December 2019, regarding https://www.atmos-chem-phys-discuss.net/acp-2019-870

Final author comments for acp-2019-870

Contents

1 Reply to referee comment RC1

from Jonas Hagen (jonas.hagen@iap.unibe.ch) on behalf of the authors.

Dear Anonymous Referee #1,

we thank you for thoroughly reviewing our manuscript. From your comments, we identify one general comment and a few specific comments, which we address individually below. We are confident, that we can address all comments, in particular those regarding the measurement noise and that the changes we make based on these comments improve the quality and value of our paper.

General comments

Referee1: This is an interesting manuscript dealing with the extraction of daily tidal signatures in winds in the stratosphere and lower mesosphere from ground-based Doppler MW measurements. The results are novel, of high interest to the community and the manuscript is in principle suitable for ACP. I do have several comments, some of them not only minor that – in my opinion – should be addressed before the paper is published.

My main concern is, whether the intermittency found in the analysis of the tidal parameters over the 7-day or 13-day time scales is real.

As displayed in Fig. 2, the day to day wind variations do not really show an obvious diurnal tidal signature, which suggests that averaging over extended periods of time is required to suppress the "noise" and to identify the tidal signature with high significance. I would like to point out that I do not question the presence of the tidal signature in the MW data set in general. The analysis of the 3-month periods is quite convincing in my opinion. But the analysis does not rule out the possibility that the relatively strong intermittency in tidal parameters is in fact due to "noise". I make some specific suggestions how to address that and which parts of the paper should be adjusted somewhat. Some of the conclusions drawn are not fully justified in my opinion.

Authors: We see that the main concern of Anonymous Referee #1 (hereafter AR1) is, that the variability in the composite of our measurement is real and not noise (instrumental or atmospheric).

Our main points that speak in favour of the variability is, (1) that the general morphology of the time dependence of the tidal parameters is consistent among all composites that we looked at and (2) that in the three-monthly mean, the reanalysis and measurement agree very well. No matter if we look at 2 hours aggregated over 13 days or 4 hours over 7 days, we see the same structure in amplitude and phase of the diurnal tide. Nevertheless, some details differ between the composites and that is what we attribute to noise. We include 6 different composits in the revised manuscript's appendix and discuss this method as a mean to test for robustness of our analysis.

That said, we think it is appropriate to somewhat weaken the conclusions. As a consequence, we now first focus on the three-monthly means before we look into the short-time variability. Further, we discuss the influence of noise more thoroughly (also see answers to specific comments).

We thank AR1 for the specific suggestions on how to improve the manuscript and are confident, that we could fully address the general comment.

Resulting Changes:

- Include 6 composites in the appendix.
- Elaborate on robustness of the composites.
- Somewhat weaken the conclusions with regard to variability.
- Change order of figures and discussion of results to focus on mean first.

Specific comments

Page 1, line 4: "Current lidar and satellite techniques measure atmospheric tides only in the temperature field and continuous measurements of the tides in the wind field of the stratosphere and lower mesosphere are not available." This statement is not entirely incorrect, but existing Doppler lidar mesaurements in principle allow studying tides in atmospheric winds, too. These measurements have been used, e.g. to investigate GW signatures in middle atmospheric winds (Baumgarten et al., Geophys. Res. Lett., 42, 10,929 – 10,936, doi:10.1002/2015GL066991). I admit these measurements are not continuous over longer periods of time.

Lidars are in principle capable of measuring atmospheric tides. As AR1 acknowledges, the big difference is the continuity of the measurements. We clarify what we mean by "continuous" and mention the capability of lidars to measure inertia gravity waves.

Commit: Mention that lidars can measure gravity waves.

Resulting Changes:

- Change line in abstract.
- Add sentence: "Current lidar instruments are able to measure inertial gravity waves in the wind field on short timescales (Baumgarten et al., 2015) and are thus in theory also suited for the observation of atmospheric tides, but the necessity of clear sky conditions reduces the availability of long term observations drastically and no observations of atmospheric tides are available to date."

Page 2, line 23: "evident above approximately 40 km altitude and the spread between them is quite large in the lower mesosphere." It would be good to provide some values here.

Thanks, we add the numbers: "Recent findings by Sakazaki et al. (2018) suggest that for the temperature field, differences between the different reanalyses and measurements are systematic in amplitude (approx. 1 K or 50 % above 40 km for northern mid-latitudes, more in tropics) and the spread between the reanalyses is quite large in the lower mesosphere (0.3 K to 1 K at approx. 60 km for northern mid-latitudes). "

Commit: Add numbers from Sakazaki paper.

Page 2, line 32: "presents" → "presented" ?

Page 2, line 34: "complimented" → "complemented"

Thanks for spotting this, we fixed the typos.

Commit: Fix typos.

Page 3, line 28: "the Doppler shift introduced to the emission line is directly proportional to the wind speed" Only the line of sight wind can be measured, which perhaps should be mentioned. If zonal and meridional winds are measured, then the radiometer must allow for different viewing directions. I suggest discussing this aspect of the instrumental setup in one or two sentences.

We add the suggested detail about viewing angles and the projection of the horizontal component to the line-of-sight.

Commit: Clarify observation method and projection of wind speeds.

Resulting Changes:

- Add sentence: "In order to be sensitive to the zonal and meridional component of the horizontal wind speed, we observe the emission line for all cardinal directions (North, East, South, West) at a low elevation angle of 22°."

Page 5, lines 4 – 9: the approach used here is essentially a "composite analysis" or "superposed epoch analysis". Perhaps you can mention these terms (or one of them), because the readers will probably be more familiar with these terms than with "aggregation scheme"

The term *composite analysis* is indeed more common and we choose to use this term, as suggested by AR1.

Commit: Composite analysis vs. aggregation.

Resulting Changes:

- Change "aggregation" to "composite" in most places.

Page 6, line 16: "In this study, we do not apply any vertical smoothing to the reanalysis data." Why not? The reanalysis data could easily be smooted with the radiometer averaging kernels. I suggest doing that. It will affect the results and it can be easily implemented. So, why not doing it?

There are two aspects we considered in our decision to present the MERRA-2 data without *vertical* smoothing.

Firstly, we use MERRA-2 data on pressure levels (Global Modeling and Assimilation Office (GMAO), 2015) that has already been down-sampled to 42 levels (see Bosilovich et al. (2016) for description of grids). As such, the vertical resolution of the pressure grid above 30 km is approximately 4 km. Additionally, we do apply a temporal smoothing with our composition. As a result, the MERRA-2 data is already smoothed.

Secondly, we see that the biggest uncertainty in the estimate of diurnal tidal amplitude comes from temporal smoothing by composition and also from instrumental noise. (The effect of vertical smoothing on the phase is negligible.) In this study we provide the comparison with MERRA2 reanalysis data in order to get a reference for amplitude and phase and see what could be expected. The vertical-smoothing error might certainly be subject of further studies.

Page 6, line 19: "We further estimate the uncertainty of the amplitude and phase for the 3-monthly mean using a bootstrapping method by re-sampling the wind time-series" How is the resampling done? Is it entirely random? There are many different ways to do that and the detailed approach chosen will directly affect the uncertainty estimates and/or the significance of the results. Please provide a brief description, how this was done.

Our sampling scheme is inspired by the "Moving Block Bootstrap (MBB)" described by (Lahiri, 2003, "Resampling Methods for Dependent Data", p.25ff).

Detailed description: Assume a $(\Delta D, \Delta H)$ composite, that is ΔD days composed with a resolution of ΔH hours (following the nomenclature of the manuscript). So, for each day of the three-month period ($N = 90$ days), we have ΔH-hourly resolved wind speeds that are dependant on the ΔD surrounding days. Given that data, we construct a synthetic 90 day period (sampling) by choosing $\frac{N}{\Delta D}$ composite days at random (with repetition). By only selecting $\frac{N}{\Delta D}$ composite days, we take into account that the composite makes the data of one day dependent on the surrounding days.

Then, for each sampled 90-day period, we take the mean for each hour of day and fit our tide model to extract the tidal parameters. We estimate the uncertainty of the mean diurnal tidal parameters with the $(0.05, 0.95)$ inter-quantile range. We also check the histogram of the parameters and note that the distribution of the amplitude of the diurnal tide resembles a Gamma distribution (makes sense, because the amplitude cannot drop below zero) and the distribution of the phase resembles a Gaussian distribution. We use the inter-quantile range to represent the distribution in our plots.

As AR1 points out, different resampling methods will result in different uncertainty estimates. We chose the method described above, because it takes the measurement noise into account as well as possible intermittency of atmospheric tides, without assuming anything about the nature of either of them.

Commit: Explain bootstrap.

Resulting Changes:

- Add reference to Lahiri (2003)
- Add short description about the resampling.

Page 7, line 10 and Figure 1: I think you didn't explain what you mean by "background winds"? Perhaps I missed. It would also be good to mention what the temporal resolution of the background winds is – probably 1 day?

Background wind in this study refers to the mean daily wind speed. Yes, the temporal resolution of the background winds as depicted is 24 hours.

Resulting Changes:

- Define what we mean by *background wind* and mention the temporal resolution.

Page 7, line 16 and Figure 2: In my opinion Fig. 2 does not convincingly demonstrate that the measurements capture the diurnal tidal signature. The "noise" (or oscillations, natural variability etc.) in the time series is (are) quite large. Apart from showing the time series over a period of 7 day, I suggest also showing a plot of the superposed tidal signatures, i.e mean diurnal variation averaged over 7 days or an extended period of time. A composite analysis will suppress the noise and show, whether a tidal signature is visually present in the data.

Figure 2 is indeed problematic for different reasons. It depicts a few days in the beginning of one month at one altitude level for one composite and one component only and the relevance of that is questionable. As AR1 suggests, we instead focus on the composite analysis over longer timer periods.

Since this figure lead to some confusion, we decided to remove it from the manuscript, but keep it as Fig. Aa in this discussion. In our opinion it is better to asses the noise from the different composites as we show them in the appendix of the revised paper.

Resulting Changes:

- Remove Figure 2 (keep it as Fig. Aa in this discussion).
- Discuss noise of measurement more extensively.
- Add diurnal cycle for three-monthly mean.

In addition, the superposed tidal signature should also be shown for the 3-month period. I imagine that this plot reveals a remarkably clear tidal signature. This would strengthen the paper significantly in my opinion.

Indeed, these plots strengthen the paper and we add them.

Commit: Add mean level plots.

Resulting Changes:

- Include the figures of the composite tidal signature for the 3 month period.

Page 7, line 24: "Further, our observations reveal an intermittency of the diurnal tidal amplitude at the resolved temporal scales of 7 to 13 days" Looking at Figure 2, I wonder whether this intermittency is real or an artifact. I'm not really convinced all the signatures attributed to the tide are actually caused by it. This intermittency may also be "noise" in the data and not real atmospheric intermittency.

The main argument, that speaks in favor of the variability (as opposed to instrumental noise) is that we see the same variability in a large set of different composites. While the composites do not agree in every detail, the general morphology is present in all of them and we would draw the same conclusions no matter which one we look at.

On the other hand, noise is present in our data and we need to discuss the limitations of our method more clearly.

Figure 2 is not meant to demonstrate the capabilities of our method and we see that it is a bit misleading.

Resulting Changes:

- Include 6 composites in the appendix.
- Elaborate on robustness of the composites.

Fig. 3a: Please comment on the vertical structure seen in the amplitude A1. Is this a retrieval artifact? Visually it reminds me of oscillations in the profile retrieval, but it certainly may have other causes.

These vertical structures in Fig. 3a (4a in revised manuscript) can also be seen in the reanalysis data (Fig. 4c in revised manuscript), even tough less pronounced and less variable, and also in the 3-monthly mean (Fig. 3a in revised manuscript) in both, measurements and reanalysis data, for the zonal wind with a minimum in amplitude at 55 km.

Since these structures are visible in the extracted amplitude of a composite retrieval, it is not straight forward to relate them to oscillations in the retrieval of wind profiles.

If it has an atmospheric cause, it might be related to mixing of different modes of the diurnal tide (upwards / downwards, trapped / propagating).

Commit: Explain vertical structure of amplitude.

Resulting Changes:

- Discuss vertical structure seen in amplitude: "The vertical structure that is obvious in Fig. 4a can also be seen in the three-monthly mean with a minimum at 55 km in models and measurements. A possible source of this structure is the mixing of different waves with different vertical wavelengths or propagation directions."

