

## List of relevant changes

### for the article "Forcing Mechanisms of the Terdiurnal Tide" by F. Lilienthal, Ch. Jacobi and Ch. Geißler

#### Text:

- The wavelength relation between DT, SDT and TDT has been described
- A proxy for nonlinear interactions between DT and SDT has been introduced and compared with the terdiurnal component of nonlinear forcing
- The model description has been significantly extended
- The description of phases and vertical wavelengths has been extended
- The discussion section has been significantly extended, especially with respect to earlier model studies
- An outlook for future work is given in the end

#### Figures and Tables:

- Fig. 4 has been added
- Fig. 12 has been corrected (same figures like in Fig. 10 were included in the earlier version)

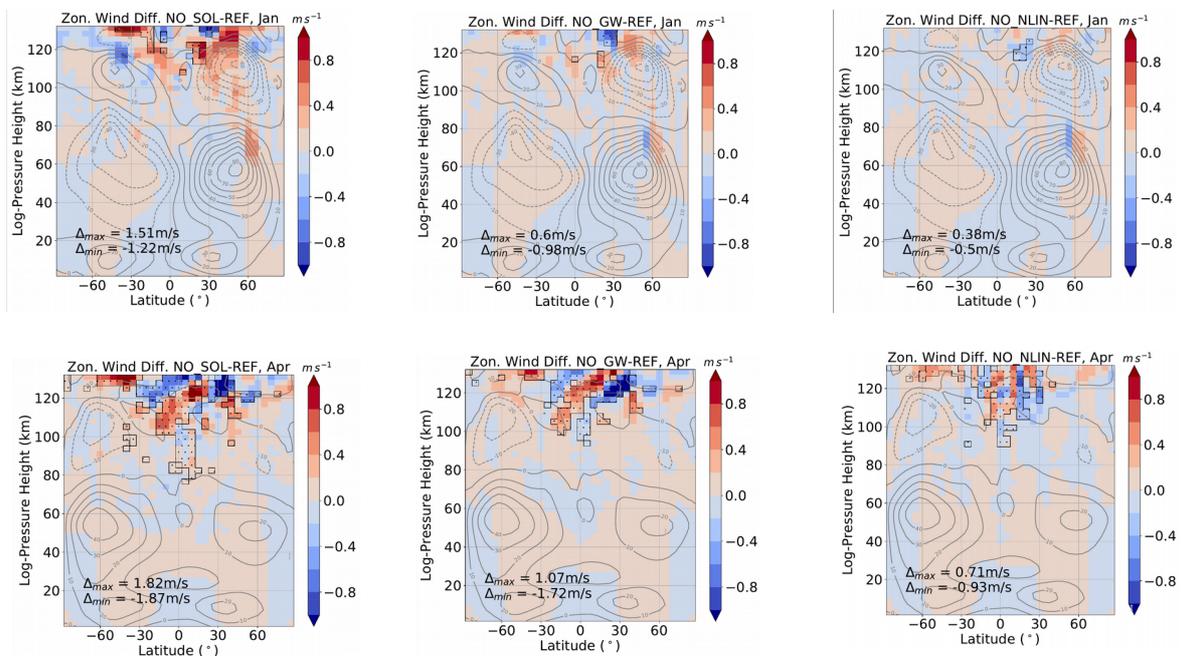
## Response to Reviewer#1

for the article "Forcing Mechanisms of the Terdiurnal Tide"  
by F. Lilienthal, Ch. Jacobi and Ch. Geißler

Again, we would like to thank the anonymous reviewer for his comments to help improve the manuscript. The reviewer's comments are repeated here in *italic*, our answers are noted below. Quotes of text passages are given with page number (P) and line numbers (L) of the revised manuscript.

*My main comment is: From the manuscript, it was not completely clear to me whether removing of forcings would alter the atmospheric background and whether an altered background could have some effect on the TDT in addition to changes in the forcing.*

In the following figures, we show the difference of the zonal mean zonal wind for the simulations NO\_SOL-REF, NO\_GW-REF and NO\_NLIN-REF for January and April. Significant changes are hatched. Contour lines show the zonal mean zonal wind in the REF simulation. The changes amount to not more than 2m/s.



Largest differences are obtained in July and reach almost 10m/s in NO\_NLIN, 6.5m/s in NO\_GW and 8m/s in NO\_SOL. These values are still of the same order like the inter-annual variability of the model (see Fig. 1 in the manuscript).

As already mentioned in our short answer on 30 May 2018, we conclude that the influence on the background circulation is relatively small when one of the forcings is removed.

We added the following sentences:

"Note that the background (monthly mean zonal mean) circulation is not significantly altered when TDT forcings are removed (not shown here). Differences amount to not more than the actual standard deviations in the REF simulation (Fig. 1). Therefore, the influence of a removed wavenumber 3 forcing is comparable to the year-to-year variation of the background state and propagation conditions for tides remain similar." (P5L1-P5L4)

1. p.2, l.7/8:

*Miyahara and Forbes (1991) used a modified Lindzen parameterization to investigate the interaction between gravity waves and tides. In this approach gravity wave physics was very simplified. It should be mentioned that more recent simulations show that details of gravity-wave tidal interactions can change if more comprehensive physics is included (for example, Ribstein and Achatz, 2016).*

Thank you for this helpful reference. It is now included in the introduction:

"Another possible excitation source are gravity wave-tidal interactions (e.g., Miyahara and Forbes, 1991; Huang et al., 2007). More recent simulations (Ribstein and Achatz, 2016) show that details of gravity wave-tidal interactions can change if more comprehensive physics is included but their analysis do not include the TDT." (P2L19-21)

2. p.3, l.9/10: Please explain in more detail:

*Why do you want to avoid the coupling between stationary planetary waves and tides?*

We added the following sentence:

"This is important because an additional secondary coupling with planetary waves leads to a more complex situation with a more complicated quantification of the individual forcing effects." (P3L23-25)

3. p.3, l.11:

*Which gravity wave parameterization is used in your simulations?*

We shifted a few sentences about the GW parameterization from the end of this section to where the parameterization is first mentioned:

"Gravity waves are calculated by an updated Lindzen-type parameterization (Lindzen, 1981; Jakobs et al., 1986) as described by Fröhlich et al. (2003b) and Jacobi et al. (2006). Due to the fact that this parameterization does not account for ionospheric effects, it is coupled with a modified parameterization after Yiğit et al. (2008), connected via the eddy diffusion coefficient which is calculated in the Lindzen scheme and then transferred to the Yiğit scheme. Gravity waves with phase speeds of 5-30 m s<sup>-1</sup> are handled by the Lindzen scheme while the Yiğit scheme is restricted to phase speeds of 35-105 m s<sup>-1</sup>. This way, the Lindzen-type parameterization affects the stratosphere and mesosphere and the Yiğit parameterization mainly takes effect in the thermosphere. Overlaps between both parameterizations are small and the forcing terms due to gravity waves are summed in the tendency equation of the model. Further parameterizations of solar and infrared radiation as well as several ionospheric effects such as Rayleigh friction, Lorentz force and ion drag are included." (P3L28-P4L3)

4. p.3, l.27:

*The statement "The last source might be gravity waves" sounds too weak! There is evidence for the interaction between gravity waves and tides. For example, on p.3, l.28, it could be mentioned that, indeed, a longitudinal variation of gravity wave activity in the tropical MLT region has been observed that may be caused by an interaction between tides and gravity waves (Trinh et al., 2018, their Fig.4).*

The sentence has been rewritten accordingly:

" The last source included in MUAM are gravity waves. Miyahara and Forbes (1991) have shown that an interaction between gravity waves and the DT can excite a TDT. Trinh et al. (2018) observed a longitudinal variation of gravity wave activity in the tropical MLT region that may also be caused by gravity wave-tidal interaction." (P4L23-26)

5. p.3, l.34:

*Latent heat release in the troposphere has a zonal wavenumber 3 structure. Do you think that this latent heat release could contribute to the forcing of the migrating TDT as was speculated by Pancheva et al. (2013)?*

Of course, latent heat is a possible source of wavenumber 3 tides, namely the TDT. However, we focus on zonal mean dynamics here. Latent heat is strongly dependent on longitude and will also excite nonmigrating tides. This is beyond the scope of this manuscript.

6. p.4, l.2: *Please clarify!*

*I think that eliminating each forcing separately is a good approach! However, does eliminating of forcings alter the atmospheric background state? If it does: How do you avoid that changes in the background state cause some variations in the TDT that are then attributed to changes in the forcing mechanisms? Or are variations of the background state negligible compared to the effect of variations in the TDT forcing?*

Please see the answer for your main (first) comment.

7. p.5, l.19/20:

*Please clarify whether the forcing at all zonal wavenumbers is "switched off" for the CTRL run.*

The sentence has been rewritten as follows:

"As a control simulation (CTRL), the wavenumber 3 component of the solar, nonlinear and gravity wave forcings are removed simultaneously." (P6L18-19)

8. p.6 about Figs. 2 and 3:

*Please explain: why are values scaled with the density factor? I think that unscaled values would be more intuitively related to TDT amplitudes in K or m/s.*

We included the following sentence for clarification:

"All forcing terms are scaled by density (factor  $\exp\{-z/(2H)\}$ ) in order to highlight the region where the forcing originates from. Therefore, the figures show the source region of tidal excitation but they do not provide any information about propagation conditions." (P7L11-13)

Note that reviewer #2 has raised a question concerning the magnitude of the solar heating in comparison to earlier model studies. To answer his question we added figures of the unscaled solar heating. However, we did not include them in our manuscript because we think that the unscaled values do not tell much about the actual forcing region.

9. p.9, l.28/29:

Here you write that "The structure of this remaining tide is not completely irregular indicating that it is possibly not owing to noise."

Still, noise could be the driver of this tidal structure. Please note that even the numerical noise of a GCM dynamical core can cause "regular oscillations". For example, it has been noted by Rind et al. (2014) that numerical noise can cause QBO-like oscillations in a model.

Thank you for these information and the helpful reference. We think that it is better to put the discussion of the CTRL amplitudes into the discussion section and therefore we removed the speculation about noise at this point. In the discussion section we modified the next-to-last paragraph as follows:

"Rind et al. (2014) have noted that numerical noise can produce regular signatures like a quasi-biennial oscillation. Therefore, noise cannot be excluded as a tidal source in the CTRL simulation. Another reasonable TDT source in our model could be originating from the thermospheric parameterizations, which include some nonlinear terms. These sources, however, are likely to be dependent on the used model and it is not likely that the remaining amplitudes in Fig. 13 have a real meteorological meaning." (P13L13-17)

### Technical Comments

- p.1, l.17: suggestion for clarification: higher wavenumbers → higher wavenumbers / higher frequencies
- p.2, l.19: have been → were
- p.3, l.33: owing to → excited by
- p.5, l.14: attributes the thermosphere → takes effect in the thermosphere
- p.5, l.25: ensembles = years ?
- p.7, l.23: is smaller. → is lower.

All your technical comments have been addressed, accordingly.

## Response to Reviewer#2

for the article "Forcing Mechanisms of the Terdiurnal Tide"  
by F. Lilienthal, Ch. Jacobi and Ch. Geißler

Again, we would like to thank the anonymous reviewer for his comments to help improve the manuscript. The reviewer's comments are repeated here in *italic*, our answers are noted below. Quotes of text passages are given with page number (P) and line numbers (L) of the revised manuscript.

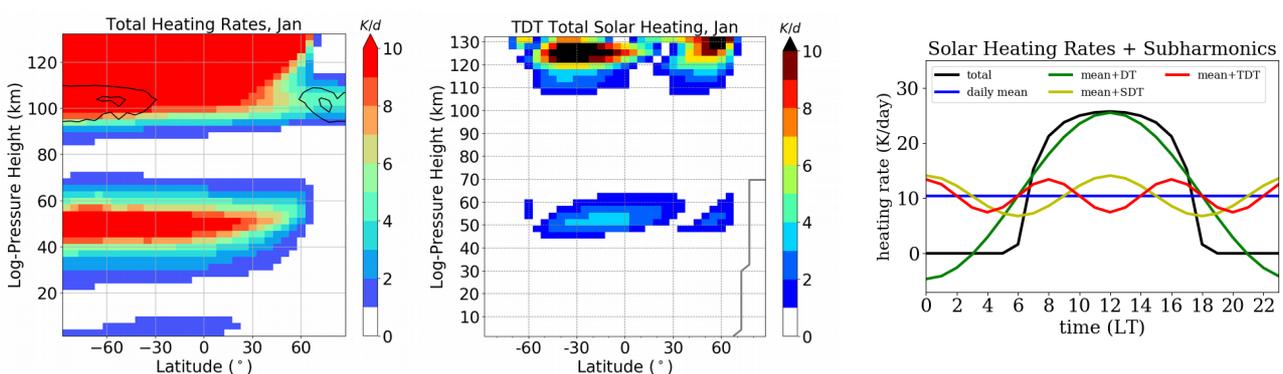
### General concerns:

*The solar forcing in the this model (discussion on Pg 7, lines 204 to 206) has a similar form (Figure 2) to that published in Smith and Orland (2001) and Du and Ward (2010) but is over an order of magnitude smaller. The UV heating parameterizations in these models are the same as the one used in the current paper. Furthermore, in the discussion of the terdiurnal amplitudes (pg 8-9, lines 257 to 285) the model amplitudes are generally significantly smaller than those observed. They are also significantly smaller than the amplitudes reported by Du and Ward (2010) in their model run. These smaller amplitudes are consistent with the difference in Solar heating between this model and earlier modelling papers noted above. The authors should investigate the source of these differences and confirm that the heating in the model is correct. Issues with the heating will affect the later sections of the paper so I have not commented on Sections 3.2 and 4.*

Please note that the solar heating rates presented in Fig. 2 are scaled by density, i.e. they are multiplied by the factor  $\exp\{-z/(2H)\}$ . The unscaled solar heating has a magnitude that is comparable to those presented by Smith and Orland (2001) and Du and Ward (2010). The following figures show the unscaled zonal mean heating rates (left), TDT component of unscaled solar heating rates (middle) and the decomposition of daily solar heating rates at 2.5°N/50km into its daily mean and tidal components which are centered around the mean value (right). We hope to convince you that the solar radiation parameterization in the model works correctly.

