locations.
4. We rewrite whole sections, for example first section of the introduction part.
5. We revised the captions of all figures as suggested by the other reviewers.
6. We have made corrections in almost every line of the revised manuscript.

Specific Comments

(R3-C2) Page 1, lines 25-26: As discussed later, this statement does not take periodic forcing terms into account.

Response to (R3-C2): Agree, we have updated the sentences (after applying multiple linear regression) (lines 28-32 of the revised manuscript) and the same is given below

"The temperature showed apparent positive responses to solar activity through all latitudes, which is more significant near the NH. Twenty-two years of monthly mean analysis shows that SH is warmer than NH during July and September and colder than NH during January and March. A cooling trend in temperature is in the range of 0.58 to 1.21 K/decade. Water vapor shows a positive trend and a strong negative correlation with the temperature."

(R3-C3) Page 3, lines 83-86: These are old references that only address a specific location and time, and discuss altitudes below the mesopause region. Why are they cited?

Response to (R3-C3): Agree, the sentence removed from the revised manuscript (lines 80-82 of the revised manuscript) and the updated sentence is given below.

"In the mesopause region, more abundant WV from increasing CH4 contributes to more frequent NLC occurrences (Lübken et al., 2018). WV content in the atmosphere controls the concentration of ozone that, in turn, affects mesospheric cooling (Smith, 2004)."

Removed sentences are visible in the track change version of the manuscript (lines 123-126).

(R3-C4) Page 3, lines 94-95: But there are certainly long data sets from ground-based microwave measurements and satellites (e.g. HALOE, SOFIE) that should be discussed.

Response to (R3-C4): Agree, we have added relevant text and updated references related to ground-based microwave measurements and satellites as suggested (lines 85-100 of the revised manuscript) and the same is given below

"Ground-based microwave radiometry is the ideal technique to monitor WV in the atmosphere, however, as compared to temperature; there have been fewer observations of WV in the upper mesosphere. There are certainly long data sets from ground-based microwave measurements and satellites. For example, long-term WV measurements made by the Sounding of the Atmosphere using the Broadband Emission Radiometry (SABER) instrument and by the Aura Microwave Limb Sounder instrument are analyzed by Yue et al. (2019). Nedoluha et al. (2022) presented ground-based microwave

measurements of mesospheric WV made by the Water Vapor Millimeter-wave Spectrometer between 1992-2021. Straub et al. (2010) and Schranz et al. (2019) estimate the vertical gradient of WV inside of the polar vortex in autumn based on microwave radiometry measurements at polar latitudes. The Aura satellite with the Microwave Limb Sounder collects global WV profiles with coverage at a fixed local time due to its sun-synchronous orbit (Livesey et al., 2006). The dependence of NLCs on WV and temperature was quantified by Hervig et al. (2015), using Observations from the Solar Occultation For Ice Experiment (SOFIE). The latest progress and applications of atmospheric WV lidar calibration have been recently reviewed by Guo et al. (2024).”.

If still we are missing any relevant references please let us know, will add them as suggested.

References

- Guo, X., Wu, D., Wang, Z., Wang, B., Li, C., Deng, Q., and Liu, D.: A review of atmospheric water vapor lidar calibration methods, Wiley Interdiscip. Rev. Water, 11, e1712, 2024.
- Hervig, M. E., Siskind, D. E., Bailey, S. M., and Russell III, J. M.: The influence of PMCs on water vapor and drivers behind PMC variability from SOFIE observations, J. Atmos. Solar-Terrestrial Phys., 132, 124–134, https://doi.org/https://doi.org/10.1016/j.jastp.2015.07.010, 2015.
- Livesey, N. J., Van Snyder, W., Read, W. G., and Wagner, P. A.: Retrieval algorithms for the EOS Microwave limb sounder (MLS), IEEE Trans. Geosci. Remote Sens., 44, 1144–1155, 2006.
- Nedoluha, G. E., Gomez, R. M., Boyd, I., Neal, H., Allen, D. R., Siskind, D. E., Lambert, A., and Livesey, N. J.: Measurements of mesospheric water vapor from 1992 to 2021 at three stations from the Network for the Detection of Atmospheric Composition Change, J. Geophys. Res. Atmos., 127, e2022JD037227, https://doi.org/https://doi.org/10.1029/2022JD037227, 2022.
- Schranz, F., Tschanz, B., Rüfenacht, R., Hocke, K., Palm, M., and Kämpfer, N.: Investigation of Arctic middle-atmospheric dynamics using 3 years of H 2 O and O 3 measurements from microwave radiometers at Ny-Ålesund, Atmos. Chem. Phys., 19, 9927–9947, 2019.
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- Yue, J., Russell III, J., Gan, Q., Wang, T., Rong, P., Garcia, R., and Mlynczak, M.: Increasing water vapor in the stratosphere and mesosphere after 2002, Geophys. Res. Lett., 46, 13452–13460, https://doi.org/10.1029/2019GL084973, 2019.

(R3-C5) Page 4, lines 111-112: 40% is a substantial amount of missing data. Does this represent frequent small gaps, or less frequent large gaps? What dimension is used for averaging? Altitude? Time? What is the weighting function?

Response to (R3-C5): Sorry, ~40% was just an estimated number which was wrong. We have corrected the information in the revised manuscript (lines 146-148 of the revised manuscript) and the same is given below

"We used 176 months of data for both the equator and the global mesopause during the study period. There are 44, and 46 missing months for NH and SH respectively (Figure 1a), and ~9% of missing months are filled with a weighted average."

For a constant altitude (let's say 80 km), we have January data for all years 2002 to 2016, except January 2008 which is missing. In such case, we can fill January 2008 with the help of neighbor January values at the same altitude. We think this way of averaging is relatively more accurate than other techniques, and we applied this way of averaging on ~9% of missing data.

(R3-C6) Page 4, lines 120-122: This statement repeats the previous sentence. Since a 60-day yaw cycle is not an even fraction of a 365-day year, the latitude coverage in selected months will shift over 22 years. Are each of your months fully populated during the full data record?

Response to (R3-C6): Repeated information is removed from the revised manuscript. The section has been significantly improved and the required information is provided in detail (lines 126-175 of the revised manuscript) and the same is given below

