Dear Reviewers:
We thank you for your thoughtful and constructive comments on our manuscript entitled “A new data set of nighttime chemical heating rates in the upper mesosphere and lower thermosphere derived from SCIAMACHY OH (9-6) emissions and SABER profiles”. All comments have been carefully considered, and the manuscript has been revised accordingly. Our responses to the individual comments are provided below.

## Response to Referee #1

Dear Reviewer:
Thank you for your comments on our manuscript entitled “A new data set of nighttime chemical heating rates in the upper mesosphere and lower thermosphere derived from SCIAMACHY OH (9-6) emissions and SABER profiles”. Those comments are very helpful for improving the quality of our manuscript. We have studied the comments carefully and made revisions accordingly. The responses to the comments are provided below.

### Major Concern:

1. “During the ENVISAT operation time, SCIAMACHY and SABER had different flight geometry, making it quite difficult to collocate the data measured by two devices in both time and space, i.e., find a sufficient number of pairs of SCIAMACHY and SABER measurements corresponding to close values of time, latitude and longitude simultaneously. Therefore, the authors, first, average the initial measured data near local time 22 hours over a month and only then start the retrieval procedures. Note all mentioned algebraic equations are nonlinear. Evidently, there is a question about the correctness of the approach, but the paper does not provide an analysis of possible errors caused by such collocation of data measured by two independent instruments.”
**Response:** Thank you for this insightful comment. We agree with the reviewer that averaging the initial measured data prior to retrieval can introduce biases due to nonlinear dependence of the retrieval algorithm on input data. In our retrieval procedure, to minimize the impact of outliers and measurement noise, we employed monthly zonal medians, rather than arithmetic means. Nevertheless, the use of medians may still introduce nonlinearity-related biases, which need to be carefully evaluated.

Since SCIAMACHY and SABER have different sampling geometries, a direct collocation to quantify this bias is challenging. However, SABER provides a unique opportunity to assess this nonlinearity error, as it offers synchronous measurements of OH radiance (2um), temperature, total density, and ozone. Although the SABER 2.0um channel differs from the SCIAMACHY (9-6) transition, both emissions are dominated by the $H+O_3$ reaction, and the functional dependence of the heating rates on temperature and reactant concentrations is mathematically analogous. Therefore, we employ SABER data to evaluate the bias caused by the pre-retrieval aggregation approach. The collisional parameters employed in the retrieval are taken from Mlynczak et al. (2013).

As our objective is to quantify the error specifically introduced by the pre-retrieval aggregation approach, we focus on the relative differences between the two methods, both using data within a 22:00 LT (± 1 h) window: (1) Median of individual retrievals, where heating rates profiles are first retrieved from each individual SABER profile and then the monthly zonal median is taken within 5° latitude bins; (2) Retrieval from median profiles (our method), where the input spectral data are first aggregated as monthly zonal medians within 5° latitude bins and then used for retrieval.

This evaluation is conducted using one full year of SABER observations from 2005. Figure 1 illustrates the mean absolute relative difference (ARD) between the two methods for different seasons and latitude bands. The black, blue, and red lines represent the ARD for the heating rates of reaction (R1) $H + O_3$, reaction (R5) $O + O + M$, and the total heating rate (R1-R7), respectively. Columns correspond to winter, spring, summer, and autumn, while rows represent latitude bands centered at 60°N, 30°N, 0°, 30°S, and 60°S, each spanning ±10°.

For reaction (R1) $H + O_3$ (black line), the bias introduced by our method is remarkably small, with relative differences generally remaining below 3%. For reaction (R5) $O + O + M$ (blue line), the bias is mostly within 10%, but can occasionally reach ~15% above 95 km. The total chemical heating rates for R1-R7 (red line) show a bias generally within ~10% in the main heating region of 85-96km. The larger discrepancies (10-20%) observed at 80 km are primarily attributed to the significantly smaller heating rates at this altitude, where minor absolute deviations translate into comparatively large relative errors.