Page 7, line 28: "is not reproduced in the reanalysis neither in amplitude nor in phase" Again, the intermittency in the data may not be real.

We think it is appropriate to somewhat weaken our conclusions and change this paragraph accordingly.

Page 8, line 4 and Figure 4: red symbols missing in Fig. 4b)

Page 8, line 4: this should be orange. Figure 4: They are there but hidden by the green symbols, which is unfortunate.

Resulting Changes:

- We changed the figure to only contain two types of symbols.

Page 8, line 3: "The green color shows the MERRA-2 reanalysis applying the same temporal aggregation of the time series to derive the tidal amplitudes as for WIRA-C, whereas the red color shows the analysis without averaging." This description is somewhat different from the description in the caption. The caption mentions smoothed and unsmoothed MERRA data. Perhaps you can use the same description in the text and the Figure caption.

Thanks, we aligned the caption with the description.

Resulting Changes:

- Align caption with description.

Page 8, line 9: "wavelength of 30 km" → "wavelength of about 30 km" ?

Thanks, we changed that.

Commit: Weaken wavelength.

Page 8, line 10: "In both data sets, the vertical wavelength increases drastically above 55 km altitude, and the phase eventually becomes constant with altitude." Well, most of the data points are missing for MERRA at altitude above 55 km, so I'm not sure this conclusion is justified for MERRA.

We agree and change the sentence accordingly.

Page 8, line 17: "The shaded area represents the statistical uncertainties of the estimated diurnal tidal amplitudes" As mentioned above, the way in which the uncertainties are determined should be explained in more detail. There are many possibilities to implement a bootstrapping technique and any uncertainty can be obtained (that's of course a bit exaggerated).

In this case we use the uncertainty from the error covariance matrix. We changed the sentence accordingly and added an explanation.

Another question about Fig. 5. The plot shows time series with 1 day resolution. I guess you are showing the results for the 7 day or 13 day analysis at the center day, right? This should be mentioned explicitly and also, whether the 7-day or the 13-day analysis is shown.

We use the 13 day aggregate in our manuscript. As mentioned above, we also present the other composites in the appendix and we would draw the same conclusions from every composite we looked at.

Resulting Changes:

- Mention which composite is presented.
- Include reference to the appendix.

Page 9 and Fig. 7: also for the Arctic case discussed here, the measurements show much more variability and intermittency than the reanalysis. And the agreement between tidal parameters extracted from measurement and model is very good if the full 3 month period is analysed, as shown in Figure 8. This good agreement is probably caused by better "noise" suppression. Again, I suggest performing a composite analysis for the different time periods. The 3-month averaged results seem to be robust, but I'm not convinced the intermittency is real.

Also for the arctic campaign, we include now a set of six composites in the appendix. The same time dependence is present in all composites, which we take as a hint that atmospheric variability is at least partly the cause for this time dependence. Anyhow, we agree that some conclusions need to be adjusted and the influence of noise needs to be discussed. (See also response to general comment.)

Page 10, line 8: "phase, indicating the presence of highly intermittent diurnal tides." or just "noise"? Noise should be excluded before drawing the conclusion you drew.

Page 10, line 18: "This is not the case for the measurements and we conclude, that the coherence time of short time scale disturbances is longer in reality than in the reanalysis model." Again, I think noise should be excluded as a potential explanation before drawing this conclusion.

We agree to weaken this conclusions and discuss the presence of noise in more detail.

Figures 4 and 8: please also show uncertainties of the phase values.

We agree.

In the process of re-plotting Fig. 4 and 8, we found that we made a mistake in unwrapping the phase for plotting. This had the effect of separating the WIRA-C and MERRA2 phase for all values of $\Phi > 12$ h.

Resulting Changes:

- Fix the wrong phase unwrapping and error bars.

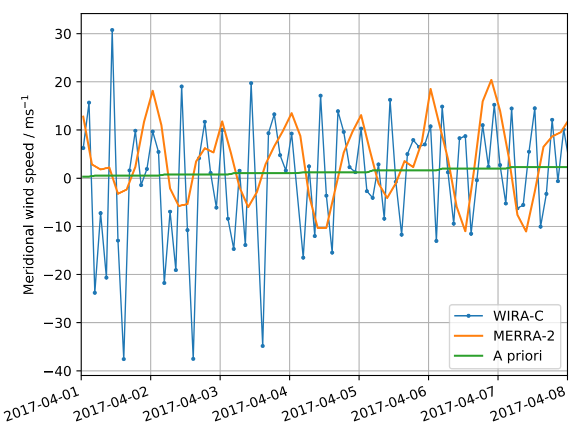
It would also be good to show a plot like Figure 2 for the Arctic results.

1 Reply to referee comment RC1

We added the figure requested by AR1 to this response as Fig. Ab (right next to the original figure 2). We decided to remove Fig. 2 from the new version of the manuscript and added some other figures instead for the tropical and arctic campaign the like.

Best regards,
Jonas Hagen

(a) Tropical (Maïdo, April 2017)



(b) Arctic (ALOMAR, September 2018)

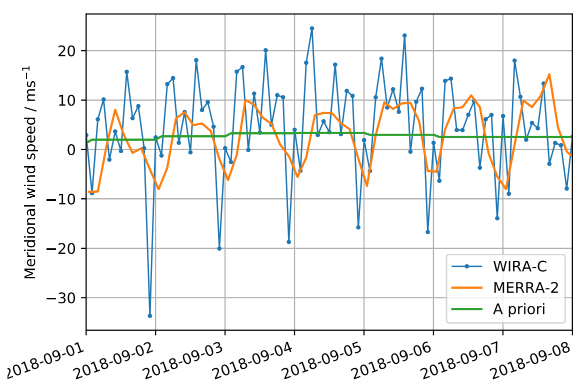


Figure A: Timeseries of retrieved meridional wind from WIRA-C at 50 hPa (approx. 53 km) for beginning of the selected time periods. Additionally, MERRA-2 reanalyses data and the a priori data used for the retrieval are shown. Temporal resolution for WIRA-C and MERRA-2 is 2 hours and 3 hours respectively.

2 Reply to referee comment RC2

from Jonas Hagen (jonas.hagen@iap.unibe.ch) on behalf of the authors.

Dear Anonymous Referee #2,

we thank you for thoroughly reviewing our manuscript. From your comments, we identify three general comments and a few specific comments, which we address individually below. We are confident, that we can address all comments, especially those regarding the comparison with the reanalysis and that the changes we make based on these comments improve the quality and value of our paper.

General comments

Referee2: First, the authors stress the importance of non-zero wind a priori for the retrieval. However, I do not see a clear conclusion of how the non-zero a priori impacts the retrievals.

Authors: Since we choose periods with stable background and good measurement response, the selection of the a priori only has a very small impact on the retrieved wind speeds. The same study would be possible with a zero-wind a priori, but we think it would be sub-optimal choice. We do have some arguments to choose a daily-mean a priori over a zero-wind a priori as we will outline below.

For the standard wind retrieval from WIRA-C we use a zero-wind a priori profile. This choice is not obvious, because generally in optimal estimation, one tries to include all a priori knowledge to constrain the optimisation. However, we do this for two main reasons, as described by Hagen et al. (2018): Firstly, wind can change within days from large positive values to large negative values under some circumstances like strong planetary wave activity, sudden stratospheric warmings or sometimes during wind reversals around equinox. The standard approach (zero wind speed a priori and large co-variance) is best suited to cover such cases, which is important to observe the above mentioned effects in year-long time series.

Secondly, it is not very obvious where to get good statistics on dynamics for long-term continuous measurements. There are different candidates, but no matter what one chooses, a big co-variance is necessary to take into account the uncertainty. This is especially the case in the context of the above mentioned disturbances. For a steady background situation, it would perhaps make sense to use some statistics form a climatology and thus reduce the co-variance and thus the uncertainties in the retrieval.

All of the above is relevant to the standard WIRA-C wind retrieval and both reasons for zero-wind a priori profiles have to be revisited for a study on different timescales like the one we present now. We specifically chose periods with no abrupt changes in the wind field (see also specific comment of RC2 about planetary wave activity in polar latitudes). And since we average over 7 to 13 days, we do have high confidence in the ECMWF model data for the mean background wind speed over these time spans. Note, that there is no time-of day dependence of the a priori profile. We retrieve the daily cycle of the wind speed solely from our measurements.

As described in the manuscript, there is something else to consider: Since we want to observe the diurnal cycle of wind speed, we need to make an effort to exclude other sources of diurnal variability from our retrieval. Relevant to the tropical campaign is the troposphere which has pronounced diurnal cycle (water vapour, clouds, precipitation). This means that observations during the after-noon have more noise than observations during night-time, for example. This would, under some circumstances, introduce a daily cycle in the wind speed, because in the after-noon hours, the retrieved wind speed tends more towards the a priori due to increased noise. If the a apriori is zero and the mean background (daily mean) wind speed is around $60\,\mathrm{m\,s^{-1}}$ this effect is hard to quantify and the tendency towards the zero-value would be systematic for after-noon hours in the tropics. This is not necessarily true for the polar latitude, where the weather varies more within days than within a day. With a daily-mean a priori wind profile the amplitude of the measured tide is always decreased by the diurnal cycle of the troposphere, if there is any effect at all.

So, in conclusion, we prefer the daily mean wind speed a priori over the zero wind a priori for the following reasons: It is possible to get a proper background that can be used for the a priori value in the periods and timescales we choose to analyze. The effect of diurnal variability of noise sources on the retrieval of the diurnal cycle is more difficult to characterize for the zero-wind a priori, whereas a daily-mean a priori leads to a smaller amplitude, if there is any effect.

Second, the comparison with MERRA-2 reanalysis requires more details (see comments below).

We improve the comparison with MERRA-2 in the following ways (more details in answers below):

- Add two figures showing the mean diurnal cycle of wind speeds for different altitudes (Fig. 2 and 7 in revised manuscript)

- Add the original (non-smoothed) MERRA-2 data for comparison (Fig. 4e, 4f, 10e and 10f in revised manuscript)
- Add plot of the zonal-to-meridional diurnal wind tide phase difference for measurement and reanalysis (Fig. 9a and 9b)

Commit: Discuss mean diurnal cycle shown in new figures.

Third, the authors should comment on the applicability/limitations of radiometer observations for the retrievals of shorter period tides (semidiurnal, etc.) and other oscillations.

We did not make any studies in that regard. In theory this would be possible with the (13,2,1) or even with a (13,2,0.5) composite that would aggregate by half-time-of-day. Clearly, it is worth mentioning that in the outlook.

Commit: Outlook on semi-diurnal tide.

Resulting Changes:

- Discuss the visibility of higher order tidal modes in Fig. 2 and 7 in revised manuscript.
- Outlook on the possibility to retrieve higher-order tidal modes.

Specific comments

Page 1 Line 3: “up to the thermosphere” would be more relevant.

Page 1 Line 4: “they are gravity waves” is confusing. Perhaps “planetary scale” or “global scale gravity waves”, to distinguish from small scale gravity waves?

Thanks for these valuable suggestions.

Commit: Thermosphere and planetary-scale

Resulting Changes:

- “ionosphere” → “thermoshpere”
- “gravity waves” → “planetary-scale gravity waves”

Page 1 Line 4: Satellite techniques also measure wind fields associated with tides, though under certain limitations, please clarify.

Page 2 Lines 9-10: This statement does not reflect the current state of knowledge. Various methods have been utilized to extract short-term variability of tides from satellite observations. A good overview of these methods is given by Ortland, JGR, 2017, doi:10.1002/2016JD025573.

Thank you for the hint we changed the manuscript accordingly (see changes).

Resulting Changes:

- Add citation: “The global coverage nevertheless enables tidal studies on shorter timescales also for instruments on these satellites (Ortland, 2017).”

Page 2 Line 21: RMR lidars can measure winds as well as temperatures in upper stratosphere / lower mesosphere. I assume the authors mean that lidars are not particularly suitable to study tidal oscillations. This needs to be clarified.

We clarify the capabilities of lidars with regard to wind and gravity wave measurements.

Commit: Mention that lidars can measure gravity waves.

Resulting Changes:

- Change line in abstract.
- Add sentence: “Current lidar instruments are able to measure inertial gravity waves on short timescales (Baumgarten et al., 2015) and are thus in theory also suited for the observation of atmospheric tides, but the necessity of clear sky conditions reduces the availability of long term observations drastically and no observations of atmospheric tides are available to date.”