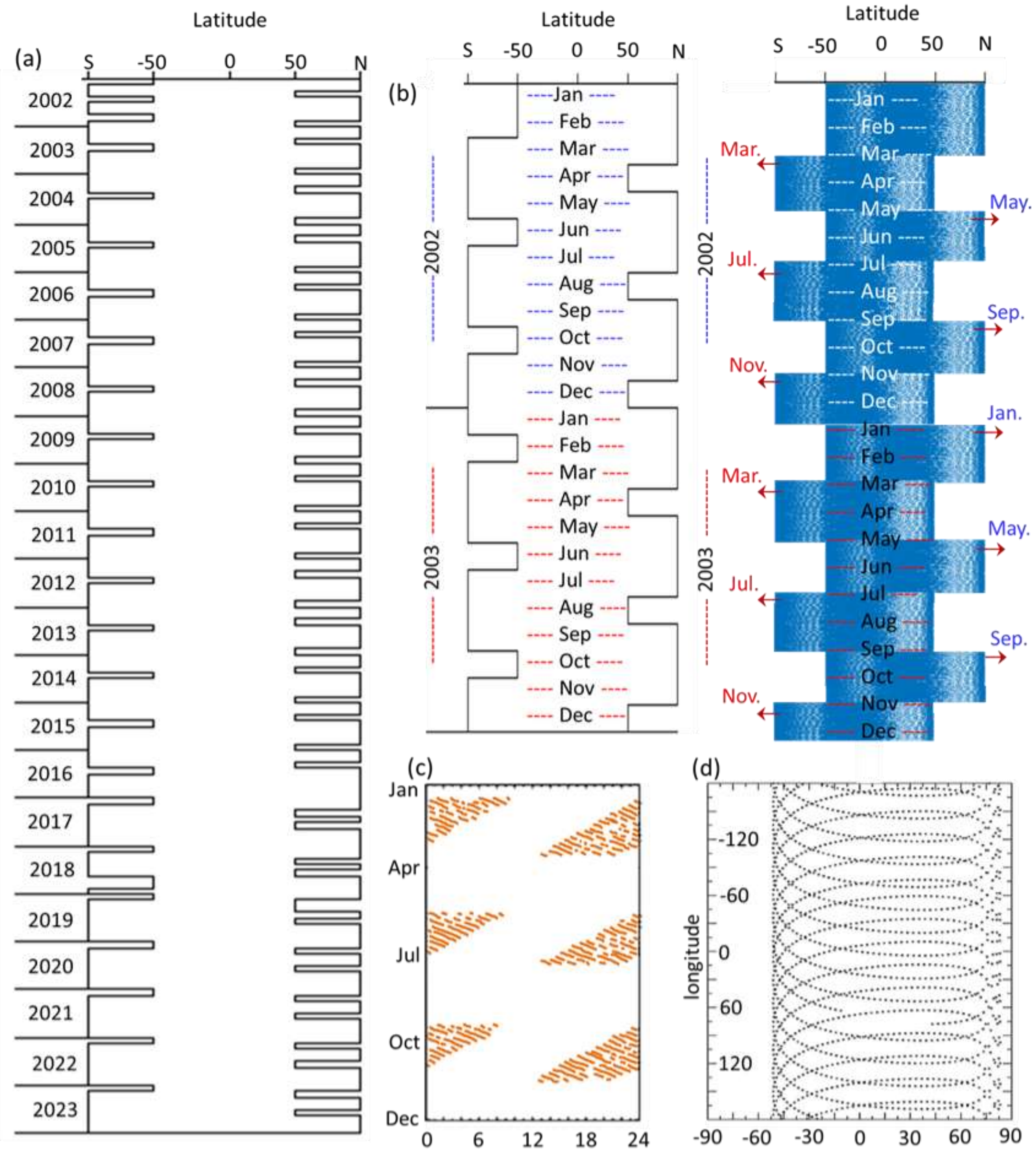
"2.2. TIMED-SABER instrument

The TIMED-SABER satellite views 90° to the right of the velocity vector of the TIMED spacecraft, and completes a full 24-hour local time coverage in 60-63 days (Russell III et al., 1999; Mlynczak et al., 2003; Figure 1). The SABER instrument scans the atmosphere from the troposphere up to the lower thermosphere and obtains vertical profiles kinetic temperature and volume mixing ratio of WV (Russell et al., 1999). The instrument performs near-global measurements and provides an excellent quality of the measured infrared limb radiances (Esplin et al., 2023). Technical description of the SABER instrument and further relevant information are discussed by Mlynczak, (1997) and Russell III et al. (1999)."

Removed sentences are visible in the track change version of the manuscript (lines 199-202).

Details related to the yaw cycle and latitude coverage are given in the response to comment number 1 above. Let me put it again for you (Figure 1)

Revised Figure 1: (page # 7)



Revised Figure 1. SABER instrument latitude coverage versus time for observation. a) Monthly data coverage in selected months versus latitude ranges from January 2002 to December 2023, excluding transitional months. b) Comparison of SABER latitude coverage and monthly data versus time during years (2002-2003). c) Typical temporal coverage of TIMED-SABER instrument measurements. d) Latitude versus longitude tangent point locations for one day of observations in its north viewing phase (83°N to 52°S) – a north viewing yaw mode.

(R3-C7) Page 5, lines 133-135: Any comment on why the 2002 profile is such an outlier in the first 4 panels of Figure 2?

Response to (R3-C7):

The following may be the possible reasons.

First, the temperature is higher during the higher solar activity periods with the highest intensity observed during the period 2002–2003. This period represents the depletion phase of the 23rd solar cycle which was more active than the 24th solar cycle.

Second, during 2002 (July to September) high latitudes in the Southern Hemisphere experienced extreme planetary wave activity (unusual warming) throughout the vertical extent sampled by SABER (Kruger et al., 2005). Short-term variability in temperature is primarily due to small-scale gravity waves and tides (Dalin et al., 2017; Zhao et al., 2020). Gravity and planetary waves (Dalin et al., 2017), and atmospheric tides (Smith, 2004) bring periodic variations in temperature.

Third, some authors excluded January 2002 and they started sampling from February 2002 (Xu et al., 2007 and Zhao et al., 2020), and we have included January 2002, which may be the reason for the relatively high profile during 2002.

References

- Dalin, P., Kirkwood, S., Pertsev, N., and Perminov, V.: Influence of solar and lunar tides on the mesopause region as observed in polar mesosphere summer echoes characteristics, J. Geophys. Res. Atmos., 122, 10–369, https://doi.org/10.1002/2017JD026509, 2017.
- Krüger, K., Naujokat, B., & Labitzke, K. (2005). The unusual midwinter warming in the Southern Hemisphere stratosphere 2002: A comparison to Northern Hemisphere phenomena. Journal of the Atmospheric Sciences, 62(3), 603–613. https://doi.org/10.1175/JAS-3316.1
- Smith, A. K.: Physics and chemistry of the mesopause region, J. Atmos. solar-terrestrial Phys., 66, 839–857, https://doi.org/10.1016/j.jastp.2004.01.032, 2004.
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(R3-C8) Pages 5-6, lines 138-143: There is a significant and well-known solar cycle signal in mesospheric temperature (noted on lines 242-249) that will greatly affect any calculated trends. Your results (which do not include any uncertainty estimate) cannot be compared to previous trends unless this contribution is addressed.

Response to (R3-C8): Agree, we have included solar cycle effects and revised all results (Pages 117 and onward of the revised manuscript) and the same is given below

"2.3. Solar cycle response

A regular variation in the occurrence of the Sun's active regions, with a periodicity of ~11- years, is called the solar cycle. Radio waves emissions from the Sun vary with the solar cycle and are enhanced (radio burst) during chromospheric or coronal events.

Since these emissions can easily be recorded (e.g., at 10.7 cm or 2.8 GHz), they are often used as an indicator of solar activity. Over the 11-year solar cycle, the solar flux varies by a factor of 2 at Lyman-α (Brasseur and Solomon, 2005). The 11-year solar cycle (Lean et al., 1997), has a direct impact on the upper atmosphere (mesopause region). At the mesospheric height, WV is strongly photo-dissociated by solar Lyman-α (Brasseur and Solomon, 1986). Ultraviolet radiation from the Sun is enhanced during the maximum of the 11-year solar cycle. Solar cycle (temperature) variations impact on WV and their relationship has been quantified by multiple researchers in the past (Brasseur and Solomon, 1986; Chandra et al., 1997; Fiedler et al., 2011; Hervig and Siskind, 2006; Siskind et al., 2013). In the present work, we include the Lyman-α solar index, the local time, seasonal and solar cycle variations of temperature, and WV during January 2002-December 2023. The Lyman-α solar index is obtained from the OMNIWeb database (https://omniweb.gsfc.nasa.gov). Figure 1(e) shows Lyman-alpha variation every month during the study period. The 23rd solar cycle ended in December 2008 and 24th solar cycle began (Figure 1e), and was minimal up to 2010. Consequently, the Lyman-□ was observed to be lower during solar minima. The period following 2010 is the solar active period of the 24th solar cycle and the corresponding variation in Lyman-α can be noticed in Figure 1e. “

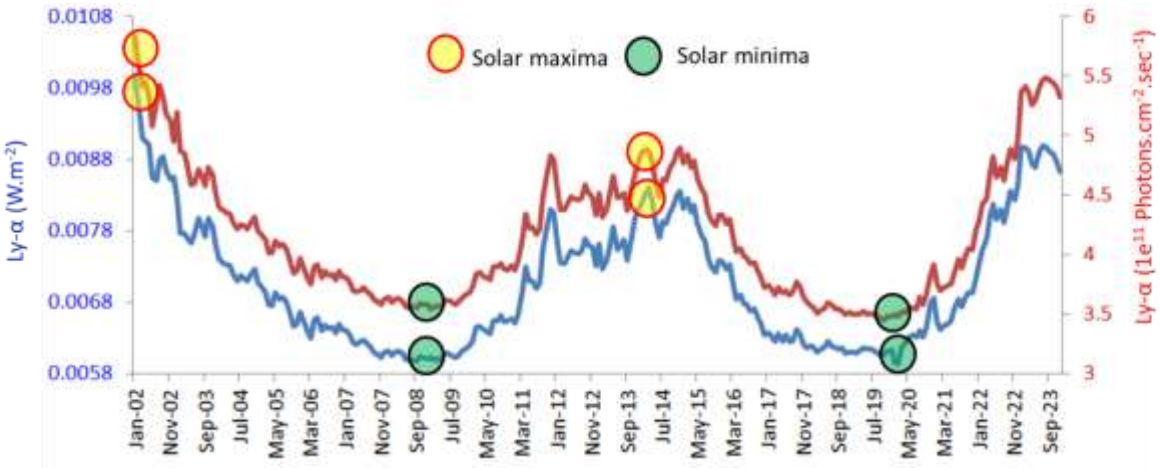
Trends significantly reduced after including solar cycle impact (using multiple linear regression analysis) as mentioned against the response of comment # 1 and the same is given below.