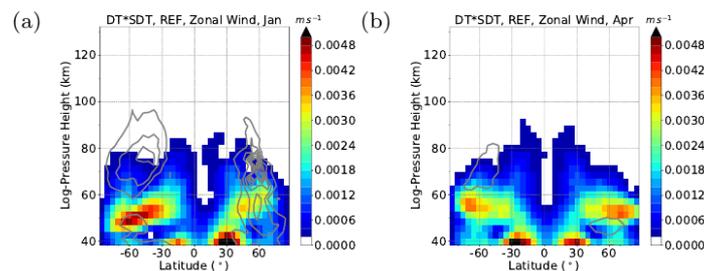
In order to avoid confusion, we mention the scaling at several additional text passages to remind the reader, e.g.:

"Figures 2 and 3 show the terdiurnal component of all forcing terms that our analysis takes into account, namely solar forcing, nonlinear forcing and forcing due to gravity wave-tide interactions. All forcing terms are scaled by density (factor  $\exp\{-z/(2H)\}$ ) in order to highlight the region where the forcing originates from. Therefore, the figures show the source region of tidal excitation but they do not provide any information about propagation conditions." (P7L10-13)



*Some discussion of the amplitudes of the diurnal and semi-diurnal tides in this model should be included. In particular, if non-linear interactions are indicated at a particular height it is important to know what the form of the parent waves is (i.e. the diurnal and semidiurnal tides). It is also possible that although there may be indications of nonlinear forcing that this forcing might not result in a propagating tide. In addition to the relationship between periods noted in this paper, there are also relationships between the horizontal and vertical wavelength that should be met for the forcing to result in a propagating component (see Teitelbaum and Vial, JGR, 1991). Consideration of these aspects of the forcing should also be discussed.*

We think that an extensive discussion of DT and SDT amplitudes exceeds the topic of the manuscript. However, we understand your concern about the existence of parent waves and want to address this issue by an additional analysis. We use the product of DT and SDT amplitudes as a proxy for nonlinear interactions which produce a TDT and we find similarities with the nonlinear forcing. Fig. 4 and a paragraph in section 3.1 have been added:



"As described above, the nonlinear terdiurnal forcing is a result of interactions between the migrating DT and the migrating SDT. These interactions can only take place if both, DT and SDT, have a considerable amplitude. To test this relation between the different subharmonics, the product of DT and SDT amplitudes serves as a proxy for the terdiurnal nonlinear forcing. Due to the fact that the forcings in Figure 3 are scaled by density, we also scaled the DT and SDT amplitudes before multiplying to show the source region of the tides. An example is shown in Figure 4 for zonal wind amplitudes. Note that amplitudes are only shown above 40 km because scaled amplitudes in the troposphere and lower stratosphere have a higher order of magnitude.

It can be seen that the product of scaled DT and SDT amplitudes reveals a similar structure like the nonlinear zonal forcing of the TDT. Both have increased branches near 50 km extending from low latitudes poleward to high latitudes and with a minimum over the equator. Such a good accordance is not seen in all parameters but the multiplied amplitudes in Figure 4 only serve as proxy. The pure existence of an overlapping DT and SDT source region does not necessarily induce an interaction." (P7L34-P8L9)

*The authors provide useful and interesting comparisons between their results and observations. Previous modelling studies are mentioned but there is no explicit comparison between the results of this paper and the previous modelling studies (i.e. latitude/height amplitudes and phases, annual variations, forcing mechanisms). This comparison is needed and would provide the reader with a better idea of how this paper advances the field.*

Thank you for this hint. We extended the discussion session and added a comparison between our results and earlier model studies (see section 4: Discussion and Conclusion).

## Issues about the model setup:

*Were there any background winds imposed during the runs?*

No, the background winds can freely develop in the model. There is only the nudging of zonal mean temperatures to correct the troposphere and lower stratosphere. This may also influence the background winds to balance the dynamics but there is no explicit forcing.

"The background winds can freely develop in the model and are only indirectly influenced via the zonal mean temperature nudging." (P3L18-19)

*Are the runs used for each month, perpetual runs for that month (i.e. no temporal evolution with the Solar elevation angle remaining constant)? Are the results for the last 30 days stable results (i.e. the model run had achieved some sort of equilibrium) and how was this determined?*

The solar elevation angle has a diurnal cycle. This is necessary for the excitation of tides. However, the zenith angle is kept constant for the first day of the respective month. This means that each model day has the same solar conditions. Therefore, each of the last 30 model days (=analysis period) is more or less equal. The background dynamics (daily mean zonal mean) remain constant and tidal amplitudes do not significantly change any more. Indeed, the number of 30 days for the analysis of each run is arbitrary. It could be 5 days, as well. The use of 30 days is just a relict of other model versions that include the daily change of zenith angle and, therefore, represent day-to-day changes during each month.

"In this model version, the sun's zenith angle does not account for day to day variations and refers to the first day of the respective month. The solar elevation angle, however, includes a diurnal cycle to account for tidal forcing." (P4L9-11)

*The authors state that there was no planetary wave forcing at the lower boundary. Was any forcing at the lower boundary included?*

No, there is no explicit wave forcing at all. At the lower boundary, only zonal mean temperature from ERA-Interim reanalysis is introduced.

"In the present version, there is no additional lower boundary forcing." (P3L19)

*How was the boundary between the free running part of the model and the nudged portion handled (step function or gradual change)?*

In the temporal dimension, the nudging is increasing gradually from the first time step and it is completely introduced after model day ~15 (see figure below). In the spatial dimension, the nudging is fully included in the first 10 height levels, and, like a step function, the nudging is zero above.

"MUAM extends from the surface (1000 hPa) to the lower thermosphere while the zonal mean temperatures in the lower 30 km (i.e. at the lower boundary and 10 height levels above) are nudged towards monthly mean ERA-Interim reanalyses of zonal mean temperature." (P3L15-17)

*When the tidal forcing started to be included, how was this made compatible with the nudging?*

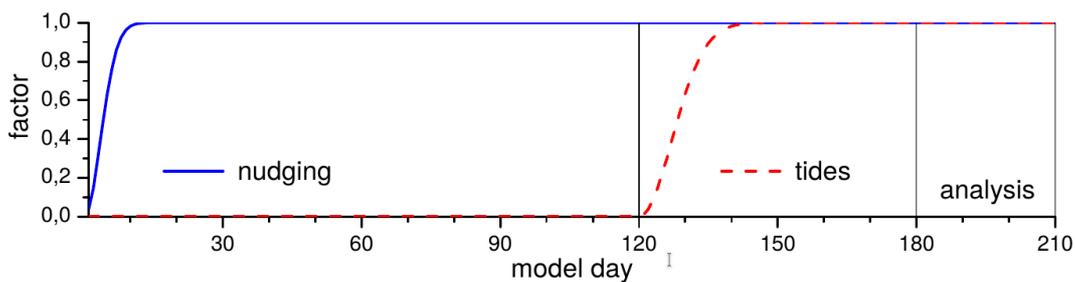
The nudging only influences the zonal mean temperature in the troposphere and lower stratosphere. Therefore, tides are not directly affected by the nudging. They may be indirectly affected as the propagation conditions depend on background dynamics, which are guided by the nudging in the lower 30km. However, the nudging also provides more realistic wave propagation conditions.

"Note that this only influences the zonal mean, while waves can still develop unaffected by the nudging." (P3L17-18)

"Note that the nudging in the troposphere/lower stratosphere is still active during that period and the model is not running completely free at any time. This, however, does not influence the tides because the nudging does only account for zonal mean temperature." (P4L13-15)

*Is the tidal forcing turned on gradually? Is the turning on of the tidal heating a step function?*

The heating rates start to be zonally variable at model 120. They are gradually increasing and reach the full tidal forcing at model day ~150. The following figure shows the temporal evolution of the nudging and tidal variation of solar heating. A factor of 1 refers to full implementation.



"In the subsequent 90 model days, heating rates are allowed to be zonally variable and tides start to propagate, gradually increasing in time. The heating rates are fully introduced after model day 154." (P4L8-9)

*How was the nudging undertaken for the 11 ensemble experiments (page 3) daily zonal means)?*

The nudging is only based on monthly mean zonal mean temperature data, not on daily mean zonal means. For each month and for each year of the ensemble we perform a different run with different monthly mean reanalysis data. With 12 months and 11 years, we get a total number of 130 different model runs. For each month, the results of the 11 years are analyzed with respect to their mean value and standard deviation.

#### **Additional comments:**

*Pg 4 line 113: What is meant by "... remove it in each model time step.". Does this mean that the wave number 3 signature is removed from the model run at each time step at each point in the model?*

Yes, this is true. We modified the sentence to:

"In order to separate these different mechanisms we analyze the wavenumber 3 component of

the respective forcing and remove it in each model time step for each latitude/altitude, separately." (P4L27-28)

And similar:

"For the analysis of the forcing mechanism we subtract the wavenumber 3 amplitude from the total heating for each time step and each latitude/altitude, separately." (P5L15-16)

*Pg 4, line 116: Include a reference to justify your decision to ignore non-migrating tides based on the source of nonmigrating tides?*

We want to point out that we do not ignore nonmigrating tides. They are simply not represented in the model because there is no non-zonal structure included which could enhance a nonmigrating tide. We added a reference for the sources of nonmigrating tides.

"This is because nonmigrating tides are usually excited by orographic sources, latent heat release or other geographically fixed effects (e.g., Andrews et al., 1987). Note that atmospheric gases such as water vapor or ozone are only included as zonal means which is different from other versions of MUAM (e.g., Ermakova et al., 2017). Therefore, we usually refer to the migrating TDT here." (P4L30-33)

*Pg 4, line 123: Please comment on whether ozone is included above 50 km. Is there a step function in the vertical profile of ozone?*

We extended the description of the ozone data as follows:

"The parameterization of solar heating in the middle atmosphere is calculated following Strobel (1978). It considers heating due to the most important gases such as water vapor, carbon dioxide, ozone, oxygen and nitrogen. The zonal mean ozone fields up to 50 km altitude are taken from the Stratosphere-troposphere Processes And their Role in Climate project (SPARC; Randel and Wu, 2007). Above 50 km, the ozone mixing ratio decreases exponentially. The second ozone maximum near 90 km is not included. Different from Jacobi et al. (2015), we restrict our simulations to ozone data of the year 2005 because we do not intend to perform a trend analysis." (P5L5-10)

*Pg 4, line 128: This should be recombination of O and O3.*

The recombination processes after Riese et al. (2004) are the following:

$O + O + M \rightarrow O_2 + M$

$O + O_2 + M \rightarrow O_3 + M$

Therefore, O<sub>2</sub> and O<sub>3</sub> are recombined and the text should be correct.

*Pg 6, line 168: Please explain in more detail how the two gravity wave parameterizations are linked. In most parameterizations the upward flux and dissipation is accounted for. How is the linkage between the upward fluxes between these two parameterizations made? It seems from later results (Figures 2 and 3 and discussion at line 217) that the largest effects are associated with the Yigit parameterization and must have come upward through the stratosphere and mesosphere. This should be discussed.*

We shifted a few sentences about the GW parameterization from the end of this section to the place where the parameterization is first mentioned and we extended the description:

"Gravity waves are calculated by an updated Lindzen-type parameterization (Lindzen, 1981; Jakobs et al., 1986) as described by Fröhlich et al. (2003b) and Jacobi et al. (2006). Due to the fact that this parameterization does not account for ionospheric effects, it is coupled with a modified parameterization after Yiğit et al. (2008), connected via the eddy diffusion coefficient which is calculated in the Lindzen scheme and then transferred to the Yiğit scheme. Gravity waves with phase speeds of 5 to 30 m s<sup>-1</sup> are handled by the Lindzen scheme while the Yiğit scheme is restricted to phase speeds of 35 to 105 m s<sup>-1</sup>. This way, the Lindzen-type parameterization affects the stratosphere and mesosphere and the Yiğit parameterization mainly takes effect in the thermosphere. Overlaps between both parameterizations are small and the forcing terms due to gravity waves are summed in the tendency equation of the model. Further parameterizations of solar and infrared radiation as well as several ionospheric effects such as Rayleigh friction, Lorentz force and ion drag are included." (P3L28-P4L3)

*Pg 6, line 173: Please make explicit that it is the wave number 3 component that is removed in the CTRL run.*

We modified the sentence to:

"As a control simulation (CTRL), the wavenumber 3 component of the solar, nonlinear and gravity wave forcings are removed simultaneously." (P6L18-19)

*Pg 6, line 175: To clarify your procedure, explicitly note that only solstice (January) and equinox (April) conditions are being analysed in this paper apart from Figure 6.*

We added the following sentences:

"In the following analysis, we focus on the months January and April to show solstice and equinox conditions. During this time, the TDT in MUAM is most prominent. Results for July and October are similar and therefore they are not shown, here." (P6L21-22)

*Pg 6, lines 179 - 181: Although it is mentioned earlier in the paper, restating that the ensembles consist of runs using data from each of the years 2000-2010 would make the paper clearer.*

The sentence has been modified as follows:

"The following results are given as a mean of the 11 ensemble members, owing to the nudging of reanalysis data for the years 2000-2010 (color shading) with the respective standard deviations (contour lines)." (P6L26-27)

*Pg 7, lines 215 - 218: The diurnal and semi-diurnal tidal amplitudes are small in the troposphere and the background does not include any planetary waves and is nudged to zonal mean temperatures. The tendency terms here likely do not have much to do with the terdiurnal tide and unless the authors have good reason to include discussion of the dynamics of this region, I suggest it be omitted.*

Please note that all forcing terms shown in the manuscript are scaled by density, i.e. the factor  $\exp\{-z/(2H)\}$  is applied. This way, we only show the source regions of nonlinear interactions. Based on the fact that tides are excited in the troposphere and lower stratosphere, we think that the discussion of (scaled) nonlinear forcing terms in that region is at least as important as in the mesosphere.

To avoid confusion, we added comments about the scaling at several parts of the manuscript,

repeatingly.

*Pg 7, lines 227 - 231: Tidal amplitudes are compared at different heights (90 km for the observations, 100 km for the model). Is there a reason for this?*

On the one hand, model amplitudes at 90km are very small and difficult to compare with satellite measurements. On the other hand, SABER temperature amplitudes in the literature have been presented for 90km and 110km (Pancheva et al., 2013; Yue et al., 2013; Moudden and Forbes, 2013) and therefore, we chose an altitude inbetween. This has been added in the text:

"Figure 7 presents the seasonal cycle of TDT amplitudes at an altitude of 106 km. Results of satellite data analyses have frequently been presented at 90 and 110 km (Pancheva et al., 2013; Yue et al., 2013; Moudden and Forbes, 2013), and therefore we choose an altitude inbetween." (P9L5-7)

*Pg 8, lines 251 - 256: In Figure 5, the phases are plotted from the ground to 130 km but the amplitude of the terdiurnal tide is only significant about ~80 km as indicated in Figure 4. The vertical wavelength determinations appear to be associated with this whole height range. They should only be associated with heights where the amplitude is significant. The wavelength determination should be discussed in more detail.*

We would like to keep the altitude range of the figures. The determination of destructive interferences in Fig. 11 is based on the phases, shown in Fig. 6 and 9. Fig. 11 also includes amplitude differences, scaled by density. These are also important in the troposphere and stratosphere. Therefore, these altitudes should be included and shown in Fig. 6, 9 and 11. However, the unscaled amplitudes in Figs. 5, 8 and 13 are insignificant below 80km and we do not see any reason for showing these altitudes.

