Response to Topical Editor

“Semidiurnal solar tide differences between fall and spring transition times in the Northern Hemisphere2

By J. Federico Conte et al. submitted to Ann. Geophys.

MS: angeo-2018-29

Comments to the Author:

The editor requests the authors to add page and line numbers to indicate the newly added or modified text in the revised manuscript.
R: Thanks for this comment. We apologize for our mistake. We should have indicated where the changes were applied. We now indicate the page and line of the modifications introduced in the revised manuscript. Please see new replies to the reviewers.

Also, the use of two different window lengths (see Rev#1, second comment and Rev#2 General comment 2) need to be discussed by the authors in more detail, e.g., geophysical pros/cons in addition to technical pros/cons.
R: Thank you. We have checked our code for processing the HAMMONIA simulations and found a small bug that was responsible for the artifacts we were seeing with windows shorter than 30 days. We used the corrected code and reprocessed the HAMMONIA outputs using a 21-day window. After analyzing the new results, we found very small differences with respect to the results using a 30-day window (that can be seen in the new figures of the manuscript, if compared with the original ones), namely, a decrease in the amplitudes of the GWs extracted from HAMMONIA (of around 10%), and a shift of 1-2 days in the timing of the fall and spring transitions. These differences clearly do not modify the conclusions of our study. Nevertheless, we now specify that the averaging window is the same for both, observations and simulations (21 days), and give the reasons for selecting this length. Please see new replies to the reviewers.

Non-public comments to the author:

The authors have responded to each of the reviewers comments, at few places the responses cannot fully clarify the concerns.
R: we have re-written some of the responses to the reviewers with answers we think better address their concerns. Please see new replies to the reviewers.

At many places the authors did not indicate where in the newly uploaded and revised manuscript (page and line numbers) their answers have been placed. It is urgently recommended doing so, otherwise it is not possible to judge if the answers are adequate.
These are the case for:
Reviewer 1: for all three comments.

Reviewer 2: “General comments” 1, 2, and 4 and “Specific comments” 6, 12, 16 .
R: Thanks. We now indicate page number and lines of the new or corrected sentences. Please see new replies to the reviewers.

Rev#2, Specific comment 17: Please apply long-wave if it is not wrong. Apparently, that “long-wave” was meant has not been clear to all readers.
R: we have added the term “long-wave”. Please see in the revised manuscript: page 10, line 5.

Rev#1, second comment AND Rev#2 General comment 2: The use of different window lengths has been discussed and questioned by both reviewers. The authors explain the longer window for the model results “to reduce numerical artefacts”. However, the concern was about a physical difference that is introduced when using 2 different window lengths. How the authors deal this aspect is not discussed. Possible cons using the two windows needs to be mentioned and discussed in the paper, as well as arguments need to be addressed in case the authors still believe that the two window sizes are the best choices.

R: thank you for this comment. As we mentioned above, we have corrected our code and reprocessed the HAMMONIA simulations using the same window length as with the observations (i.e., 21 days). With the exception of a change of ~10% in the amplitudes of the long-scale GWs extracted from HAMMONIA and a shift of 1-2 days in the time of occurrence of the fall and spring transitions, we haven’t found differences with respect to the case of the 30-day averaging window. Nevertheless, as the editor correctly pointed out, using different size windows could introduce different physics in the comparisons. Hence, we now base our analysis on the 21-day window for both, observations and simulations.
The reason for selecting a 21-day window is explained in the manuscript; briefly, given the number of unknowns to be determined from the simulations we need to consider a 21-day window in order to obtain a robust solution after applying least squares (please see in the revised manuscript: page 6, lines 9-11).

Response to anonymous referee #1

“Semidiurnal solar tide differences between fall and spring transition times in the Northern Hemisphere2

By J. Federico Conte et al. submitted to Ann. Geophys.

MS: angeo-2018-29

General Comments:
This paper is dedicated to research of semidiurnal solar tide (S2) behavior during the fall and spring transition times in Northern Hemisphere. Radar wind measurements by three meteor radars located at different mid-latitude sites have been used to investigate above-mentioned tide. It is observed an evident decrease of S2 during every autumn while the time of the decrease occurrence varies from year to year. There is the spring decrease as well but it is not so sudden. The next task that has been performed is to assess the contributions of different semidiurnal tidal components. To solve this problem the Hamburg Model of the Natural and Ionized Atmosphere (HAMMONIA) has been used. It is obtained that during the fall both migrating (SW2) and non-migrating westward propagating (SW1) semidiurnal tidal components decrease during the fall. During the spring, they behave in different ways. The observed behavior of the total semidiurnal tide S2 is mainly driven by superposition of SW2 and SW1 components. This is a good paper, which provides the readers with new information on the seasonal variations of semidiurnal tides. I believe that it will be accepted for publication in Ann. Geophys. after minor revision without an additional review.
I recommend that authors consider the following comments when revising the manuscript.

We would like to thank this anonymous referee for taking the time to read and revise our manuscript. Below, you can find the response to each comment.

Specific Comments:

Page 2, lines 1-2: It should be noted that another possible source of non-migrating tides is a nonlinear interaction between migrating tides and stationary planetary waves (SPWs). The results obtained demonstrate that during seasonal transitions the SW2 and SW1 changes simultaneously. This fact indicates that they are not independent and connected through the nonlinear interaction with SPW1. It would be useful to include a short discussion of this possibility in the conclusion.
R: thank you for this comment. We have added a paragraph explaining why we did not consider non-linear interaction between tides and stationary planetary waves in our analysis (no substantial planetary wave activity was found in the model during the fall and spring times). **<u>Please see in the revised manuscript: page 7, lines 33-34, and page 8, lines 1-2.</u>**
Nevertheless, we would like to point out that some of the co-authors have recently published an article where they study non-linear interactions between the semidiurnal solar tide and SPW1 using wavelet transforms, but during sudden stratospheric warming events (He et al., 2017 https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2017JA024630).

Page 3, line 5 and page 6, line 4: It is not clear why the different windows in analysis of measurements (21-days) and when the authors investigate the tides and planetary waves (30 days) have been used. The observations show a strong intra-seasonal variability of atmospheric tides and it is not correctly to use

different bins in the analysis. For a future, I would like to suggest the complex Morlet wavelet transform to investigate the intra-seasonal variability of atmospheric tides.
R: Thank you very much for this comment. We explain now in the manuscript the reason for selecting a 21-day window: the number of daily unknowns to be determined from the model outputs, at each pressure level, is 111. Squared, this is 12,321. A fitting window of 21 days is large enough to obtain a robust solution after applying least squares (21 [days] x 8 [time points] x 96 [longitude points] = 16,128). **Please see in the revised manuscript: page 6, lines 9-11.**

Furthermore, we have reprocessed HAMMONIA outputs using a 21-day window and present now our analysis based on this averaging window length. Both, simulations and observations are now analyzed using the same averaging window size: 21 days. Before, we hadn't done that because we had found that some artifacts were produced (in the simulations outputs) when using a window smaller than 30 days. We revised our code and found a bug responsible for this. Hence, we re-analyzed HAMMONIA outputs using a 21-day window and found no differences (compared to the results obtained with a 30-day window), with the exception of ~10% smaller amplitudes in the GWs extracted from the simulations and a shift of 1-2 days in the time of occurrence of the S2 fall and spring transitions. In other words, our conclusions remain the same, but now are based on the correct comparison. **Please see in the revised manuscript: new Figures 3, 4 and 5.**

Page 6, line 12: It would be useful to explain shortly the difference between the total semidiurnal tide (S2) and SW2+SW1 (at least when we consider the results of simulation).
R: Thanks for this comment. We have added a couple of sentences describing the difference between the total S2 tide and SW2+SW1. **Please see in the revised manuscript: page 7, lines 5-6.**

Technical corrections:

Page 2, line9 and page 10, line 17: It is better to use "time interval" instead of "time period".
R: Thanks for this suggestion. We have changed "time period" to "time interval". **Please see in the revised manuscript: page 2, lines 6 and 9.**

Response to anonymous referee #2

"Semidiurnal solar tide differences between fall and spring transition times in the Northern Hemisphere2

By J. Federico Conte et al. submitted to Ann. Geophys.

MS: angeo-2018-29

The current paper focuses on differences in variability of semidiurnal solar tide (S2) between autumn and spring in the Northern Hemisphere. The differences were first described using wind data observed by meteor radars at three stations: one at high latitude (Andenes) and two at mid-latitudes (Juliusruh and Tavistock). In brief, S2 was found to decrease suddenly at all observed altitudes in autumn, while in spring S2 decreases more gradually and the decrease occurs earlier at lower altitudes than at higher altitudes. In order to explain these differences, the authors considered contributions from dominant semidiurnal tidal components (SW1 and SW2) provided by HAMMONIA simulation. The authors found that differences in variabilities of both SW1 and SW2 mostly lead to different variabilities of S2 during autumn and spring. In addition, gravity wave (GW) activity observed by meteor radars is stronger in autumn than in spring. This, as suggested by the authors, may also contribute to differences in S2 behavior via GW-tide interaction.