Page 3 Line 3-4: This sentence is out of place and should be (re)moved. The radiometer should be introduced first.

We assume that RC2 means Page 3 Line 1-2 and agree that the sentence is out of place. We changed the introduction of microwave radiometry accordingly.

Commit: Rearrange introduction of WIRA-C

Resulting Changes:

- Moved introduction of WIRA-C to the proper paragraph.

Page 5 Line 24-33: I believe this method of tidal decomposition has been applied before, also by the authors of this study, e.g., Stober et al., 2017; McCormack et al., 2017. References to the earlier works are needed.

RC2 suggests to cite earlier work that used a simple harmonic-oscillation model to extract tidal parameters from measurements. We included the suggested references, plus others (see changes). We also included a sentence about the relevant difference to the earlier work.

Resulting Changes:

- Added citations and relation to earlier work in introduction.

Page 6 Line 7-9: This needs to be further discussed. Basically this requires some stationarity, both in tidal amplitude and in phase. Perhaps the limitations of retrievals should be also discussed in the Summary section.

The referenced sentences are: "We assume that the retrieval of averaged spectra yields the average wind speed, so windowing and aggregation can be considered equivalent. This assumption might not hold in the context of fast changes in the wind field and we thus prefer periods of a stable wind background for our detailed analysis."

We agree that the condition for doing composite analysis is stationarity of the observed quantity. This applies to the background as well and thus we perform our analysis only on selected periods with a reasonably stable background.

There is only very little known about the short-time behaviour of tides. We agree, that a stable amplitude and phase is required for a proper composite analysis, but we just do not know this a priori. Based on temperature lidar observations with high temporal resolution, Baumgarten and Stober (2019), for example, provides evidence that tides can indeed be highly intermittent.

As suggested, we discuss this further in the Conclusions section.

Commit: Limitation with regard to stationarity.

Commit: Outlook on non-stationarity.

Resulting Changes:

- Discuss limitations of composite retrievals with regard to stationarity.
- Added outlook regarding requirement of stationary background.

Page 6 Line 31: I am not sure if the chosen interval for Andenes campaign satisfies the proposed criteria. Stronger planetary wave activity starts already in early November.

Planetary waves are indeed active in November 2018 in Andenes as we note in the manuscript (page 8, line 30 of original manuscript): "Both wind components indicate some variability due to waves on temporal scales of a few days, in particular, the meridional wind indicates an onset of the planetary wave activity towards the end of the observation period."

We nevertheless chose this period because in these months, the weather was good (good measurement response), planetary wave activity was low in at least two months and it did not include a wind reversal (that happened just before our period).

We discuss the possible influence of planetary wave activity in the results section.

Page 7 Line 10-11: I do not I understand the term "composite" here. Do the authors refer to superposed epoch analysis? If they simply refer to complementing WIRA-C with MERRA-2 data, it is better to avoid the "composite" term. More importantly, the authors should detail how the WIRA-C data are complemented with MERRA-2. The representation in Fig. 1 is not clear. When the hatched area goes to higher altitudes (e.g., in meridional winds) – does this correspond to gaps in the WIRA-C dataset?

We should not use the term composite in the context of background winds, it is indeed just wrong usage of the word. Fig. 1 in the discussion paper shows a simple overlay, showing WIRA-C data where available (with high quality) and MERRA2 data as visual background. If the hatched area goes higher this does not mean that there is a gap in the WIRA-C data. It just means, that the quality limits were not satisfied for this altitude at that day for the retrieval of daily mean wind speeds.

Commit: Say complemented instead of composite.

Resulting Changes:

- We clarified the description of Fig. 1, it now reads: "The meteorological background wind field for the selected period at the Maïdo observatory is shown in Fig. 1 as measured by WIRA-C, complemented with MERRA-2 reanalysis for lower altitudes.".

Page 7 Line 17 and Fig. 2: The text says "approx. 53 km" but the Fig.2 capture says "approx. 52 km".

Page8 Line 16: Again a mismatch: the text says 55 km altitude and the figure capture says 53 km.

Thanks. We fixed that.

Line 31-32 and Fig.3-4: Fig.3 shows, the short term variability is not at all reflected in the reanalysis. From Fig. 4 we can see that the original and smoothed reanalysis show very similar mean behavior (which is not surprising). How would Fig. 3 look if the non-smoothed MERRA-2 reanalysis is analyzed?

Page 9 Line 6-11 and Fig.7: Again, the smoothed reanalysis does not reflect the short term variability. How would the amplitudes of non-smoothed reanalysis look?

We add amplitude and phase of the non-smoothed MERRA2 data as Fig. 4 and Fig. 10 in revised manuscript.

The non-smooth MERRA2 data shows more tidal variability, as is expected. We have already discussed the non-smoothed data in the context of Fig. 5 and 9 in the original manuscript (Fig. 5 and 11 in revised manuscript), which also show original MERRA2 data and add two paragraphs to discuss the new figures.

Page 8 Line 14-15 and Fig. 4 a-b: Would be useful if the authors add a plot of phase differences between zonal and meridional components as a function of altitude, similar to Fig. 4b, but only the phase differences.

Line 17-21: Again I would suggest to plot the phase differences as a function of altitude.

The phase difference is an interesting quantity to look at, and we already discuss its behaviour in the manuscript, thus it is a good idea to include this plots. We added plots of the phase difference between zonal and meridional wind components for both campaigns as Fig. 9 in revised manuscript.

Commit: Include phase difference plots.

Resulting Changes:

- Include phase difference plots (Fig. 9 in revised manuscript) and references.

Page 8 Line 14-15 and Fig. 4 a-b: It is surprising to see good mean agreement in zonal component behavior, but poor agreement in meridional above 55 km.

Indeed. Assimilation data of the reanalysis model is limited in these altitudes, and this deviation might thus originate from the forecast model itself or boundary conditions imposed on the model. The difference is only visible in the top-most of the 42 pressure levels, so while this is interesting, we can hardly interpret it.

Best regards,
Jonas Hagen

References

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3 Changes in revised manuscript

First measurements of tides in the stratosphere and lower mesosphere by ground-based Doppler microwave wind radiometry

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Abstract.

Atmospheric tides are important for the vertical coupling in the atmosphere from the stratosphere down to the troposphere and up to the ~~ionosphere~~thermosphere. They are planetary-scale gravity waves with well-known periods that are integer fractions of a day and can be observed in the temperature or wind field in the atmosphere. ~~Current lidar and satellite techniques~~ Most lidar techniques and satellites measure atmospheric tides only in the temperature field and continuous measurements of the tides in the wind field of the stratosphere and lower mesosphere are ~~not available~~rare, even though with modern lidars they would be feasible. In this study, we present measurements of the diurnal tide in the wind field in the stratosphere and lower mesosphere by ground based microwave wind radiometry for two different campaigns in tropical and polar regions. Further, we compare our measurements to MERRA-2 reanalysis data. In the three-monthly mean, we find a good ~~overall correspondence~~ correspondence in the amplitude and phase of the diurnal tide between measurements and reanalysis with the most important features of the diurnal tides represented in both data sets. When looking at shorter timescales, we find ~~an intermittency of the diurnal tide that is not represented in the MERRA-2 reanalysis data~~ significant differences in the data sets. We make an attempt to examine these differences and discriminate between atmospheric variability and noise and present some hints for intermittent diurnal tides. We conclude, that continuous ground based observations of tides in the middle atmospheric wind field are feasible, ~~even on short timescales of 7 to 13 days, and thus~~ and deliver consistent results for the mean amplitude and phase of the diurnal tide in the 3-monthly mean. We further discuss the limitations with regards to short timescale observations of tides and the possibility to provide additional insight to middle atmospheric dynamics that is complementary to temperature observations and reanalysis data.

1 Introduction

Atmospheric tides are global-scale waves with well-known periods that are integer fractions of a day. They are the result of the periodic solar forcing of the temperature and wind fields and gravity as restoring force. Just as other gravity waves, tidal waves can propagate up or downwards, be reflected and ultimately deposit energy in the atmosphere when they break. This transportation and deposition of energy can cause secondary waves and other disturbances, resulting in a vertical coupling between the horizontal layers of the atmosphere and leads to an exchange of energy and momentum between the forcing regions and the dissipation altitudes. Ultimately, tides in the stratosphere and mesosphere region can affect weather phenomena like for example the diurnal cycle of tropical rainfall (Woolnough et al., 2004; Sakazaki et al., 2018).

Due to the global nature of atmospheric tides, they have been studied over decades using models (Lindzen, 1971; Forbes and Wu, 2006; Wang et al., 2016) or global observations from satellites (Oberheide et al., 2009; Häusler et al., 2010; Pancheva and Mukhtarov, 2011). Considering the observational results Oberheide et al. (2011) introduced a climatology based model of atmospheric tides covering the most relevant diurnal and semi-diurnal tidal modes at altitudes between 80 km to 400 km. While atmospheric tides are well understood and modeled (Hagan et al., 1999) on a global and seasonal scale, very little is known about tides on a local and sub-seasonal scale.

Tides in the temperature field have been extracted from satellite observations (Sakazaki et al., 2012; Forbes and Wu, 2006; McLandress et al., 1996; Oberheide et al., 2009) and have been compared to different reanalysis data sets by Sakazaki et al. (2018) from the stratosphere to the lower mesosphere. Satellites, however, often need several weeks to sample a full diurnal cycle for a specific location due to their orbit and therefore are not capable to resolve tidal variations at short timescales. Satellites with a sun-synchronous orbit, like for example Aura MLS, overpass each location on earth at two local times specific to this location and thus sample the diurnal cycle of a specific location with only 12 h resolution. The global coverage nevertheless enables tidal studies on shorter timescales also for instruments on these satellites (Ortland, 2017).

Ground based measurements of tides in the temperature field have been performed by day-light-capable lidars for the stratosphere by Kopp et al. (2015); Baumgarten and Stober (2019) and from meteor radar temperatures (Stober et al., 2008) in the mesosphere and lower thermosphere (MLT) region. Meteor radar and MF-radar observations are also suitable to obtain tides in the wind fields (Portnyagin et al., 1993, 2004; Merzlyakov et al., 2009; Jacobi, 2012; Wilhelm et al., 2019). Current lidar instruments are able to measure inertial gravity waves in the wind field on short timescales (Baumgarten et al., 2015) and are thus in theory also suited for the observation of atmospheric tides, but the necessity of clear sky conditions reduces the availability of long term observations drastically and no observations of atmospheric tides are available to date.

Rogers et al. (2016) derived the local solar time variation of wind at 95 km altitude by integrating a 5 year data set from different ozone radiometers. Rocket soundings of the tides in the wind and temperature field have been performed by Lindzen and Chapman (1969) up to the upper stratosphere but have never been repeated again.

Note that no observations of tides in the wind field for the stratosphere and lower mesosphere have so far been performed.

This leaves reanalyses data with high temporal resolution like ERA5 and MERRA-2 as the only source for the wind field in studies about atmospheric tides. These products typically depend on satellite measurements and, thus, tides in upper atmospheric region are poorly constrained. Recent findings by Sakazaki et al. (2018) suggest that for the temperature field, differences between the different ~~models~~ reanalyses and measurements are ~~evident above approximately 40 km altitude~~ systematic in amplitude (approx. 1 K or 50 % above 40 km for northern mid-latitudes, more in tropics) and the spread between ~~them~~ the reanalyses is quite large in the lower mesosphere (0.3 K to 1 K at approx. 60 km for northern mid-latitudes).

