Dear Profs. John Plane, Jan Laštovička, reviewer#2, and Martin Mlynczak:

Thanks very much for taking your time to review our manuscript "*Trends of the high latitude mesosphere temperature and mesopause revealed by SABER (ID: egusphere-2024-396)*". We thank the reviewers for the time, insight, and effort that they have put into reviewing our manuscript. Those comments are all valuable and very helpful for revising and improving our paper.

Accordingly, we have uploaded a copy of the original manuscript with all the changes highlighted by using the track changes mode in MS Word. Appended to this letter is our point-by-point response to the comments raised by the reviewers. The original comments by reviewers use black, and our response is located below the comments and uses blue font.

Yours sincerely,
Xiao Liu, Jiyao Xu, Jia Yue, Yangkun Liu, and Vania F. Andrioli

Responses to the comments from Reviewer#2

The paper highlights the MLT temperature trend in high latitudes through a new innovated SABER data processing algorithm that solves the previous issue (fixed 60-day window) regarding the forward drifting of SABER local time coverage, while mitigating properly the embedded bias due to seasonal variations through the assistant of MSIS2.0. The results show mostly cooling trends around the globe with sporadic spots of warming, which is consistent with the numerical studies. The author states that the revealed large cooling at high latitudes MLT demonstrates the high sensitivity to the global climate change in this area. Note that similar statement has been raised by the climate studies focusing on the troposphere and stratosphere. The manuscript and figures are mostly clean, and I just have a few minor questions that need the author to address.

Response: Thank you very much for your time involved in reviewing the manuscript and your very encouraging comments. Please find the point-to-point responses below.

Comments:

1. Based on equation 1, removing kt_{UT} from the mean $\overline{T}_d$ should give mean $\overline{T}_{d0}$, instead of the residual term. Please clarify.

Response: Thanks for your careful reading. In the new version, this point has been clarified as:

$$\overline{T}_d = \overline{T}_{d0} + kt_{UT} + \overline{T}_{res}. \tag{1}$$

Here, $\overline{T}_{d0}$ is the mean temperature in each YC. t_{UT} is the universal time with a unit of day, k represents the linear variation of $\overline{T}_d$ in each YC. After removing $\overline{T}_{d0}$ and the linear variation (kt_{UT}) from $\overline{T}_d$, we get a residual temperature $\overline{T}_{res}$ of each YC.

2. Some of the trend profiles at high altitudes (geometric height) in figure 6 showing near or more than 10 K/decade near 100 km and above, even considering the fitting uncertainty. I feel these cooling trends are a little excessive. The author might want to double check the data quality or the algorithm for this altitude range.

Response: Following your comment, we discussed the uncertainties of the SABER temperature and their possible impacts on the extreme cooling trend. To make the discussions clearly, we rearrange the section of Discussions (Section 4) as three subsections:

Sec. 4.1 for “The reliability of trends in the MLT region at latitudes lower than 50°N/S”;

Sec. 4.2 for “The reliability of trends in the MLT region at latitudes higher than 50°N/S”;

Sec. 4.3 for “The reliability of the mesopause trends”.

The Sec. 4.1 and 4.3 do not change much. The main revisions are included in Sec. 4.2 and in the Appendix. In Sec. 4.2, the uncertainties of SABER temperature measurements on the derived trends are discussed on the following three aspects: (1) the SABER measurement errors for temperature; (2)

the drivers’ uncertainties in retrieving the SABER temperature; (3) the impacts of the measurement uncertainties on the derived trends.

The detailed revisions in the text are provided below:

(1) The description on the SABER measurement errors for temperature (in the Introduction)

The operational SABER temperature profile covers an altitude range of ~15–110 km. The uncertainties of SABER temperature profile are height dependent. For a single temperature profile, its uncertainties are summarized at https://spdf.gsfc.nasa.gov/pub/data/timed/saber/ and are of ~1.8–2.3 K at z=60–80 km, ~5.4–8.4 K at 90–100 km, and ~8.4–29.2 K at 100–110 km under the condition of vertical resolution of 2 km (Remsberg et al., 2008; Rezac et al., 2015; Dawkins et al., 2018)”.