“2.3.1. Multiple linear regression analysis

To investigate the long-term trends (temperature and WV) and the solar response of the mesopause temperature, a three-component harmonic fit is applied to remove the seasonality from the monthly data series. Then a multiple linear regression model is performed to solar activity, linear trend, and residual temperatures versus constant. Applying the regression analysis to latitude-averaged temperature and WV provides a more statistically significant value of their trends. Lyman-α flux is a proxy for solar activity, so the monthly mean of Lyman-α solar flux is used in multiple linear regression equation (1) as a measure of solar variability. Multiple linear regression analysis technique has been used by multiple authors in the past (e.g., Chandra et al., 1997; Hervig et al., 2015, 2016; Yue et al., 2019). To analyze the temperature and WV trends using multiple linear regression with the inclusion of the solar cycle and time we applied the following multiple regression analysis for trend estimation.

$$\mathbf{Temperature\ or\ WV = C_o + C_1(Lyman.\alpha) \quad + \ C_2(time) + error} \qquad \mathbf{(1)}$$

Where C_0 is constant (intercept), C_1 and C_2 are regression coefficients characterizing the linear long-term trend (temperature and WV per year) and solar activity term. We calculate temperature and WV trends using multiple linear regression involving monthly temperature and WV (SABER) data over time. Before applying the multiple regression model we calculate solar radiation according to monthly data sets. For example, Monthly means of the Lyman-α index are computed for each month, yielding 176 points for both global and equator."



A subpart of Figure 1: Lyman- α index during January 2002-December 2023.

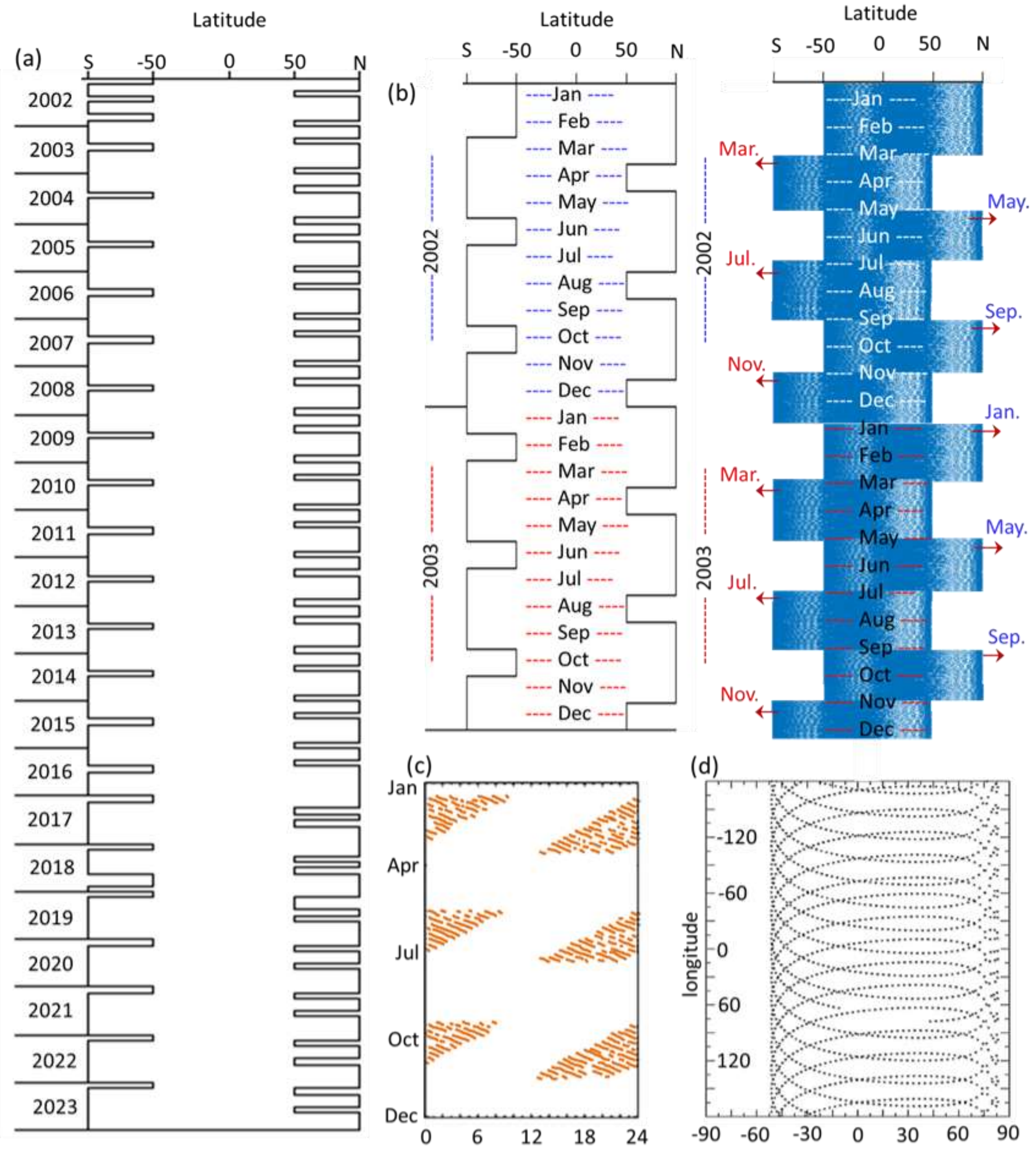
(R3-C9) Page 6, lines 154-156: This statement seems very simplistic, given that your "global" average only includes small latitude bands near each pole and at the Equator. There is also significant altitude dependence that can vary between months and years.

Response to (R3-C9): In the revised manuscript we have removed the mentioned statement (visible in the track change version). The global mesopause term used in this article does not include small latitude bands near each pole and at the equator but includes all latitude ranges of the mesopause scanned by the SABER instrument. This is one of the maximum spatial coverage covering both the hemispheres alternatively. Still, there are some limitations and uncertainties on the global scale that are related to the yaw cycle/mixing of northern and southern hemisphere data, etc. We have mentioned these limitations in the last section of the revised manuscript (lines 126-175 of the revised manuscript) and the same is given below

“2.2. TIMED-SABER instrument

The TIMED-SABER satellite views 90° to the right of the velocity vector of the TIMED spacecraft, and completes a full 24-hour local time coverage in 60-63 days (Russell III et al., 1999; Mlynczak et al., 2003; Figure 1). The SABER instrument scans the atmosphere from the troposphere up to the lower thermosphere and obtains vertical profiles kinetic temperature and volume mixing ratio of WV (Russell et al., 1999). The instrument performs near-global measurements and provides an excellent quality of the measured infrared limb radiances (Esplin et al., 2023). Technical description of the SABER instrument and further relevant information are discussed by Mlynczak, (1997) and Russell III et al. (1999). TIMED satellite rotates 180° about its yaw axis and provides latitude coverage continuously in the range of 53°S to 83°N and then switching to 83°S to 53°N every ~60 days (Russell III et al., 1999). Due to the asymmetrical latitudinal coverage of the SABER instrument, there are some missing measurement months at high latitudes (52°N-83°N or 52°S-83°S). Multiple studies (e.g; Forbes et al., 2021; Liu et al., 2017; Das, 2021) are limited to the latitude band ~50°S to ~50°N, mainly due to the TIMED ~60 days yaw cycle. In the present study, we have included high-latitude regions from both hemispheres along with some missing data. For example, coverage of high northern latitudes included July in the early years, but not during the recent several years (2017-2023)………” Please have a look at this section in the revised manuscript for full details.