Recently, the temporal variability of tides at the MLT as lower forcing of the ionospheric and thermospheric systems become more and more important (e.g., Liu, 2016). There are currently several Global Circulation Models (GCM) developed, which are supposed to describe consistently the vertical coupling between the middle atmosphere and the ionospheric/thermospheric system (Pancheva et al., 2012; Yiğit et al., 2016; Liu et al., 2018). In particular, the short term variability of the tidal forcing is essential for driving the more complex neutral-ionospheric coupling in the upper atmosphere. McCormack et al. (2017) presented a comparison between a meteorological reanalysis from the Navy Global Environment Model - High Altitude (NAVGEM-HA) and several world wide distributed meteor radars indicating substantial day-to-day variability of the winds and tides. Recently, Baumgarten and Stober (2019) ~~presents~~ presented a 10-day continuous lidar observation conducted with the Kühlungsborn Rayleigh-Mie-Raman lidar and estimated the tidal variability using an adaptive spectral filter technique (Stober et al., 2017) and ~~complimented~~ complemented these observations with reanalysis data to investigate the phase relations of temperature and wind tides. However, lidar observations require cloud free conditions, which usually limits the continuity of such time series. ~~The~~

In this study, we use measurements from the ground-based microwave Doppler wind radiometer WIRA-C, that can provide continuous measurements of the ~~variability in the wind fields at altitudes which are hardly accessible by other remote sensing techniques.~~

~~Over the past years, ground based microwave Doppler wind radiometers have proven their capability to measure continuously and reliably the mean winds (Rüfenacht et al., 2014; Hagen et al., 2018)~~ wind fields in the stratosphere and ~~mesosphere. Rüfenacht et al. (20 performed an initial validation of the technique with other ground based instruments, e.g. the ALOMAR lidar and the Andenes meteor radar~~lower mesosphere (Hagen et al., 2018). The biggest advantage of the radiometers compared to many other ground based remote sensing instruments is their ability to measure continuously and independent of daylight and light clouds. Further, their compact design makes it rather easy to deploy these instruments at remote locations and enables their autonomous operation. Rüfenacht et al. (2018) performed an initial validation of the technique with other ground based instruments, e.g. the ALOMAR lidar and the Andenes meteor radar. Particularly compared to lidar, radiometers often have a much coarser vertical and temporal resolution. Rüfenacht et al. (2016) examined the spectrum of the wind oscillations for radiometric measurements and model data for periods down to 5 days, which is the lower limit of such an analysis due the low temporal resolution of wind radiometry. In this study, we present a method to investigate sub-day periods of oscillations with microwave wind radiometry by applying a different pre-processing to the measured spectra.

Specifically, we present a method to infer diurnal tides and their variability in the wind field in the stratosphere and lower mesosphere. After a short introduction to the measurement principle and analysis methods, we present the measurements from two WIRA-C campaigns, one was conducted on La Réunion island at tropical latitudes and the other one on Andøya island at polar latitudes. We show that our instrument is able to capture the mean diurnal wind tide over the course of a three-month period, and we compare our measurements to the meteorological reanalysis MERRA-2 (Global Modeling and Assimilation Office (GMAO), 2015) with respect to the amplitude and phase behaviour. We do this comparison for three-monthly means as well on shorter timescales (days/weeks) to reveal some differences between the observations and the reanalysis.

The manuscript is structured as follows. In section 2 we present a summary of the instrument and the campaigns. The data analysis and retrievals are described in section 3. Our results are presented in section 4 and our conclusions are given in section 5.

2 The WIRA-C instrument and campaigns

2.1 Instrument

The WIRA-C instrument is a Doppler microwave wind radiometer. As described in detail by Hagen et al. (2018), it measures the $142\,\mathrm{GHz}$ ozone rotational emission line with a high spectral resolution of $12.5\,\mathrm{kHz}$. Because the ozone molecules are moving with the mean air flow, the Doppler shift introduced to the emission line is directly proportional to the line-of-sight wind speed. ~~The~~ In order to be sensitive to the zonal and meridional component of the horizontal wind speed, we observe the emission line for all cardinal directions (North, East, South, West) at a low elevation angle of 22°. Further, the pressure broadening effect allows the retrieval of altitude resolved wind profiles in an altitude range from $30\,\mathrm{km}$ to $75\,\mathrm{km}$ on a $3\,\mathrm{km}$ vertical grid with $12\,\mathrm{km}$ vertical resolution.

WIRA-C has an un-cooled but temperature-stabilized receiver with a low receiver noise temperature due to a state-of-the-art low noise amplifier that directly amplifies the observation frequency of $142\,\mathrm{GHz}$. Despite the low noise, integration times of $12\,\mathrm{hours}$ to $24\,\mathrm{hours}$ are typically applied in the standard retrievals. These long integration times are required to achieve a signal-to-noise ratio that is sufficient for a retrieval of wind speed.

WIRA-C operates autonomously and automatically and the measurements are independent of daylight and light clouds with interruptions only during rain or heavy snowfall. Additionally WIRA-C uses a tipping curve calibration scheme and, thus, only needs very minimal maintenance, most of which can be done remotely. As a result, the WIRA-C instrument is especially well suited for campaigns as well as long-term monitoring observations.

The forward-model for the retrieval is supplied by the ARTS software package (Buehler et al., 2018). The inversion of the measured spectra is performed by an optimal estimation method (OEM) developed by Rodgers (2000). We use the OEM algorithm that has recently been implemented directly into the ARTS software.

Optimal estimation is a method, where the ill-posed inversion problem is regularized by an a priori profile and a corresponding co-variance matrix. It is well suited for the inversion of atmospheric measurements, because the mean background state is often known reasonably well. This applies to this study in particular, where the mean background wind speed is known from models and measurements to a reasonable extent and the diurnal cycle can be understood as a perturbation of the background state that we can retrieve from the measurements.

Different quality control parameters can be derived for an optimal estimation of a profile. The most important to us is the measurement response, that estimates the sensitivity of the retrieved quantity to actual changes in the observed system (as opposed to sensitivity to the a priori profile). Ideally this measurement response is one, with 0.8 or 0.6 being acceptable numbers.

2.2 Campaigns

WIRA-C has been on two major campaigns so far. The first campaign started in August 2016 and took place in the southern hemisphere at the Maïdo observatory on La Réunion Island (France) (Baray et al., 2013), located in the Indian ocean at 21 °S, 55 °E. The Maïdo observatory is located at an altitude of $2200\,\mathrm{m}$ a.s.l., which provides ideal conditions for radiometry. At this altitude there is less absorption due to tropospheric water vapor which could be a problem in the tropics at lower altitudes. For tropical latitudes around ±30°, the global scale wave model GSWM (Hagan et al., 1999) predicts a high amplitude of the diurnal tide compared to more polewards or more equatorial latitudes. The campaign ended in January 2018 and we refer to this as the tropical campaign.

For the second (and still ongoing) campaign, WIRA-C was moved to arctic latitudes in June 2018. The instrument is located at the ALOMAR observatory on Andøya (Norway) at 69 °N, 16 °E. We refer to this as the arctic campaign. The ALOMAR observatory is located on mount Ramnan, at 370 m a.s.l. and hosts many other remote sensing instruments e.g., the ALOMAR Rayleigh-Mie-Raman lidar, an Fe-lidar and several radars in the vicinity. The water vapor cycle at ALOMAR is dominated by the tropospheric weather pattern of the marine climate and variable within days rather than within a day.

3 Data processing

For the standard WIRA-C time series retrievals as used in previous studies, the spectra are integrated over continuous blocks of 12 or 24 hours resulting in a time series of wind speed with the same resolution (Hagen et al., 2018). Typically, for the tropical site, an integration over 12 hours from sunrise to sunset is performed. However, for the retrieval of the daily cycle we now aggregate the measurements of the same time of day over multiple days to perform a composite analysis. Typically we use a window of 7 or to 13 days and aggregate by time of day with a 2 to 4 hour resolution. This gives a total integration time of 14 and 26 hoursrespectivelyaround 20 hours, centered around a central day. We refer to this aggregation scheme the different composites by $(\Delta D, \Delta H)$ where ΔD indicates the number of days and ΔH the number of hours for the integrationkernel. The schemes . The main composite used in this study are denoted as is $(13,2)$and (7,2). For example, we collect all measurements taken between midnight and 02h00 over 13 days and integrate them together, which gives a total integration time of 26 hours.

After integration we run the wind retrieval for the WIRA-C instrument. For MERRA-2 reanalysis data we apply the same integration kernel composition directly on the model data to get the same temporal smoothing that we have to apply to our measurements. In addition, for some evaluations, we skip the aggregation of reanalysis data and instead run the following analysis directly on the original we also analyse the original reanalysis data.

A major difference to the retrieval described by Hagen et al. (2018) is that we use a non-zero wind a priori profile that corresponds to the mean wind background. This mitigates the effect of the diurnal variability of the troposphere on our measurements. If a zero-wind a priori is used, increased noise during daytime could lead to an over-estimation of tidal amplitudes in the subsequent analysis, because the retrieved wind speed would be closer to zero (and thus possibly further away from the background) in case of increased noise during daytime. In contrast, a mean-background a priori in combination with poor measurement response would lead to an underestimation of tidal amplitudes. This is especially important for locations with high diurnal variability (like our tropical site) or frequent rainfall (like our arctic site close to the sea). We extract the mean wind background from ECMWF operational data and average over the full 13 days centered around the (13,2) aggregation window respectivelycomposite and analogous for the other composites. Like this, our a priori wind profile does not include any tidal information at all. For the ozone a priori data, we ~~use a mean profile for the specific time of day averaged over the full aggregation window length~~compose WACCM data from Schanz et al. (2014) analogous to our measurements.

Once we have retrieved the wind profiles (or extracted them from the reanalysis data), we fit a simple tidal model to extract amplitude and phase information. The simple model for an arbitrary observable quantity y has the form of

$$y(t) = c + \sum_{k=1...N} A_k \cos(t\frac{2\pi}{P_k} - \phi_k) \tag{1}$$

$$= c + \sum_{k=1..N} \left[a_k \cos(t\frac{2\pi}{P_k}) + b_k \sin(t\frac{2\pi}{P_k}) \right] \tag{2}$$

where $P_k = 24, 12, 8, ...$ h is the period of the diurnal, semi-diurnal and ter-diurnal tide. In this study we use $N = 1$ and only consider the diurnal tide, but we write down the full basis in (2) to point out that the components for $k = 1, 2, 3, \ldots$ are orthogonal and can thus be treated separately. We apply a least squares optimization on (2) for the zonal and meridional wind component and assume the same weight for all wind measurements. Additionally, we estimate the uncertainty of the fit from the error co-variance matrix of the adjusted parameters.

Equation (1) defines the phase ϕ_k as the time of day when the corresponding wind component has its maximum. Note, that we present phases in units of mean solar time, so for example a phase of $10\,\mathrm{h}$ means that the maximum occurs $2\,\mathrm{h}$ before noon of the mean solar day. The amplitude A_1 and phase ϕ_1 of the diurnal tide are finally given by

$$A_1 = \sqrt{a_1^2 + b_1^2} \tag{3}$$

$$\phi_1 = \mathrm{arctan2}\left(ab_1, ba_1\right) \in (-\pi, \pi]. \tag{4}$$

Since we average over ~~13~~ multiple days prior to the retrieval, we do not apply a windowing function for the fitting of the tide as it is often suggested to compensate for the intermittency of waves. We assume that the retrieval of averaged spectra yields the average wind speed, so windowing and aggregation can be considered equivalent. This assumption might not hold in the context of fast changes in the wind field and we thus prefer periods of a stable wind background for our detailed analysis. Especially we do not attempt to retrieve tidal parameters during strong planetary wave activity, nor in the context of extreme events like sudden stratospheric warmings. Further, we consider non-tidal gravity waves to be filtered out by the vertical smoothing of the instrument of about $12\,\mathrm{km}$.

Vertical smoothing (artificially or due to instrumental properties) decreases tidal amplitudes depending on the vertical wavelength of the observed tides. If the vertical wavelength is infinite (tidal phase is constant with altitude), the amplitude is not affected, whereas at typical vertical wavelengths of the diurnal tide of around $30\,\mathrm{km}$, the smoothing can reduce the observed amplitude by up to 0.25. In this study, we do not apply any vertical smoothing to the reanalysis data.

To check for the significance and robustness of the diurnal tidal parameters, we compare the outcome for different composites. We run the same analysis for the (13,2), (11,2), (9,3), (9,2), (7,4) and (7,3) composites, which provide different samplings of the same observable. The similarities and differences among all the composites indicate how robust the parameters are and allow us to estimate the influence of noise from instrumental and atmospheric sources in a qualitative way.

We also compute the mean amplitude and phase over a larger time span (three months) by averaging the wind field prior to fitting the tide-model. ~~By doing so, we assume that we observe the same coherent tidal mode over the whole time period. We further~~ We estimate the uncertainty of the amplitude and phase for the 3-monthly mean using a bootstrapping method ~~by re-sampling the wind time-series and therefore the~~ that follows the Moving Block Bootstrap (Lahiri, 2003, p.25ff). For a $(\Delta D, \Delta H)$ composite time series, we sample a synthetic three-month period (91 days) by choosing $\frac{91}{\Delta D}$ composite days at random and estimate the diurnal tidal parameters of the mean diurnal cycle for each sample. The distribution of the parameters ~~. This captures~~ gives us an estimate on the uncertainty due to observational errors as well as due to phase variability during the period of observation.