The paper is scientifically interesting. It is generally well written and clearly structured. It also has an adequate length and pertinent title and abstract.

We would like to thank this anonymous referee for taking the time to read and review our paper. The response to each comment can be found below. Also, we have attached a new version of the manuscript so the referee can see the applied changes.

General comments:

1. The introduction mentions only one possible reason, which could lead to S2 differences between autumn and spring (tide-tide interaction). Another possible reason, as you discussed later in your manuscript, could be GW-tide interaction. Although it is not the main topic of the current paper, I think GW-tide interaction should be briefly mentioned in the introduction.

R: thank you for this comment. We have added a sentence with a proper reference on this matter. **Please see in the revised manuscript: page 2, lines 15-17.**

2. To estimate the tidal information from meteor radar measurements, a running window of 21 days was used. For HAMMONIA simulation, a 30-day window was used. Can you please explain: (1) the reason why 21 days and 30 days were chosen? and (2) why is the window for wind observations different from the window for simulated wind?

R: Thank you very much for this comment. Firstly, we now explain in the manuscript the reason for selecting a 21-day window: the number of daily unknowns to be determined from the model outputs, at each pressure level, is 111. Squared, this is 12,321. A fitting window of 21 days is large enough to obtain a robust solution after applying least squares (21 [days] x 8 [time points] x 96 [longitude points] = 16,128). **Please see in the revised manuscript: page 6, lines 9-11.**

Secondly, we have reprocessed HAMMONIA outputs using a 21-day window and present now our analysis based on this averaging window size. Both, simulations and observations are now analyzed using the same averaging window size: 21 days. Before, we hadn't done that because we had found that some artifacts were produced (in the simulations outputs) when using a window smaller than 30 days. We revised our code and found the bug responsible for this. Hence, we re-analyzed HAMMONIA outputs using a 21-day window and found no differences (compared to the results obtained with a 30-day window), with the exception of ~10% smaller amplitudes in the GWs extracted from the simulations and a shift of 1-2 days in the time of occurrence of the fall and spring transitions. In other words, our conclusions remain the same, but now are based on the correct comparison, given that we are using the same averaging window size for both, observations and simulations. **Please see in the revised manuscript: new Figures 3, 4 and 5.**

Further, extracting tides from HAMMONIA simulation took into account PWs, but extracting tides from radar measurements did not consider PWs. This difference should be explained in the manuscript.
R: thank you very much for this comment. We also fitted HAMMONIA wind simulations without explicitly considering the PWs (as in the case of meteor radar measurements). The mean winds and tides determined in this second case were very similar to those obtained with the explicit inclusion of PWs, and hence we decided not to consider the results of this second fitting. We now explain this in the manuscript. **Please see in the revised manuscript: page 6, line 11, and page 7, lines 1-2.**

3. For all figures in the manuscript, please add a vertical grid or at least 2 vertical lines for each spring and autumn. This will help the readers very much to follow the variability (decrease) of tidal components that you described in the text.
R: thank you for this comment. We have added vertical white dashed lines in all our figures for days of the year 90 and 275, so the readers can better understand our results. **Please see in the revised manuscript the new figures and also the captions, where we indicate that the vertical white dashed lines mark the days of the year 90 and 275.**

4. The fall decrease occurs earlier in HAMMONIA simulation than in the observations. This can be seen for all 3 locations and very clearly for Juliusruh and Tavistock. Please describe and explain this fact in your paper.
R: thanks. This is mentioned in the manuscript. Nevertheless, we have modified a few sentences and added new ones so this is clearer for the readers. **Please see in the revised manuscript: page 7, lines 18-21, and page 8, lines 6-7.**

Specific comments:
Below, the first number is the page number and the second number is the line number or line numbers, separated by a forward slash. For example, 2/5 refers to page 2, line 5; 3/10-12 means page 3 lines 10 to 12.

1. 1/19: PW → PWs
R: thanks. We have made this correction. **Please see in the revised manuscript: page 1, line 19.**

2. 1/20: GW → GWs
R: thanks. We have corrected this. **Please see in the revised manuscript: page 1, line 20.**

3. 1/22: "they have typical periods ...". Some rewording may be needed. My suggestion: "The most dominant tide components have periods .."
R: thanks. We have re-written this sentence in a different way. **Please see in the revised manuscript: page 1, lines 22-23.**

4. 2/14: It is helpful for the readers to introduce again the abbreviations (SW2 and SW1) here in parentheses
R: thanks. We have included the acronyms again. Please see in the revised manuscript: page 2, lines 14-15.

5. 3/13: "The mean winds .." → "The zonal mean winds .."
R: thanks for this. We have corrected the sentence. Please see in the revised manuscript: page 3, line 13.

6. 4/14: Which part of GW spectrum can be seen by your measurements? Please specify the observed GW spectrum.
R: thanks. Now we have specified that the meteor radar observations allow us to see GWs with periods larger than 2 hours. Please see in the revised manuscript: page 4, lines 17-18.

7. 4/23-26: Do you have any explanation for the earlier decrease during the years 2009, 2012, 2013 and the lower amplitude during 2013?
R: sadly, no. We have investigated some possible agents that might be causing these differences (e.g., solar activity levels, proximity to strong warmings the following winter, etc.) but found nothing convincing. We are currently investigating the influence of polar jet oscillations on thermal tides and we think it might be related to that, but unfortunately we cannot prove this yet.

8. 4/28: What is the reason of more variability during the spring?
R: again, sadly we do not have an answer to this question. We believe that the observed variability during the spring could be connected, e.g., to late warmings. Late stratospheric warmings have been observed during March/April of, e.g., 2005 and 2015. We think this late warmings might be partially introducing more variability in the MLT region. But, again we need to further investigate this.

9. 4/30: Can you please explain why the duration is longer at high latitudes than at middle latitudes?
R: as in the case of point 7., we still cannot explain this. That is one of the reasons why we also want to estimate the impact of SW1 directly from the observations (mentioned in the manuscript) in order to see if this longer duration at high latitudes has some connection with the planetary wave activity.

10. 5/10: Is it possible to turn off the GW parameterizations and see how much GW-tide interaction influences S2 variability?
R: in theory, it could be done. However, we have used HAMMONIA simulations that were already stored in Hamburg MPI servers. To run new simulations would be time consuming and sadly, H. Schmidt is extremely busy with other projects right now. Nonetheless, in future studies we plan to "play" with different GW parameterizations using other models (such as WACCM-X and CMAT-2).

11. 7/14: Do you also see the annual variability in HAMMONIA simulation?
R: No. We see very similar behaviors during all the 20 years used in the study.

12. 7/14: Please mention that the fall decrease in simulation occurs earlier than in observations. Further, the simulated S2 amplitude is higher than observed S2 amplitude. Can you please also comment on that?
R: These features are already mentioned in the manuscript.

13. 7/28: “These differences are reproduced .. model" → “These differences are reproduced .. model to a certain extent"

R: thanks. We have applied the suggested change. Please see in the revised manuscript: page 8, line 5.

14. 8/0: Title of Fig. 4: CMOR → Tavistock?

R: thanks. We have changed the title accordingly. Please see in the revised manuscript: Fig. 4.

15. 9/8: For observations, you showed the phase analysis for S2 (Fig. 4). For simulation, why don't you show the phase analysis for the same S2? why did you choose SW2 instead?

R: well, for two main reasons. Firstly, because we fitted each tidal component separately. Hence, mixing the phases of all tidal components contributing to S2 would be misleading. Secondly, because after realizing that SW2 strongly dominates the behavior of S2 during the fall, we mainly focused our study on this component (in the simulations).

16. 9/25: I agree with the authors that GW-tide interaction requires a thorough analysis, given that not only the simulation, but also your observations contain only a certain part of the GW spectrum, and different parts of the GW spectrum can interact differently with tides. The interaction of other parts of the GW spectrum with S2 cannot be estimated here and may also influence the S2 variability. Maybe you should add one sentence here to clarify that fact.

R: thanks. We have added a sentence on this matter. Please see in the revised manuscript: page 9, line 35, and page 10, line 1.

17. 9/27: “the GW activity" → “the long-wave GW activity"

R: thanks for this comment. We have applied this change. Please see in the revised manuscript: page 10, line 5.

18. 9/30: Would you conclude that long-wave GWs suppress the migrating semidiurnal tide SW2 amplitude?

R: we think that the GW-tide interaction could be one of the causes of the fall decrease of SW2. However, we still don’t have sufficient evidence to firmly conclude this, and that is why we are only suggesting that GWs could be involved.