The wavelength determination has not been analyzed numerically, only by interpretation of vertical phase gradients (see Figs. 6 and 9). We added a sentence describing the method.

"The TDT phases are shown in Fig. 6. At each latitude, the corresponding vertical wavelength can be obtained from the vertical phase gradient. The wavelength is taken as the vertical distance between two points of identical phases. A full span of phases should be covered inbetween, and for upward propagating waves, the phase gradient for the determination should be negative." (P8L32-34)

*I have also attached a commented pdf of the paper with some suggestions for improvements to the writing.*

Thank you very much, we carefully considered and implemented your suggestions.

# Forcing Mechanisms of the Terdiurnal Tide

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**Abstract.** Using a nonlinear mechanistic global circulation model we analyze the migrating terdiurnal tide in the middle atmosphere with respect to its possible forcing mechanisms, i.e. the absorption of solar radiation in the water vapor and ozone band, nonlinear tidal interactions, and gravity wave-tide interactions. In comparison to the forcing mechanisms of diurnal and semidiurnal tides, these terdiurnal forcings are less well understood and there are contradictory opinions about their respective relevance. In our simulations we remove the wavenumber 3 pattern for each forcing individually and analyze the remaining tidal wind and temperature fields. We find that the direct solar forcing is dominant and explains most of the migrating terdiurnal tide's amplitude. Nonlinear interactions due to other tides or gravity waves are most important during local winter. Further analyses show that the nonlinear forcings are locally counteracting the solar forcing due to destructive interferences. Therefore, tidal amplitudes can become even larger for simulations with removed nonlinear forcings.

## 10 1 Introduction

Atmospheric waves such as solar tides play a crucial role ~~for~~ in the dynamics of the mesosphere/lower thermosphere (MLT) region. ~~They~~ Tides are global-scale oscillations with periods of a solar day (24 h) or its subharmonics (12 h, 8 h, etc.). They are mainly ~~owing to the result of~~ absorption of solar radiation in the water vapor (troposphere) and ozone (stratosphere) region. Tidal amplitudes ~~are growing~~ grow with increasing height due to the decrease of density and conservation of energy (e.g., Chapman and Lindzen, 1970; Andrews et al., 1987). In the MLT, tides can reach wind amplitudes comparable to the magnitude of the horizontal mean wind.

Due to the fact that diurnal tides (DTs) and semidiurnal tides (SDTs) usually have larger amplitudes than the harmonics of higher wavenumbers/higher frequencies, they have attracted more attention in the past and are therefore relatively well understood. However, there are observations of terdiurnal tides (TDTs) showing local amplitudes comparable to those of DTs during some months of the year (Cevolani and Bonelli, 1985; Reddi et al., 1993; Thayaparan, 1997; Younger et al., 2002; Jacobi, 2012). Observations using midlatitude radar measurements show large TDT amplitudes in autumn and early winter (Beldon et al., 2006; Jacobi, 2012). Namboothiri et al. (2004) also obtained slightly larger amplitudes in winter than in summer while Thayaparan (1997) and Jacobi (2012) additionally emphasize the occurrence of TDTs during spring.

Satellite observations have been used to analyze the TDT on a global scale (Smith, 2000; Moudden and Forbes, 2013; Pancheva et al., 2013; Yue et al., 2013). Yue et al. (2013) presented TDT wind amplitudes from the Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) Doppler Interferometer (TIDI) of more than  $16 \text{ m s}^{-1}$  at  $50^\circ \text{ N/S}$  above 100 km with

an additional peak in the meridional component at about 82 km between 10 and 20° N. They ~~could identify~~ identified the first symmetric (3,3) mode ~~with peaks up to (peaking at 8 K above the equator and at midlatitudes, obtained)~~, using temperatures from Sounding of the Atmosphere using Broadband Emission Radiometry (SABER). At an altitude of 90 km, Moudeden and Forbes (2013) found the largest amplitudes above the equator during equinoxes (6 – 8 K), and also at 60° N during May (7 K) and at 60° S during during October (5 K) using ~~10-10~~ years of SABER temperature data.

Model studies of the TDT are mainly ~~attributed to~~ concerned with the analysis of forcing mechanisms (Akmaev, 2001; Smith and Ortland, 2001; Huang et al., 2007; Du and Ward, 2010). This was motivated by the idea that TDTs are not only the consequence of diurnal solar heating but are additionally excited by ~~gravity wave-tidal interactions (e.g., Miyahara and Forbes, 1991; Huang et al. by~~ nonlinear interactions between DTs and SDTs (e.g., Glass and Fellous, 1975; Teitelbaum et al., 1989). The theory for ~~those these~~ nonlinear interactions has been outlined by ~~Beard et al. (1999), stating~~ Teitelbaum and Vial (1991) and later by Beard et al. (1999). They state that the period of a ~~wave (child wave  $P_3$ )~~ resulting from nonlinear interaction is linked to the periods of the ~~interacting parent~~ waves  $P_1$  and  $P_2$  through  $\frac{1}{P_3} = \frac{1}{P_1} + \frac{1}{P_2}$ . The same holds for the wavenumbers. If we consider such a pure nonlinear TDT which is only a result of the interaction between DT and SDT, this means that the wavelength relation between these tides must be:

$$\lambda_{TDT} = \frac{\lambda_{DT}\lambda_{SDT}}{\lambda_{DT} + \lambda_{SDT}} \quad (1)$$

where  $\lambda_{DT}$ ,  $\lambda_{SDT}$  and  $\lambda_{TDT}$  are the vertical wavelengths of the DT, SDT and TDT, respectively. However, it should be noted that, in a real atmosphere with unknown contributions of different forcings, this criteria is only sufficient but not necessary to proof the existence of nonlinear interactions. For example, the wavelengths created by nonlinear interactions may not be detected if the solar TDT is stronger and superposes the nonlinear TDT. For the same reason, a weak correlation between DT/SDT and TDT amplitudes is not necessarily meaningful.

Another possible excitation source are gravity wave-tidal interactions (e.g., Miyahara and Forbes, 1991; Huang et al., 2007). More recent simulations (Ribstein and Achatz, 2016) show that details of gravity wave-tidal interactions can change if more comprehensive physics is included but their analysis do not include the TDT.

Teitelbaum et al. (1989) performed the first model study on the nonlinear forcing of the TDT and they concluded that the nonlinear interactions and the direct solar forcing lead to comparable terdiurnal amplitudes. Smith and Ortland (2001) used a nonlinear model with specified DT and SDT fields at the lower boundary. They switched off the terdiurnal solar component on the one hand and removed the direct solar forcing of SDTs on the other hand. As a result, they found that the solar forcing is dominant at middle and high latitudes while nonlinear interactions mainly contribute at low latitudes. A similar approach was applied by Akmaev (2001). They stated that the heating due to absorption of solar radiation in the ozone region is the main source for TDTs, while a noticeable nonlinear contribution is only seen during equinoxes. Huang et al. (2007) used a fully nonlinear tidal model with specified diurnal and semidiurnal thermotidal heating. ~~Therefore~~ In this model, the occurrence of TDT amplitudes was only possible due to nonlinear interactions, and they ~~have been were~~ significant in the MLT. Another model study about TDT forcing mechanisms was performed by Du and Ward (2010). They analyzed model output from the Canadian Middle Atmosphere Model (CMAM) with self-consistent tides due to radiative heating, convective processes and

latent heat release. They performed a correlation analysis of DTs and SDTs with TDTs on a seasonal and short-term scale. They concluded that nonlinear interactions are not essential for the generation of TDTs but solar heating is the major source. To summarize, there are only few ~~model-modeling~~ studies about the forcing mechanisms of TDTs, and they do not provide a consistent ~~imageperspective~~. Nonlinear interactions seem to play a ~~certain-tangible~~ role in TDT forcing but to what extent is heavily under debate. ~~Therefore, we want to~~ To shed more light on ~~that-matter-by-using-this-matter-we-have-used~~ a nonlinear global circulation model ~~to-explore-this-issue~~. To this end we performed model simulations with ~~simultaneous~~ nonlinear and solar terdiurnal forcing ~~at-a-time, and additional model experiments~~. ~~Additional model experiments were undertaken, each~~ with one of the forcing mechanisms switched off, in order to analyze TDT amplitudes due to ~~the-forcings~~ each forcing, separately. The paper is arranged as follows: The model and the numerical experiments are described in Sect. 2. Section 3 presents the results of the simulations, starting with an overview on the climatology of the reference TDT in the model. The second part of this section describes the TDTs that are obtained when certain forcings are removed. Finally, in Sect. 4 the results from Sect. 3 are discussed and summarized.

## 2 Description of the Model and the Experiments

We use the nonlinear Middle and Upper Atmosphere Model (MUAM) to investigate the forcing mechanisms of tides with wavenumber 3. MUAM is a 3-dimensional mechanistic model based on the COMMA-LIM (Cologne Model of the Middle Atmosphere – Leipzig Institute for Meteorology) model, which is described in detail by Fröhlich et al. (2003a, b). The more recent version of the model, MUAM, is documented by ~~Pogoreltsev et al. (2007)~~ Pogoreltsev et al. (2007); Pogoreltsev (2007) and Lilienthal et al. (2017). MUAM extends from the surface (1000 hPa) to the lower thermosphere while the ~~zonal mean temperatures in the~~ lower 30 km ~~are nudged with~~ (i.e. at the lower boundary and 10 height levels above) are nudged towards monthly mean ERA-Interim reanalyses of zonal mean temperature. ~~Here, we Note that this only influences the zonal mean, while waves can still develop unaffected by the nudging. The background winds can freely develop in the model and are only indirectly influenced via the zonal mean temperature nudging. In the present version, there is no additional lower boundary forcing. We perform ensemble simulations for each experiment by using 11 different years (2000-2010) as-of monthly mean reanalysis input data, e.g. our results for January are the average of 11 simulations, nudged with 11 different years of January reanalysis data.~~ In contrast to MUAM model experiments performed by Pogoreltsev et al. (2007) or by Jacobi et al. (2015), stationary planetary waves at the lower boundary are not explicitly forced for these model experiments in order to avoid coupling between stationary planetary waves and tides. ~~This is important because an additional secondary coupling with planetary waves leads to a more complex situation with a more complicated quantification of the individual forcing effects.~~ The model has a horizontal resolution of  $5 \times 5.625^\circ$  and a vertical resolution of 2.842 km in logarithmic pressure height with a constant scale height of  $H = 7$  km. ~~Parameterizations of gravity waves,-~~ Gravity waves are calculated by an updated Lindzen-type parameterization (Lindzen, 1981; Jakobs et al., 1986) as described by Fröhlich et al. (2003b) and Jacobi et al. (2006). Due to the fact that this parameterization does not account for ionospheric effects, it is coupled with a modified parameterization after Yigit et al. (2008), connected via the eddy diffusion coefficient

which is calculated in the Lindzen scheme and then transferred to the Yiğit scheme. Gravity waves with phase speeds of 5 to  $30 \text{ m s}^{-1}$  are handled by the Lindzen scheme while the Yiğit scheme is restricted to phase speeds of 35 to  $105 \text{ m s}^{-1}$ . This way, the Lindzen-type parameterization affects the stratosphere and mesosphere and the Yiğit parameterization mainly takes effect in the thermosphere. Overlaps between both parameterizations are small and the forcing terms due to gravity waves are summed in the tendency equation of the model. Further parameterizations of solar and infrared radiation as well as several ionospheric effects such as Rayleigh friction, Lorentz force and ion drag are included.

MUAM experiments analyzing TDTs have been performed by Fytterer et al. (2014) who compared the simulated TDT wind shear with global lower ionospheric sporadic E occurrence rates. Additionally, Krug et al. (2015) presented a seasonal climatology of the migrating TDTs based on MUAM simulations.

In the ~~used configuration~~ configuration used here, the model incorporates a spin-up of 120 model days. Within that time, zonal mean heating rates (no tides) are building up a background climatology. In the following subsequent 90 model days, heating rates are allowed to be zonally variable and tides start to propagate, gradually increasing in time. The heating rates are fully introduced after model day 154. In this model version, the sun's zenith angle does not account for day to day variations and refers to the first day of the respective month. The solar elevation angle, however, includes a diurnal cycle to account for tidal forcing. The last 30 model days are analyzed and presented here. ~~A~~ They represent the mean state of the respective months with an equilibrium of background winds and temperature. Tidal amplitudes remain almost constant and show only small day-to-day variations. Note that the nudging in the troposphere/lower stratosphere is still active during that period and the model is not running completely free at any time. This, however, does not influence the tides because the nudging does only account for zonal mean temperature. The background climatology for zonal wind, meridional wind and temperature during solstice (January) and equinox (April) conditions is given in Fig. 1 (details see section 3.1). This simulation does not include any modifications ~~on of the~~ tides and therefore serves as a reference, named REF in the following (see also Table 1).

Within the model there are three mechanisms that may excite TDTs: solar heating, nonlinear interactions between tides and gravity wave-tidal interactions. The first one, the diurnal variation of solar heating rates, creates atmospheric tides self-consistently. This mechanism is known to be the most important factor for the forcing of DTs and SDTs (e.g., Andrews et al., 1987). The second mechanism is related to nonlinear interactions between different tides. Following Beard et al. (1999), the interaction between a DT and a SDT can lead to the forcing of a TDT. The last source ~~might be gravity waves which can be modulated by tides and therefore produce waves with periods and wavenumbers equal to tides. This may lead to an enhancement of TDTs~~ included in MUAM are gravity waves. Miyahara and Forbes (1991) have shown that an interaction between gravity waves and the DT can excite a TDT. Trinh et al. (2018) observed a longitudinal variation of gravity wave activity in the tropical MLT region that may also be caused by gravity wave-tidal interaction.

In order to separate these different mechanisms we analyze the wavenumber 3 component of the respective forcing and remove it in each model time step for each latitude/altitude, separately. We do not consider the temporal dimension for this analysis because wavenumber spectra prove that TDTs in the model are strongest for wavenumber 3 (migrating TDTs) and negligible for other wavenumbers (nonmigrating TDTs, not shown here). This is because nonmigrating tides are usually owing to excited by orographic sources, latent heat release or other ~~local effects that are not considered within the frame of this~~

model geographically fixed effects (e.g., Andrews et al., 1987). Note that atmospheric gases such as water vapor or ozone are only included as zonal means which is different from other versions of MUAM (e.g., Ermakova et al., 2017). Therefore, we usually refer to the migrating TDT here. The following results are obtained from five ensemble simulations in total, eliminating each forcings separately (NO\_SOL, NO\_NLIN and NO\_GW), allowing all forcings (REF) and eliminating all forcings (CTRL). An overview is given in Table 1.