4 Results

From both campaigns we select a three months period, based on the following criteria. First we look for periods with stable background wind conditions. Due to the composition (maximum 13 day~~composite analysis~~) for the wind retrieval, we prefer time intervals with no extreme meteorological events, e.g. sudden stratospheric warmings (SSW), and a low planetary wave activity because this might impact the retrieval of tidal amplitudes.

Further, we only considered time intervals with a good overall measurement response, which corresponds mainly to little precipitation. Another important aspect for the data analysis is the continuity of the observations (minimal instrumental downtime) to avoid issues in compiling the temporal averages.

Considering the above mentioned criteria we decided to focus on two campaign intervals from April to June 2017 at Maïdo and from September to November 2018 at Andenes (ALOMAR). ~~We expect for both periods only a weak planetary wave activity and rather stable background conditions.~~

This gives us two time-series, one for the tropical campaign and one for the arctic campaign, for which we perform the previously described analysis. We use local mean solar time for all plots and phases in this study, which is simply a fixed offset depending on longitude. For the tropical campaign at $55.5°$ longitude, this is an offset to UT of $3.7\,\mathrm{hours}$. For the arctic campaign at $15.7°$ longitude, the offset of local mean solar time to UT is $1\,\mathrm{hour}$.

4.1 Results for the tropical campaign

For the tropical campaign, we selected the ~~time span~~ period from April to June 2017. This period is at the beginning of austral winter where reanalysis as well as measurements show a steady background of strong eastward winds with a small meridional component and relatively low planetary wave activity. Moreover, during this rather dry season, WIRA-C performed well and measured continuously with a good measurement response.

The meteorological background wind field for the selected period at the Maïdo observatory is shown in Fig. 1 as ~~a composite of~~ measured by WIRA-C~~measurements and~~ , complemented with MERRA-2 reanalysis for lower altitudes. The zonal and meridional winds indicate some variability at temporal scales of a few days. Characteristic for the zonal winds are westward winds below $40\,\mathrm{km}$ altitude and a strong zonal eastward stratospheric jet from $45\,\mathrm{km}$ to $70\,\mathrm{km}$ altitude, which intensifies at the beginning of May. Meridional winds exhibit a steady change between southward and northward winds within a few days. Corresponding to the zonal wind enhancement, meridional winds become more southward at beginning of May above a height of $60\,\mathrm{km}$.

Figure ?? shows the retrieved meridional wind speed from WIRA-C with $2\,\mathrm{hour}$ temporal resolution together with MERRA-2 reanalysis data for the $50\,\mathrm{hPa}$ altitude level (approx. $53\,\mathrm{km}$) for 7 days in April 2017. The mean value of the reanalysis and the measurement are close to $0\,\mathrm{m\,s^{-1}}$. The diurnal cycle with a clear 1-day period is readily visible from the reanalysis data, while the measurement does also include higher frequency components which are mostly dominant during the first days.

The diurnal tidal amplitude A_1 and phase Φ_1 during the whole period are presented The average diurnal cycle on different altitudes over the whole three month period is shown in Fig. 4. The upper two panels (Fig. 4a and 4b) show the 2 for WIRA-C retrievals. The lower two panels (Fig. 4c and 4d) are obtained by running the analysis on the measurements and MERRA-2 reanalysis. The WIRA-C diurnal tidal amplitudes reach a maximum at the beginning of the campaign of about $16\,\mathrm{m\,s^{-1}}$ to $20\,\mathrm{m\,s^{-1}}$ for both components. During the second phase of the campaign we observe smaller tidal amplitudes of approximately $4\,\mathrm{m\,s^{-1}}$ to $12\,\mathrm{m\,s^{-1}}$. Further, our observations reveal an intermittency of the diurnal tidal amplitude at the resolved temporal scales of 7 to 13 days. The phase plot also reflects this intermittency in time and also in the vertical domain. During this campaign there is an obvious pattern of In both data sets, the diurnal tide phase modulated with a period of approximately a month.

Comparing the WIRA-C observations to MERRA-2 points out that the intermittency of the diurnal tidal zonal and meridional wind is not reproduced in the reanalysis neither in amplitude nor in phase. However, the mean behaviour seems to be in good agreement to the observations and the general morphology of is readily visible. The reanalysis data seems not to contain any other modes than the diurnal tide in amplitude and phase seems to agree between measurements and reanalysis.MERRA-2, like our measurements , also shows larger diurnal tidal amplitudes at the beginning of the tropical campaign in April, which then decrease in May and June. However, the short term diurnal tidal variability seems to be not well-reflected in the reanalysis dataand the tide model from Eq. (2) fully fits the data. The measurements expose some more variability, especially at higher altitudes and during the afternoon hours. This is related to increased noise in the measurement in the afternoon hours, which is most prominent for the westwards observation direction (and thus only seen in zonal wind retrievals) due to local weather patterns at the Maïdo observatory on La Réunion Island.

The agreement between MERRA-2 and the WIRA-C wind retrievals with respect to the mean behaviour can be assessed in Fig. 3. The left panel (Fig. 3a) shows the amplitude of the zonal and meridional mean diurnal cycle over the entire campaign period for WIRA-C and MERRA-2. Both data sets show a similar profile with relatively low amplitudes of less than $5\,\mathrm{m\,s^{-1}}$ below $55\,\mathrm{km}$ and slightly higher amplitudes for the meridional component. Figure 3b shows the same for the vertical phase behaviour. The green color shows the MERRA-2 reanalysis applying the same temporal aggregation of the time series to derive the tidal amplitudes as for WIRA-C, whereas the red color shows the analysis without averaging. The profiles of measurements and reanalysis are in agreement with respect to the amplitudes and phases up to an altitude of 55 km for the tropical location where the reanalysis data lies within or is close to the limits of confidence of our measurements. The amplitude of the diurnal tide agrees for the measurement and reanalysis within or close to their limits of confidence. Above 55 km altitude, an increased discrepancy is evident for the meridional wind between MERRA-2 and the radiometer.

The phase of the mean daily cycle measured by WIRA-C as shown in Fig. 3b indicates a vertical wavelength of about 30 km. Approximately the same vertical wavelength is found in the reanalysis. In both data setsAbove 55 km altitude, the vertical wavelength increases drastically above 55 km altitude, of our measurements increases drastically and the phase eventually becomes constant with altitude. Evidently, the tide seen by WIRA-C lags behind the tide represented in the reanalysis by 5 hours at the lower most altitude levels. Currently, we cannot explain this offset.

Further, in Fig. 3b it can be seen Figure 9a shows the phase difference between zonal and meridional diurnal tide. Measurements and reanalysis show a remarkable agreement and show that the meridional tide leads the zonal tide by approximately 6 hours (90° phase angle) in the measurements as well as in the reanalysis as is expected for the southern hemisphereas is expected for the southern hemisphere.

Besides the tri-monthly mean, we show the diurnal tidal amplitude A_1 and phase Φ_1 versus time for the whole period in Fig. 4. The upper two panels (Fig. 4a and 4b) show the WIRA-C retrievals. The central two panels (Fig. 4c and 4d) are obtained from the composed MERRA-2 reanalysis, whereas the bottom two panels (Fig. 4e and 4f) show the data for the original MERRA-2 reanalysis. These figures present the outcome for the (13, 2) composite only and we provide five more composites in the appendix in Fig. A1 and Fig. A2 for the tropical campaign. The WIRA-C diurnal tidal amplitudes reach a maximum at the beginning of the campaign of about $16\,\mathrm{m\,s^{-1}}$ to $20\,\mathrm{m\,s^{-1}}$ for both components. During the second phase of the campaign we observe smaller tidal amplitudes of approximately $4\,\mathrm{m\,s^{-1}}$ to $12\,\mathrm{m\,s^{-1}}$. The vertical structure that is obvious in Fig. 4a can also be seen in the three-monthly mean (Fig. 3a) with a minimum at 55 km in reanalysis and measurements. A possible source of this structure is the mixing of different tidal waves with different vertical wavelengths or propagation directions.

Further, our observations show a strong time dependence of the diurnal tidal amplitude and phase at the resolved temporal scales of 7 to 13 days. We observe the same morphology in the time series for all composites (Fig. A1 and Fig. A2) and take this as a hint that the variability is not only due to noise. Nevertheless, there are some differences between the different composites, especially in the absolute values of the amplitudes that are most probably related to instrumental noise. The phase on the other hand is more robust and the time series of the diurnal tidal phase has the same structure in all composites and exposes a pattern of the diurnal tidal phase modulated with a period of approximately a month.

Compared to the WIRA-C observations, the MERRA-2 reanalysis data shows a constant amplitude and phase over time in the composite analysis (Fig. 4c and 4d). The original MERRA-2 data as shown in Fig. 4c and 4d is less constant over time and phase and amplitude expose a high day-to-day variability. However, the mean behaviour seems to be in good agreement to the observations and the general morphology of the diurnal tide in amplitude and phase seems to agree between measurements and reanalysis.

Figure 5 shows a comparison of the time series between WIRA-C and the MERRA-2 reanalysis at an altitude of 55 km. The shaded area represents the statistical uncertainties of the estimated diurnal tidal amplitudes taken from the co-variance of the adjusted parameters. In addition to the MERRA-2 reanalysis that has been smoothed with our integration kernel, we show the tidal analysis of the original MERRA-2 data. This comparison indicates how the diurnal tidal amplitude decreases with time over the campaign period and how intermittent the and increases again during the campaign in the measurements as well as in the reanalysis. MERRA-2 and our measurements show larger diurnal tidal amplitudes are. This intermittency of the tide is only partly seen in the reanalysisat the beginning of the tropical campaign in April, which then decrease in May and June.

4.2 Results for the arctic campaign

From the ongoing arctic campaign in Andenes (ALOMAR), we selected September, October and November 2018 for our analysis. The measurement response during these months is between 0.8 and 1.2 between 42 and 62 km and between 0.7 and 1.3 between 39 and 69 km and therefore acceptable for the whole altitude range we cover. We did not choose this period to start earlier because of the biannual wind reversal that took place just before September 2018 and, on the other end, did not expand this period to December because of the major sudden stratospheric warming that took place in this winter (Schranz et al., 2019) .

For this period, the meteorological situation is dominated by the fall transition in the stratosphere. The corresponding background wind field retrieval from WIRA-C is shown in Fig. 6. The campaign period starts at the end of summer with a weak eastward zonal jet between 45 km to 55 km altitude, which evolves into a typical polar vortex until November covering nearly all observed altitudes from 40 km to 70 km. Meridional winds are dominated by a southward flow at the beginning of the campaign period, which then reverses into a northward wind regime at the end of October. Both wind components indicate some variability due to waves on temporal scales of a few days, in particular, the meridional wind indicates an onset of the planetary wave activity towards the end of the observation period.

Figure 7 shows the diurnal cycle, averaged over the three months during the arctic campaign. The reanalysis data is well fitted by our diurnal tide model on all altitudes, but presence of a semi-diurnal component is indicated by the slight oscillation of the reanalysis data around the diurnal tide model fit. The WIRA-C measurements are well represented by the simple diurnal tide model, while containing some higher frequency oscillations that could originate in higher mode oscillation as well as measurement noise.

Figure 8 shows amplitude and phase profiles of the mean daily cycle of this period. Measurements and reanalysis mostly agree and show the same structure of the diurnal tidal amplitude and phase. Still as seen in Fig. 8a, WIRA-C measures a higher diurnal amplitude than the reanalysis suggests. Here, the offset in amplitude seems to be systematic since for the most part, the profiles do not agree within their limits of confidence even though they show the same structure.

The phase of the mean daily cycle is shown in Fig. 8b. Both data sets show a situation with infinite vertical wavelength above 45 km. The maximum of the diurnal tide is around noon and 18h local time for the zonal and meridional component respectively.

The phase difference between zonal and meridional component in the three-monthly mean is shown in Fig. 9b. Above 45 km, the zonal tide leads the meridional tide by 6 hours (90° phase angle), as expected for the northern hemisphere. Below 45 km, the phase of the zonal component starts to deviate in the measurements and gets behind the meridional tide at approximately 40 km altitude.