Semidiurnal solar tide differences between fall and spring transition times in the Northern Hemisphere

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Abstract. We present a study of the semidiurnal solar tide (S2) during the fall and spring transition times in the northern hemisphere. The tides have been obtained from wind measurements provided by three meteor radars located at: Andenes (69° N, 16° E), Juliusruh (54° N, 13° E) and Tavistock (42° N, 81° W). During the autumn, S2 is characterized by a sudden and pronounced decrease occurring every year and at all height levels. The spring transition also shows a decrease of S2, but not sudden and that ascends from lower to higher altitudes during an interval of $\sim$ 15 to 40 days. To assess contributions of different semidiurnal tidal components, we have examined a 20-year free run simulation by the Hamburg Model of the Neutral and Ionized Atmosphere (HAMMONIA). We found that the differences exhibited by the S2 tide between equinox times are mainly due to distinct behaviors of the migrating semidiurnal and the non-migrating westward propagating wave number 1 tidal components (SW2 and SW1, respectively). Specifically, during the fall both, SW2 and SW1 decrease, while during the spring time SW2 decreases but SW1 remains approximately constant or decreases only slightly. The decrease shown by SW1 during the fall occurs later than that of SW2 and S2, which indicates that the behavior of S2 is mainly driven by the migrating component. Nonetheless, the influence of SW1 is necessary to explain the behavior of S2 during the spring. In addition, a strong shift in the phase of S2 (of SW2 in the simulations) is also observed during the fall. Our meteor radar wind measurements show more gravity wave activity in the autumn than during the spring, which might be indicating that the fall decrease is partly due to interactions between SW2 and gravity waves.

1 Introduction

It is well known that the mesosphere and lower thermosphere (MLT) variability is strongly influenced by a large variety of waves that dynamically interact and couple different regions of the terrestrial atmosphere. Global scale waves include planetary waves (PWs), which have periods of $\sim$ 2-30 days, as well as thermal tides, which have periods that are harmonics of the solar day (e.g., Rossby, 1939; Forbes, 1984). Gravity waves (GWs), on the other hand, are local scale waves characterized by shorter vertical wavelengths and periods of minutes to a few hours (e.g., Fritts and Alexander, 2003). Thermal tides are mainly excited by solar heating of water vapor and ozone. Due to the excitation processes, the dominant tidal components have periods of one solar day (24 h) and its two first harmonics, i.e., 12 h and 8 h. When the tides propagate Sun-synchronously, they are identified as migrating. The non-migrating tides are primarily excited by tropospheric latent heat release and may be westward or eastward propagating (Hagan and Forbes, 2002, 2003). Another source of non-migrating tides is the non-linear interaction between migrating tides and stationary planetary waves (e.g., Angelats i Coll and Forbes, 2002).

Given that tides are the dominant waves in the MLT region, they play a significant role in coupling processes by, for example, modifying the propagation conditions for other waves (e.g., Eckermann and Marks, 1996; Smith, 2012). Although there is considerable tidal variability at different seasons, analyses of the tidal seasonal behavior show that solar tides exhibit significant variations mainly during time intervals with strong changes in the mean winds, e.g., during sudden stratospheric warming events (e.g., Charlton and Polvani, 2007; Fuller-Rowell et al., 2010). The spring and fall transitions also show strong changes in the mean winds (e.g., Shepherd et al., 1999; Taylor et al., 2001; Matthias et al., 2015). Hence, one may expect an enhanced and different response of the tides during these time intervals. Previous studies have investigated the behavior of solar tides during equinox times (e.g., Riggin et al., 2003; Pancheva et al., 2009). More recently, Chau et al. (2015) reported a persistent and sudden decrease of the semidiurnal solar tide (S2) in the northern hemisphere during the September/October months. However, they did not provide an explanation of this observed sharp decrease of S2. Laskar et al. (2016) speculated that the enhanced S2 amplitudes observed during August/September over Andenes (northern Norway) and Juliusruh (northern Germany) might be due to in-phase interaction between the migrating semidiurnal (SW2) and the non-migrating westward propagating wave number 1 semidiurnal (SW1) tidal components, but they could not verify this due to a lack of global datasets. Recent studies have also examined the mechanisms of how gravity waves influence solar tides in the middle and upper atmosphere (e.g., Yiğit and Medvedev, 2017). All this motivated us to further investigate the differences in the response of the S2 tide between the spring and fall transition times in the northern hemisphere using both, observations and model simulations.

The structure of this paper is as follows. In Section 2, we present and describe the tidal features in both, radar measurements and model simulations. Section 3 is used to discuss the comparison of observations with model simulations, in order to explain the differences seen in the behavior of the semidiurnal solar tide between equinoxes. Conclusions are given in Section 4.

2 Results

2.1 Semidiurnal solar tide as measured by meteor radars

Specular meteor radars constitute an excellent tool to study winds in the mesosphere and lower thermosphere region (e.g., Hocking et al., 2001; McCormack et al., 2016). These remote sensing instruments continuously observe winds in the height range extending from $\sim$ 75 up to 105 km, with a typical vertical resolution of 2 km (e.g., Stober et al., 2017). From these wind measurements, it is possible to extract detailed information about the mean winds and tides, as well as planetary waves and gravity waves (e.g., Hocking and Thayaparan, 1997; Hoffmann et al., 2007).

In this work, we have analyzed wind measurements provided by three meteor radars located at Andenes (69.3° N, 16° E), Juliusruh (54.6° N, 13.3° E) and Tavistock (42.3° N, 80.8° W). The tidal information has been estimated by means of a least square technique. Assuming that the zonal (u) and meridional (v) winds result from the superposition of a mean wind (U_0 and V_0, respectively) plus oscillations of different periods, we independently fit the observations in each horizontal component with sinusoidal functions of periods T_i equal to 24, 12 and 8 h in order to account for the diurnal, semidiurnal and terdiurnal solar

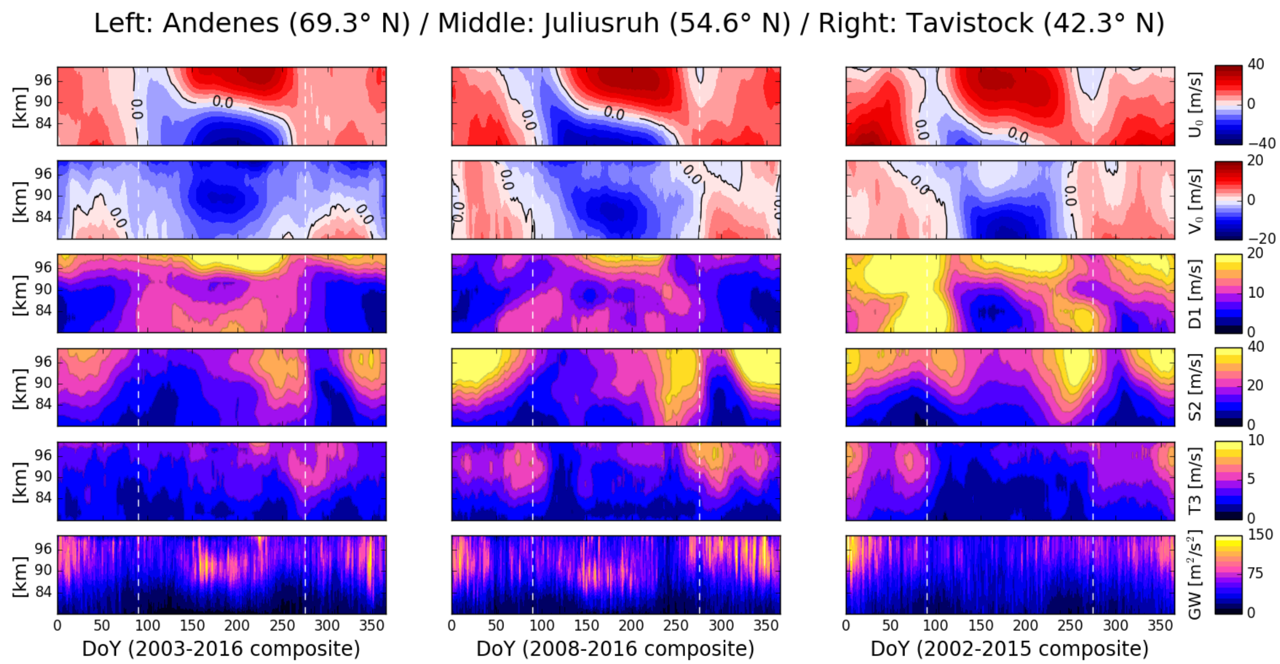

Figure 1. Composites of mean zonal (U_0) and meridional winds (V_0), diurnal, semidiurnal and terdiurnal solar tides (D1, S2 and T3, respectively), and GW kinetic energy over: (left) Andenes, (middle) Juliusruh and (right) Tavistock. The vertical white dashed lines indicate DoYs 90 and 275. The composites were determined for the entire yearly datasets available at the time this study was initiated.

tides,

$$(u,v) = (U_0, V_0) + \sum_{i=1}^{3} A_{(u,v)_i} \cos\left(2\pi \frac{(t-\phi_{(u,v)_i})}{T_i}\right); \qquad (1)$$

where $A_{(u,v)_i}$ and $\phi_{(u,v)_i}$ represent the amplitude and phase, respectively, of the different tidal components. In this way, assuming that the tidal phases are stable within the selected running window, daily values of the mean winds, and the amplitude and phase of each tide were determined in bins of 21 days shifted by 1 day. Besides, information on the gravity wave activity is provided by the residuals of the fitting process, since they contain most of the wave-like perturbations different than tides and planetary waves.