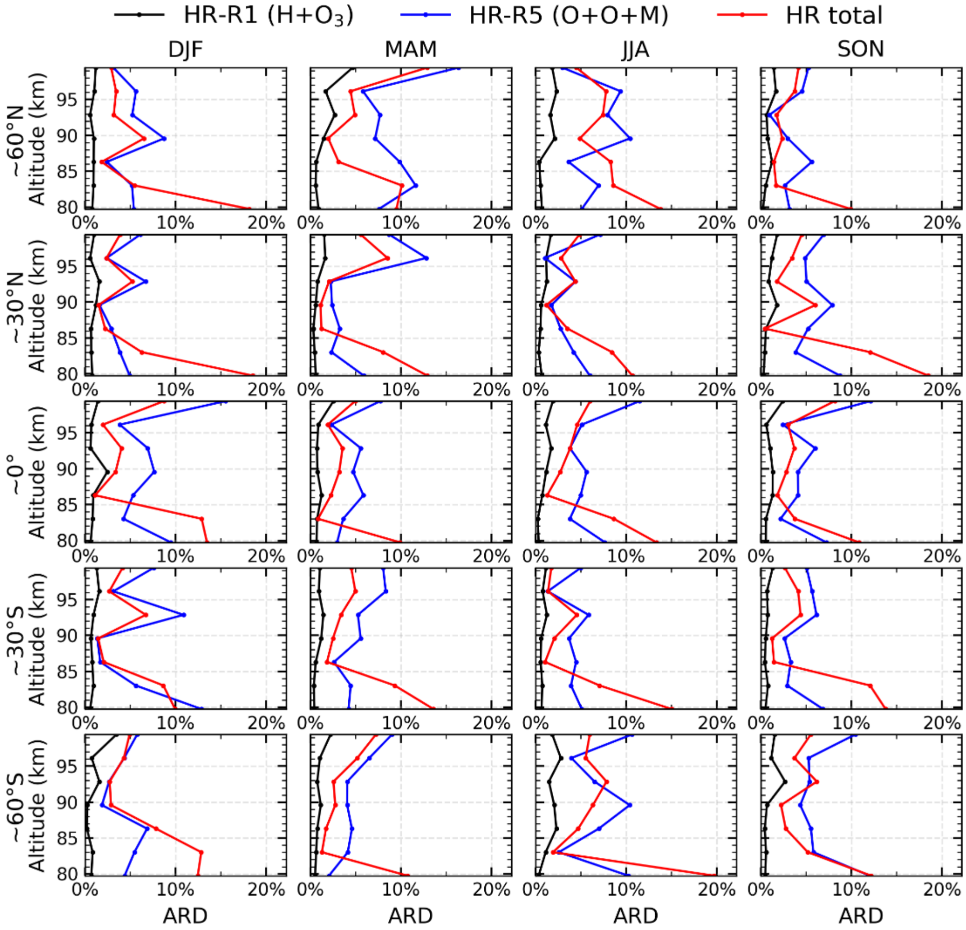

Figure 1. Mean absolute relative difference between the two methods across different seasons and latitude bands for the heating rates of reaction (R1) H + $O_3$ (black), reaction (R5) O + O + M (blue), and the total chemical heating rate (R1–R7; red).

Furthermore, to provide a statistical quantification for the uncertainty analysis in our manuscript, we calculated the annual mean of the absolute relative difference for all monthly zonal profiles in 2005, as shown in Figure 2. It shows that for the H + $O_3$ reaction, the bias introduced by our retrieval strategy remains below 3%. For the O + O + M reaction, the bias is generally within 10%. The bias for the total chemical heating rate is within 5-15%.

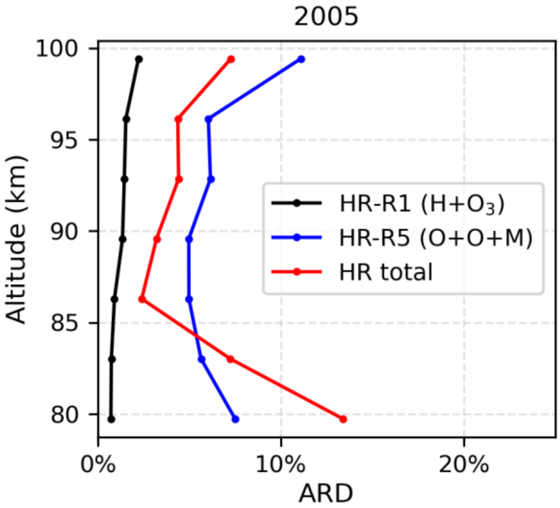

Figure 2. Annual mean absolute relative difference between the two methods for all monthly zonal profiles in 2005 for the H + $O_3$ heating rate (R1), the O + O + M heating rate (R5), and the total chemical heating rate (R1–R7).

Comparing these uncertainty values with the uncertainties induced by other retrieval parameters presented in Section 3.1 (e.g., temperature and quenching rates), we find that the error introduced by the pre-retrieval median approach is smaller than those associated with other dominant sources of uncertainty (30%-60%). Therefore, the systematic bias caused by the non-linearity of the aggregation process is relatively minor and does not significantly affect the main conclusions of this study.