Dawkins, E. C. M., Feofilov, A., Rezac, L., Kutepov, A. A., Janches, D., Höffner, J., Chu, X., Lu, X., Mlynczak, M. G., and Russell, J.: Validation of SABER v2.0 operational temperature data with ground-based lidars in the mesosphere-lower thermosphere region (75–105 km), J. Geophys. Res. Atmos., 123, 9916–9934, https://doi.org/10.1029/2018JD028742, 2018.

(2) The discussions on the drivers’ uncertainties in retrieving the SABER temperature (in Sec. 4.2)

The main causes of the operational SABER temperature systematic uncertainties are the lack of accurate knowledge of atomic oxygen and carbon dioxide during the retrieval process. The atomic oxygen provided to the operational SABER temperature retrieval algorithm is from NRLMSISE-00 (Picone et al., 2002). Below 100 km, no atmospheric observations of atomic oxygen are incorporated. Thus, the uncertainty of atomic oxygen influences the uncertainties of temperature from ~75 km to 110 km, in particular, above 100 km. The carbon dioxide provided to the operational SABER temperature retrieval algorithm is the monthly average value from WACCM (Dawkins et al., 2018; Picone et al., 2002). Thus, there is no local time variation in carbon dioxide used in the operational SABER temperature retrieval algorithm. This will induce uncertainties of SABER temperature and thus the uncertainties of trends above 75 km.

(3) The discussions on the impacts of the measurement uncertainties on the derived trends through Monte Carlo simulation (in Sec. 4.2 and Appendix):

In Sec 4.2, the followings have been included:

These uncertainties in temperature may not be constant or stable in time or in space. To explore the impacts of the uncertainties in SABER temperature on the derived trends, we performed Monte Carlo simulations by assuming the uncertainties in SABER temperature following a uniform distribution in the range of ±25K. In each time of Monte Carlo simulation, in each YC and at each pressure level and within a latitude band of 10°, the SABER samplings (more than 5000 data) are added by random numbers following the uniform distribution in the range of ±25K. Then same procedure described in Sec. 2.1–2.3 was repeated to derive trends. The Monte Carlo simulations were performed 5000 times (see Appendix). The main result is that the uncertainties of ±25K in SABER samplings would induce a mean temperature variation of ~1–3 K and a false trend ~0.5–1.2 K/decade at high latitudes. This is mainly because mean temperature is calculated from more than 5000 data in each YC within a latitude band of 10°, which reduces the standard deviation by a factor of ~1/250 based on central limit theory. It must be noted that the actual distributions of the uncertainties in SABER samplings caused by atomic oxygen and carbon dioxide are unknown. The Monte Carlo simulation only provides a reference result by assuming the uncertainties following uniform distributions. This may not be valid for the case of SABER temperature systematic errors. So may not be valid. We only include it in the Appendix.

In the Appendix, the followings have been included:

Around 10^{-4} hPa, the uncertainties of SABER temperature measurements are around 25 K at mid-latitudes and are likely higher at high latitudes. These uncertainties are mainly attributed to the uncertainties of atomic oxygen and carbon dioxide, which were used in the operational SABER temperature retrieval algorithm. Moreover, these uncertainties in temperature may not be constant or stable in time or in space. To explore the impacts of the uncertainties in SABER temperature on the derived trends, we performed Monte Carlo simulations by assuming the uncertainties in SABER temperature following a uniform distribution in the range of ±25K. In each time of Monte Carlo simulation, in each YC and at each pressure level and within a latitude band of 10°, the SABER samplings (more than 5000 data) are added by random numbers which follows the uniform distribution in the range of ±25K. Then same procedure described in Sec. 2.1–2.3 was repeated to derive trends. The Monte Carlo simulations were performed 5000 times to get convincing results.