Revised Figure 1: (page # 7)



Revised Figure 1. SABER instrument latitude coverage versus time for observation. a) Monthly data coverage in selected months versus latitude ranges from January 2002 to December 2023, excluding transitional months. b) Comparison of SABER latitude coverage and monthly data versus time during years (2002-2003). c) Typical temporal coverage of TIMED-SABER instrument measurements. d) Latitude versus longitude tangent point locations for one day of observations in its north viewing phase (83°N to 52°S) – a north viewing yaw mode.

Uncertainties related to high latitude regions: (line numbers 713 and onward)

“Section 6. Associated uncertainties and limitations

The possible sources of uncertainties during the analysis of long-term temperature and WV are mentioned below.

1. **Large uncertainty is related to the analysis of temperature and WV over SH and NH (above ~53^0 latitudes) and has a relatively larger bias in results as compared to the results over the equator. The yaw cycle is ~60 days, and only one polar region (SH or NH) is observed in each yaw cycle, and the selected polar regions are only alternatively observed half of a year owing to the yawing of the TIMED satellite. In other words, the latitudinal coverage is governed by a 60-day yaw cycle that allows observations of latitudes from 83^{o}S to 52^{o}N in the south-viewing phase or from 53^{o}S to 82^{o}N in the North-viewing phase (further details are given in the text). Multiple studies (e.g; Forbes et al., 2021; Liu et al., 2017; Mlynczak et al., 2022; Das, 2021) are limited to the latitude band ~50°S to ~50°N. In the present study, we have included high-latitude regions from both hemispheres along with some missing months. Missing months are usually April, August, or December in the NH and February, June, or October in the SH. As a result, the choice of these months for high latitudes introduces a systematic bias in the time series.**
2. **Temperature and WV trends over NH and SH are calculated for six months because April and December data were insufficient for long-term trends over NH. Similarly, June and October data was limited for SH trend estimation. Therefore, trends over the equator are more accurate than those of NH and SH trends.**

   "

So, we present our results along with the above-mentioned uncertainties in the revised text.

(R3-C10) Page 8, lines 201-204: The large variation in water vapor mixing ratio over this altitude range (as shown in Figures 2b and 2f) means that a simple average will be dominated by values from the lowest portion of the profile.

Response to (R3-C10): Agree this is a source of uncertainty for the current article and we have mentioned it in the revised manuscript (lines 747-749 of the revised manuscript) and the same is given below.

"The large variation in the WV mixing ratio over the mesopause altitude range (as shown in Figure 2) means that our simple average can be dominated by values from the lowest portion of the profile."

We have introduced a new section (Associated uncertainties and limitations) in the revised manuscript and and above text related to simple averaging is one of its points.

(R3-C11) Pages 8-9, lines 204-206: Solar activity-induced variations will greatly affect any calculated trends in water vapor, as discussed previously for your temperature analysis.

Response to (R3-C11): Agree, we have included solar cycle effects (lines 176-196 of the revised manuscript) and revised all results and the same is given below

"2.3. Solar cycle response

A regular variation in the occurrence of the Sun's active regions, with a periodicity of ~11- years, is called the solar cycle. Radio waves emissions from the Sun vary with the solar cycle and are enhanced (radio burst) during chromospheric or coronal events. Since these emissions can easily be recorded (e.g., at 10.7 cm or 2.8 GHz), they are often used as an indicator of solar activity. Over the 11-year solar cycle, the solar flux varies by a factor of 2 at Lyman-α (Brasseur and Solomon, 2005). The 11-year solar cycle (Lean et al., 1997), has a direct impact on the upper atmosphere (mesopause region). At the mesospheric height, WV is strongly photo-dissociated by solar Lyman-α (Brasseur and Solomon, 1986). Ultraviolet radiation from the Sun is enhanced during the maximum of the 11-year solar cycle. Solar cycle (temperature) variations impact on WV and their relationship has been quantified by multiple researchers in the past (Brasseur and Solomon, 1986; Chandra et al., 1997; Fiedler et al., 2011; Hervig and Siskind, 2006; Siskind et al., 2013). In the present work, we include the Lyman-α solar index, the local time, seasonal and solar cycle variations of temperature, and WV during January 2002-December 2023. The Lyman-α solar index is obtained from the OMNIWeb database (https://omniweb.gsfc.nasa.gov). Figure 1(e) shows Lyman-alpha variation every month during the study period. The 23rd solar cycle ended in December 2008 and 24th solar cycle began (Figure 1e), and was minimal up to 2010. Consequently, the Lyman-α was observed to be lower during solar minima. The period following 2010 is the solar active period of the 24th solar cycle and the corresponding variation in Lyman-α can be noticed in Figure 1e. "

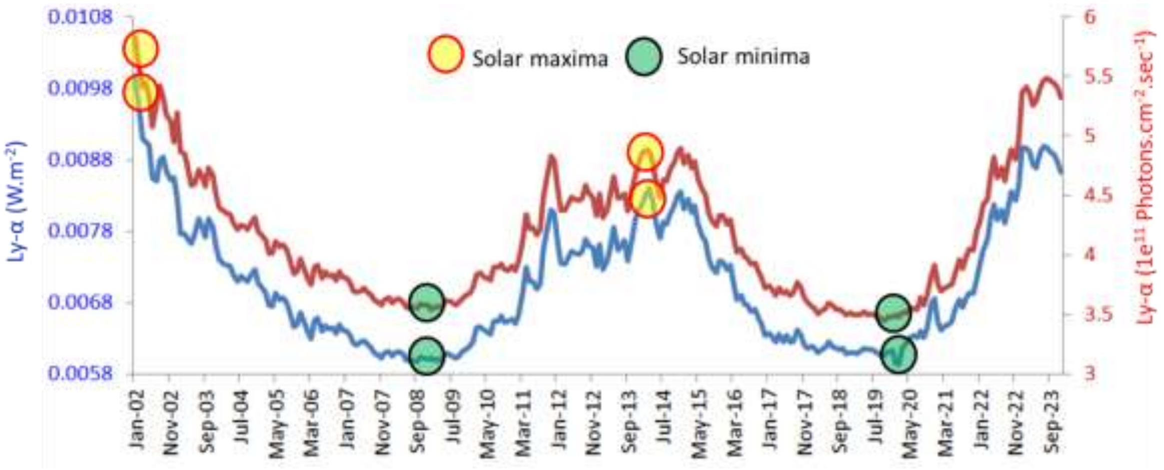
Trends significantly reduced after including solar cycle impact (using multiple linear regression analysis) as mentioned against the response of comment # 1 and the same is given below.

"2.3.1. Multiple linear regression analysis

To investigate the long-term trends (temperature and WV) and the solar response of the mesopause temperature, a three-component harmonic fit is applied to remove the seasonality from the monthly data series. Then a multiple linear regression model is performed to solar activity, linear trend, and residual temperatures versus constant. Applying the regression analysis to latitude-averaged temperature and WV provides a more statistically significant value of their trends. Lyman-α flux is a proxy for solar activity, so the monthly mean of Lyman-α solar flux is used in multiple linear regression equation (1) as a measure of solar variability. Multiple linear regression analysis technique has been used by multiple authors in the past (e.g., Chandra et al., 1997; Hervig et al., 2015, 2016; Yue et al., 2019). To analyze the temperature and WV trends using multiple linear regression with the inclusion of the solar cycle and time we applied the following multiple regression analysis for trend estimation.

$$\text{Temperature or WV} = C_o + C_1(\text{Lyman}.\alpha) \quad + \; C_2(\text{time}) + \text{error} \qquad (1)$$

Where C_0 is constant (intercept), C_1 and C_2 are regression coefficients characterizing the linear long-term trend (temperature and WV per year) and solar activity term. We calculate temperature and WV trends using multiple linear regression involving monthly temperature and WV (SABER) data over time. Before applying the multiple regression model we calculate solar radiation according to monthly data sets. For example, Monthly means of the Lyman-α index are computed for each month, yielding 176 points for both global and equator."