Note that the background (monthly mean zonal mean) circulation is not significantly altered when TDT forcings are removed (not shown here). Differences amount to not more than the actual standard deviations in the REF simulation (Fig. 1). Therefore, the influence of a removed wavenumber 3 forcing is comparable to the year-to-year variation of the background state and propagation conditions for tides remain similar.

The parameterization of solar heating in the middle atmosphere is calculated following Strobel (1978). It considers heating due to the most important gases such as water vapor, carbon dioxide, ozone, oxygen and nitrogen. Thereby, zonal mean ozone fields up to 50 km altitude are taken from the Stratosphere-troposphere Processes And their Role in Climate project (SPARC; Randel and Wu, 2007). Above 50 km, the ozone mixing ratio decreases exponentially. The second ozone maximum near 90 km is not included. Different from Jacobi et al. (2015), we restrict our simulations to ozone data of the year 2005 because we do not intend to perform a trend analysis. The volume mixing ratio for carbon dioxide has been chosen according to measurements from Mauna Loa Observatory, also for the year 2005-2005 (e.g., 378ppm for January; NOAA ESRL Global Monitoring Division, 2018). Chemical heating due to recombination of  $O_2$  and  $O_3$  (Riese et al., 1994) and heating due to extreme ultra violet radiation (EUV) are added. This is described in more detail by Fröhlich et al. (2003a).

In the NO\_SOL simulation, the total heating rate of all heating contributions is analyzed using a Fourier transform to separate the tidal components. For the analysis of the forcing mechanism we subtract the wavenumber 3 amplitude from the total heating for each time step and each grid-point latitude/altitude, separately. The result of this simulation is a wavenumber 3 tide that is only due to nonlinear interactions and gravity wave effects.

In order to separate the nonlinear forcing we modify the nonlinear terms in the tendency equations of the model (e.g., Jakobs et al., 1986), i.e. in the advection terms in the zonal (Eq. (2)) and meridional (Eq. (3)) momentum equations as well as temperature advection (Eq. (4)):

$$\mathbf{v} \cdot (\nabla u) = \frac{u}{a \cos \phi} \frac{\partial u}{\partial \lambda} + \frac{v}{a \cos \phi} \frac{\partial (u \cos \phi)}{\partial \phi} + \frac{w}{\rho_0} \frac{\partial}{\partial z} (\rho_0 u), \quad (2)$$

$$\mathbf{v} \cdot (\nabla v) = \frac{u}{a \cos \phi} \frac{\partial v}{\partial \lambda} + \frac{v}{a \cos \phi} \frac{\partial (v \cos \phi)}{\partial \phi} + \frac{w}{\rho_0} \frac{\partial}{\partial z} (\rho_0 v), \quad (3)$$

$$\mathbf{v} \cdot (\nabla T) = \frac{u}{a \cos \phi} \frac{\partial T}{\partial \lambda} + \frac{v}{a \cos \phi} \frac{\partial (T \cos \phi)}{\partial \phi} + \frac{w}{\rho_0} \frac{\partial}{\partial z} (\rho_0 T) \quad (4)$$

where  $\mathbf{v}$  is the wind vector,  $u$  and  $v$  are the horizontal wind components,  $w$  is the vertical wind component and  $T$  is the temperature.  $a$  is Earth's radius,  $\phi$ ,  $\lambda$  and  $z$  are latitude, longitude and altitude, respectively, and  $\rho_0$  is the reference density at

a given height  $z$ . Additionally, the adiabatic contribution included in the temperature equation in principle has to be taken into consideration because it includes nonlinear coupling:

$$\left. \frac{\partial T}{\partial t} \right|_{adiab} = \frac{RwT}{m'c_p H}, \quad (5)$$

- 5 with  $R$  as the gas constant for dry air,  $m'$  the ratio of molecular weights at the respective altitude and at 1000 hPa and  $c_p$  is the specific heat at constant pressure.

Linearizing these equations, i.e.  $T \approx \bar{T} + T'$ ,  $w \approx \bar{w} + w'$ , etc., results in a separation of purely nonlinear (wave-wave) interactions, wave-background interactions and pure background processes. For example, the adiabatic term from Eq. (5) may be written as

$$10 \left. \frac{\partial T}{\partial t} \right|_{adiab} \approx \frac{R}{m'c_p H} \cdot (\bar{w}\bar{T} + \bar{w}T' + w'\bar{T} + w'T') \quad (6)$$

and the terms on the right-hand side of Eqs. 2-4 are treated similarly. The last term in the bracket of Eq. (6) describes nonlinear wave-wave interaction. From these terms of wave-wave interactions we removed the  $k = 3$  amplitudes analogous to the modification of the solar heating terms in the NO\_SOL simulation. Removing the nonlinear interactions will result in a combination of solar and gravity wave driven TDT (Run NO\_NLIN).

The simulations NO\_SOL and NO\_NLIN are very similar to the approach presented by Akmaev (2001) and Smith and Ortland (2001). Additionally, we consider gravity waves for the generation of TDTs. ~~Gravity waves are calculated by an updated The contributions of both gravity wave routines (the Lindzen-type parameterization (Lindzen, 1981; Jakobs et al., 1986) as described by Fröhlich et al. (2003b) and Jacobi et al. (2006). Due to the fact that this parameterization does not account for ionospheric effects, it is coupled with a modified parameterization after Yiğit et al. (2008), connected via the eddy diffusion coefficient. Note that the and the modified Yiğit parameterization mainly attributes the thermosphere while the Lindzen-type parameterization affects the stratosphere and mesosphere. This way, overlaps between both parameterizations are small and the contributions of both routines)~~ to the tendency terms can be simply summed up. The total acceleration of the mean flow due to gravity waves is finally subject to a Fourier filtering of wavenumber 3, equal similar to the one for the heating rates and the nonlinear terms. As a result, TDTs of solar and nonlinear origin are remaining (NO\_GW simulation).

As a control simulation (CTRL), ~~solar as well as the wavenumber 3 component of the solar~~, nonlinear and gravity wave forcings are removed simultaneously. This is done in order to test to what degree all sources of TDTs are captured, and if the model produces further TDTs of either numerical or physical origin.

30 In the following analysis, we focus on the months January and April to show solstice and equinox conditions. During this time, the TDT in MUAM is most prominent. Results for July and October are similar and therefore they are not shown, here.

### 3 Results

#### 3.1 Reference Simulation: TDT Climatology

The REF simulation includes solar, nonlinear and gravity wave forcing for all wavenumbers. Therefore, it serves as a reference for the following all the experiments. The following results are given as a mean of all the 11 ensembles (color shading) members, owing to the nudging of reanalysis data for the years 2000-2010 (color shading) with the respective standard deviations (contour lines).

In Fig. 1 we provide a background climatology of the MUAM zonal mean circulation for solstice (Fig. 1a-c) and equinox (Fig. 1d-f) for the parameters zonal wind (a,d), meridional wind (b,e) and temperature (c,f). The color coding denotes the 11-year means, while the standard deviations are given as black contour lines.

Comparing the MUAM climatology with empirical climatologies such as CIRA86 (Fleming et al., 1990), the radar based GEWM (Portnyagin et al., 2004) or the satellite based UARS (Swinbank and Orland, 2003) we find good agreements agreement but with slightly larger westerly jets and weaker easterly jets during January in MUAM.

We notice that the model produces small year-to-year variations below 100 km in the southern hemisphere and south of 30° N. There, the standard deviation  $\sigma$  is very small, mostly below  $\sigma(T) = 1$  K ( $\sigma(u) = 2$  m s<sup>-1</sup>,  $\sigma(v) = 0.25$  m s<sup>-1</sup>). Model variations for middle and high latitudes in the northern hemisphere are larger with standard deviations up to  $\sigma(T) = 6$  K ( $\sigma(u) = 12$  m s<sup>-1</sup>,  $\sigma(v) = 2$  m s<sup>-1</sup>) during January and  $\sigma(T) = 2$  K ( $\sigma(u) = 2$  m s<sup>-1</sup>,  $\sigma(v) = 0.75$  m s<sup>-1</sup>) for April. Maxima of the standard deviation are located at about 60° N. These variations have their origin in the year-to-year variability of the polar vortex which is realistic to have for which a range of several K, especially during winter, is realistic. Due to the fact that MUAM assimilates the zonal mean temperature up to 30 km altitude, this model variability represents a realistic atmospheric variability, too.

Figures 2 and 3 show the terdiurnal component of all forcing terms that our analysis takes into account, namely solar forcing, nonlinear forcing and forcing due to gravity wave-tide interactions. All forcing terms are scaled by density (factor  $\exp\{-z(2H)^{-1}\}$ ) in order to highlight the region where the forcing originates from. Therefore, the figures show the source region of tidal excitation but they do not provide any information about propagation conditions.

Figure 2 refers to thermal parameters including temperature advection (a,b), the nonlinear component of adiabatic heating (c,d), heating due to gravity waves (e,f) and direct solar heating (g,h). Note that the color scales in Fig. 2 are equal but not continuous in order to cover the magnitudes of all forcings while keeping them comparable to each other. For the thermal forcing of the TDT it can be seen that the direct solar forcing dominates in the troposphere and stratosphere. This is because of the strong absorption of solar radiation by tropospheric water vapor and stratospheric ozone. In the mesosphere (80-100 km), nonlinear effects are mainly responsible for the forcing of terdiurnal fluctuations. Due to absorption of EUV radiation, there is again some solar forcing in the lower thermosphere (Fig. 2g,h at about 120 km altitude) that is comparable to nonlinear thermal forcing (Fig. 2a,b). In this region, heating due to gravity wave effects (Fig. 2e,f) plays a major role. The nonlinear adiabatic heating effect (Fig. 2c,d) is weak everywhere compared to the other forcings and will therefore be neglected in our further considerations.

Figure 3 is similar to Fig. 2 but refers to wind parameters scaled by density, including nonlinear zonal (a,b) and meridional (c,d) wind advection as well as zonal (e,f) and meridional (g,h) acceleration due to gravity waves. In the zonal wind, in the troposphere and stratosphere, the nonlinear forcing is clearly dominating over gravity wave effects. Zonal gravity wave forcing becomes strong above 100 km. In January, there is an additional maximum of gravity wave induced terdiurnal forcing (Fig. 3e) near 80 km between 30 and 60° N which cannot be observed in April (Fig. 3f). For meridional wind patterns, gravity wave forcing only plays a role between 80 and 100 km (Fig. 3g,h), its magnitude being comparable to those of the advective nonlinear forcing (Fig. 3c,d). In the stratosphere and mesosphere, nonlinear advection is the most important source for the meridional component.

Generally, direct solar forcing is weaker during April (Fig. 2h) than during January (Fig. 2g), but most nonlinear forcings (Fig. 2a,b and Fig. 3a-d) become stronger in April and are therefore more dominant during equinox.

As described above, the nonlinear terdiurnal forcing is a result of interactions between the migrating DT and the migrating SDT. These interactions can only take place if both, DT and SDT, have a considerable amplitude. To test this relation between the different subharmonics, the product of DT and SDT amplitudes serves as a proxy for the terdiurnal nonlinear forcing. Due to the fact that the forcings in Figure 3 are scaled by density, we also scaled the DT and SDT amplitudes before multiplication to show the source region of the tides. An example is shown in Figure 4 for zonal wind amplitudes. Note that amplitudes are only shown above 40 km because scaled amplitudes in the troposphere and lower stratosphere have a higher order of magnitude.

It can be seen that the product of scaled DT and SDT amplitudes reveals a similar structure like the nonlinear zonal forcing of the TDT. Both have increased branches near 50 km extending from low latitudes poleward to high latitudes and with a minimum over the equator. Such a good agreement is not seen in all parameters but the multiplied amplitudes in Figure 4 only serve as proxy. The pure existence of an overlapping DT and SDT source region does not necessarily induce an interaction.

TDT amplitudes are presented for April (Fig. 5a-c) and January (Fig. 5d-f). In contrast to the forcings, they are not scaled by density. Zonal wind amplitudes become stronger in April (Fig. 5e) compared to January (Fig. 5b) above 110 km but this is not the case for the temperature and meridional wind amplitude. Amplitudes at 100 km altitude reach only about 1.5 K and 4 m s<sup>-1</sup> (zonal/meridional wind). This is much smaller than observed by radars (e.g., Thayaparan, 1997; Namboothiri et al., 2004; Beldon et al., 2006; Jacobi, 2012) and by satellite measurements (e.g., Moudden and Forbes, 2013; Pancheva et al., 2013; Yue et al., 2013). They reported amplitudes of about 5-6 m s<sup>-1</sup> at 90 km (Thayaparan, 1997; Namboothiri et al., 2004) during equinoxes and local winter with a minimum during summer. These radars are located between 40-50° N and in these regions, Fig. 5 also shows large-larger wind amplitudes during winter and equinoxes. Beldon et al. (2006) and Jacobi (2012) observe a maximum larger than 10 m s<sup>-1</sup> (95 km) during autumn/early winter and a smaller one during spring. The absence of a mid-winter maximum can be explained by the location of the radars (> 50° N) which is northward of the region with a winter maximum as can be seen in Fig. 5b,c.

However, considering only the maximum-maxima does not give a good comparison between seasons, but-and the height-latitudinal structure is more important. Especially in temperature (Fig. 5a) and zonal wind (Fig. 5b) we note a double-peak structure in January with maxima at very low latitudes and a minimum at the equator. This turns into a triple-peak structure in April (Fig. 5d,e) with maxima slightly more poleward (30° N/S) and directly at the equator. This structure is also visible in

SABER measurements by Pancheva et al. (2013) for March and December. In the meridional wind, the TDT has not such a clear structure in January (Fig. 5c), with several maxima between  $\pm 60^\circ$ , the strongest one appears near the equator. In April (Fig. 5f), it has four distinct peaks with maxima at low and midlatitudes but, opposite to temperature and zonal wind, a minimum at the equator. These reversed maxima and minima for zonal and meridional wind component are expected and can be explained by the wave structure itself.

The standard deviation of tidal amplitudes is relatively small and reaches not more than 10 % of the total amplitude. Thus, our results prove to be robust in structure and strength.

The ~~phases of TDT~~ TDT phases are shown in Fig. 6. ~~Vertical~~ At each latitude, the corresponding vertical wavelength can be obtained from the vertical phase gradient. The wavelength is taken as the vertical distance between two points of identical phases. A full span of phases should be covered inbetween, and for upward propagating waves, the phase gradient for the determination should be negative. Where the amplitude is large, vertical wavelengths turn out to be longer ~~where the amplitude is large and shorter where~~, i.e. the vertical phase gradients are small. Where the amplitude is small, wavelengths are shorter with larger phase gradients. Thayaparan (1997), Namboothiri et al. (2004) and Jacobi (2012) report a similar relationship with vertical wavelengths being short in summer when the amplitude minimizes. Typically, the wavelengths in Fig. 6 reach 100 km and more. In January (Fig. 5a-c), the structure of phases appears to be more complex while in April (Fig. 5d-f) there are large areas of constant phase, especially at low latitudes.