Since the cooling trends are very large in YC3 and at 75°N, especially around the pressure levels of around 10^{-4} hPa, we show in Figure A the impact of the random uncertainties of SABER temperature on the derived trends in YC3 and at 75°N. The uncertainties of ±25K in SABER samplings induce the mean temperature ($\bar{T}_{bk}^{2002}$) varying in the range of ±2 K (Fig. Aa1) with standard deviation of 0.5 K (Fig. Aa2) at 10^{-4} hPa. This in turn induces the trends varying in the range of ±0.6 K/decade (Fig. Ab1) with standard deviation of 0.15 K/decade (Fig. Ab2) at 10^{-4} hPa. The altitude profile of $\bar{T}_{bk}^{2002}$ by assuming a zero uncertainty is similar to that calculated by assuming the uncertainties of ±25K (Fig. Ac1). The differences of the maximum and minimum of $\bar{T}_{bk}^{2002}$ among the 5000 times of Monte Carlo simulations are ~1–2 K below 5×10^{-4} hPa and are ≥3 K around 10^{-4} hPa (Fig. Ac2). The altitude profile of trend by assuming a zero uncertainty is similar to that calculated by assuming the uncertainties of ±25K (Fig. Ad1). The differences of the maximum and minimum of trends among the 5000 times of Monte Carlo simulations are ~0.5 K/decade below 10^{-3} hPa and are ~0.5–1.2 K/decade around 10^{-4} hPa (Fig. Ad2). This example illustrates that the uncertainties of ±25K in SABER samplings would induce a mean temperature variation of ~1–3 K and a false trend ~0.5–1.2 K/decade at high latitudes.