It must be noted that from ground-based single station measurements it is not possible to decompose the observed tides into different wave numbers, which implies that we cannot differentiate between migrating and non-migrating tidal components.

In Fig. 1, we present a composite for the three sites considered in this study of the mean zonal (U_0) and meridional (V_0) winds, the total amplitude of the diurnal (D1), semidiurnal (S2), and terdiurnal (T3) solar tides, and a proxy for the gravity wave kinetic energy. The latter is estimated by adding and then dividing by 2 the squared residuals in the zonal and meridional components. The mean zonal winds exhibit similar characteristics over the three sites: eastward zonal winds during winter, and a tilted wind reversal during the summer, with eastward winds above and westwards below and the height at which the wind reversal is observed decreasing with latitude. The meridional winds blow toward the equator throughout the summer, and mainly poleward during the winter. The semidiurnal solar tide is the main interest of this study. Nevertheless, we are also presenting our results on the diurnal and terdiurnal solar tides to stress that the S2 tide dominates at middle and high latitudes, as previously reported (e.g., Manson et al., 1999; Hoffmann et al., 2010). By simple comparison, one can see that S2 shows the largest amplitudes of the three tidal components. D1 does show significantly strong amplitudes during winter and early spring over Tavistock, but they are still a few $m\ s^{-1}$ smaller than those corresponding to S2. The seasonal behavior of S2 is characterized by strong amplitudes during the winter, that slowly ascending from lower to higher altitudes decrease during the spring time, to end with very low values during the summer. During the early fall, S2 amplitudes recover and reach values similar to (or even larger than) those observed during winter and that extend to lower altitudes than the rest of the year ($\sim$ 81 km). Finally, during the fall the S2 tide abruptly decreases its amplitude at all height levels. This pronounced decrease is seen every year at the three locations, and extends for a period of $\sim$ 15 days or more, depending on the year.

The seasonal behavior of the gravity waves is different than that of the S2 tide. From the bottom panels of Fig. 1, it can be seen that GWs show significant activity during the winter at all three locations, but that it is considerable during summer only over Andenes and Juliusruh. On the other hand, GWs exhibit a clear pattern during equinox times over the three sites: there is more activity during the fall than in the spring. This is clearest over Juliusruh, where an enhancement in the GW activity can be seen at approximately the same time the S2 tide abruptly decreases. The terdiurnal solar tide has a period of 8 h, which falls almost in the middle of the spectrum of typical GW periods (our measurements allow us to see GWs with periods larger than 2 h). Since the wavelength information was not available for this study, we were not able to decompose the T3 tide into the 8 h tidal wave and the GWs with that same period. Hence, to better assess the GW activity, the T3 tide must be included in the analysis. The seasonal variability of T3 presents some similarities with that of the GWs, although the amplitude enhancement seen in the fall at around the same time S2 starts decreasing is more pronounced in the case of T3.

The time of occurrence of the S2 tide fall decrease varies from year to year. This can be deduced from Fig. 2, where we present the annual variability of the semidiurnal solar tide during the period 2008-2015, at all three locations. Over Andenes and Juliusruh, S2 starts decreasing earlier than on average during the years 2009, 2012 and 2013 (around day of the year [DoY] 270), and later during 2015 (around DoY 280). In the case of Tavistock, the years 2012 and 2013 show the earliest start of the S2 fall decrease ($\sim$ DoY 265), and again 2015 shows the latest ($\sim$ DoY 295). Besides an earlier start of the fall decrease, the year 2013 also shows the lowest S2 amplitudes previous to the decrease, over all three locations. Compared to autumn, there is more variability during the spring, specially at high latitudes, where two consecutive years may exhibit a difference of $\sim$ 20 days in the commencement of the reduction of S2 amplitudes. The duration of the fall decrease also varies from year to year, and between different latitudes. At high latitudes, it tends to be $\sim$ 5-10 days longer than at middle latitudes (with 2009 showing the longest decrease), while over Julisuruh and Tavistock it extends for approximately the same amount of days (with the longest decrease observed during 2010 and 2011, respectively).

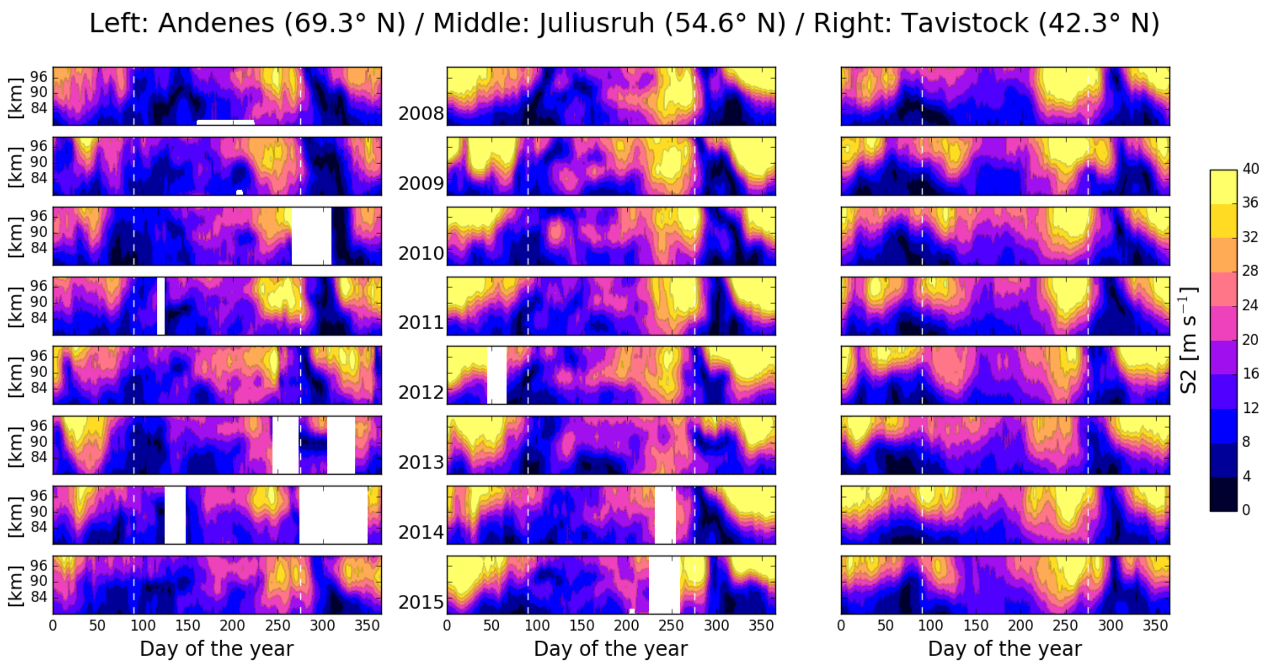

Figure 2. Semidiurnal solar tide (S2) observed during the time period (from top to bottom) 2008-2015, over: (left) Andenes, (middle) Juliusruh and (right) Tavistock. Data gaps are shown in white. The vertical white dashed lines indicate DoYs 90 and 275. The selected years correspond to the period with available data at the three locations.

2.2 Tides in the HAMMONIA model simulations

Motivated by our observations presented above, in this study we focus on the differences exhibited by the S2 tide between the spring and fall transition times. In order to investigate possible distinct behaviors of the different migrating and non-migrating semidiurnal tidal components, we have analyzed a 20-year simulation by the Hamburg Model of the Neutral and Ionized Atmosphere (HAMMONIA).

HAMMONIA is a spectral model that consists of a vertical extension of the MAECHAM5 model (Giorgetta et al., 2006; Manzini et al., 2006) coupled to the MOZART3 chemical model (Kinnison et al., 2007). The atmospheric dynamics, chemistry and radiation processes are considered interactively from the Earth's surface up to 1.7 x 10^{-7} hPa ($\sim$ 250 km). Orographic gravity waves are parameterized according to Lott and Miller (1997), while non-orographic gravity waves are taken into account following Hines (1997a, b). The 3-hour model outputs used in this study were obtained from a 20-year time-slice HAMMONIA simulation with constant boundary conditions typical for solar minimum and greenhouse gas concentrations of the 1990s, with a triangular truncation at wave number 31, corresponding to a resolution of 3.75° in latitude and longitude, and with 67 pressure levels. For a detailed description of the model, we refer the reader to Schmidt et al. (2006).