A subpart of Figure 1: Lyman- α index during January 2002-December 2023.

(R3-C12) Page 9, lines 224-225: Where is this result shown?

Response to (R3-C12): We provide a relevant source of the information (lines 319-320 of the revised manuscript) and the same is given below

"WV in the polar region is relatively higher in summer than in winter (Hervig et al., 2003). This may be due to upwelling transport in the summer hemisphere from lower altitudes towards the mesopause (Körner and Sonnemann, 2001). "

References

Hervig, M., McHugh, M., and Summers, M. E.: Water vapor enhancement in the polar summer mesosphere and its relationship to polar mesospheric clouds, Geophys. Res. Lett., 30, https://doi.org/10.1029/2003GL018089, 2003.

Körner, U. and Sonnemann, G. R.: Global three-dimensional modeling of the water vapor concentration of the mesosphere-mesopause region and implications with respect to the noctilucent cloud region, J. Geophys. Res. Atmos., 106, 9639–9651, https://doi.org/10.1029/2000JD900744, 2001

(R3-C13) Pages 9-10, lines 237-238: But Figure 2 only shows global averages, not individual latitude ranges.

Response to (R3-C13): We have revised Figure 2 and have included additional latitude ranges. The mentioned sentence does not fit with the flow of information and is deleted from the revised text (visible in the track change version). The revised Figure 2 (Page number 11) is given below

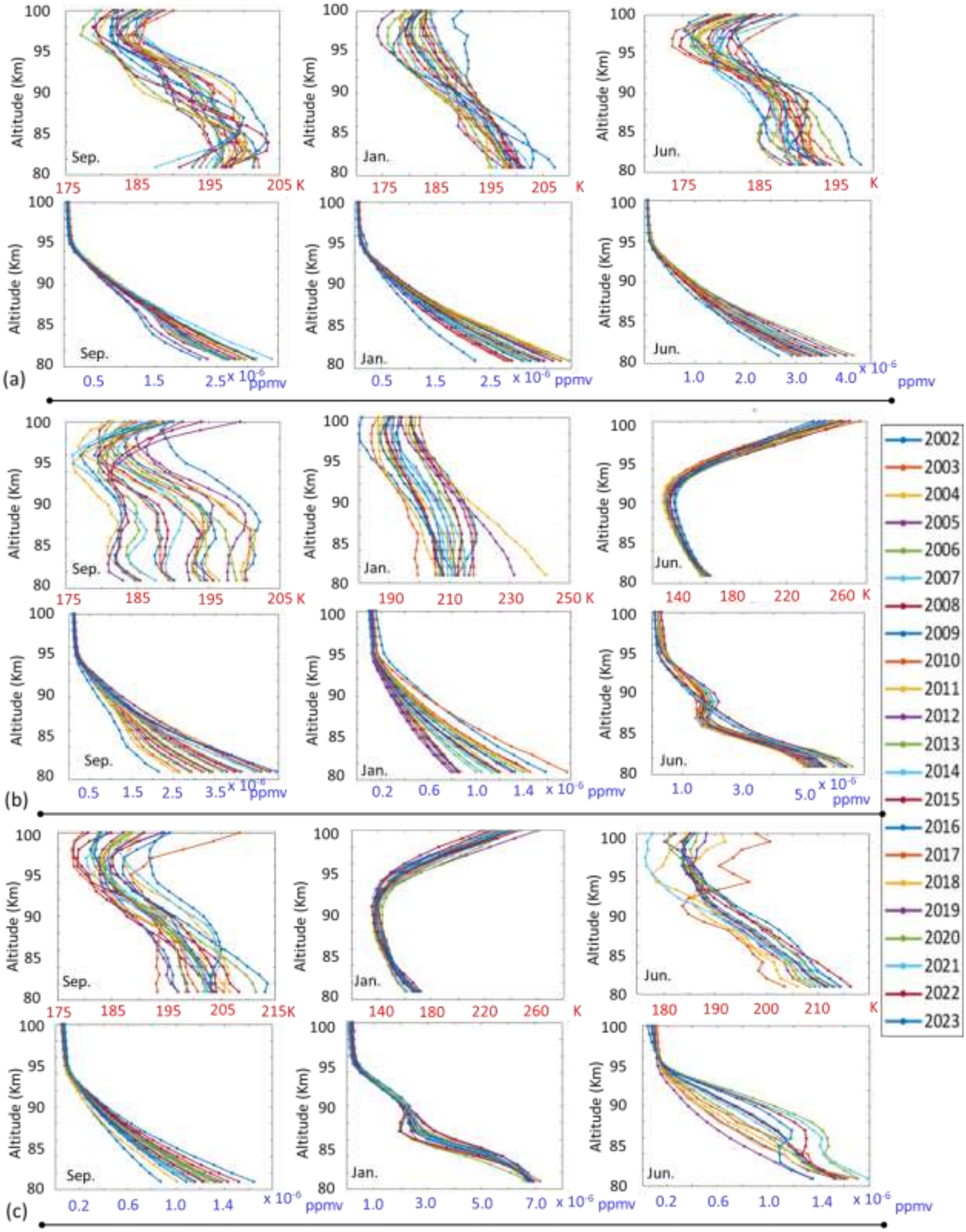
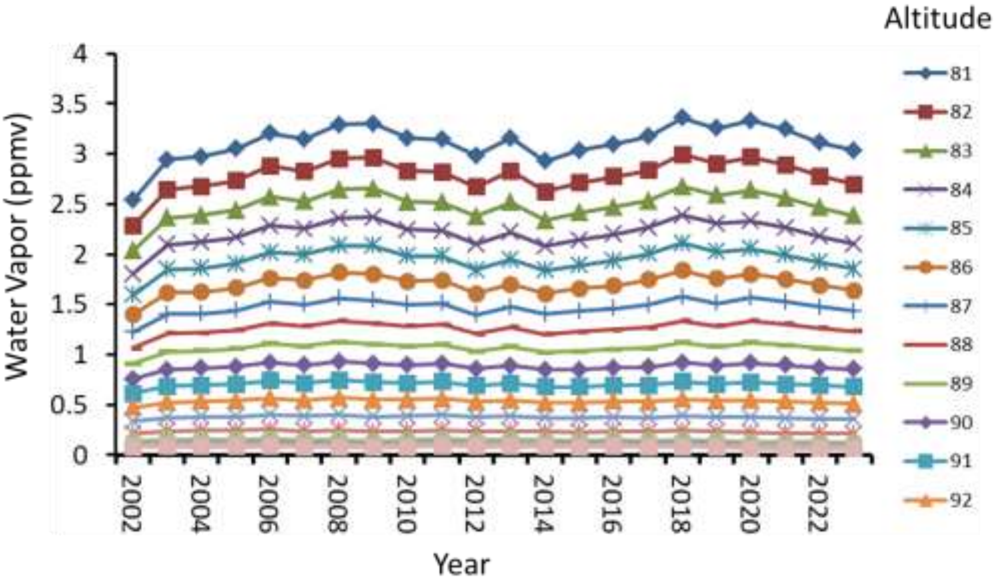


Figure 2. Temperature and water vapor gradient between 80-100 km altitudes from SABER observations at the three selected latitude bins during 200-2023. a) Equator (0° ± 1º). b) Northern hemisphere (80°N ± 1º). (c) Southern hemisphere (80°S ± 1º), in the indicated months, by averaging all January, June, and September values from 2002 to 2023.

(R3-C14) Page 10, lines 238-239: Again, Figure 2 only shows results averaged over 80-100 km, so what is the basis for this statement?

Response to (R3-C14): We have revised Figure 2 by including additional months from selected three latitude bins (page 11 of the revised manuscript) as shown in the above response.

The basis of the mentioned sentence was below Figure which is not shown in the manuscript.



(R3-C15) Page 10, lines 252-254: There are numerous studies during the last 30 years with more advanced models.