Figure 7 presents the seasonal cycle of TDT amplitudes at an altitude of 106 km. Results of satellite data analyses have frequently been presented at 90 and 110 km (Pancheva et al., 2013; Yue et al., 2013; Moudden and Forbes, 2013), and therefore we choose an altitude inbetween. The temperature TDT at this altitude (Fig. 7a) appears to be strongest during equinoxes near the equator (3.0 K) and at midlatitudes (30-40° N/S). The amplitudes in autumn (2.2 K) are larger than those in spring (1.6 K). Further maxima are reached during local winter at 30-40° N/S (2.6 K at northern hemisphere and 2.3 K at southern hemisphere). For latitudes poleward of 50° N/S, amplitudes are much ~~smaller~~ lower and peak during summer ( $< 1.1$  K).

The structure of MUAM temperature amplitudes is generally confirmed by SABER measurements (e.g., Moudden and Forbes, 2013; Pancheva et al., 2013; Yue et al., 2013) who reported maxima of about 5 K during equinoxes near the equator at 90 km altitude. Note that this amplitude is almost twice as large as the one obtained from our model simulations even though the altitude is smaller. For midlatitudes, Moudden and Forbes (2013) also found maxima during northern winter (3-4 K at 30-50° N, 90 km) but not during southern winter. This is in contrast to the results of Pancheva et al. (2013) and Yue et al. (2013) who found maxima during equinoxes and local winter in both hemispheres (110 km altitude) which qualitatively agrees well with our results at 106 km near 40° N/S.

Maxima in zonal wind (Figs. 7b) and meridional wind TDT (Figs. 7c) are also found during local winter at midlatitudes and they are slightly larger in the northern hemisphere ( $5.9 \text{ m s}^{-1}$  in both components) than in the southern hemisphere ( $4.7 \text{ m s}^{-1}$  in both components). During equinoxes, the maxima are smaller and located close to the equator (zonal wind only,  $< 4.0 \text{ m s}^{-1}$ ), at low latitudes (meridional wind only,  $< 4.3 \text{ m s}^{-1}$ ) and at midlatitudes (zonal and meridional wind  $< 3.8 \text{ m s}^{-1}$ ).

Zonal and meridional amplitudes at midlatitudes (40-50° N/S) agree well with TIDI measurements (Yue et al., 2013) showing maxima during equinoxes at both hemisphere and during southern winter. However, the northern winter maximum is not seen

in the zonal wind analysis by Yue et al. (2013). Another meridional wind peak is reported by Yue et al. (2013) near 30° N during July which can be found in our simulations, as well. However, amplitudes tend to be underestimated by a factor of about 3-4.

Some differences between model results and satellite measurements may be explained by the orbit of the satellite, passing high latitudes less frequently and leading to larger uncertainties in these latitudes. However, this cannot explain the large discrepancies in the magnitude of the TDT. Smaller model amplitudes may be owing to processes that are not included in the simulations such as latent heat release.

### 3.2 Separating the Forcings

In order to obtain the effect of each individual forcing on the amplitude of the TDT we performed the simulations with different forcings switched off, as listed in Table 1.

NO\_SOL represents a TDT that is only owing to nonlinear and gravity wave effects because wavenumber 3 direct solar heating is removed in the whole model domain. Therefore, possible sources of this wave are nonlinear interactions between other tides, i.e. between the DT and the SDT, and gravity wave-tide interactions only. Remaining amplitudes and phases are shown in Figs. 8 and 9. As expected, the amplitudes are strongly reduced. However, they are not completely extinguished. In all parameters there is a clear maximum at northern midlatitudes (about 60° N) during January reaching 4 K  $\pm$  0.6 K (temperature), 5 m s<sup>-1</sup>  $\pm$  1.2 m s<sup>-1</sup> (zonal wind) and 4 m s<sup>-1</sup>  $\pm$  0.8 m s<sup>-1</sup> (meridional wind) above 120 km. In the zonal wind component there is a secondary maximum at about 30° N as well. During April, the maxima are shifted towards the equator with similar amplitudes like in January. This indicates that secondary terdiurnal forcing is most evident during local winter which can be confirmed from the annual cycle of the NO\_SOL simulation (not shown here). TDT phases from this simulation (Fig. 9) are much more irregular compared to the REF simulation (Fig. 6) and show shorter vertical wavelengths no longer than 50 km for those latitudes where TDT amplitudes are strong.

The simulation NO\_NLIN only includes direct solar forcing and gravity wave-tide interactions. Therefore, it does not include nonlinear interactions. Figure 10 shows the mean amplitude differences between the NO\_NLIN and REF ensembles where red (blue) colors denote larger (smaller) amplitudes in NO\_NLIN. Welch's t-test was applied and areas with  $\alpha < 0.01$  are hatched. It turns out that decreased amplitudes are not the only consequence of the removed nonlinear forcing but there are also areas where the amplitude has increased. This result can be mainly observed during January in all parameters. The strongest increase of about 3 K (3 m s<sup>-1</sup>) is located where the REF amplitude reaches its maximum. There, the amplitude in the NO\_NLIN simulation is about 25% larger compared to the REF simulation. Another large red area is located at about 60° N at an altitude of 110 km. In this area the amplitudes in the REF simulation are relatively small (not more than 2 K and 2 m s<sup>-1</sup>), but the differences between the simulations reach similar values so that the NO\_NLIN amplitudes are twice as strong as the REF amplitudes.

In April only weak enhancements of about 0.5–1.5 K (0.5–2 m s<sup>-1</sup>) appear for individual grid points and these are not located in the areas of larger amplitudes. Generally, the negative amplitude differences dominate and areas of positive change seem to

be negligible.

We do not show the phases of the NO\_NLIN simulation and the NO\_GW simulation here because either of these simulations still includes the solar forcing which dominates the other remaining forcing, respectively, and therefore phases almost look the same like those shown in Fig. 6 for the REF simulation.

- 5 In order to investigate the positive difference in amplitude it is useful to compare phase shifts  $\Delta\phi$  between the NO\_NLIN TDT (with solar and gravity wave forcing) and the NO\_SOL TDT (with nonlinear and gravity wave forcing). The gravity wave forcing appears in both simulations and therefore the phase shift between the tides according to these simulations can be mainly attributed to the phase shift between a pure solar wave and a pure nonlinear wave. The differences of the background wind and therefore tidal propagation conditions between the simulations are small. For  $120^\circ < \Delta\phi < 240^\circ$  destructive interferences are possible which may lead to a decrease in amplitude for the case of superposition.

10 Figure 11 shows the amplitude differences as presented in Fig. 10 but now scaled by density (factor  $\exp\{-z(2H)^{-1}\}$ ) to show the source of the positive amplitude differences. Here, the hatched areas show regions of destructive interferences ( $120^\circ < \Delta\phi < 240^\circ$ ) between the phases of NO\_NLIN and NO\_SOL occur. It can be clearly seen that the red areas and the destructive interferences match almost perfectly for both January and April conditions and for all parameters.

- 15 Figure 12 shows the mean amplitude differences between the NO\_GW and REF ensembles. For this simulation, positive amplitude differences occur at several heights/latitudes, when removing the gravity wave-tide interactions as a forcing of TDTs. In this case destructive interference seems to be more independent from the season and can be seen in January and April alike. However, the regions where the zonal wind amplitude is increased are rather small. This increase is most expressed around  $60^\circ$  N and 110 km altitude during January. Note that this area is positive for meridional and zonal wind alike and also appears in the NO\_NLIN simulation (Fig. 10). For the temperature and meridional wind component we find, as in Fig. 10, that amplitudes in regions with strong REF amplitudes are even enhanced when removing the wavenumber 3 gravity wave forcing. Furthermore, the amplitude changes in Fig. 12 reach larger values during April compared to January which can be explained by larger TDT reference amplitudes during April. Generally, all amplitude differences are stronger for NO\_GW than for NO\_NLIN.

The CTRL simulation represents TDT amplitudes due to effects that have not been considered in the previous simulations.

- 25 So there still exist other sources in the model. Figure 13 shows the TDT amplitudes for the CTRL simulation. Note that the scale is different from Fig. 5 to cover the much smaller magnitudes. The structure of this remaining tide is not completely irregular ~~indicating that it is possibly not owing to noise~~. However, the amplitudes are small with maximum values below 1 K,  $1.2 \text{ m s}^{-1}$  (zonal wind) and  $1.4 \text{ m s}^{-1}$  (meridional wind). During January, maxima are located in the northern hemisphere at low and midlatitudes and during April at the equator (temperature) and at southern low and midlatitudes (wind).

30

#### 4 Discussion and Conclusion

The results of our REF simulation present a climatology and structure of the TDT that generally agrees with observations and earlier model studies. ~~However,~~ MUAM produces relatively small amplitudes for the TDT, e.g.  $5 \text{ m s}^{-1}$  for the zonal wind com-

ponent at 106 km altitude during winter or  $12 \text{ m s}^{-1}$  at an altitude of 120 km during April. In fact, it is an ongoing question that numerical models tend to underestimate tides, at least for some regions or seasons (e.g., Smith, 2012; Pokhotelov et al., 2018). In opposite to reports by Cevolani and Bonelli (1985); Reddi et al. (1993); Thayaparan (1997); Yue et al. (2013) Cevolani and Bonelli (1985); Yue et al. (2013) the TDT in our simulations does not reach the magnitude of a typical DT or SDT. However, this property of the TDT was mainly reported on short-term scales of only few days which are not represented by MUAM.

MUAM simulations show strongest wind amplitudes at midlatitudes ( $30\text{-}50^\circ \text{ N}$ ) during winter with smaller maxima during spring and autumn. This is in accordance to radar measurements at these latitudes (e.g., Thayaparan, 1997; Namboothiri et al., 2004) who observed amplitudes of at least  $5 \text{ m s}^{-1}$  during the whole year except during summer. At slightly larger latitudes ( $50\text{-}60^\circ \text{ N}$ ), the winter maxima disappear and those near the equinoxes become more important as reported by (e.g., Beldon et al., 2006; Jacobi, 2012). There are also agreements with satellite analyses by Moudden and Forbes (2013), e.g., during equinoxes maxima appear at the equator and at midlatitudes. However, Moudden and Forbes (2013) observe those maxima to be more poleward (at about  $60^\circ \text{ N/S}$ ) than we do ( $30\text{-}40^\circ \text{ N/S}$  in MUAM). They also find that winter maxima are located about  $30\text{-}40^\circ \text{ N}$  while poleward of  $55^\circ$  the maxima appear during summer.

The TDT in model simulations by Smith and Ortland (2001) has wind maxima near  $50^\circ \text{ N/S}$  of the respective winter hemisphere. This is slightly more equatorward but generally agrees with our results. They have peak amplitudes of about  $10 \text{ m s}^{-1}$  being about twice as large as in MUAM. In our model, the zonal wind amplitudes at low latitudes are generally weaker than at midlatitudes. Slightly enhanced amplitudes can be seen at low latitudes of the summer hemisphere and during equinoxes above the equator. This structure is similar to the TDT by Smith and Ortland (2001) at 97 km and by Du and Ward (2010) at 95 km but vanishes at higher altitudes (Du and Ward, 2010). The temperature amplitude in our model has a strong maximum during equinoxes at the equator and at midlatitudes. This is not seen in earlier simulations (Du and Ward, 2010) but agrees with observations (e.g. Beldon et al., 2006; Jacobi, 2012; Moudden and Forbes, 2013).

Based on former model studies and in order to investigate the forcing mechanisms of the TDT we present further model simulation where possible forcings are switched off individually. In addition to the methods used by, e.g. Akmaev (2001); Smith and Ortland (2001); Huang et al. (2007) or Du and Ward (2010), who focus on direct solar heating and nonlinear interactions between tides only, we also consider gravity wave-tide interactions as suggested by, e.g. Miyahara and Forbes (1991); Huang et al. (2007) Miyahara and Forbes (1991); Huang et al. (2007).

Removing the direct terdiurnal solar heating leads to a significant decrease in amplitude (see Fig. 8) and therefore we conclude that the solar forcing is the most important and dominating TDT source amongst all possible mechanisms. With respect to the relevance of the solar forcing, our results generally agree with earlier simulations by Smith and Ortland (2001); Akmaev (2001) and Du and Ward (2010). However, the remaining amplitudes of our simulations amount to several K or  $\text{m s}^{-1}$ , at few latitudes/altitudes reaching about one third to one half of the total amplitude. This gives rise to the assumption that nonlinear interaction between tides and/or gravity waves should also be considered as an important forcing. The „left-over amplitudes“, which include nonlinear and gravity wave induced forcing, exhibit a maximum at northern low and midlatitudes during January and April alike and phases for this tide are much more complex than the original ones (Figs. 8 and 9). Huang et al. (2007) also underline the importance of nonlinear interactions but they obtain pure nonlinear tidal amplitudes up to  $15 \text{ m s}^{-1}$  and 12 K during equinoxes

nar 100 km. These amplitudes are much larger than in MUAM. In contrast, the simulations by Smith and Orland (2001) reveal that nonlinear interactions are weak and only contribute at low latitudes.

Removing the nonlinear tidal interactions leads to an increase in amplitude for some heights/latitudes during January by up to 2 K ( $3 \text{ m s}^{-1}$ ). Despite Smith and Orland (2001) and Akmaev (2001) used the same procedure to analyze the solar and nonlinear forcing contribution, they did not observe this behavior of increased amplitudes. However, Smith et al. (2004) studied the forcing mechanisms of the quarterdiurnal tide (period of 6 h) and they have seen a similar feature. They conclude that the nonlinear forcing may rather reduce than enhance the tide. This can be explained by destructive interferences between the purely solar forced ~~TDT~~-tide and the nonlinearly forced ~~TDT~~-tide. Due to the destructive phase shift the waves are counteracting each other and therefore reduce the amplitude when appearing together in the REF model simulation.

Similar results are obtained for removing the terdiurnal gravity wave-tide interactions but an increase in amplitude in this case is observed for both January and April conditions. Here, the zonal wind component is not affected by this positive amplitude change but temperature and meridional wind.

This conclusion supports the results of Smith and Orland (2001) and partly those of Akmaev (2001) who found some minor nonlinear contributions but assume the solar forcing to be a major source. While Smith and Orland (2001) also obtain largest nonlinear contribution at low and middle latitudes, Akmaev (2001) point out that nonlinear interactions take place during equinoxes. However, Akmaev (2001) only analyzed a latitude of  $44^\circ \text{ N}$  where amplitudes seem to maximize during equinoxes and therefore one may conclude that nonlinear interactions generally come into play where the TDT is large. Therefore, we cannot agree with Du and Ward (2010) who concluded that nonlinear interactions are negligible. However, we did not perform a correlation analysis between DTs, SDTs and TDTs and therefore we cannot directly compare the results. Furthermore, our simulations do not agree with Huang et al. (2007) who obtain very large wind amplitudes over  $15 \text{ m s}^{-1}$  and temperature amplitudes over 10 K in the MLT region for TDTs due to nonlinear interactions only. However, they also find nonlinear amplitude maxima during equinoxes at low and middle latitudes which is in agreement with our results.