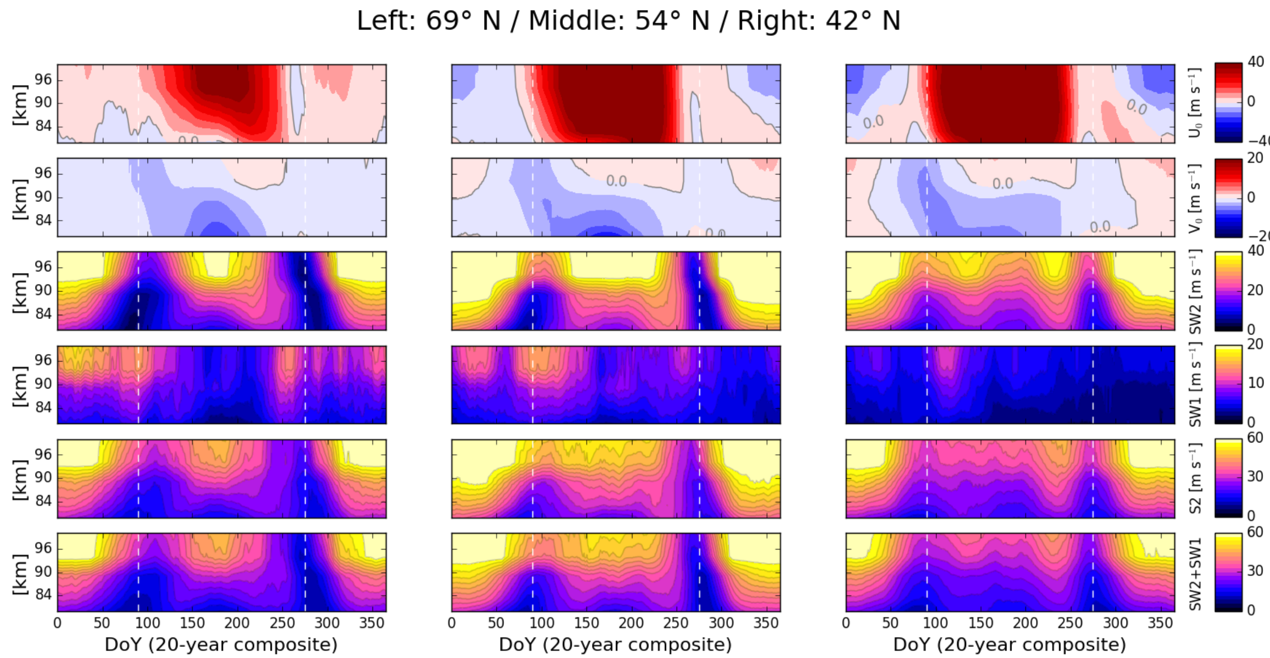

Figure 3. HAMMONIA composites of the simulated mean zonal (U_0) and meridional winds (V_0), migrating semidiurnal (SW2), non-migrating westward propagating wave number 1 semidiurnal (SW1), and total semidiurnal (S2) solar tides, and SW2+SW1, over: (left) Andenes, (middle) Juliusruh and (right) Tavistock. The vertical white dashed lines indicate DoYs 90 and 275.

To extract the tides and planetary waves, a similar fitting technique to that presented in the previous subsection was applied to the zonal and meridional winds simulated by HAMMONIA. The global coverage of the model outputs allows us to investigate different migrating and non-migrating components. Hence, at any given latitude and pressure level the following tides and planetary waves were fitted in a 21-day window shifted by 1 day,

$$\Omega = \Omega_0 + \sum_{l=1}^{4}\sum_{m=-3}^{3} B_{l,m}\cos\left(2\pi\frac{(t-m\lambda-\psi_{l,m})}{P_l}\right) + $$
$$+ \sum_{i=1}^{3}\sum_{s=-4}^{4} A_{i,s}\cos\left(2\pi\frac{(t-s\lambda-\phi_{i,s})}{T_i}\right). \quad (2)$$

Here, Ω represents either the zonal or the meridional wind, and Ω_0 its mean; s, m indicate the wave numbers (negative for a westward propagating wave) of tides and PWs, respectively; λ is the geographic longitude; $A_{i,s}$ and $\phi_{i,s}$ are the respective amplitude and phase of tides with periods T_i equal to 24, 12 and 8 hours; and $B_{l,m}$ and $\psi_{l,m}$ are the respective amplitude and phase of planetary waves with periods P_l equal to 2, 5, 10 and 16 days. The number of daily unknowns to be determined from the model outputs is 111. A fitting window of 21 days is then large enough to obtain a satisfactory solution after applying least squares (21 [days] x 8 [time points] x 96 [longitude points] = 16,128 > 111^2 = 12,321). HAMMONIA outputs were also fitted without the explicit inclusion of PWs. The mean winds and tides determined in this case showed no substantial differences with those obtained fitting Eq. (2), and therefore are not considered in this study.

Figure 3 shows composites for similar geographic coordinates than Andenes, Juliusruh and Tavistock, of the simulated mean zonal (U_0) and meridional (V_0) winds, the total amplitudes of the migrating semidiurnal (SW2) and the non-migrating westward propagating wave number 1 semidiurnal (SW1) solar tides, the amplitude of the total semidiurnal solar tide (i.e., the sum of all semidiurnal tidal components fitted in HAMMONIA, or simply S2), and the total amplitude of $SW2 + SW1$. The altitude range is the same as that of the meteor radar observations. However, in the case of the model the heights are approximated since its outputs are given in pressure levels. From Fig. 3, it can immediately be seen that the amplitudes of the mean zonal (meridional) wind are larger (smaller) than in the observations. Tidal amplitudes are also larger in the simulations than in the observations. The reversal of the mean zonal wind during summer is seen $\sim 10\ km$ lower than in the observations, a difference that can be partially attributed to the approximated height calculated at each pressure level. Other discrepancies can be seen during winter at middle latitudes, where the simulated mean zonal winds are mainly westward. On the other hand, winter time mean zonal winds are eastward at high latitudes, in agreement with the observations. The simulated mean meridional winds are mainly equatorward during summer below $\sim 91\ km$, also in agreement with the observations. However, the poleward winds typically seen in meteor radar measurements during winter are not as evident in the simulations, specially at high latitudes. The simulated SW2 tidal component exhibits similarities with the observed S2 tide: strong amplitudes in winter and both, the spring and fall transition times are characterized by a decrease in the activity of SW2, with the decrease seen in the fall being significantly more pronounced and occurring rapidly at all height levels. On the other hand, the amplitudes of SW2 during summer are considerably larger than those of the observed S2, while the SW2 fall decrease occurs earlier ($\sim$ 25 days) and lasts a few more days than in the case of the observed S2. The fall decrease of the simulated total semidiurnal (S2 in Fig. 3) solar tide also takes place $\sim$ 25 days earlier than in the observations.

The amplitude and seasonal behavior of SW1 are quite different. From Fig. 3, one can clearly see that the amplitudes of this tidal component never reach values larger than 20 $m\ s^{-1}$ and that the lowest values are mainly seen during the summer and the fall. In the spring, SW1 amplitudes over Andenes and Juliusruh remain approximately constant during the first half of the season, and slightly decrease during the second one. Over Tavistock, SW1 exhibits similar amplitude values throughout most of the spring. During the fall over Andenes and Juliusruh, SW1 amplitudes start decreasing around one week later than SW2, and they reach the lowest values approximately one month after SW2 does. Over Tavistock, SW1 exhibits extremely low amplitudes the entire summer and fall. The rest of the semidiurnal tidal components extracted from HAMMONIA outputs have very small to negligible amplitudes, and are not shown here. The seasonal behavior of S2 and $SW2 + SW1$ is exactly the same (Fig. 3). The largest differences in amplitude are of only a few $m\ s^{-1}$, mainly during summer and early fall. Moreover, the amplitude and seasonal behavior of S2 are very similar to those of SW2, specially during the fall, which suggests that the behavior of the total semidiurnal tide is mainly driven by SW2.