Revisions in the manuscript:

The discussion of the nonlinearity-induced uncertainty has been incorporated into Section 3.1 (Uncertainty analysis) and Appendix A (Lines 380-409). The error bars in Figure 1 of the revised manuscript have been updated accordingly.

Lines 191-193: “In addition, the use of monthly zonal median data prior to retrieval can introduce biases due to the nonlinear dependence of the retrieval algorithm on its inputs. This nonlinearity-induced uncertainty is evaluated using synchronous SABER observations, as detailed in Appendix A.”
Line 205: “The nonlinearity-induced uncertainty is estimated to be below 3%”
Line 212: “The nonlinearity-induced uncertainty is approximately 10%”
Line 220: “The nonlinearity-induced uncertainty is in the range of 5-15%.”
Lines 380-409: See Appendix A of the revised manuscript for details.

2. “The authors compared new CHR data with SABER data and revealed essential systematic differences. At the same time, the article does not provide convincing reasons to believe that the quality of the new CHR data is better than SABER CHR data, which exceeds significantly the new data in spatiotemporal resolution.”
**Response:** Thank you for this comment. We fully agree and acknowledge that the SABER dataset possesses significantly superior spatiotemporal resolution compared to SCIAMACHY. However, the use of SCIAMACHY also has its own distinct advantages.

Compared to SABER chemical heating retrievals based on the 2.0 um OH emission, our retrieval using SCIAMACHY OH (9-6) emissions rely on a simpler and more direct photochemical model. This approach depends on fewer dynamical and spectroscopic parameters and therefore minimizes the propagation of uncertainties associated with multi-step cascade modeling.

In addition, it is scientifically valuable to have more than one determination of the heating rate. This is especially the case since there are few observations and many potential sources of uncertainty. SCIAMACHY provides measurements independent of SABER, serving as an independent constraint. Even when using identical background atmospheres, systematic differences remain in the retrieval results, which is a crucial scientific finding, representing the systematic uncertainties arising from instrumental and retrieval parameters (Zhu et al., 2018, 2020; Wu et al., 2025). Therefore, the value of this new dataset is not to claim one dataset is definitively better, but to provide a new dataset for reference and discussion, helping the community better understand the uncertainties in the mesopause energy budget.

We have added statements on the research motivation in revised manuscript:

Lines 72-74: “Given the considerable uncertainties in deriving heating rates from airglow observations, independent determinations using different instruments and retrieval approaches are essential for characterizing systematic biases and building confidence in the results.”
Lines 349-352: “The retrieval using OH (9-6) emissions relies on a relatively simple and direct photochemical model, which depends on fewer dynamical and spectroscopic parameters and therefore minimizes the propagation of uncertainties associated with multi-step cascade modeling.”
Lines 365-368: “Even when using identical background atmospheres, systematic differences remain in the retrieval results, which is a crucial scientific finding, representing the systematic uncertainties arising from instrumental and retrieval parameters (Zhu and Kaufmann,2018; Wu et al., 2025).”
Lines 372-374: “Since there are few observations and many potential sources of uncertainty involved, having more than one independent determination of the heating rate is scientifically valuable. SCIAMACHY provides measurements independent of SABER and thus serves as an important observational constraint on UMLT chemical heating.”

3. “In addition, there are no restrictions on obtaining CHR data at the altitudes of 80-85 km, where, according to Kulikov et al. (ACP, 2023, 2024), the equilibrium conditions of nighttime O3, OH, and HO2 may be disturbed.”
**Response:** Thank you for this helpful comment. We agree that at the altitudes of 80-85 km, dynamical transport can significantly perturb the nighttime chemical equilibrium of $O_3$, OH, and $HO_2$, as discussed by Kulikov et al. (2023, 2024). This limitation was not sufficiently discussed in our manuscript.

Our retrieval is based on SCIAMACHY OH (9-6) emission, which is directly proportional to the production rate of OH(v) via reaction (R1) H + $O_3$, as described in Eq. (1) of the manuscript. Although [O] in the loss term is derived assuming ozone equilibrium, at 80-85 km the quenching of OH(v) is dominated by collisions with $N_2$ and $O_2$, while quenching by O is 2-3 orders of magnitude smaller (Smith et al., 2010, Fig.1). As a result, the inferred reaction rate for (R1) H + O3 and its associated heating rate are relatively insensitive to deviations from the ozone equilibrium assumption at this altitude range. Consequently, the retrieved [H] is also only weakly affected by the ozone equilibrium assumption.