Finally, a control simulation (CTRL) tested the TDT amplitude for all three considered forcings removed simultaneously to check whether there is a remaining weak forcing that has not been considered, yet. Amplitudes for that simulation are relatively small ( $< 0.6 \text{ K}$  and  $< 1.5 \text{ m s}^{-1}$ ) but have a clear structure with maxima at  $50^\circ \text{ N/S}$  during local winter. We conclude that there is another possible weak ~~TDT~~ Rind et al. (2014) have noted that numerical noise can produce regular signatures like a quasi-biennial oscillation. Therefore, noise cannot be excluded as a tidal source in the model, e.g., in CTRL simulation. Another reasonable TDT source in our model could be originating from the thermospheric parameterizations, which include some nonlinear terms. These sources, however, are likely to be dependent on the used model and it is not likely that the remaining amplitudes in Fig. 13 have a real meteorological meaning.

In the future, it would be interesting to analyze nonmigrating tides, as well. Therefore, we need to include additional sources such as latent heat release or 3-dimensional ozone and water vapor (e.g., Ermakova et al., 2017). As we have seen, gravity waves are a crucial parameter for tidal forcing and they also have a large influence on the background circulation of the middle atmosphere. Therefore, the coupling of two different gravity wave parameterization is going to be replaced by the original

[whole atmosphere scheme after Yiğit et al. \(2008\).](#)

*Code availability.* The MUAM model code can be obtained from the corresponding author on request.

*Author contributions.* F. Lilienthal designed and performed the MUAM model runs. C. Jacobi together with F. Lilienthal drafted the first  
5 version of the text. C. Jacobi and C. Geißler contributed to the analysis and interpretation of the results.

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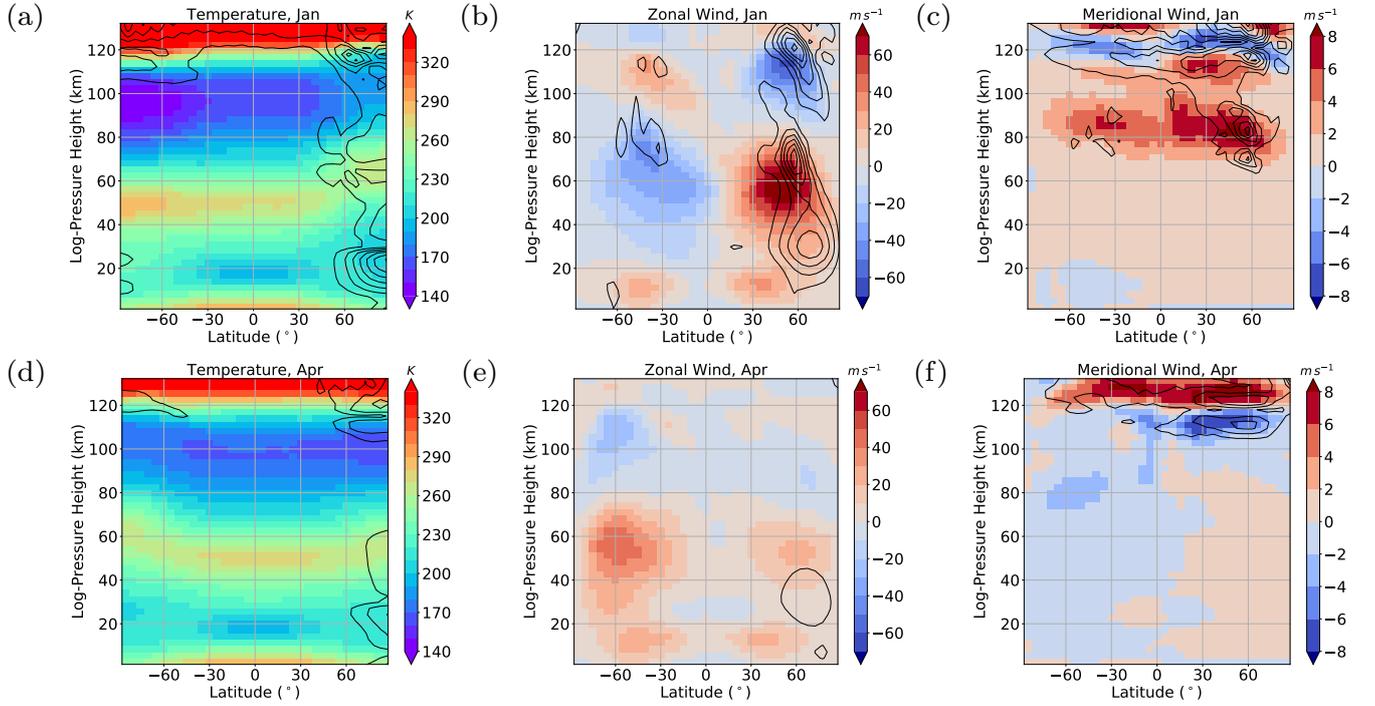
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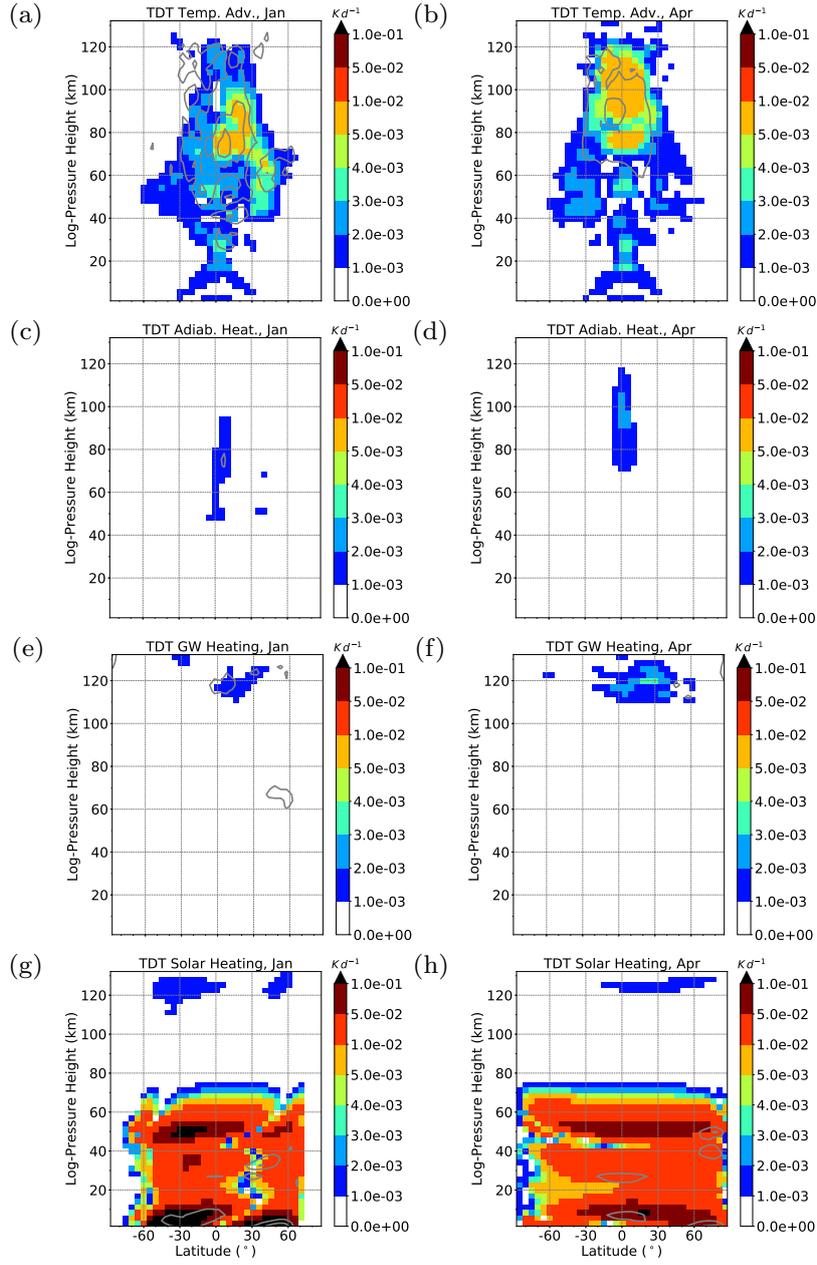
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**Table 1.** Overview on the different simulations.

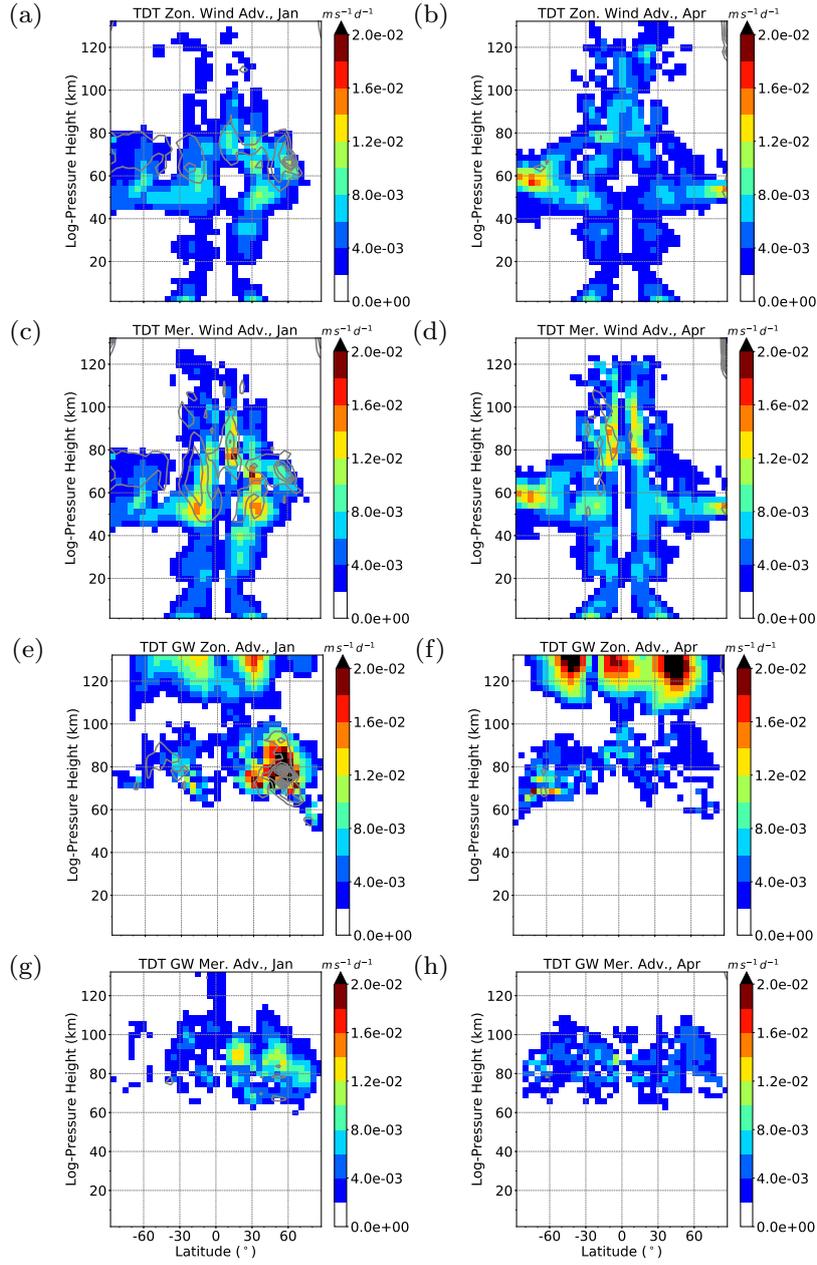
Simulation	Description	solar forcing	nonlinear forcing	gravity wave forcing
REF	Reference with all forcings	on	on	on
NO_NLIN	Effect of removed nonlinear forcing	on	off	on
NO_SOL	Effect of removed solar forcing	off	on	on
NO_GW	Effect of removed gravity wave forcing	on	on	off
CTRL	Control without all forcings	off	off	off



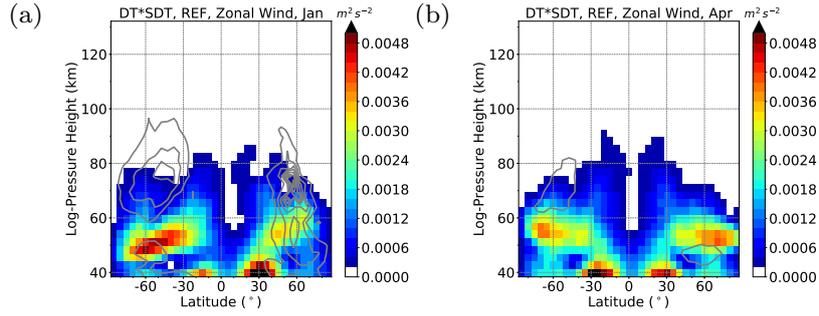
**Figure 1.** From left to right: REF zonal mean temperature, zonal wind and meridional wind. Top: Solstice (January) conditions. Bottom: Equinox (April) conditions. Results are [obtained using an 11-year mean average of assimilation data the 11 ensemble members \(color shading\)](#). Standard deviations are added as black contour lines in intervals of 1 K (temperature),  $2 \text{ m s}^{-1}$  (zonal wind) and  $0.25 \text{ m s}^{-1}$  (meridional wind).