Response to (R3-C15): Agree, we have used/cited relatively latest references (eg: Berger and von Zahn, 2002; Korner and Sonnemann, 2001; von Zahn and Berger, 2003; Grygalashvyly and Sonnemann, 2006; Rong et al., 2012) in multiple places of the revised text and the same is given below.

Lines (333 of the revised manuscript)

"Models suggest that the water vapor mixing ratio at 90 km altitude is around 1–2 ppmv (Berger and von Zahn, 2002; Korner and Sonnemann, 2001; von Zahn and Berger, 2003)."

Lines (352 of the revised manuscript)

"Korner and Sonnemann, (2001) demonstrated that values of the mean zonal component of vertical wind velocity reach about 1-2 cm s−1 at 80-90 km altitude."

References

Berger, U. and Von Zahn, U.: Icy particles in the summer mesopause region: Three-dimensional modeling of their environment and two-dimensional modeling of their transport, J. Geophys. Res. Sp. Phys., 107, SIA-10, https://doi.org/10.1029/2001JA000316, 2002.

Grygalashvyly, M. and Sonnemann, G. R.: Trends of mesospheric water vapor due to the increase of methane–A model study particularly considering high latitudes, Adv. Sp. Res., 38, 2394–2401, https://doi.org/10.1006/j.asr.2006.09.010, 2006.

Körner, U. and Sonnemann, G. R.: Global three-dimensional modeling of the water vapor concentration of the mesosphere-mesopause region and implications with respect to the noctilucent cloud region, J. Geophys. Res. Atmos., 106, 9639–9651, https://doi.org/10.1029/2000JD900744, 2001.

Rong, P. P., Russell III, J. M., Hervig, M. E., and Bailey, S. M.: The roles of temperature and water vapor at different stages of the polar mesospheric cloud season, J. Geophys. Res. Atmos., 117, https://doi.org/10.1029/2011JD016464, 2012, 2012.

Von Zahn, U. and Berger, U.: Persistent ice cloud in the midsummer upper mesosphere at high latitudes: Three-dimensional modeling and cloud interactions with ambient water vapor, J. Geophys. Res. Atmos., 108, https://doi.org/10.1029/2002JD002409, 2003.

(R3-C16) Page 10, line 257: Table 1 mixes different selections for latitude coverage, seasonal coverage, long-term temporal coverage, and data sources. It is hard to know what conclusions could (or should) be drawn.

Response to (R3-C16): We have revised the Table as suggested by the other two reviewers (pages number 14, 15, and 16 of the revised manuscript) and the same is given below. In comparison to the previous table, the revised version of Table 1 has detailed and relevant information, please have a look.

Table 1. Temperature and water vapor content comparisons with past studies in mesopause

Trend K/decade	Avg. Temp	Altitude (km)	Location/Season/Data source	References
Temperature				
Min:	184.54 K	80-100	Global/summer (Jun. and Jul.)/ SABER	This study
0	188.20 K		Global/winter (Jan. and Dec.)/ SABER	
	162.64 K		80°N ± 1° / summer (Jun. and Jul.)/SABER	
	201.14 K		80°N ± 1° / winter (Jan. and Dec.)/SABER	
Max:	193.21 K		80°S ± 1° / summer (Jun. and Jul.)/SABER	
-1.21	161.14 K		80°S ± 1° / winter (Jan. and Dec.)/SABER	
	185.81 K		0° ± 1° / summer (Jun. and Jul.)/SABER	
	188.95 K		0° ± 1° / winter (Jan. and Dec.)/SABER	
Min: 0	130-190K	80-100	83°N to 83°S- all latitudes/ SABER	Zhao et al., 2020
	188±2 K		83°N/Northern hemisphere / SABER	
Max:	135±2 K		83°S/Southern hemisphere / SABER	
-1.4	158±2 K		0°/Equator / SABER	
	139 K	90	80°S/January/ SABER	Wang et al., 2022
	180 K	86	40°S/January/ SABER	
	129 K	90	80°N/July/ SABER	
	161 K	83	55°N/July/ SABER	
	160 K	~100	30°N/ around equinoxes (March)/ SABER	Xu et al., 2007
	185 K	~80	30°N/ around equinoxes (March)/ SABER	
	124 K	~100	80°N /solstice period (June)/ SABER	
	135 K	~80	80°N /solstice period (June)/ SABER	
	133 K	~100	80°N /solstice period (December)/ SABER	
	143 K	~80	80°N /solstice period (December)/ SABER	

	~126 K	80-100	Summer polar region/ SABER	
	~190 K	80-100	Winter polar region/ SABER	
	156-162 K	84	45–50°N/ summer night time (Aura/MLS)	Dalin et al., 2023
	152-157 K	84	50–55°N/ summer night time (Aura/MLS)	
	147-151 K	84	55–60°N/ summer night time (Aura/MLS)	
	151-159 K	89	45–50°N/ summer night time (Aura/MLS)	
	147-153 K	89	50–55°N/ summer night time (Aura/MLS)	
	141-146 K	89	55–60°N/ summer night time (Aura/MLS)	
-2.5	~177.6 K	97	41°N - 42°N / non summer months /Na lidar	Yuan 2019
-2.3	~177.6 K	92	41°N- 42°N /non winter months / Na lidar	
-3.8	~177.6 K	97	41°N - 42°N / winter /Na lidar	
-1.75	~177.6 K	92	41°N- 42°N /summer / Na lidar	
-2.3	160-230 K	87	51°N/ all seasons/SABER instrument	Offermann et al., 2010
Up	158-238 K	87	51°N/ all seasons/OH	
To	160-232 K	87	48°N/ all seasons/SABER instrument	
-6.0	145-235 K	87	48°N/ all seasons/ OH	
-6.8		~100	41°N (Lidar + SABER + Model)	She et al., 2009
-1.5	~184K	~91	41°N/January (Lidar + SABER + Model)	
- 0.64	~200 K	~85	41°N/January Na lidar	
-0.64	160-245 K	85-86	41°N/all seaons/Na lidar	She et al., 2015
-2.8	160-235 K	91-93	42°N/all seasons/Na lidar	
-0.23		87	69°S/winter /Hydroxyl airglow	French et al., 2005
-0.5		80-95	±52° latitude (WACCM-Model)	Garcia et al., 2019
-2.4	160-173 K	80-100	~57°N / summer mesopause (ground-based)	Dalin et al., 2020
-0.4	202-218 K	80-100	~57°N/winter (ground-based)	
-0.89	194-202 K	87	51° N/annual mean	Kalicinsky et al., 2016
	185-201 K	87	48◦ N/annual mean	
-4.0	135 K	90	78ºN/summer MLS on the Aura satellite.	Hall et al., 2012
	~200 K	90	78ºN/winter / radar observation	
-1.2	146-154 K	83	55–61°N/ annual /LIMA and MIMAS model	Lübken et al., 2018
-2.9	160-230 K	98.5	41°N/all season/ Na lidar	She and Krueger, 2004
-2.1	198-228 K	80-100	63°N/ January/ SABER	Ammosov et al., 2014
	196-215 K	80-100	63°N/ February/ SABER	
-2		80-100	middle & subpolar latitudes /summer/ model	Grygalashvyly et al., 2014
-0.5			middle & subpolar latitudes/ winter/ model	
-2.2		80-100	Middle latitudes/Airglow measurement	Perminov et al., 2014
-0.24	140-170 K	80 - 84	64–74°N/ all season/SOFIE	Hervig et al., 2015
-0.5	145-166 K	80-84	77°N /Satellite instrument and Model	Hervig et al., 2016
-1.2	140-220 K	87	68°S/ winter/ OH nightglow	French et al., 2020a
-0.3	~196 K	87	23-26°S /March-April/SABER & airglow	Noll et al., 2017
	145-235 K	~87	74°N /spectrometric observations of the OH	Medvedeva and Ratovsky, 2023
Water vapor mixing ratio				
	~1.30 ppmv	80-100	Global/summer/ SABER	This study
	~1.20 ppmv		Global/winter/ SABER	
	~1.90 ppmv		80°N ± 1º /summer/SABER	
	~0.49 ppmv		80°N ± 1º /winter/SABER	
	~0.67 ppmv		80°S ± 1º / summer/SABER	
	~2.30 ppmv		80°S ± 1º /winter/SABER	
	~1.20 ppmv		0° ± 1º /summer/SABER	
	~1.10 ppmv		0° ± 1º /winter/SABER	
	4.2-5.1 ppmv	84	45–50°N/ summer night time (Aura/MLS)	Dalin et al., 2023
	4.5-5.4 ppmv	84	50–55°N/ summer night time (Aura/MLS)	
	4.7-5.6 ppmv	84	55–60°N/ summer night time (Aura/MLS)	
	3.1-3.6 ppmv	89	45–50°N/ summer night time (Aura/MLS)	
	3.3-3.9 ppmv	89	50–55°N/ summer night time (Aura/MLS)	
	3.3-3.9 ppmv	89	55–60°N/ summer night time (Aura/MLS)	
	1-8 ppmv	80 - 84	64–74°N/ all season/SOFIE	Hervig et al., 2015
	5.4-5.8 ppmv	80-84	77°N /Satellite instrument and Model	Hervig et al., 2016
	0-7.0 ppmv	80-100	66°-79°N/SOFIE on AIM & ALOMAR lidar	Hervig et al., 2009a
	1-2 ppmv	95	66°-79°N/satellite measurement	