Figure 10 shows extracted amplitudes and phases of the diurnal tide for the arctic campaign over time and altitude. The panels on the left (Fig. 10aand 10c , 10c and 10e)) show the diurnal tidal amplitude A_1 for the WIRA-C measurements and the MERRA-2 composite and original reanalysis respectively. In the measurements, the diurnal tide is stronger in September than it is in October and reaches nearly $20\,\mathrm{m\,s^{-1}}$ in the meridional component by end of September. Again, this is most probably related to augmentation of tides by weaker background wind speed caused by the seasonal wind reversal that took place at the end of August to beginning of September 2018. But also during October and November, diurnal tidal amplitudes are quite strong, often up to or more than $15\,\mathrm{m\,s^{-1}}$. This is different for the composite reanalysis data, where amplitudes are generally lower than $10\,\mathrm{m\,s^{-1}}$. In the non-smoothed reanalysis data, tidal amplitudes of more than $15\,\mathrm{m\,s^{-1}}$ are also reached.

The extracted diurnal tidal phase Φ_1 is shown in Fig. 10b and Fig. 10d for the measurement and reanalysis respectively. In general, the reanalysis shows a very stable phase with the maximum of the diurnal tide at noon local time for the zonal component and 18h local time for the meridional component. Only in November, the phase becomes more variable and exposes some structure . This which might be related to the onset of planetary wave activity. This applies to the smoothed and orignal MERRA-2 data equally and is in strong contrast to the measurements, where the diurnal tidal phase is highly variable with time and altitude on the presented timescales. The measurements do not indicate a stable phase but suggest a more intermittent behavior compared to the reanalysis of diurnal tidal.

Figure 8 shows amplitude and phase profiles of the mean daily cycle of this period. With all the variability averaged out, the measurements and reanalysis mostly agree and show the same structure Because this time-dependence is present in all composites with the same morphology, we partly attribute it to the intermittency of the diurnal tidal amplitude and phase. Still as seen in Fig. 8a, WIRA-C measures a higher diurnal amplitude than the reanalysis suggests. Here, the offset in amplitude seems to be systematic since for the most part, the profiles do not agree within their limits of confidence even though they show the same structure. tide while the exact value of the phase might still be subject to noise.

The phase of the mean daily cycle is shown in As for the tropical campaign, we discuss the (13,2) composite and provide a total of six composites in the appendix (Fig. 8b.Both data sets show a stable situation with infinite vertical wavelength above 45 km. The maximum of the diurnal tide is around noon and 18h local time for the zonal and meridional component respectively. Below 45 km, the phase of the zonal component starts to deviate in the measurements and matches the meridional

~~phase at approximately 40 km altitude. Above 45 km, the phase difference between zonal and meridional component is about 6 hours (90° phase angle) and the zonal component leads the meridional component, as expected for the northern hemisphere~~A3 and Fig. A4). Again we see the same morphology and time-dependence of amplitude and phase in all composites. While the amplitude is less consistent among the composites due to noise, the phase is more robust.

Figure 11 shows the time series for one specific altitude level (53 km) and additionally shows the amplitudes of the original reanalysis data, that has not been ~~averaged with our integration kernel~~composed over multiple days. Especially in November, the original reanalysis data shows a variability that is comparable or even stronger compared to the measurements. By applying the ~~integration kernel~~composition, this variability is averaged out from the reanalysis data but not entirely from the WIRA-C measurements. This indicates that the coherence time of short timescale disturbances of the diurnal tide might actually be longer than the reanalysis predicts. Notably, the measured amplitude features a disturbance around September 24th, where the zonal amplitude is close to zero and the meridional amplitude exhibits a maximum. Similar dynamics are not represented in the reanalysis data, not even in the ~~analysis of the~~ (not-smoothed) original reanalysis data.

4.3 Summary

We presented measurements of the diurnal tide in the wind field in the stratosphere and lower mesosphere. To our knowledge, these are the first direct observations of tides in the wind field in the middle atmosphere (30 km to 70 km) with ground based instruments. In contrast to the standard time series retrievals applied in previous studies, we apply a composite analysis and superpose spectra for the same time-of-day ~~aggregation~~ over several days~~that is well suited for tidal studies. This aggregation~~. This composite analysis enables us to resolve tidal structures in the wind field.

To investigate the results of our method, we applied our analysis to two three-month periods from different campaigns, one from the southern hemisphere and one from the northern hemisphere.

The averaged data over the three month periods showed basic and well-known properties of the diurnal tide with different details for the northern and southern hemisphere. Notably we observed an increasing amplitude with altitude, reasonable vertical wavelengths and a 6 hours (90° phase angle) shift between zonal and meridional component with the leading component being different for the the austral and boreal locations.

We ~~observed an augmented diurnal tide in the context of weak background wind speeds after seasonal wind reversals. Looking at shorter timescales, we observe strong temporal variability of the amplitudes and especially of the phase, indicating the presence of highly intermittent diurnal tides.~~

~~Further, we~~ compared our wind measurements to the MERRA-2 reanalysis which has already been compared by Sakazaki et al. (2018) to other data sets with regard to tides in the temperature field. We find a good over-all-correspondence between reanalysis and measurements in the amplitude of the diurnal tide in the wind field and temporal evolution thereof. Further the amplitude and phase profiles for the 3-monthly mean wind field correspond between the radiometer and the meteorological reanalysis, mostly within their uncertainties for the tropical campaign and with a small offset for the arctic campaign. While the phase of the diurnal tide is very stable in the reanalysis data, especially in the polar region and sometimes even stationary, we see a big temporal variation of the phase in our measurements which persists among different composites.

While these intermittent structures are present to some extent in the reanalysis data as well, they are averaged out by our 13-day integration kernel. This is not the case for the measurements and we conclude, that the coherence time of short time scale disturbances is longer in reality than in Further, we presented a time-series of the diurnal tidal amplitude and phase over two three-month periods. We observed an augmented diurnal tide in the context of weak background wind speeds after seasonal wind reversals. Looking at shorter timescales, we observe strong temporal variability of the amplitudes and especially of the phase. Certainly, the reanalysis modeltime dependence of the diurnal tidal phase has to be investigated in further studies. Since we see the same time dependence in all our composites, we conclude that intermittent diurnal tides could be a possible explanation.

5 Conclusions

In summary, we find that reanalysis and measurements agree on the tidal component in the 3-monthly mean daily cycle. We conclude, that the MERRA-2 reanalysis captures the amplitude and phase of the mean diurnal tide reasonably well when averaging over 3 months or longer. When looking at shorter timescales, obvious differences between model and measurements appear. We can explain some of the differences like the augmented tide in context of weak background winds and also observe other notable differences like the variable phase in measurements that are not represented in the MERRA-2 product. Since the general morphology of the variable phase is the same among all composites, we conclude that it might be caused by actual atmospheric variability of the tide. While these intermittent structures are present to some extent in the reanalysis data as well, they are averaged out when we apply the 13-day smoothing that is equivalent to the composite of our measurement. A possible explanation would be, that the coherence time of short time scale disturbances of the diurnal tide is longer and variability is in general stronger in reality than in the reanalysis model. On the other hand, our study is based on a composite analysis, and we assume that the diurnal tide is reasonably stationary during our 7 or 13-day window. Baumgarten and Stober (2019), based on temperature lidar observations with high temporal resolution, provide some evidence that tides can be highly variable and composition windows should be no longer than a few days.

Further studies could develop more elaborate methods to extract tidal information from radiometer data and further constrain the uncertainty on the extracted parameters. Diurnal tide measurements from daylight-capable lidar or even from rocket campaigns would be a possible source of comparison data. Also other models, for example NAVGEM-HA, could provide further comparison data on different time-scales.

In this study, we focused on the diurnal tidal component only. Future studies could as well address the semi-diurnal component using the same or different composites.

We required a stationary background and focused on selected periods which satisfy this condition. Further studies could investigate the necessity or this requirement and retrieve tides while taking a variable background into account.

Ground-based microwave radiometers are capable to measure continuously over decades and can be deployed in tropical and arctic polar latitudes with minimal maintenance and deployment effort. This makes these instruments very valuable to observe dynamics in the atmosphere, especially from 30 km to 70 km altitude where observations are scarce. Since tidal waves on sub-seasonal and regional scales play an important role in the dynamics of the atmosphere, such observations are highly valuable.

Data availability. The retrieved wind fields (WIRA-C level 2 data) for the two 3-month periods are available from the zenodo public repository (doi:10.5281/zenodo.3468900).

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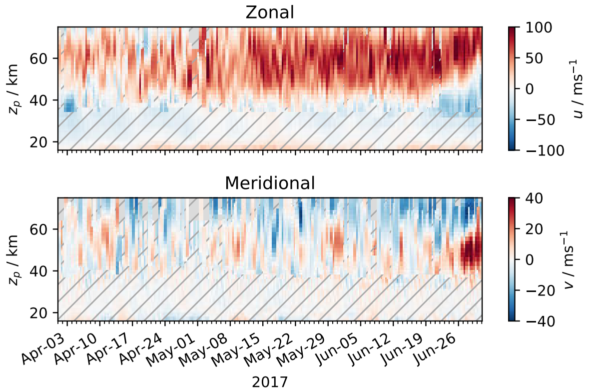


Figure 1. Background wind speed measured by WIRA-C complemented with MERRA-2 reanalysis data (hatched area) for the tropical campaign. Note the different scales for the zonal and meridional component.

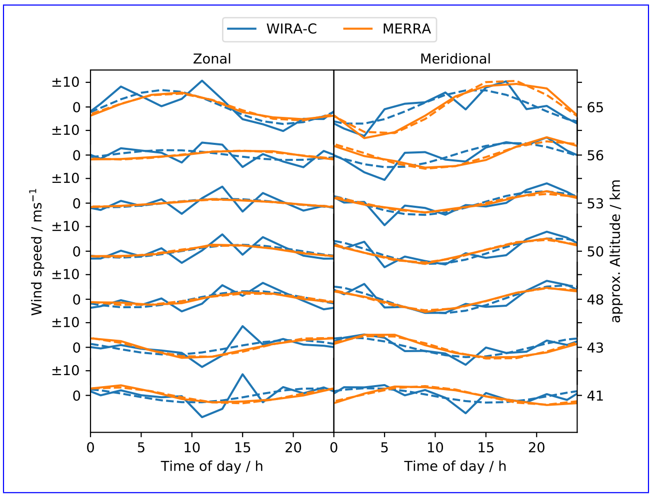


Figure 2. Timeseries Mean daily cycle of retrieved zonal and meridional wind from WIRA-C at 50 hPa (approx. 52 km) speeds in different altitudes for beginning of April 2017 the three months during the tropical campaign . Additionally, from MERRA-2 reanalyses data and WIRA-C. Dashed lines indicate the a priori data used for best fit of the retrieval are shown. Temporal resolution for WIRA-C and MERRA-2 is 2 hours and 3 hours respectivelydiurnal tide model.