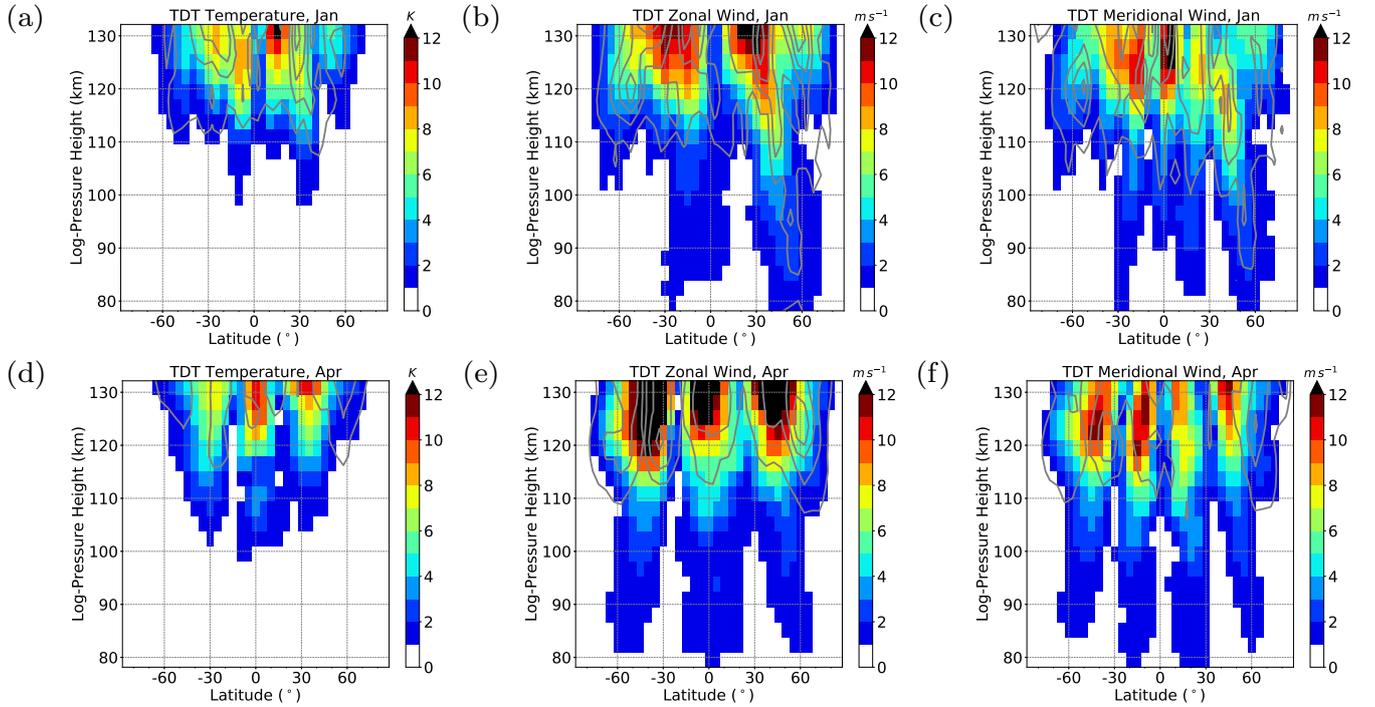
**Figure 2.** Terdiurnal component of thermal tendency terms in the REF simulation for January conditions (left) and April conditions (right). Amplitudes are scaled by density (factor  $\exp\{-z(2H)^{-1}\}$ ). Results are [obtained using an 11-year mean average of assimilation data the 11 ensemble members](#) (color shading). Standard deviations ( $\sigma$ ) are added as gray contour lines. From top to bottom: temperature advection (nonlinear component of Eq. (4),  $\Delta\sigma = 2 \cdot 10^{-3}$ ), adiabatic heating (nonlinear component of Eq. (5),  $\Delta\sigma = 2 \cdot 10^{-3}$ ), heating due to gravity wave activity (tendency term from gravity wave parameterization,  $\Delta\sigma = 2 \cdot 10^{-3}$ ) and solar heating (tendency term from solar radiation parameterization,  $\Delta\sigma = 1 \cdot 10^{-4}$ ). Note that the color scale is not continuous.



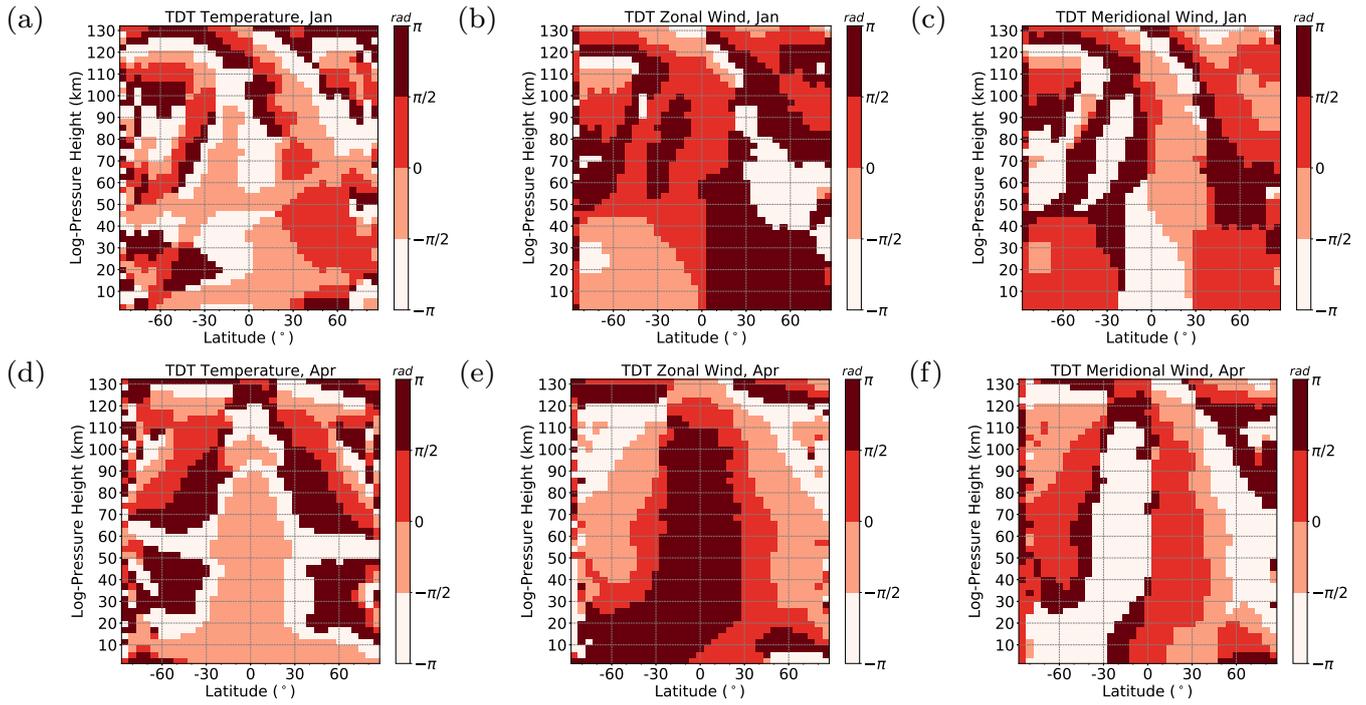
**Figure 3.** Tertiurnal component of zonal and meridional wind acceleration terms in the REF simulation for January conditions (left) and April conditions (right). Amplitudes are scaled by density (factor  $\exp\{-z(2H)^{-1}\}$ ). Results are obtained using an 11-year mean average of assimilation data the 11 ensemble members (color shading). Standard deviations ( $\sigma$ ) are added as gray contour line. From top to bottom: zonal wind advection (nonlinear component of Eq. (2),  $\Delta\sigma = 5 \cdot 10^{-4}$ ), meridional wind advection (nonlinear component of Eq. (3),  $\Delta\sigma = 5 \cdot 10^{-4}$ ) and zonal and meridional acceleration due to gravity waves (tendency terms from gravity wave parameterization,  $\Delta\sigma = 2 \cdot 10^{-3}$ ).



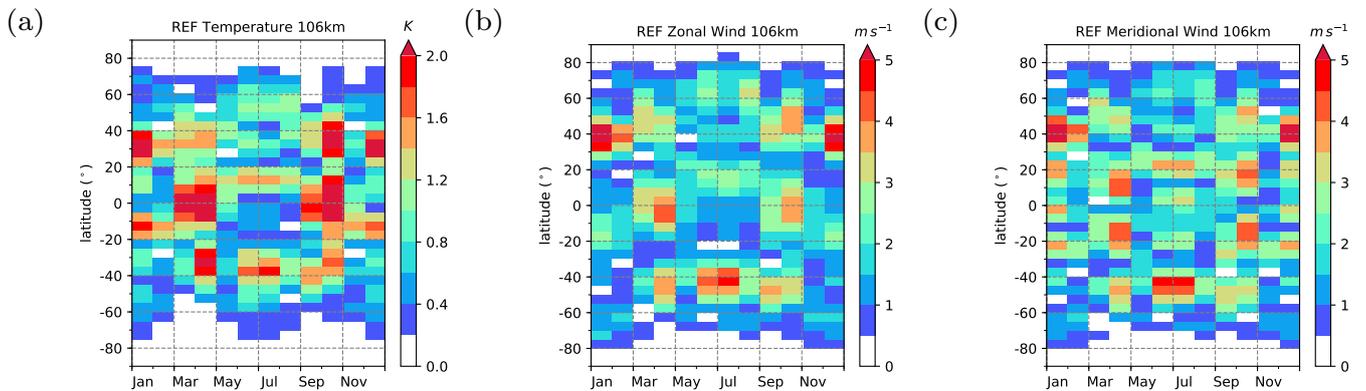
**Figure 4.** Product of DT and SDT amplitudes, both of them scaled by density (factor  $\exp\{-z(2H)^{-1}\}$ ). Results are an average of the 11 ensemble members (color shading). Standard deviations ( $\sigma$ ) are added as gray contour lines with  $\Delta\sigma = 0.001 \text{ m}^2 \text{ s}^{-2}$ .



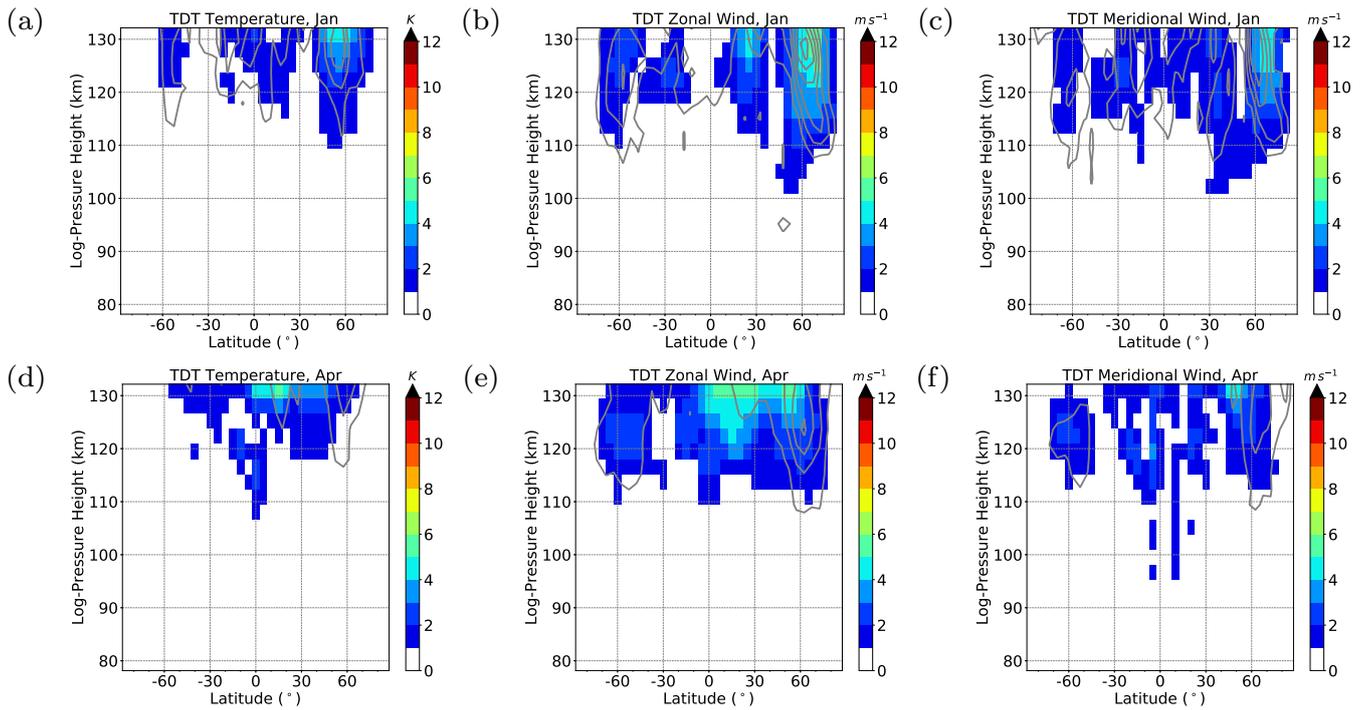
**Figure 5.** Zonal mean TDT amplitudes (colors, REF). From left to right: Temperature, zonal wind, meridional wind. Top: Solstice (January) conditions. Bottom: Equinox (April) conditions. Standard deviation (gray contour lines) is given in steps of 0.2, starting at 0.2, in each parameter.



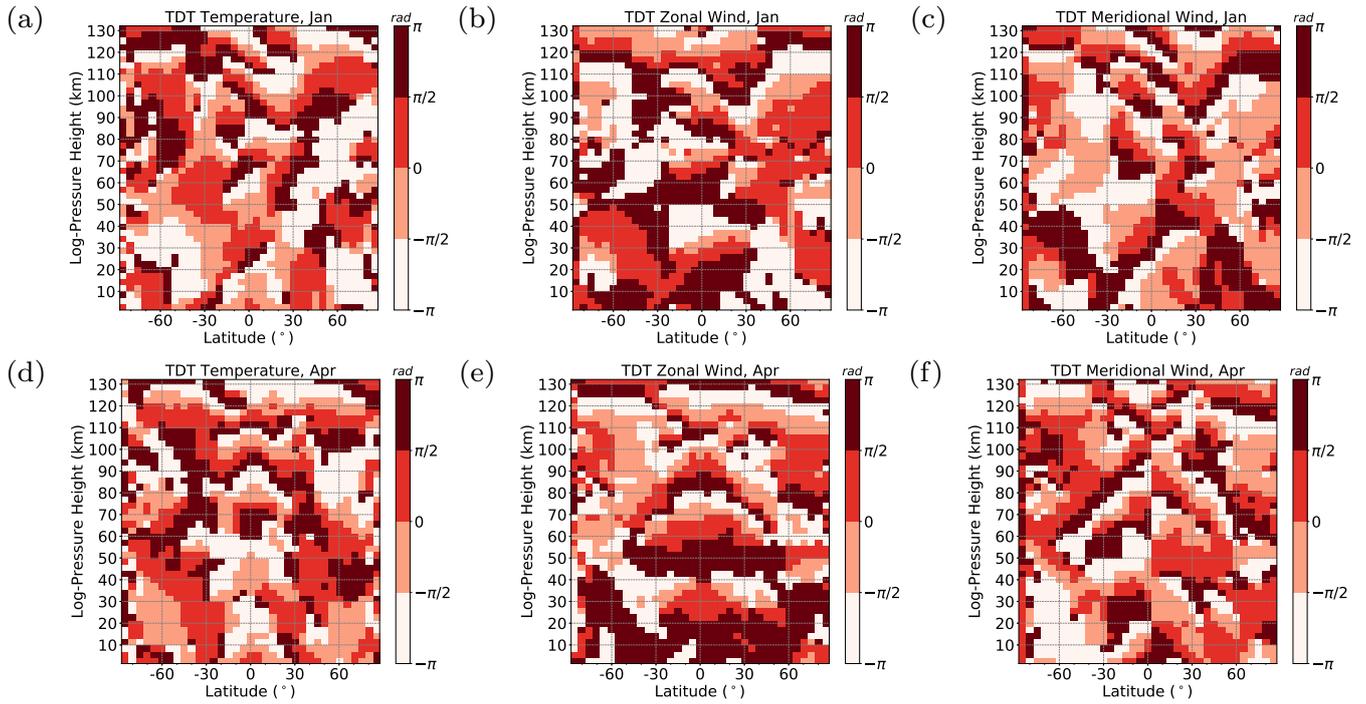
**Figure 6.** Zonal mean TDT phases (REF). From left to right: Temperature, zonal wind, meridional wind. Top: Solstice (January) conditions. Bottom: Equinox (April) conditions.