Given that one of the sources of non-migrating tides is the non-linear interaction between migrating tides and stationary planetary waves (e.g., He et al., 2017), we also analyzed the PWs extracted from HAMMONIA outputs. However, we found

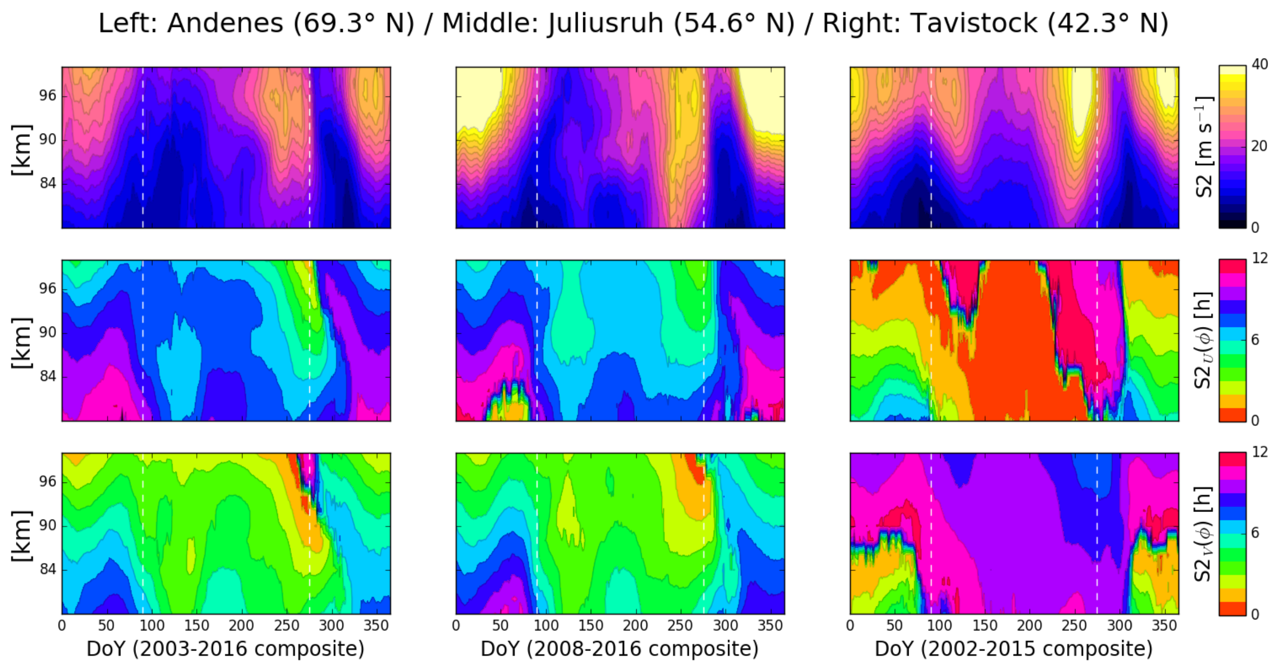

Figure 4. Composites of the semidiurnal solar tide (S2) and its phase in the zonal and meridional components, over: (left) Andenes, (middle) Juliusruh and (right) Tavistock. The vertical white dashed lines indicate DoYs 90 and 275.

very low to negligible PW activity during equinox times, and no significant differences between the spring and fall transition times over all the locations considered in this study. Substantial PW activity was detected in the model only during winter.

3 Discussion

The semidiurnal solar tide observed over Andenes, Juliusruh and Tavistock exhibits significant differences between the spring and fall transition times. These differences are reproduced by the HAMMONIA model to a certain extent. Although there are obvious discrepancies in the time of occurrence and duration of the fall decrease (it occurs around one month earlier in the simulations), as well as in the tidal amplitudes during the spring, the features that characterize the tidal behavior during equinox times are similar in observations and simulations. Further, previous studies have already shown good agreement between observed tides and those simulated by HAMMONIA (e.g., Yuan et al., 2008). Therefore, we assume that one can use the analysis of the simulated tides to explain the behavior of S2 in the observations.

Although both equinox time periods are characterized by a reduction in the activity of the S2 tide, the decrease observed in the fall is abrupt, more pronounced and it happens at all height levels at approximately the same time (Fig. 1). Furthermore, despite year-to-year changes in its duration and time of occurrence, the S2 fall decrease repeats every single year at both, middle and high latitudes (Fig. 2). Laskar et al. (2016) suggested that a possible explanation of this feature may be that distinct migrating and non-migrating components of S2 behave differently during these periods. After extracting the tides from HAMMONIA simulations, we found that the simulated S2 tide is primarily determined by SW2 and SW1, which happen to present distinct behaviors during the spring and fall transition times. From Fig. 3, it can be seen that during the spring, SW2 decreases but SW1 maintains similar amplitude values or slightly decreases. During the fall, both tides decrease, although SW1 does it later. One can thus postulate that since SW1 does not decrease significantly during the spring, this allows the S2 tide to maintain larger amplitudes than those observed during the fall. On the other hand, it seems that the influence of SW1 in the fall is not as relevant, given that this tidal component decreases later than SW2, but S2 decreases at the same time and with the same intensity as SW2. In other words, the observed S2 tide decreases during both equinox time periods because SW2 decreases, but during the spring the reduction of S2 is not as pronounced due to sustained higher amplitudes of SW1. In the fall, the observed decrease of S2 is more pronounced due to a more intense and longer decrease of SW2.

To further investigate the fall decrease, we have analyzed the phases of S2 and SW2. Forbes and Vial (1989) used model simulations to reproduce the phase change of the semidiurnal solar tide during equinox times, although they claimed that the phase transition is more rapid during the spring. From Fig. 4, where we present a composite of the phases of the observed S2 in both horizontal components at the three locations considered in this work (we have included S2 total amplitudes for the purpose of a better comparison), one can see a clear shift in the phase of S2 at the time of the fall decrease. The late spring also shows changes in the phase, but these are not as pronounced and rapid as during the fall, specially over Andenes and Juliusruh, where both, the zonal and meridional components show changes in the phase of $\sim 2\ h$ or more (over Tavistock, the phase changes in the meridional component are smaller). The behavior of the phase in the case of the simulated SW2 is similar: in both horizontal components, it exhibits a shift of $\sim 2\ h$ that manifests during the fall, when the amplitudes of SW2 abruptly decrease. This can be seen in Fig. 5, where besides the amplitude and phases of SW2, we also present the mean zonal wind (top panels) and the gravity waves (bottom panels) extracted from HAMMONIA, at Andenes, Juliusruh and Tavistock. The latter were obtained in the same way as for the observations.

Atmospheric tides are strongly influenced by mean winds and other types of waves (e.g., McLandress, 2002). Particularly, gravity waves propagating up from the troposphere cannot reach higher altitudes than those where their phase velocities match the wind velocity (e.g., Holton, 1983). However, during the fall transition time, the zonal wind in the stratosphere and mesosphere reverses from westward to eastward (see Fig. 5). Espy and Stegman (2002) showed that this reversal of the wind allows GWs to freely propagate upwards and reach the MLT region. Therefore, it is possible that the change seen in the phase of S2 is the result of interactions between this tide and GWs (e.g., Fritts and Vincent, 1987). By comparing Fig. 1 and Fig. 4, one can see that the enhancement of the gravity wave activity detected during the fall occurs at approximately the same time the phase of S2 shifts significantly. In the case of HAMMONIA simulations, the gravity wave activity also enhances considerably during the fall (Fig. 5). Andenes does not show such a strong enhancement, although it is clear that there is more GW activity during the fall than in the spring. GWs may naturally result from model simulations (e.g., Shepherd et al., 2000), but they strongly depend on the resolution of the model. As mentioned before, HAMMONIA runs at T31, which means that the smallest waves resolved by the model will have a length of more than 1000 km. This clearly imposes limitations to our analysis, since the gravity waves extracted from HAMMONIA simulations will only represent a small part of the actual GW spectrum and different parts of the latter may interact differently with S2. On the other hand, given that parameterized gravity waves can act only where they break (e.g., Sarin et al., 1996), a thoroughly analysis of the mean flow is necessary in order to assess their impact on the tidal behavior. This is clearly out of the scope of the present study. Nonetheless, if one takes into consideration that the results based on the simulated gravity waves are only applicable to long scale waves, it follows that observations and model simulations reveal that the long-wave GW activity enhances at approximately the same time the semidiurnal solar tide exhibits a strong shift in its phase and a pronounced decrease in its amplitude. Consequently, one may speculate that the change seen during the fall in the phase of the S2 tide, as well as the decrease of its amplitude, are partly due to interactions between SW2 and gravity waves. Future efforts will be focused on direct comparisons of the observed SW2 with GWs, as well as with planetary waves. For that, we plan to use multiple radars to separate SW2 and SW1 from the actual measurements, by means of a phase differencing technique (He et al., 2018).

Given that the semidiurnal solar tide is produced mainly by solar heating of the ozone located in the stratosphere region (e.g., Chapman and Lindzen, 1970), the sudden and strong changes exhibited by S2 during the fall may also be related to changes in the ozone concentration. Ozone variability has already been considered in previous studies in order to partially explain the seasonal and longitudinal variability of S2 (e.g., Jacobi et al., 1999). Consequently, we also investigated the ozone levels simulated by the HAMMONIA model. We found no significant differences in the ozone concentration between the spring and fall transition times. Compared to the spring, the ozone levels are slightly reduced during the fall. However, this difference is not large enough so as to attribute the sudden decrease of S2 to a depletion of ozone.