In contrast, the densities of O, OH, and $HO_2$ derived from chemical equilibrium relationships are more sensitive to the validity of the equilibrium assumption. This can introduce larger uncertainties in the heating rates for reactions (R3-R7) at 80-85 km. However, for (R5) O +O +M, our primary focus is on its dominant heating layer located above 85 km (Fig. 3 in our manuscript), and thus the main results for this reaction are largely unaffected.

For the total chemical heating at 80-85 km, uncertainties may be larger due to the partial contribution of reactions relying on equilibrium assumptions. Nevertheless, since reactions R1 and R2 together account for roughly half of the total chemical heating in this altitude range, the results still can provide a reasonable estimate of the magnitude of chemical heating.

Revisions in the manuscript:

We have discussed the potential impact of this limitation on our retrieval results in Section 3.1 (Uncertainty analysis) in Lines 222-232:

"It should be noted that the retrieval relies on the assumption of chemical equilibrium for $O_3$, OH, and $HO_2$. This assumption may not hold in the 80-85 km altitude range, depending on season and latitude (Kulikov et al., 2018, 2023, 2024). However, the retrieved [H] and the heating rate of Reaction (R1) are only weakly affected. This is because the reaction rate $k_1[H][O_3]$ is determined by the observed OH (9-6) emission and the total OH (v = 9) loss rate. At 80-85 km, the total loss rate is dominated by radiative decay and quenching by $O_2$ and $N_2$, while the contribution from atomic oxygen quenching is two to three orders of magnitude smaller (Smith et al., 2010, Fig. 1). Thus, errors in [O] caused by the equilibrium breakdown do not significantly propagate to the R1 heating rates. In contrast, the densities of O, OH, and $HO_2$ derived from chemical equilibrium relationships are more sensitive to the validity of the equilibrium assumption, potentially introducing larger uncertainties in the heating rates for Reactions (R3-R7) at 80–85 km. Nevertheless, for Reaction (R5) O + O + M, our primary focus is on its dominant heating layer located above 85 km, and thus the main results for this reaction are largely unaffected."

## Specific comments:

1. Lines 110-115. The authors claim that the chemical production and loss of nighttime

ozone are in equilibrium within the range 80–96 km and further apply this assumption to the chemical heating rate retrieval in this altitude range. This contradicts the results of Kulikov et al. (JGR 2018, ACP 2023) showing that the lower boundary of the ozone balance depends on the season and latitude and can be located at an altitude of several kilometers above 80 km. In particular, Kulikov et al. (ACP 2023) presented the spatiotemporal evolution of this boundary retrieved from the SABER/TIMED data in 2002–2021. Below, one can see the time evolution of monthly mean altitude of this boundary at different latitudes reprinted from Figure 11 of the paper.
**Response:** Thank you for this comment. We agree that our previous statement implying ozone chemical equilibrium across ~80-96 km was not sufficiently precise. As shown by Kulikov et al. (2023), the lower boundary of nighttime ozone chemical equilibrium depends on season and latitude and typically varies at approximately 80-85 km.

However, as discussed in our response to Major Concern 3, we conducted a detailed analysis on the impact of this equilibrium assumption. The results indicate that the dominant heating source, reaction (R1) H + $O_3$ is only weakly affected by this assumption at 80-85km. While for reaction (R5) O + O + M and the total chemical heating rates, deviations from ozone equilibrium may introduce additional uncertainty; however, the altitude region below 85 km does not correspond to the main heating region and therefore does not significantly affect our primary conclusions.

We have revised lines 138-143 to explicitly acknowledge that the lower boundary of ozone chemical equilibrium is variable and can rise above 80 km depending on season and latitude. We have also added a discussion in Section 3.1 (Uncertainty analysis), Lines 222-232, to clarify the impact of this limitation on our retrieval results.