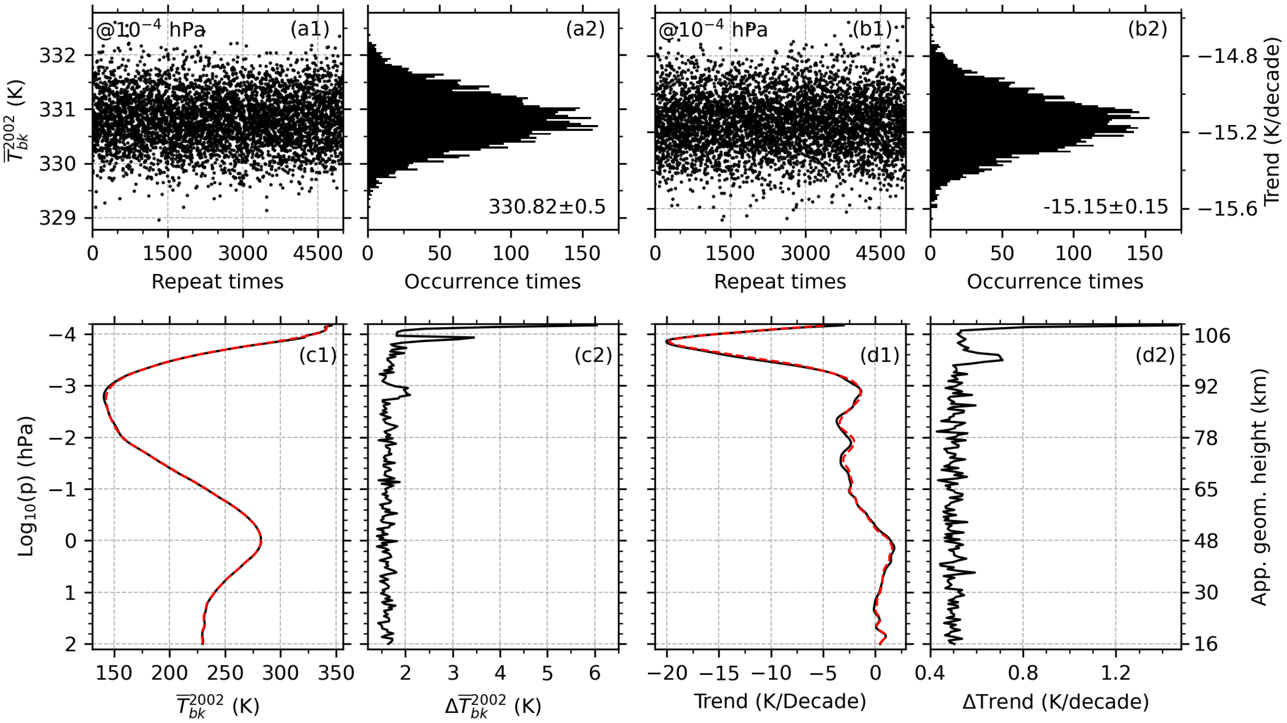

Figure A. The impacts of uncertainties of ±25K in SABER temperature on the derived trends in YC3 and at 75°N during 5000 times of Monte Carlo simulation. (a1) and (a2): the mean temperature calculated from SABER sampling ($\bar{T}_{bk}^{2002}$) and its histogram at 10^{-4} hPa; (b1) and (b2): the trend and its histogram at 10^{-4} hPa; (c1) and (d1): the altitude profiles of $\bar{T}_{bk}^{2002}$ by assuming zero uncertainty (black) and uncertainties of ±25K (dashed-black); (c2) and (d2) altitude profile of the difference between the maximum and minimum of $\bar{T}_{bk}^{2002}$ and trend.

Another Monto Carlo simulation is performed to test the impacts of the uncertainties of ±25K on the mean temperature (180 K) by changing the sampling points. During 5000 times of simulations (Figures R1 and R2, which are only shown here but not in the text), the mean temperature and its standard deviation are 179.956±4.5 K if there are 10 samplings; the mean temperature and its standard deviation are 179.977±1.43 K if there are 100 samplings; the mean temperature and its standard deviation are 179.997±0.20 K if there are 5000 samplings. This indicates that the increasing samplings can reduce the measurement uncertainties efficiently. Although the uncertainties of SABER samplings are as large as ±25K at high latitudes, its impact on the trends are insignificant in the highly averaged results. This is mainly because mean temperature is calculated from more than 5000 data in each YC within a latitude band of 10°, which reduces the standard deviation by a factor of ~1/250 based on central limit theory. It must be noted that the actual distributions of the uncertainties in SABER samplings are unknown. The Monte Carlo simulation only provides a reference result by assuming the uncertainties following uniform distribution. This may not be valid for the case of SABER temperature systematic errors. We only include it in the Appendix.

The followings are the description of the central limit theory (CLT) but not included in the text:

The mathematic basis of the highly averaged result has very small standard deviations is the central limit theory (CLT) in probability and statistics. Suppose random variables $\{X_i\}_{i=1}^{n}$ *are independent and identically distributed and have an expectation of* μ *and standard deviation of* σ*, the distribution function,*

$$F_n(x) = P\left\{\frac{\sum_{i=1}^{n} X_i - n\mu}{\sigma\sqrt{n}} \le x\right\},$$

has limitation of,

$$\lim_{n\to\infty} F_n(x) = \lim_{n\to\infty} P\left\{\frac{\sum_{i=1}^{n} X_i - n\mu}{\sigma\sqrt{n}} \le x\right\} = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{x} e^{-\frac{t^2}{2}}dt.$$

The CLT states that if one take sufficiently large samples from a population, the samples' means will be normally distributed, even if the population isn't normally distributed. Thus, X follows the normal distribution of $N(\mu, \sigma/\sqrt{n})$.