1 ppmv	90	78°N/ summer/1-D model	Murray and Jensen, 2010
3 ppm	86	67.9°N- Polar region/Summer/Model	Gumbel et al., 2003
2.3 ppmv	85	Mid-latitude /Jul./Ground-based microwave	Bevilacqua et al., 1983
1.6 ppmv	85	Mid-latitude /Sep./Ground-based microwave	
1.0 ppmv	85	Mid-latitude /Jan./Ground-based microwave	
1.2 ppmv	85	Mid-latitude /Apr./Ground-based microwave	
0.1 ppmv	85	Mid-latitude /Dec./Ground-based microwave	
1.1 ppmv	85	Mid-latitude /Apr./Ground-based microwave	
0-7.0 ppmv	80-100	66°-79°N/SOFIE on AIM & ALOMAR lidar	Hervig et al., 2009a
1-2 ppmv	95	66°-79°N/satellite measurement	
1.5-4.5 ppmv	80	69ºN/Ground-based microwave	Seele and Hartogh, 1999
2-2.5 ppmv	85	Polar summer/Jun., Jul., Aug.,/ground-based	
0.2 ppmv	84	67ºN/3-D model /	Von Zahn & Berger, 2003
3 ppmv	80-83	50ºN-80ºN/3-D model /	
~2.0 ppmv	80-83	50ºN-80ºN/3-D model /	
~1.5 ppm	90	72.5ºN /Jul., Aug./3D-Model and HALOE	Körner & Sonnemann, 2001
~3.5 ppm	85	72.5ºN /Jul., Aug./3D-Model and HALOE	
~5.1 ppm	80	72.5ºN /Jul., Aug./3D-Model and HALOE	
1.0 ppmv	~83	65°–70°N /winter / HALOE measurement	Hervig et al., 2003
8.0 ppmv	~83	65°–70°N /summer / HALOE measurement	
0.45 - 4.81 ppmv	80-94	78°N/ summer/Model,	Lubken et al., 2004
~4.5 ppmv	80	78°N/ summer/Model,	
3.4 ppmv	85	78°N/ summer/Model,	
1.98 ppmv	90	78°N/ summer/Model,	
2-4 ppmv	82	55°N–55°S/SABER	Yue et al., 2019
~3.5 ppmv	80	19.5°N/ Sep./Spectrometer mouna	Nedoluha et al., 2022

(R3-C17) Page 12, lines 280-283: This statement says that you have confirmed previous work. Any new information?

Response to (R3-C17): Agree, the mentioned statement is relevant for another section 2.3 “Solar cycle response”, and moved the statement from the previously mentioned location to section 2.3. We removed the whole section because the section had little new information.

(R3-C18) Page 15, lines 335-338: See previous questions about shift in yaw dates during SABER mission and impact on sampling. Note that the April data in Figure 5b only begin in 2017. Is the large trend in September temperature and water vapor affected by sampling changes?

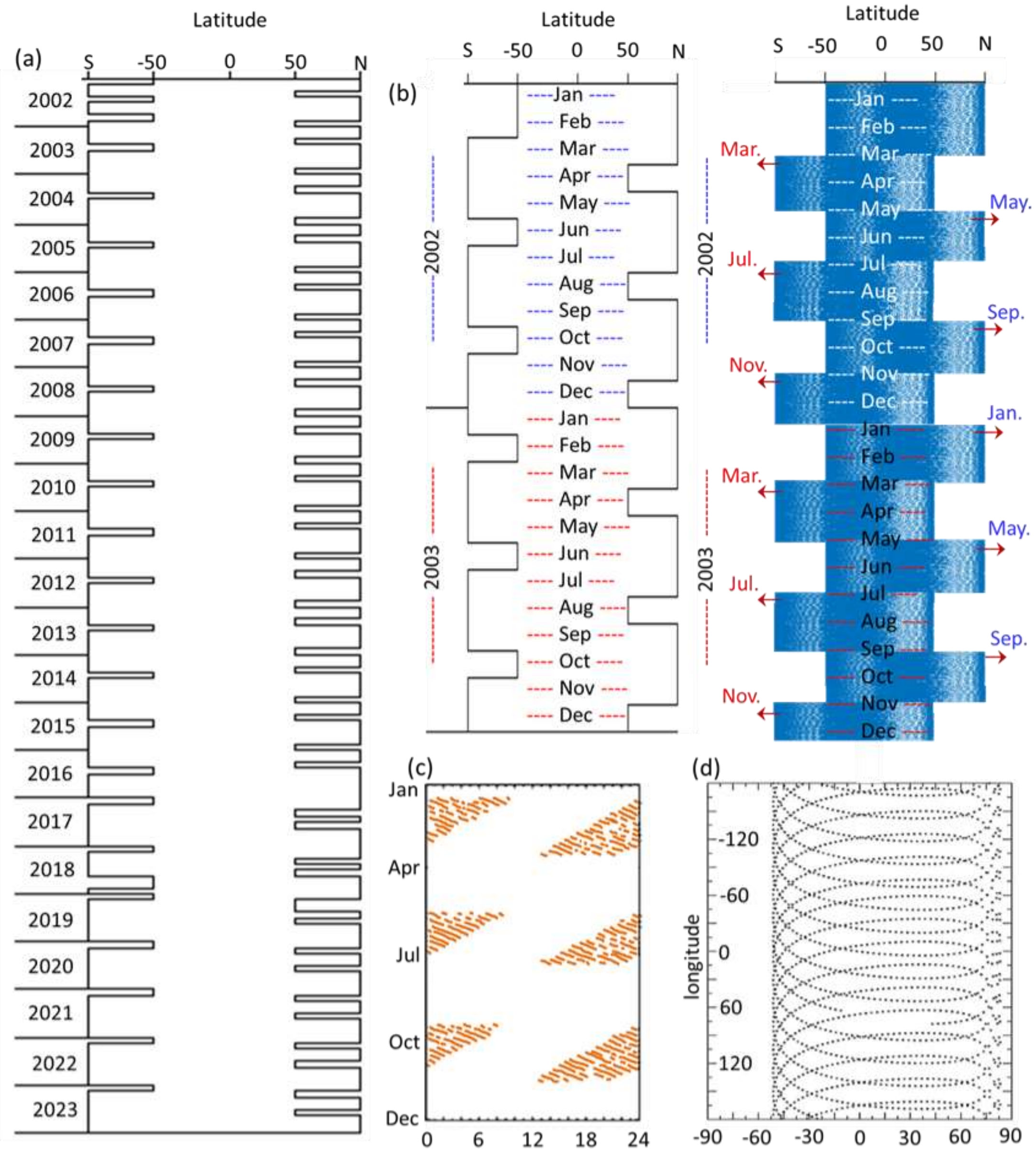
Response to (R3-C18): Shift in yaw dates, SABER instruments latitudes and time relation, and Monthly data coverage are discussed in detail in the revised manuscript (lines 126 and onward of the revised manuscript).