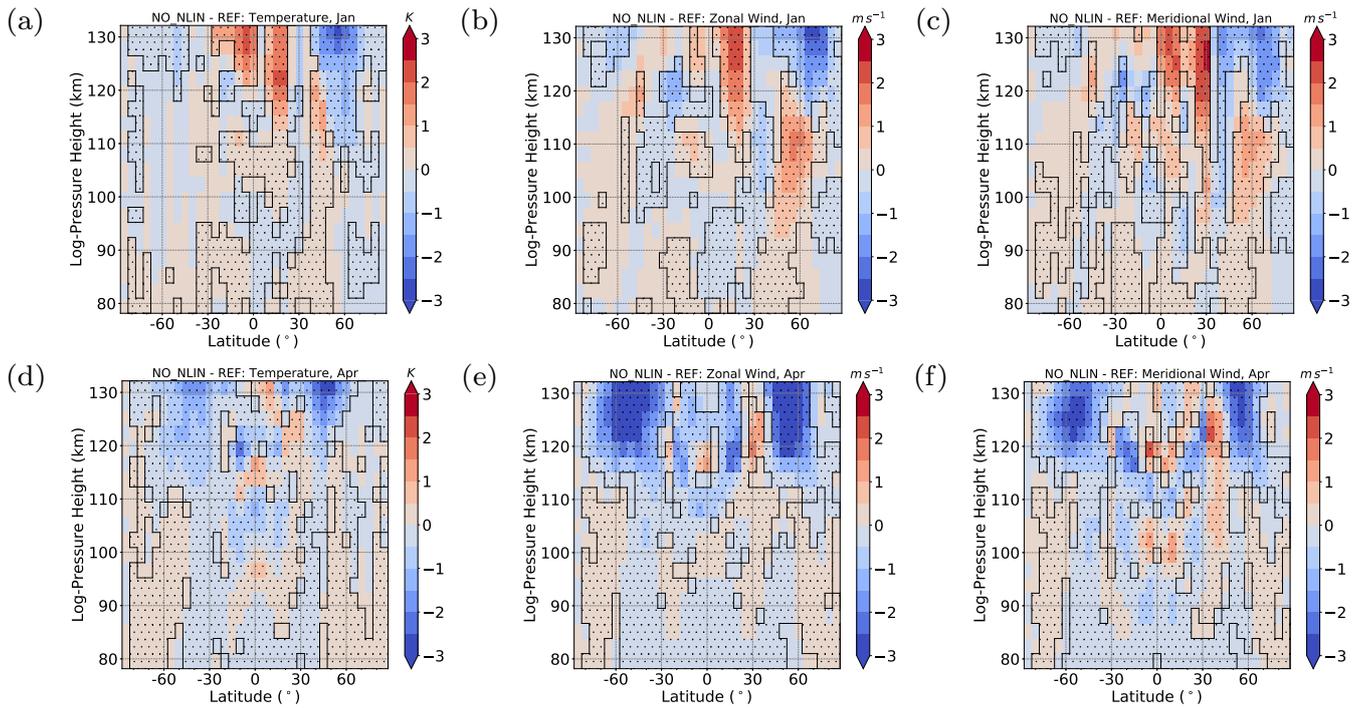
**Figure 7.** REF monthly mean TDT amplitudes at an altitude of  $\approx 106$  km. From left to right: temperature, zonal wind component, meridional wind component.



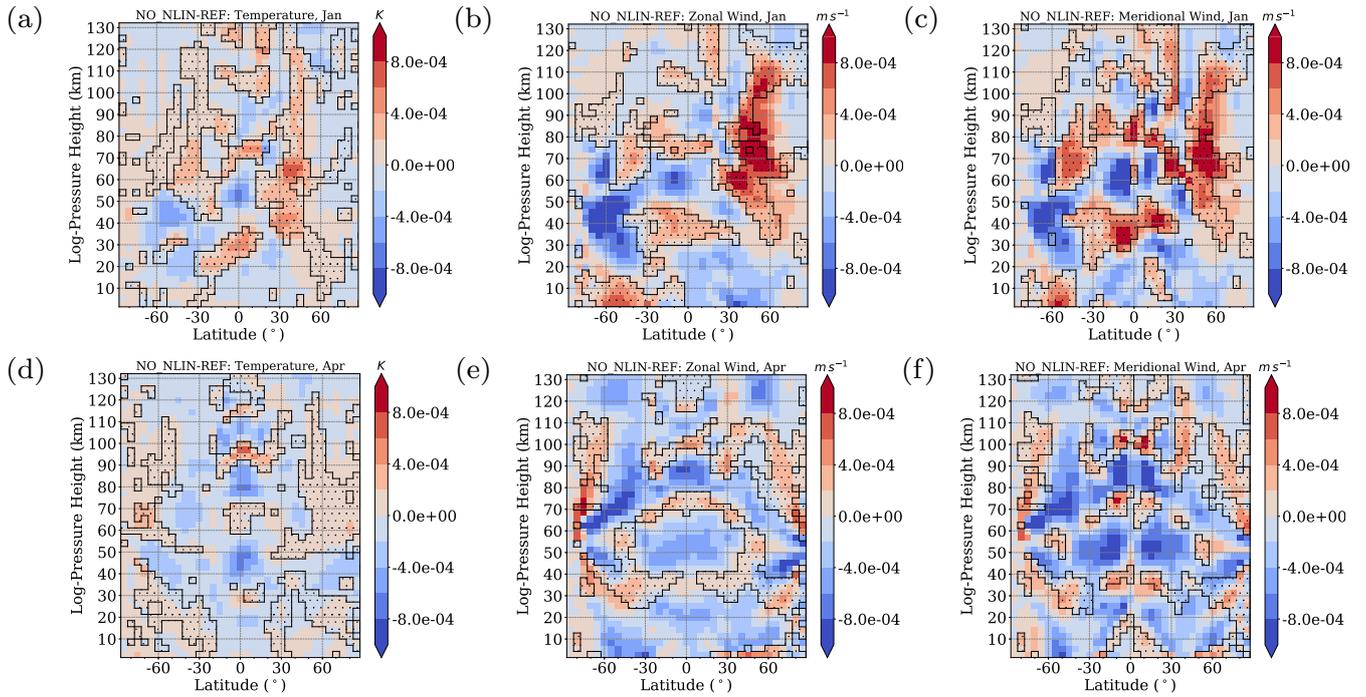
**Figure 8.** As in Fig. 5 but for NO\_SOL simulation.



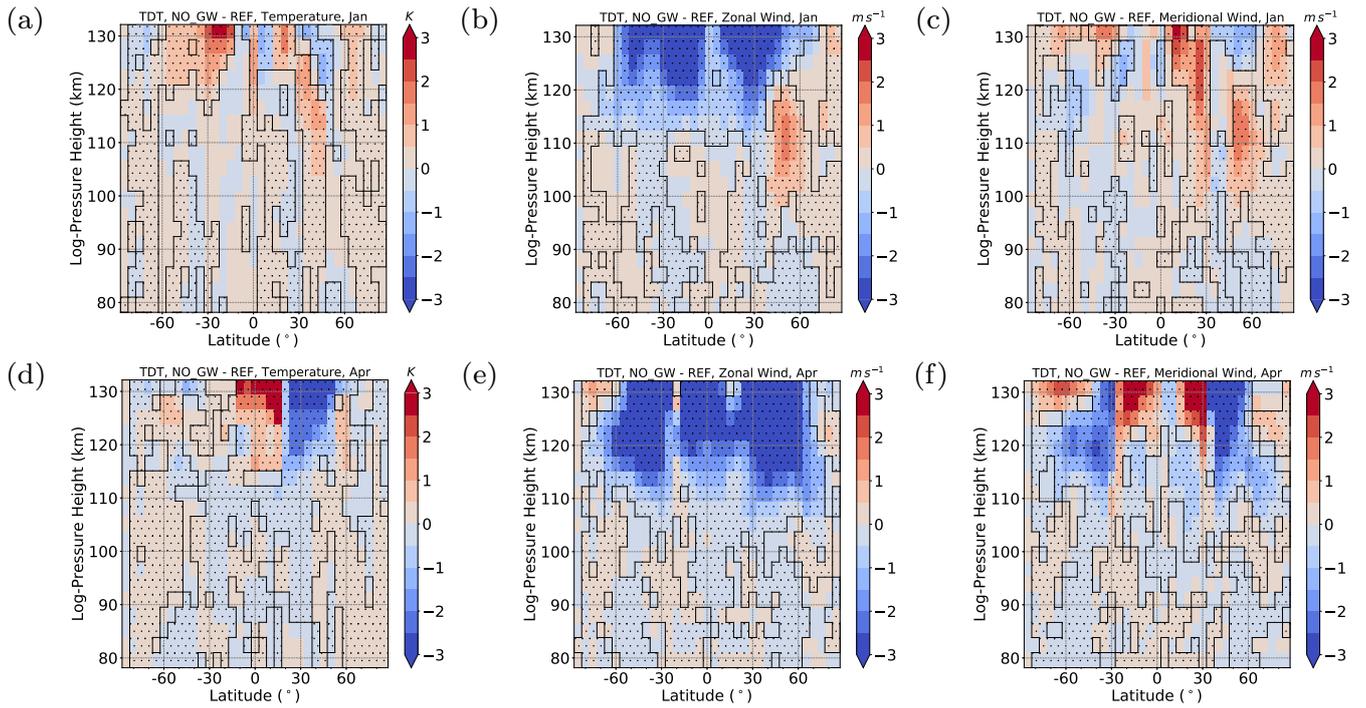
**Figure 9.** Zonal mean TDT phases (NO\_SOL). From left to right: Temperature, zonal wind, meridional wind. Top: Solstice (January) conditions. Bottom: Equinox (April) conditions.



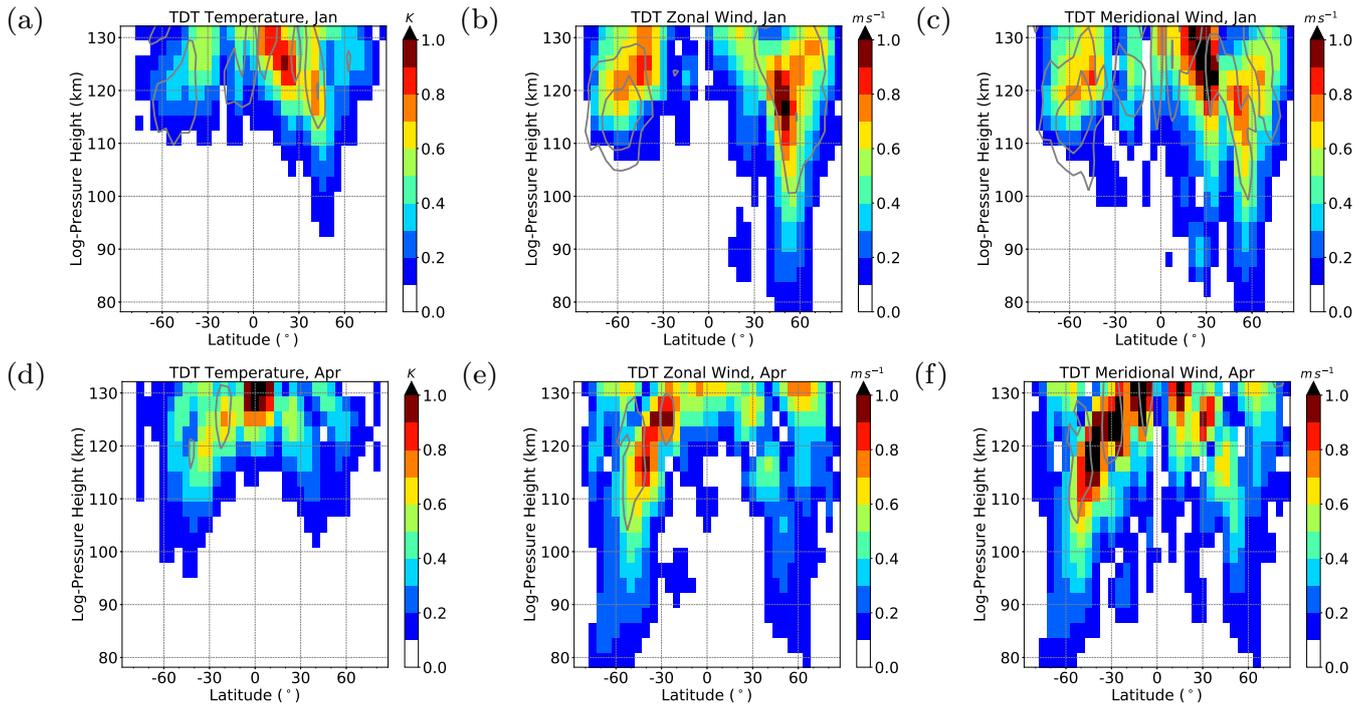
**Figure 10.** Difference of TDT amplitudes between NO\_NLIN and REF simulation. Red colors denote larger NO\_NLIN simulation amplitudes and blue colors denote larger REF simulation amplitudes. Significant areas ( $\alpha < 0.01$ ) are hatched. From left to right: Temperature, zonal wind, meridional wind. Top: Solstice (January) conditions. Bottom: Equinox (April) conditions.



**Figure 11.** Difference of TDT amplitudes between NO\_NLIN and REF simulation, scaled by  $\exp\{-z(2H)^{-1}\}$ . Red colors denote larger NO\_NLIN simulation amplitudes and blue colors denote larger REF simulation amplitudes. Areas of destructive interferences ( $120^\circ \leq \Delta\Phi \leq 240^\circ$ ) between NO\_NLIN and NO\_SOL phases are hatched. From left to right: Temperature, zonal wind, meridional wind. Top: Solstice (January) conditions. Bottom: Equinox (April) conditions.



**Figure 12.** As in Fig. 10 but for NO\_GW simulation.



**Figure 13.** As in Fig. 5 but for CTRL simulation. Note that scales are different. Standard deviation (gray contour lines) is given in steps of 0.05, starting at 0.05, in each parameter.