The uniform distribution in the range of $[a, b]$*, its expectation and standard deviation are* $\mu = (a+b)/2$ *and* $\sigma = (b-a)/\sqrt{12}$*, respectively. According to CLT, the uncertainties of ±25K will induce an uncertainty of* $50/\sqrt{12 \times 5000} \approx 50/245 = 0.204\text{K}$*. This support the Monte Carlo simulations of ±0.20 K if there are 5000 samplings.*

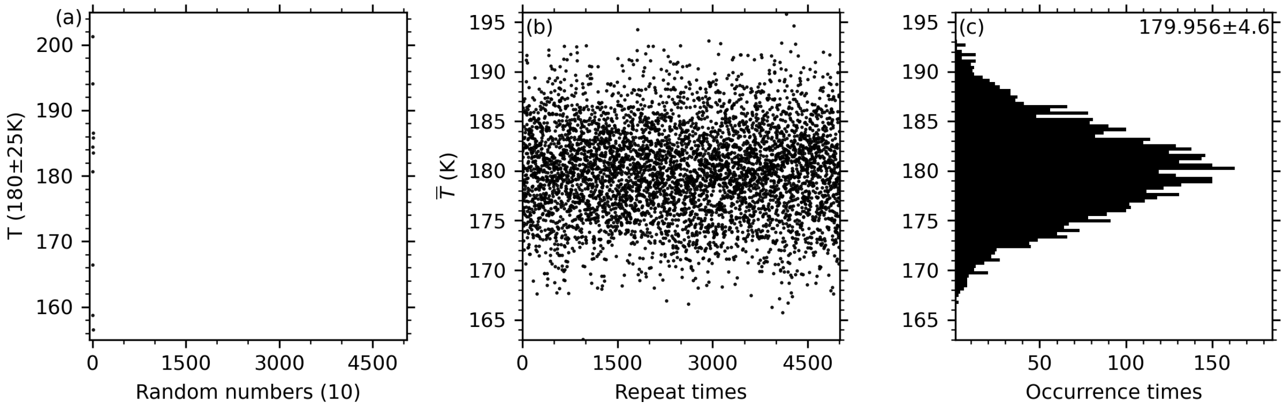

Figure R1. *Monte Carlo simulation on the influences of 10 samplings on the mean and standard deviation of the uniform distribution of ±25K with mean of 180 K. (a) an example of the 10 samplings;*

(b) and (c) show, respectively, the means and their histogram during 5000 times Monte Carlo simulations. The mean and standard deviation are labelled on the top right corner of (c).

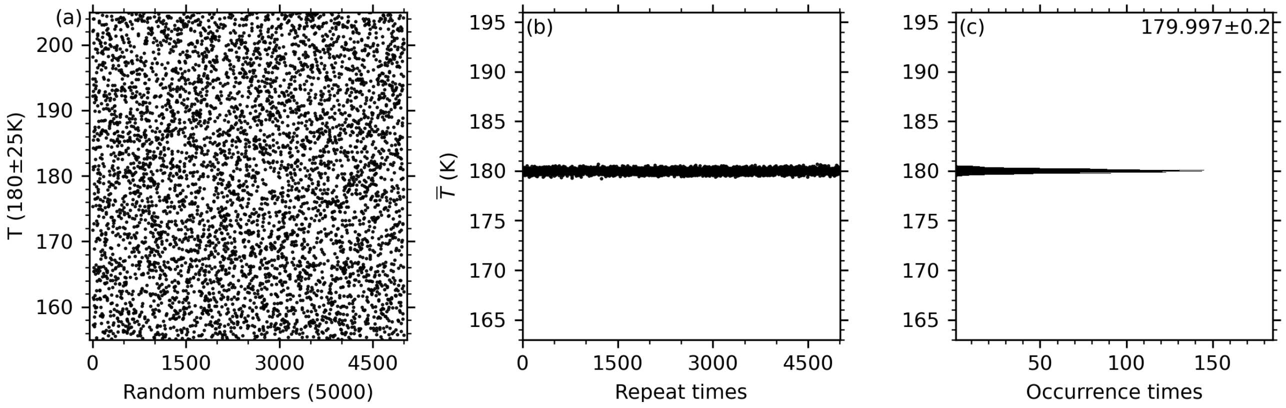

Figure R2. *Same caption as Fig. R1 but for 5000 samplings.*

3. Line 42, "highest latitudes" why not just say high latitudes?

   Response: Following your suggestion, the "highest latitudes" is revised as "high latitudes".