(a) WIRA-C Amplitude A_1

(b) Phase Φ_1

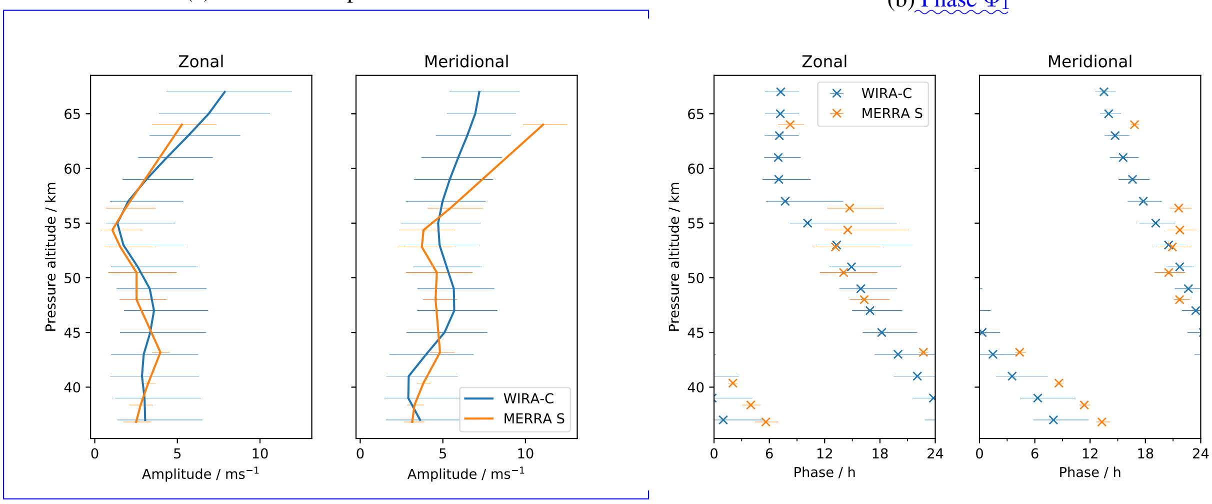
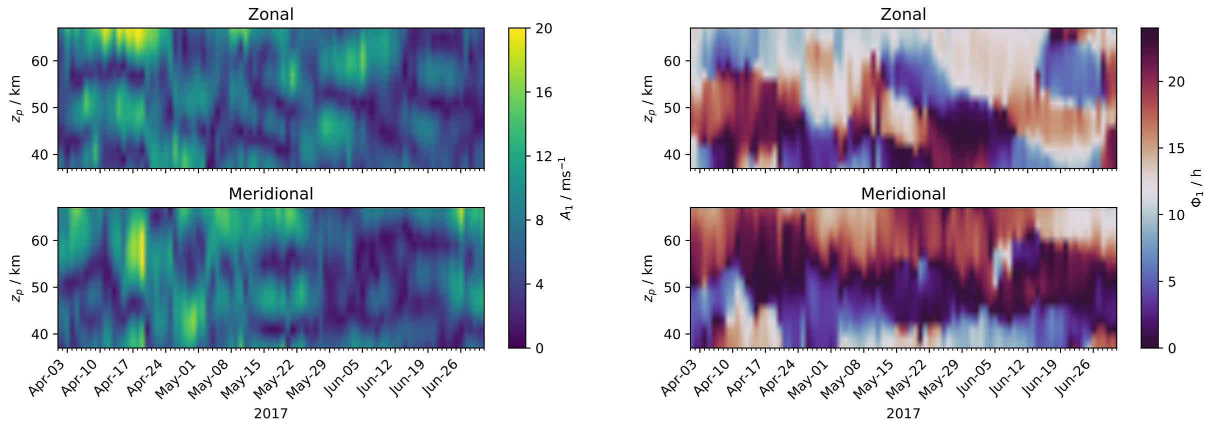
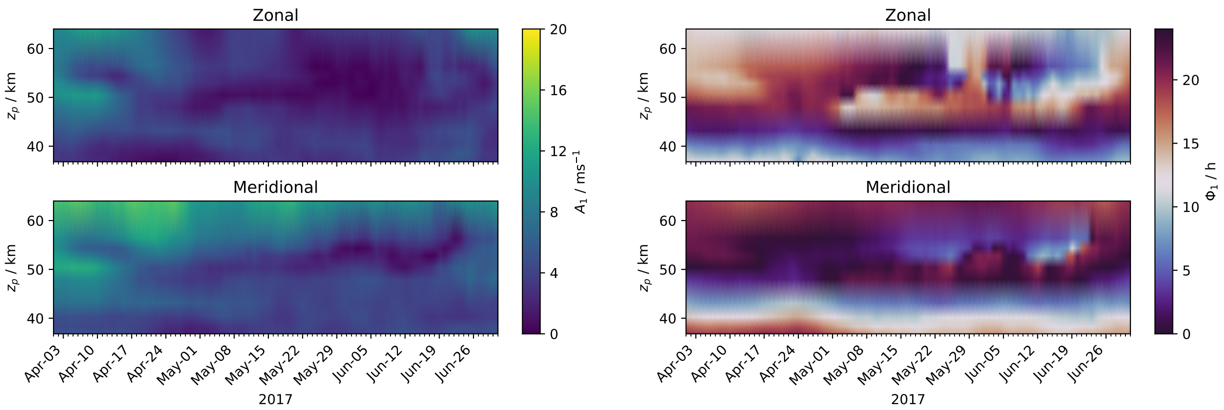


Figure 3. Amplitude and phase of mean daily cycle over three months from MERRA-2 reanalysis and WIRA-C measurements from the tropical campaign. Error bars indicate 95% confidence limits. Phase is equivalent to solar time of maximum.

(a) WIRA-C composite Amplitude A_1 (b) WIRA-C composite Phase Φ_1

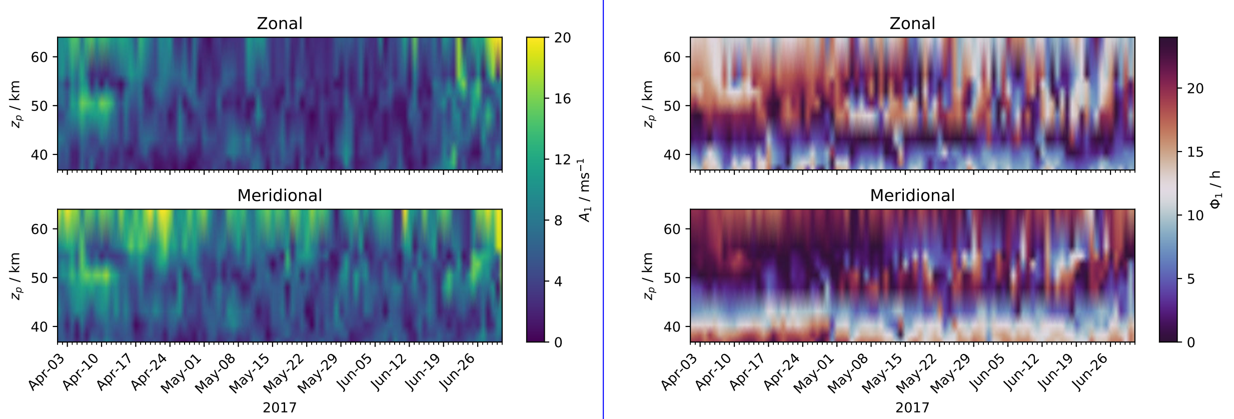


(c) MERRA-2 composite Amplitude A_1 (d) MERRA-2 composite Phase Φ_1



~~Amplitude and phase of the diurnal tide over three months from WIRA-C measurements (,) and smoothed MERRA-2 reanalysis (,) during the tropcal campaign at the Maïdo observatory.~~

(e) MERRA-2 Amplitude A_1 (f) MERRA-2 Phase Φ_1



~~Amplitude and phase of mean daily cycle over three months from MERRA-2 reanalysis (from original and smoothed data) and WIRA-C measurements from the tropical campaign. Error bars indicate 95% confidence limits. Phase is equivalent to solar time of maximum.~~

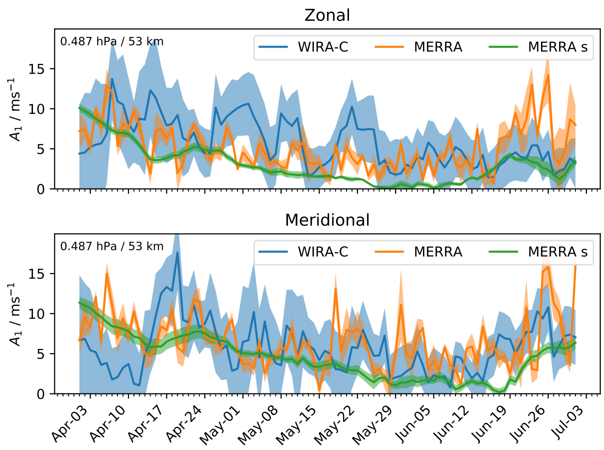


Figure 5. Time series of zonal and meridional diurnal tide amplitudes during the tropical campaign for measurements (WIRA-C), MERRA-2 reanalysis (MERRA) and reanalysis smoothed (MERRA s) at an altitude level of $53\,\mathrm{km}$ with corresponding errors of the model fit as shaded area.

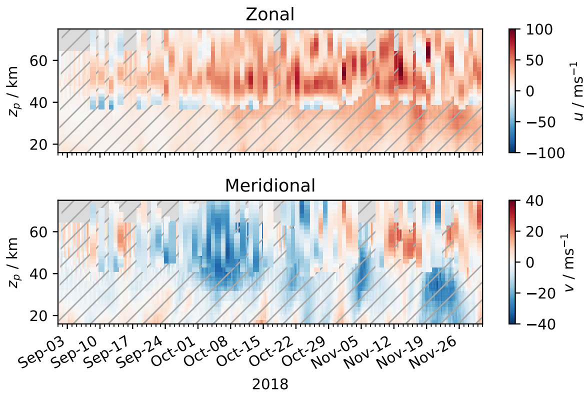


Figure 6. Background wind speed measured by WIRA-C complemented with MERRA-2 reanalysis data (hatched area) for the arctic campaign. Note the different scales for the zonal and meridional component.

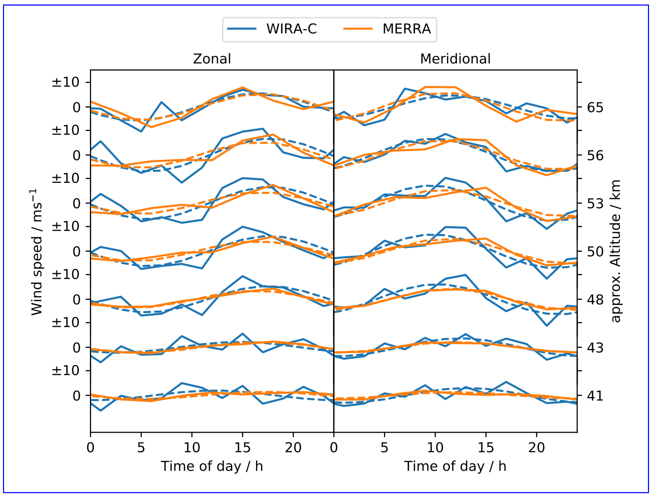


Figure 7. Mean daily cycle of zonal and meridional wind speeds in different altitudes for the three months during the arctic campaign from MERRA-2 and WIRA-C. Dashed lines indicate the best fit of the diurnal tide model.

(a) ~~WIRA-C~~ Amplitude A_1

(b) Phase Φ_1

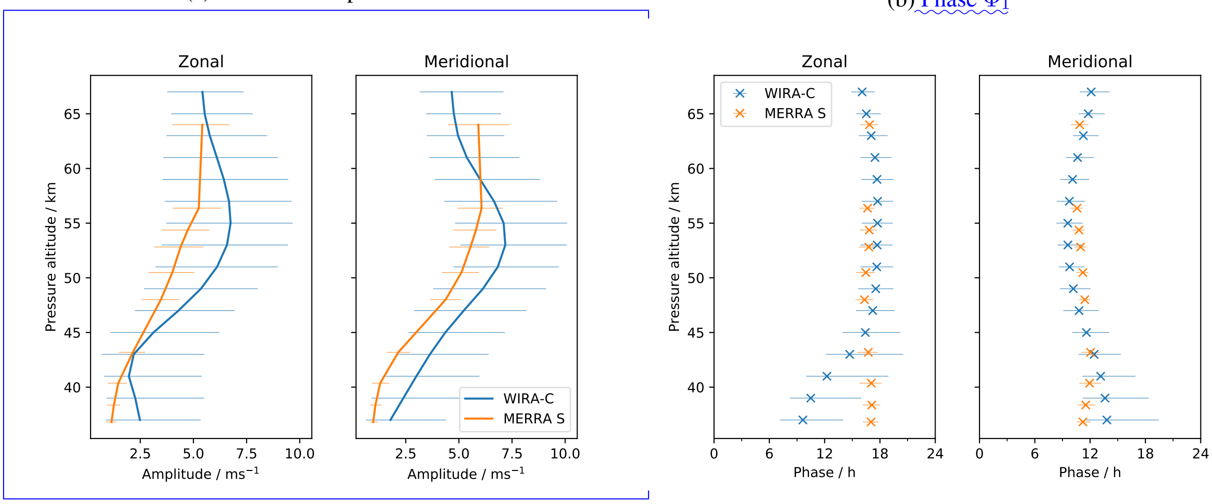


Figure 8. Amplitude and phase of mean daily cycle over three months from MERRA-2 reanalysis and WIRA-C measurements from the arctic campaign. Error bars indicate 95% confidence limits. Phase is equivalent to solar time of maximum.