4 Conclusions

Based on comparisons of meteor radar measurements with HAMMONIA model simulations, we showed that the differences exhibited by the semidiurnal solar tide (S2) observed at middle and high latitudes of the northern hemisphere between equinox times are mainly due to distinct behaviors of the migrating semidiurnal (SW2) and the non-migrating westward propagating wave number 1 semidiurnal (SW1) tidal components. Specifically, during the fall both, SW2 and SW1 decrease, while during the spring time SW2 decreases but SW1 remains approximately constant or decreases only slightly. The decrease shown by SW1 during the fall occurs later than that of SW2 and S2, which indicates that the behavior of S2 is mainly driven by the migrating component. Nonetheless, the influence of SW1 is necessary to explain the behavior of S2 during the spring. Contributions by other semidiurnal tidal components were found to be very small to negligible.

In addition, we have shown that during the fall transition, at approximately the same time the observed S2 tide decreases, a downward propagated phase shift (of $\sim 2\ h$ or more) can be seen in both horizontal components of this tide. The same feature was found in the model simulations, but in both horizontal components of SW2. Furthermore, our meteor radar observations show an increase in the gravity wave activity during this time interval, possibly indicating that the phase shift, and the decrease in the amplitude of the semidiurnal solar tide, may be partly due to interactions between SW2 and gravity waves.

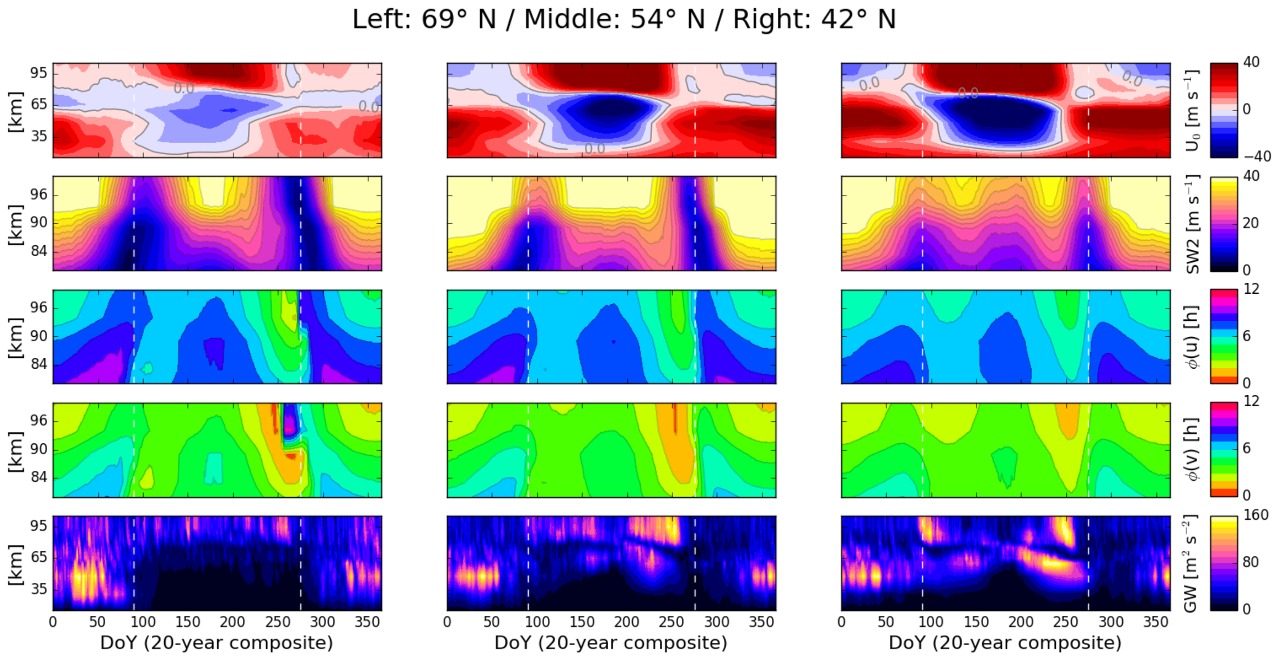

Figure 5. HAMMONIA composites of the simulated mean zonal (U_0) wind, the migrating semidiurnal solar (SW2) tide, SW2 phases in the zonal ($\phi(u)$) and meridional ($\phi(v)$) components, and gravity wave kinetic energy over: (left) Andenes, (middle) Juliusruh and (right) Tavistock. The vertical white dashed lines indicate DoYs 90 and 275. Notice the different height range in the case of U_0 and the GWs.

Data availability. The Andenes and Juliusruh meteor radar data are available upon request from G. Stober. To get access to Tavistock meteor radar data and/or HAMMONIA model simulations, please contact P. Brown and/or H. Schmidt.

Competing interests. The authors declare that they have no competing interests.

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References

Angelats i Coll, M. and Forbes, J. M.: Nonlinear interactions in the upper atmosphere: The s = 1 and s = 3 nonmigrating semidiurnal tides, J. Geophys. Res.: Space Phys., 107, https://doi.org/10.1029/2001JA900179, 2002.

Chapman, S. and Lindzen, R. S.: Atmospheric Tides, D. Reidel Publishing Co., p. 200pp, 1970.

Charlton, A. J. and Polvani, L. M.: A New look at stratospheric sudden warmings, Part I: Climatology and modeling Benchmarks, Journal of Climate, 20, 470–488, https://doi.org/10.1175/JCLI3994.1, 2007.

Chau, J. L., Hoffmann, P., Pedatella, N. M., Matthias, V., and Stober, G.: Upper mesospheric lunar tides over middle and high latitudes during sudden stratospheric warming events, J. Geophys. Res.: Space Phys., 120, 3084–3096, https://doi.org/10.1002/2015JA020998, 2015.

Eckermann, S. D. and Marks, C. J.: An idealized ray model of gravity wave-tidal interactions, J. Geophys. Res., 101, 21 195–21 212, 1996.

Espy, P. J. and Stegman, J.: Trends and variability of mesospheric temperature at high-latitudes, Physics and Chemistry of the Earth, Parts A/B/C, 27, 543–553, https://doi.org/https://doi.org/10.1016/S1474-7065(02)00036-0, 2002.

Forbes, J. M.: Middle atmosphere tides, J. Atmos. Terr. Phys., pp. 1049–1067, 1984.

Forbes, J. M. and Vial, F.: Monthly simulations of the solar semidiurnal tide in the mesosphere and lower thermosphere, Journal of Atmospheric and Terrestrial Physics, 51, 649–661, https://doi.org/https://doi.org/10.1016/0021-9169(89)90063-9, 1989.

Fritts, D. C. and Alexander, M. J.: Gravity wave dynamics and effects in the middle atmosphere, Reviews of Geophysics, 41, https://doi.org/10.1029/2001RG000106, 2003.

Fritts, D. C. and Vincent, R. A.: Mesospheric momentum flux studies at Adelaide, Australia: Observations and a gravity wave-tidal interaction model, Journal of the Atmospheric Sciences, 44, 605–619, 1987.

Fuller-Rowell, T., Wu, F., Akmaev, R., Fang, T.-W., and Araujo-Pradere, E.: A whole atmosphere model simulation of the impact of a sudden stratospheric warming on thermosphere dynamics and electrodynamics, J. Geophys. Res.: Space Phys., 115, https://doi.org/10.1029/2010JA015524, 2010.

Giorgetta, M. A., Manzini, E., Roeckner, E., Esch, M., and Bengtsson, L.: Climatology and forcing of the quasi-biennial oscillation in the MAECHAM5 model, Journal of Climate, pp. 3882–3901, 2006.

Hagan, M. E. and Forbes, J. M.: Migrating and nonmigrating diurnal tides in the middle and upper atmosphere excited by tropospheric latent heat release, J. Geophys. Res., 107(D24), https://doi.org/10.1029/2001JD001236, 2002.

Hagan, M. E. and Forbes, J. M.: Migrating and nonmigrating semidiurnal tides in the upper atmosphere excited by tropospheric latent heat release, J. Geophys. Res., 108(A2), https://doi.org/10.1029/2002JA009466, 2003.

He, M., Chau, J. L., Stober, G., Hall, C. M., Tsutsumi, M., and Hoffmann, P.: Application of Manley-Rowe relation in analyzing nonlinear interactions between planetary waves and the solar semidiurnal tide during 2009 sudden stratospheric warming event, J. Geophys. Res.: Space Phys., 122, 10,783–10,795, https://doi.org/10.1002/2017JA024630, 2017.

He, M., Chau, J. L., Stober, G., Li, G., Ning, B., and Hoffmann, P.: Relations between semidiurnal tidal variants through diagnosing the zonal wavenumber using a phase differencing technique based on two ground-based detectors, J. Geophys. Res.: Atmos., 123, https://doi.org/10.1002/2018JD028400, 2018.

Hines, C. O.: Doppler-spread parameterization of gravity wave momentum deposition in the middle atmosphere. Part 2: Broad and quasi monochromatic spectra, and implementation, J. Atmos. Sol.-Terr. Phy., 59, 387–400, 1997a.