Lines 138-143: "Recent studies indicate that the lower boundary of the nighttime ozone chemical equilibrium depends on season and latitude and can be located several kilometers above 80 km (Kulikov et al., 2018, 2023). The potential impact of deviations from chemical equilibrium is discussed in Sect. 3.1 and is found to be limited for the primary heating structures considered in this study. Therefore, we adopt 80 km as the nominal lower boundary for the retrieval. Under this equilibrium assumption, the following relation holds:"

2. Lines 122-127. The authors noted here: "These densities are inferred assuming chemical equilibrium, with the lower boundary altitude ranging from 73 to 85 km depending on season and latitude (Kulikov et al., 2024b)." Nevertheless, as one can see from text and Figures of this paper, the chemical heating rate is calculated in the altitude range of 80-96 km, regardless of season and latitude.
**Response:** Thanks for this comment. Because direct measurements of atomic oxygen and hydrogen in the 80-100 km region are challenging, the assumption of ozone chemical equilibrium is commonly adopted in retrieval studies (e.g., Smith et al., 2010; Xu et al., 2012; Mlynczak et al., 2013, 2018). In addition, the chemical heating from the dominant exothermic reaction H + $O_3$ is only weakly sensitive to the ozone

equilibrium assumption at 80-85 km, making it reasonable to start the retrieval at 80 km.

However, we acknowledge that the breakdown of ozone equilibrium at 80-85 km may significantly affect the inferred [O], [OH], and [$HO_2$] and the associated chemical heating rates.

We have added a discussion in Section 3.1 (Uncertainty analysis), Lines 222-232, as shown above in Major Concern 3, to clarify the impact of this limitation on our retrieval results.

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Xu, J., Gao, H., Smith, A. K., and Zhu, Y.: Using TIMED/SABER nightglow observations to investigate hydroxyl emission mechanisms in the mesopause region, *J. Geophys. Res.-Atmos.*, 117, D02103, https://doi.org/10.1029/2011JD016342, 2012.

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Zhu, Y., Kaufmann, M., Chen, Q., Xu, J., Gong, Q., Liu, J., Wei, D., and Riese, M.: A comparison of OH nightglow volume emission rates as measured by SCIAMACHY and SABER, *Atmos. Meas. Tech.*, 13, 3033–3042, https://doi.org/10.5194/amt-13-3033-2020, 2020.

# Response to Referee #2

## General comment:

A general comment would be to add a few more sentences on the magnitude of the other relevant heating terms (diabatic solar heating, impact of breaking GW, adiabatic heating) and perhaps also radiative cooling terms. This will allow the reader to better appreciate the importance of the chemical heating in the mesopause region.
**Response:** Thank you for this helpful comment. We have revised the Introduction to include a comparative overview of the major energy budget terms in the mesopause region. Recognizing that these terms vary with altitude, we focus on representative peak magnitudes within the 80-100 km altitude range to provide context. Specifically, we include estimates of radiative cooling, solar heating, chemical heating, and dynamical effects. This comparison highlights the important role of chemical heating in the region's energy budget.

The revised text is provided below (Lines 25-39):

“To better appreciate the importance of chemical heating in the mesopause region, we consider representative peak magnitudes of the major energy budget terms in the 80-100 km altitude range. Radiative cooling in this region is dominated by $CO_2$ 15 µm emission, with magnitudes typically ~15 K/day (States et al., 2000; Mlynczak et al., 2022, 2024). This cooling is balanced by various heating terms. The diurnally averaged solar heating due to ultraviolet absorption by $O_2$ and $O_3$ typically amounts to ~10 K/day, while chemical heating rates are estimated to reach magnitudes of ~10-15 K/day (Mlynczak and Solomon, 1993; Mlynczak, 2000). Regarding dynamical effects, processes such as gravity wave breaking and adiabatic motions can produce large local heating or cooling rates, reaching several tens of K/day in localized layers or during transient events (e.g., Lübken, 1997; Gardner and Yang, 1998; Vincent, 2015; Grygalashvyly et al., 2024). However, on a global and annual mean basis, the total energy input from solar radiation and chemical reactions is generally considered sufficient to account for the radiative cooling by $CO_2$ (Mlynczak et al., 2013, 2018), while the net contribution of dynamical effects is estimated to be relatively small.

Given the significant contribution of chemical heating to the energy budget, accurate quantification of its rates is crucial. Furthermore, such quantification provides important insights into mesospheric inversion layers (Ramesh et al., 2017) and enables energetic constraints on the concentrations of key reactive species, such as atomic oxygen (Mlynczak et al., 2013)."

## Specific comments:

Line 9: "accounting for roughly one-third to one-half of the total heating above ~86 km."

The total chemical heating or the total overall heating (including GW and solar?). I think you only mean the chemical heating here.

**Response:** Thank you for this comment. We agree that the original wording was ambiguous and have revised the text accordingly.

Revised text (Line 9): "accounting for roughly one-third to one-half of the total chemical heating above ~86 km."