4. Line 95, "lower heights", please be more specific, troposphere or stratosphere? Or just say lower altitudes.

   Response: The CO_2 data used in the LIMA model were measured at Mauna Loa (19°N, 155°W) and were considered according to observations in the troposphere (Lübken et al., 2021).

   In the new version, we have specified "lower heights" as "troposphere". The revised sentence is "…the negative trend of noctilucent clouds altitudes (~83 km) was primarily caused by the increasing CO_2 in the troposphere during…".

5. Line 121, 60-day

   Response: It is revised in the new version.

6. Figure 4 caption. I do not see red and green dots, but purple and blue ones. Also, it is very difficult to tell the "+" signs. May want to change the symbol.

   Response: You are right. This sentence is revised as "The purple and blue dots indicate the heights of the mesopause and stratopause, respectively". The "+" signals are too small to readable. We have changed them as shaded points. The revised figure and its caption are shown below and are also included in the text.

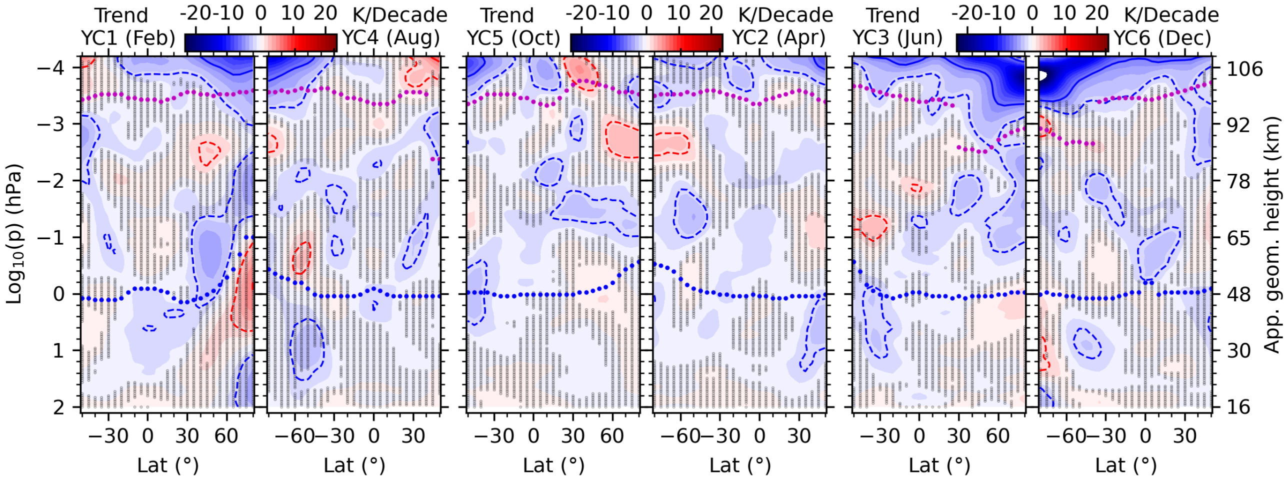

Figure 4. Trends of the corrected mean temperature in the six YCs. The solid and dashed contour lines indicate ±6 and ±2 K/decade, respectively. The purple and blue dots indicate the heights of the mesopause and stratopause, respectively. The regions marked by shaded points indicate that trends are not significant with reference to the 95% the confidence level. The approximate geometric height is label on the last panel.

7. Line 370, “higher heights”, again please be specific. And replace all the “heights” with “altitudes”.

Response: Here, the “higher heights” is specified as “Above 5×10^{-3} hPa”. Following your suggestion, we replaced replace all the “heights” with “altitudes” in the new version.