Hines, C. O.: Doppler-spread parameterization of gravity wave momentum deposition in the middle atmosphere. Part 1: Basic formulation, J. Atmos. Sol.-Terr. Phy., 59, 371–386, 1997b.

Hocking, W., Fuller, B., and Vandepeer, B.: Real-time determination of meteor-related parameters utilizing modern digital technology, J. Atmos. Sol.-Terr. Phy., pp. 155–169, https://doi.org/https://doi.org/10.1016/S1364-6826(00)00138-3, 2001.

Hocking, W. K. and Thayaparan, T.: Simultaneous and collocated observations of winds and tides by MF and meteor radars over London, Canada (43°N, 81°W), during 1994–1996, Radio Science, 32, 833–865, 1997.

Hoffmann, P., Singer, W., Keuer, D., Hocking, W. K., Kunze, M., and Murayama, Y.: Latitudinal and longitudinal variability of mesospheric winds and temperatures during stratospheric warming events, J. Atmos. Sol.-Terr. Phy., 69, 2355–2366, https://doi.org/10.1016/j.jastp.2007.06.010., 2007.

Hoffmann, P., Becker, E., Singer, W., and Placke, M.: Seasonal variation of mesospheric waves at northern middle and high latitudes, J. Atmos. Sol.-Terr. Phy., 72, 1068–1079, https://doi.org/http://dx.doi.org/10.1016/j.jastp.2010.07.002, 2010.

Holton, J. R.: The Influence of Gravity Wave Breaking on the General Circulation of the Middle Atmosphere, Journal of the Atmospheric Sciences, 40, 2497–2507, https://doi.org/10.1175/1520-0469(1983)040<2497:TIOGWB>2.0.CO;2, 1983.

Jacobi, C., Portnyagin, Y. I., Solovjova, T. V., Hoffmann, P., Singer, W., Fahrutdinova, A. N., Ishmuratov, R. A., Beard, A. G., Mitchell, N. J., Muller, H. G., Schminder, R., Kürschner, D., Manson, A. H., and Meek, C. E.: Climatology of the semidiurnal tide at 52–56°N from ground-based radar wind measurements 1985–1995, J. Atmos. Sol.-Terr. Phy., 61, 975–991, https://doi.org/https://doi.org/10.1016/S1364-6826(99)00065-6, 1999.

Kinnison, D. E., Brasseur, G. P., Walters, S., Garcia, R. R., Marsh, D. R., Sassi, F., Harvey, V. L., Randall, C. E., Emmons, L., Lamarque, J. F., Hess, P., Orlando, J. J., Tie, X. X., Randel, W., Pan, L. L., Gettelman, A., Granier, C., Diehl, T., Niemeier, U., and Simmons, A. J.: Sensitivity of chemical tracers to meteorological parameters in the MOZART-3 chemical transport model, J. Geophys. Res.: Atmos., 112, https://doi.org/10.1029/2006JD007879, 2007.

Laskar, F. I., Chau, J. L., Stober, G., Hoffmann, P., Hall, C. M., and Tsutsumi, M.: Quasi-biennial oscillation modulation of the middle- and high-latitude mesospheric semidiurnal tides during August–September, J. Geophys. Res.: Space Phys., 121, 4869–4879, https://doi.org/10.1002/2015JA022065, 2016.

Lott, F. and Miller, M. J.: A new subgrid-scale orographic drag parameterization: Its formulation and testing, Quart. J. Roy. Meteor. Soc., 123, 101–127, 1997.

Manson, A., Meek, C., Hagan, M., Hall, C., Hocking, W., MacDougall, J., Franke, S., Riggin, D., Fritts, D., Vincent, R., and Burrage, M.: Seasonal variations of the semi-diurnal and diurnal tides in the MLT: Multi year MF radar observations from 2 to 70°N, and the GSWM tidal model, J. Atmos. Sol.-Terr. Phy., 61, 809–828, 1999.

Manzini, E., Giorgetta, M. A., Esch, M., Kornblueh, L., and Roeckner, E.: The influence of sea surface temperatures on the Northern winter stratosphere: Ensemble simulations with the MAECHAM5 model, Journal of Climate, pp. 3863–3881, 2006.

Matthias, V., Shepherd, T. G., Hoffmann, P., and Rapp, M.: The Hiccup: a dynamical coupling process during the autumn transition in the Northern Hemisphere – similarities and differences to sudden stratospheric warmings, Ann. Geophys., 33, 199–206, https://doi.org/10.5194/angeo-33-199-2015, 2015.

McCormack, J., Hoppel, K., Kuhl, D., de Wit, R., Stober, G., Espy, P., Baker, N., Brown, P., Fritts, D., Jacobi, C., Janches, D., Mitchell, N., Ruston, B., Swadley, S., Viner, K., Whitcomb, T., and Hibbins, R.: Comparison of mesospheric winds from a high-altitude meteorological analysis system and meteor radar observations during the boreal winters of 2009/2010 and 2012/2013, J. Atmos. Sol.-Terr. Phy., https://doi.org/https://doi.org/10.1016/j.jastp.2016.12.007, 2016.

McLandress, C.: The seasonal variation of the propagating diurnal tide in the mesosphere and lower thermosphere. Part I: The role of gravity waves and planetary waves, J. Atmos. Sci., 59, 893–906, https://doi.org/10.1175/1520-0469(2002)059<0893:TSVOTP>2.0.CO;2, 2002.

Pancheva, D., Mukhtarov, P., and Andonov, B.: Global structure, seasonal and interannual variability of the migrating semidiurnal tide seen in the SABER/TIMED temperatures (2002–2007), Ann. Geophys., 27, 687–703, https://doi.org/10.5194/angeo-27-687-2009, 2009.

Riggin, D., Meyer, C., Fritts, D., Jarvis, M., Murayama, Y., Singer, W., Vincent, R., and Murphy, D.: MF radar observations of seasonal variability of semidiurnal motions in the mesosphere at high northern and southern latitudes, J. Atmos. Sol.-Terr. Phy., 65, 483–493, 2003.

Rossby, C.-G.: Relation between variations in the intensity of the zonal circulation of the atmosphere and the displacements of the semipermanent centers of action, J. Mar. Res., 2, 38–55, 1939.

Sarin, V. B., Forichon, M., and Le Treut, H.: Parameterization and influence of the orographic gravity-wave drag in the LMD-GCM, Mathematical and Computer Modelling, 24, 71–84, https://doi.org/https://doi.org/10.1016/0895-7177(96)00108-2, 1996.

Schmidt, H., Brasseur, G. P., Charron, M., Manzini, E., Giorgetta, M. A., Diehl, T., Fomichev, V. I., Kinnison, D., Marsh, D., and Walters, S.: The HAMMONIA Chemistry Climate Model: Sensitivity of the Mesopause Region to the 11-year Solar Cycle and CO_2 Doubling, Journal of Climate, 19, 3903–3931, https://doi.org/https://doi.org/10.1175/JCLI3829.1, 2006.

Shepherd, G. G., Stegman, J., Espy, P., McLandress, C., Thuillier, G., and Wiens, R. H.: Springtime transition in lower thermospheric atomic oxygen, Geophys. Res. Lett., 104, 213–223, https://doi.org/10.1029/98JA02831, 1999.

Shepherd, T. G., Koshyk, J. N., and Ngan, K.: On the nature of large-scale mixing in the stratosphere and mesosphere, J. Geophys. Res., 105, 12,433–12,446, https://doi.org/10.1029/2000JD900133, 2000.

Smith, A. K.: Global Dynamics of the MLT, Surveys in Geophysics, 33, 1177–1230, 2012.

Stober, G., Matthias, V., Jacobi, C., Wilhelm, S., Höffner, J., and Chau, J. L.: Exceptionally strong summer-like zonal wind reversal in the upper mesosphere during winter 2015/16, Ann. Geophys., 35, 711–720, https://doi.org/10.5194/angeo-35-711-2017, 2017.

Taylor, M. J., Pendleton, W. R., Liu, H.-L., She, C. Y., Gardner, L. C., Roble, R. G., and Vasoli, V.: Large amplitude perturbations in mesospheric OH Meinel and 87-Km Na lidar temperatures around the autumnal equinox, Geophys. Res. Lett., 28, 1899–1902, https://doi.org/10.1029/2000GL012682, 2001.

Yiğit, E. and Medvedev, A. S.: Influence of parameterized small-scale gravity waves on the migrating diurnal tide in Earth's thermosphere, J. Geophys. Res.: Space Phys., 122, 4846–4864, https://doi.org/10.1002/2017JA024089, 2017.

Yuan, T., Schmidt, H., She, C. Y., Krueger, D. A., and Reising, S.: Seasonal variations of semidiurnal tidal perturbations in mesopause region temperature and zonal and meridional winds above Fort Collins, Colorado (40.6°N, 105.1°W), J. Geophys. Res.: Atmos., 113, https://doi.org/10.1029/2007JD009687, 2008.