Line 21: "The stored chemical energy is subsequently released as heat through various exothermic reactions"

A certain part of it is also emitted as radiation (airglow), right?

**Response:** Thanks for pointing this out. We agree that a fraction of the stored chemical energy is emitted as radiation. The text has been revised accordingly to clarify this point.

Revised text (Line 22): "The stored chemical energy is subsequently released primarily as heat, and partly as airglow radiation, through various exothermic reactions"

Line 72: "covering latitudes typically from 30S to 50N and 0 to 80N"

This is a bit unclear? When are the different ranges covered?

**Response:** We thank the reviewer for pointing this out. First, we apologize for a typo in the original text regarding the latitude range. The text "30°S to 50°N" was incorrect; it was intended to be 50°S to 30°N. To improve clarity and reflect the full seasonal coverage, we have revised the sentence to state that the coverage varies seasonally between 50°S and 80°N.

The latitudinal region covered by SCIAMACHY limb observations varies seasonally, as shown in Figure 1. This variation is driven by the seasonality of solar illumination geometry. Furthermore, these measurements do not cover the entire latitude range on the night side of the Earth, because blocks of limb measurements are interrupted by calibration measurements (Bovensmann et al., 1999). Specifically, the coverage of 0° to 80°N corresponds to the Northern Hemisphere winter, while the coverage of 50°S to 30°N corresponds to the Northern Hemisphere summer.

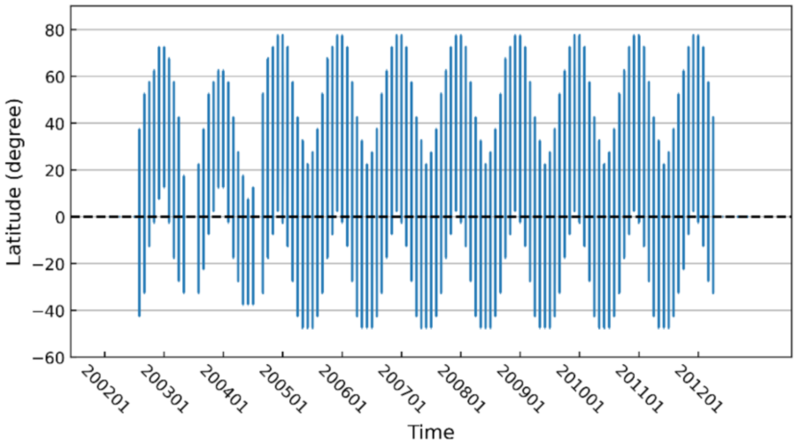

Figure 1. Latitude coverage of SCIAMACHY limb nighttime observations. (Sui et al., 2024)

Revised text (Lines 87-88): “The latitudinal region covered by SCIAMACHY limb observations varies seasonally between 50°S and 80°N, depending on the solar illumination geometry and calibration measurements performed on the night side of the satellite orbit (Bovensmann et al., 1999; Sui et al., 2024).”

Line 84: “the data from both instruments were processed into monthly zonal medians” How is the "median profile" determined exactly? By taking the median at every altitude? Please explain.

**Response:** Thank you for this comment. The median profile was determined by calculating the median of all valid measurements within each monthly latitude bin at each altitude level independently.

Revised text (Line 101): “the data from both instruments were processed into monthly zonal medians calculated independently at each altitude level”

Same paragraph: Due to the drifting TIMED orbit, there will only be SABER measurements on a few days per month within a 2 hour local time bin? How does this affect the analysis? It would be good to mention how many days of SABER measurements per month are used for the analysis.

**Response:** Thank you for this insightful comment. Due to the drifting TIMED orbit, SABER does not provide continuous daily sampling at a fixed local time. As a result, measurements within the 22:00 LT (± 1 h) window are available only on a limited number of days per month.

We performed a statistical analysis of the SABER sampling frequency for one example year (2005). Globally, each month contains 18-31 days with coverage within the 22:00 LT (± 1 h) window. When considering the 22:00 (± 1 h) window and 5° latitude bins, each latitude bin contains on average about 9 sampling days per month. Approximately 75% of the bins are sampled on more than 5 days, and about 40% are sampled on more than 10 days.

The primary impact of this limited sampling is the potential aliasing of short-term variability into the monthly statistics, leading to increased statistical uncertainty at individual latitude bins. However, it is unlikely to introduce a systematic bias. The sampling pattern is determined by orbital geometry rather than by atmospheric conditions, and monthly zonal medians are used instead of means, which reduces sensitivity to transient outliers.