“2.2. TIMED-SABER instrument

The TIMED-SABER satellite views 90° to the right of the velocity vector of the TIMED spacecraft, and completes a full 24-hour local time coverage in 60-63 days (Russell III et al., 1999; Mlynczak et al., 2003; Figure 1). The SABER instrument scans the atmosphere from the troposphere up to the lower thermosphere and obtains vertical profiles kinetic temperature and volume mixing ratio of WV (Russell et al., 1999). The instrument performs near-global measurements and provides an excellent quality of the

measured infrared limb radiances (Esplin et al., 2023). Technical description of the SABER instrument and further relevant information are discussed by Mlynczak, (1997) and Russell III et al. (1999). TIMED satellite rotates 180° about its yaw axis and provides latitude coverage continuously in the range of 53°S to 83°N and then switching to 83°S to 53°N every ~60 days (Russell III et al., 1999). Due to the asymmetrical latitudinal coverage of the SABER instrument, there are some missing measurement months at high latitudes (52°N-83°N or 52°S-83°S). Multiple studies (e.g; Forbes et al., 2021; Liu et al., 2017; Das, 2021) are limited to the latitude band ~50°S to ~50°N, mainly due to the TIMED ~60 days yaw cycle. In the present study, we have included high-latitude regions from both hemispheres along with some missing data. For example, coverage of high northern latitudes included July in the early years, but not during the recent several years (2017-2023)………” Please have a look at this section in the revised manuscript for full details.

Revised Figure 1: (page # 7)



Revised Figure 1. SABER instrument latitude coverage versus time for observation. a) Monthly data coverage in selected months versus latitude ranges from January 2002 to December 2023, excluding transitional months. b) Comparison of SABER latitude coverage and monthly data versus time during years (2002-2003). c) Typical temporal coverage of TIMED-SABER instrument measurements. d) Latitude versus longitude tangent point locations for one day of observations in its north viewing phase (83°N to 52°S) – a north viewing yaw mode.

We are sorry to say that previous trends were not correct and new trends are used in the text. Revised trends are given below

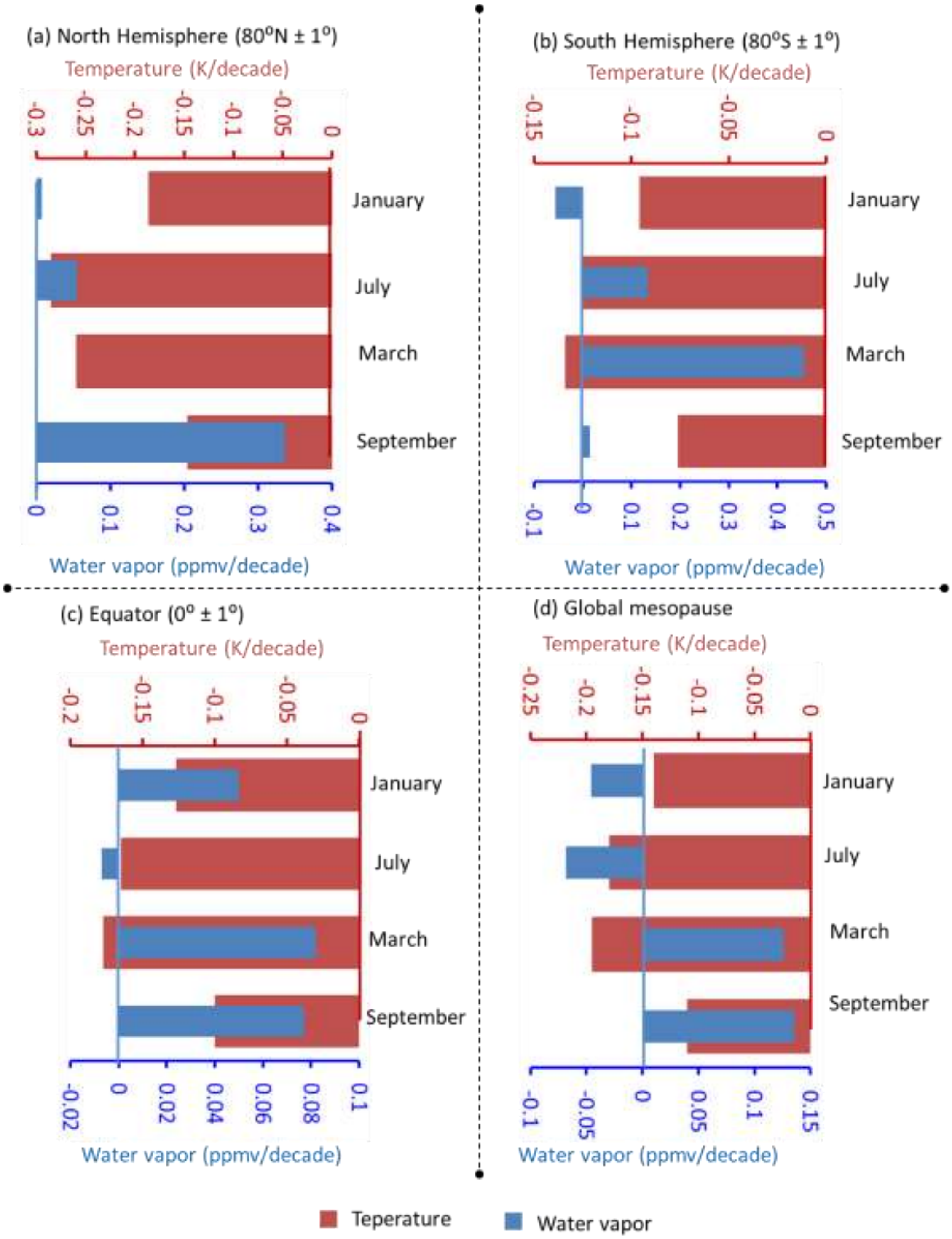


Figure 9. Temperature and water vapor trends during selected four months as indicated. a) Temperature and WV trends over NH (80⁰N ± 1⁰). b) Temperature and WV trends over SH (80⁰S ± 1⁰). c) Temperature and WV trends over the equator (0⁰ ± 1⁰). d) Temperature and WV trends on the global scale.

(R3-C19) Page 17, lines 350-354: Water vapor content at these low altitudes (81-83 km) will be affected by sublimation of PMC particles that settle from higher altitudes.

Response to (R3-C19): Thank you, we have provided additional text as suggested (lines 469-470 of the revised manuscript) and the same is given below

"WV content at low altitudes (81-83 km) is affected by the sublimation of polar mesospheric cloud particles that settle from higher altitudes. The impact of polar mesospheric clouds on the surrounding WV (via dehydration and sublimation) is discussed by Hervig et al. (2015) and by Lübken and Berger, (2011)."

References

Hervig, M. E., Siskind, D. E., Bailey, S. M., and Russell III, J. M.: The influence of PMCs on water vapor and drivers behind PMC variability from SOFIE observations, J. Atmos. Solar-Terrestrial Phys., 132, 124–134, https://doi.org/10.1016/j.jastp.2015.07.010, 2015

Lübken, F. and Berger, U.: Latitudinal and interhemispheric variation of stratospheric effects on mesospheric ice layer trends, J. Geophys. Res. Atmos., 116, 2011.

(R3-C20) Page 17, lines 375-376: Note that January/December is summer in the Southern Hemisphere, not winter.

Response to (R3-C20): Sorry for this mistake, we have updated the sentences as suggested (lines 492-494 of the revised manuscript) and the same is given below

"During summer (January/December), temperature first decreased up to 92 km altitude and then increased to 93 km and onward altitudes."

(R3-C21) Page 27, line 586: It's not clear why you say "performed the measurements" when the paper only analyzes SABER data.

Response to (R3-C21): Agree, we have modified the sentences as suggested (line 807 of the revised manuscript) and the same is given below

"CG and SK initiated the idea; CG and DG analyzed and required calculations; CG, DG, and YY wrote the manuscript draft; SK and XG reviewed and edited the manuscript."

Thanks to anonymous reviewer 3 for his/her constructive comments and suggestions.

------------------------ End of the response to reviewer 3 -------------------------