Furthermore, the analysis focuses on monthly representative heating rate profiles and their seasonal and latitudinal variations, rather than resolving day-to-day variability at individual latitude bins. The resulting fields exhibit coherent and smooth large-scale patterns, consistent with known tidal and seasonal structures (see Figs. 2–8).

In summary, while the limited number of sampling days may slightly increase random uncertainty at some latitude bins, it does not affect the main conclusions regarding the seasonal and latitudinal structures discussed in this study.

We have added a clarification in Lines 103-109:

"Due to the precessing orbit of the TIMED satellite, SABER measurements within the 22:00 LST window are available on a limited number of days per month. A statistical analysis for 2005 shows that each month includes 18-31 days with measurements in the 22:00 LST (±1 h) window. When aggregated into 5° latitude bins, each bin contains on average about 9 sampling days per month; approximately 75% of the bins are sampled on more than 5 days, and about 40% on more than 10 days. Despite this limited temporal sampling, the use of monthly zonal medians effectively reduces the influence of short-term atmospheric variability and outliers, providing representative climatological profiles."

Line 95: "Under optically thin conditions, the volume emission rate for a transition v→v' depends linearly on the upper-state population and the corresponding Einstein A-coefficients."
I'm not sure what the intention behind this statement is, but I think that the VER itself (at a specific point in the atmosphere) depends linearly on the upper-state population and the Einstein coefficients also for non optically thin conditions.
**Response:** Thank you for pointing this out. We agree that the VER depends linearly on the upper-state population and the Einstein coefficients, regardless of the optical depth.

Our original intention was to highlight that, under optically thin conditions, radiative transfer effects (such as self-absorption) along the line of sight can be neglected, allowing the observed radiance to be directly related to the local VER.

We have revised the text to clarify this point in Lines 119-122:

"Under optically thin conditions, radiative transfer effects along the line of sight can be neglected, allowing the observed radiance to be directly related to the local volume emission rate (VER). The VER for a transition v→v' depends linearly on the upper-state population and the corresponding Einstein A-coefficients."

Equation (1): the equation is perhaps wrong. What are your units of "volume emission rate". Usually the units are photons / s / cm^3. If this is the case then the factor of E_96 is wrong. Please specify the units of VER and correct, if necessary.
**Response:** Thank you for pointing this out. The volume emission rate (VER) is defined as photons / s / cm^3. We have clarified the units in the manuscript in Line 127 and removed the factor E_96 from Equation (1).

Equations (3) and (4): How are these equations solved? (3) depends on [HO2] and (4) on [OH]?
**Response:** Thank you for this question. Equations (3) and (4) form a coupled set of algebraic equations for [OH] and [$HO_2$]. Under the assumption of local chemical equilibrium, they are solved simultaneously to obtain the two species.

We have clarified this in the manuscript in Line 154-156:

"Equations (3) and (4) form a coupled set of algebraic equations for [OH] and [$HO_2$], which are solved simultaneously under the assumption of chemical equilibrium."

Line 132: "The stored energy is released back into heat through two main pathways:" Why "back"? The chemical energy was never in the thermal energy pool, right? And: part of the chemical energy is emitted as EM-radiation (airglow).
**Response:** Thank you for pointing this out. We agree that the use of "back" was inaccurate and a portion of this energy is radiated as airglow. We have revised the sentence to remove "back".

Revised text (Line 163): "The stored energy is released primarily as heat through two main pathways"

Line 178: "The total RSS uncertainty for Reaction (R5) is estimated to be 45-60%"
Why only up to 60% if the temperature effect only already leads to uncertainties of up to 60%?
**Response:** Thank you for this comment. For most perturbation sources considered in the uncertainty analysis, positive and negative perturbations lead to comparable changes in the derived heating rates. However, the retrieval exhibits a pronounced asymmetric response to temperature perturbations. For example, at about 96 km, a positive temperature perturbation can induce a ~60% change in the R5 heating rate, whereas a negative perturbation induces a smaller response of ~30%. In our original manuscript, we used the average magnitude (~45%) as a representative uncertainty associated with temperature when estimating the RSS. While this approach captures the typical sensitivity, it does not explicitly reflect the upper bound of the uncertainty.

To address this, we have re-evaluated the total RSS by using the maximum temperature-induced perturbation for the temperature term when estimating the upper uncertainty bound. Consequently, the total RSS uncertainty range for Reaction

(R5) has been updated to 45-80% in the revised manuscript. The error bars in Figure 1 of the revised manuscript have been updated accordingly.

Revised text (Line 213): "The total RSS uncertainty for Reaction (R5) is estimated to be 45-80%"

Line 188: "for the seven chemical reactions and their total, calculated using Eq. (5)"
I suggest moving "calculated using Eq. (5)" behind "for the seven chemical reactions."
**Response:** Thank you for this suggestion. We have revised the text accordingly to avoid ambiguity.

The revised text in Line 234: "for the seven chemical reactions calculated using Eq. (5) and their total"

Line 203: "Further calculations show"
"Further calculations" are not something complicated but just adding the results for R1 to R4?
Same sentence: the total heating from the odd-hydrogen reactions does not decrease with altitude over the entire altitude range shown, right? And the total heating by the odd-oxygen reactions does not increase with altitude over the entire altitude range. Please limit the statement accordingly.
**Response:** Thank you for this helpful comment. We agree that the wording "Further calculations show" in the original manuscript was unclear and potentially misleading. In this context, "further calculations" refer to the relative contributions from the odd-hydrogen reactions (R1-R4) and the odd-oxygen reactions (R5-R7) to the total chemical heating. These relative contributions decrease and increase with altitude, respectively, over the entire altitude range shown (80-100 km).

The manuscript has been revised accordingly in Lines 252-255:

"We further evaluated the relative contributions of odd-hydrogen reactions (R1-R4) and odd-oxygen reactions (R5-R7) to the total chemical heating over the 80-100 km altitude range. The results show that the relative contribution from the odd-hydrogen reactions decreases with altitude, whereas that from the odd-oxygen reactions increases. The two contributions become comparable near 92 km."

Figure 2, 3 etc.: I suggest mentioning in the Fig. caption that the results are for 22:00 LST, because some of the signatures are tidal (as is discussed below).
**Response:** Thank you for this suggestion. We have revised the figure captions (Figures 2, 3, etc.) to explicitly state that the results correspond to 22:00 LST.

Line 226: Space missing in "atitude.In"
**Response:** Thank you for pointing this out. The missing space has been corrected in Line 271.

Line 261: “which is driven by the semiannual cycle of the migrating diurnal tide.”
It would be good to provide a reference here.

**Response:** Thank you for this helpful suggestion. We have added appropriate references to support this statement (Zhang et al., 2006; Smith et al., 2013) in Line 306.

Line 293: “These discrepancies are expected, as they directly reflect the known systematic differences in atomic oxygen and hydrogen densities retrieved from SCIAMACHY and SABER, which have been analyzed in detail by Zhu and Kaufmann (2018) and Wu et al. (2025), respectively.”
Please elaborate this a bit more. How big are the differences in [O] and [H] and what are the effects on the heating rate estimates.

**Response:** Thank you for this helpful suggestion. We have expanded the discussion to quantify the differences in atomic hydrogen and atomic oxygen and to clarify how these differences affect the heating rate estimates. Because the same background atmospheric inputs (temperature, ozone, and total number density) are used in this comparison, the R1 heating rate scales linearly with [H], so the relative differences in the R1 heating rates follow the relative differences in [H]. In contrast, the R5 heating rate scales with $[O]^2$, meaning that relative differences in [O] are amplified in the heating-rate comparison (approximately twice the fractional [O] difference, to first order).

The quantitative differences in [H] and [O] and their effects on the heating rates are described in the revised manuscript Lines 338-346:

“Under the same background atmospheric inputs (temperature, ozone, and total number density), these discrepancies are expected, as they directly reflect the known systematic differences in atomic oxygen and hydrogen densities retrieved from SCIAMACHY and SABER (Zhu and Kaufmann, 2018; Wu et al., 2025). For Reaction (R1), the heating rate is linearly proportional to the atomic hydrogen density. Consistent with the heating rate differences, the SABER-retrieved [H] is approximately 35% higher than the SCIAMACHY values at 96 km, but 20-45% lower below 92 km. In contrast, the heating rate of Reaction (R5) depends on the square of the atomic oxygen density, which amplifies the impact of differences in [O]: SABER-retrieved [O] is higher than SCIAMACHY by 5-10% at 95-96km, whereas below 90 km, SABER [O] is lower than the SCIAMACHY values by about 25-45%, leading to much larger discrepancies (40-80%) in the resulting heating rates.”

Once again, thank you for taking the time to review our manuscript and for your helpful comments.

Sincerely,
Xiaolin Wu and Yajun Zhu for all authors

## *References:*

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