(a) Tropical, 21 °S (b) Polar, 69 °N

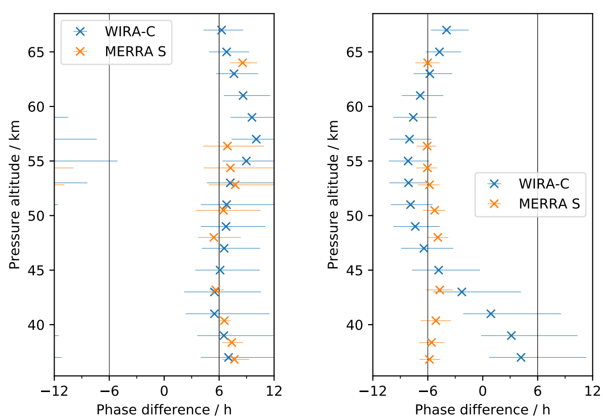
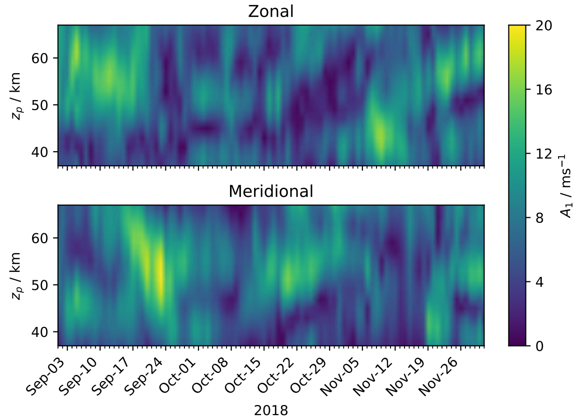
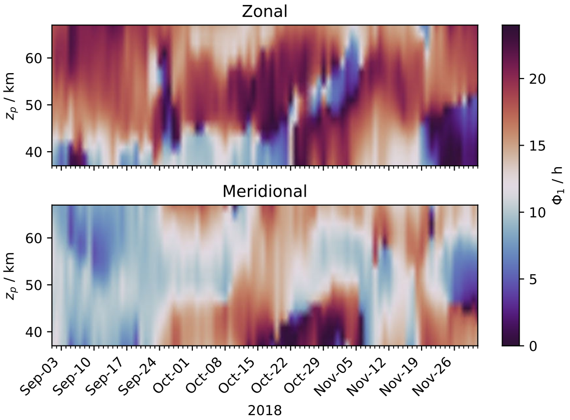


Figure 9. Phase difference between meridional and zonal diurnal wind tide ($\Delta\phi = \phi_{\mathrm{merid}} - \phi_{\mathrm{zonal}}$) for the tropcal and arctic campaigns in WIRA-C measurements and MERRA-2 reanalysis.

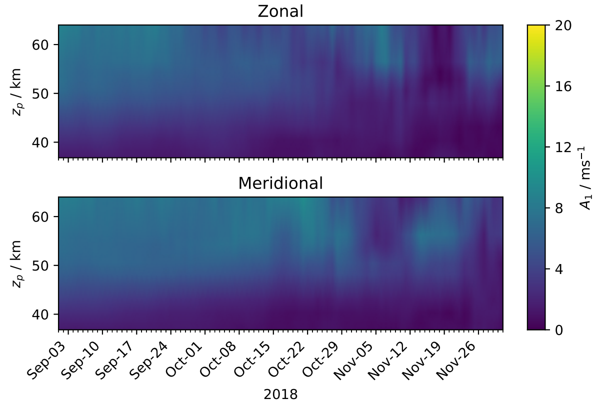
(a) WIRA-C composite Amplitude A_1



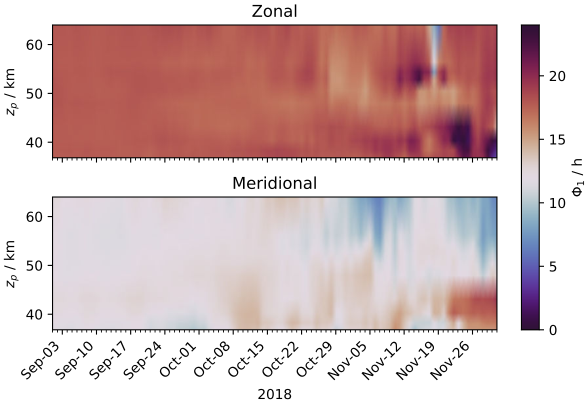
(b) WIRA-C composite Phase Φ_1



(c) MERRA-2 composite Amplitude A_1

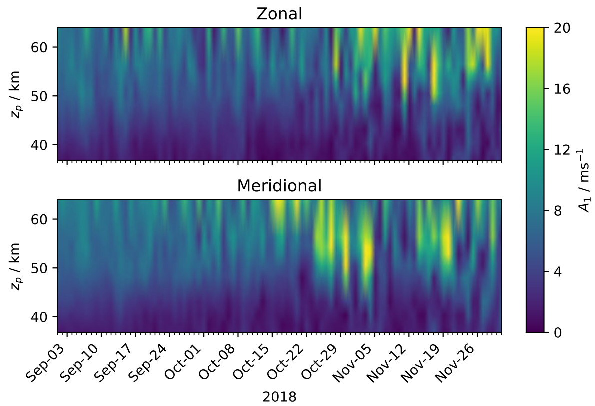


(d) MERRA-2 composite Phase Φ_1

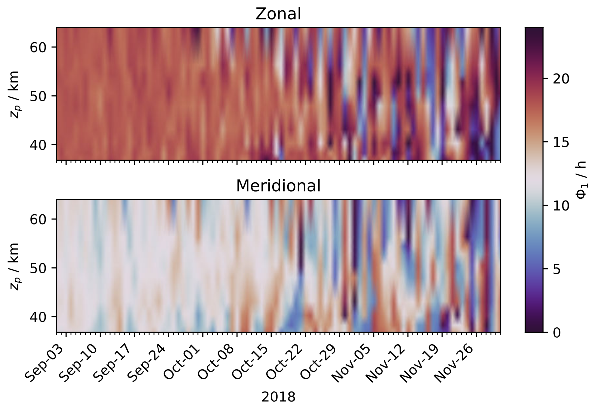


~~Amplitude and phase of the diurnal tide over three months from WIRA-C measurements (,) and smoothed MERRA-2 reanalysis (,) during the arctic campaign at the ALOMAR observatory.~~

(e) MERRA-2 Amplitude A_1



(f) MERRA-2 Phase Φ_1



~~Amplitude and phase of mean daily cycle over three months from MERRA-2 reanalysis (from original and smoothed data) and WIRA-C measurements from the arctic campaign. Error bars indicate 95% confidence limits. Phase is equivalent to solar time of maximum.~~

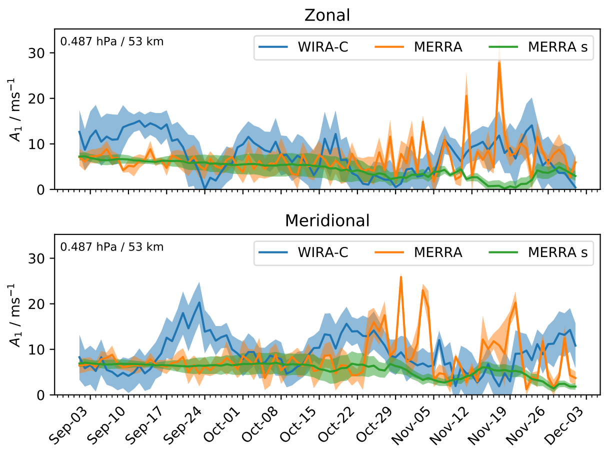


Figure 11. Time series of zonal and meridional diurnal tide amplitudes during the arctic campaign for measurements (WIRA-C), MERRA-2 reanalysis (MERRA) and reanalysis smoothed (MERRA s) at an altitude level of 53 km with corresponding errors of the model fit as shaded area.

Appendix A: Diurnal tide amplitude and phase for all composites

Figures A1, A2, A3, A4 contain panels with the extracted amplitude and phase of the diurnal tide in the wind field for six different composites of the WIRA-C wind measurements. We refer to the different composites by $(\Delta D, \Delta H)$ where ΔD indicates the number of days and ΔH the number of hours for the integration, the total integration time is thus given by $\Delta D \times \Delta H$ and ranges from $21\,\mathrm{h}$ to $28\,\mathrm{h}$ for the presented composites. We select these six composites because they all have an integration time of around $24\,\mathrm{h}$ and provide different window lengths (7 to 13 days) and different resolutions (2 to 4 hours).

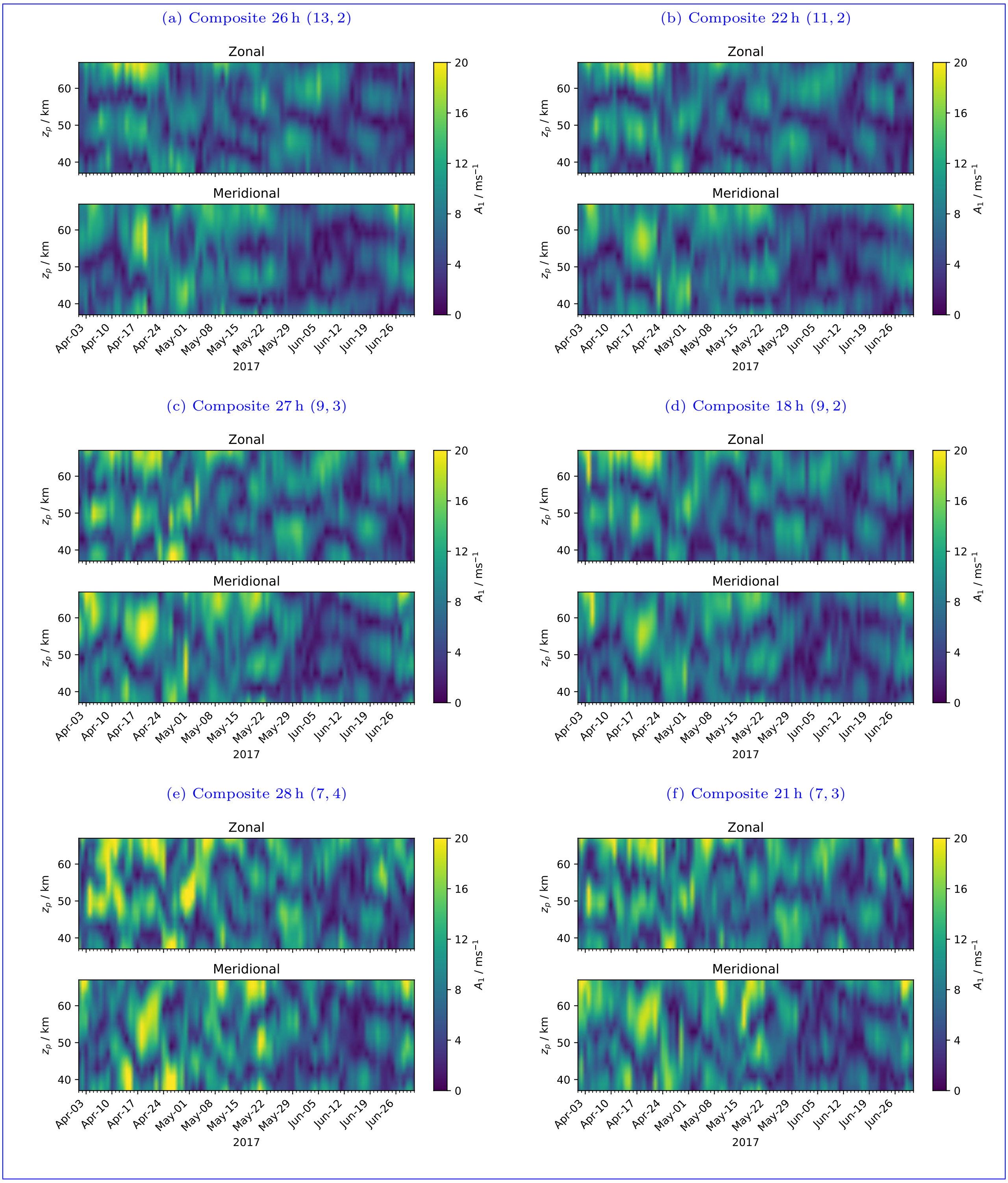


Figure A1. Tropical campaign: Amplitude of the diurnal tide for six different composites with a similar total integration time of 21 h to 28 h ordered by window length.

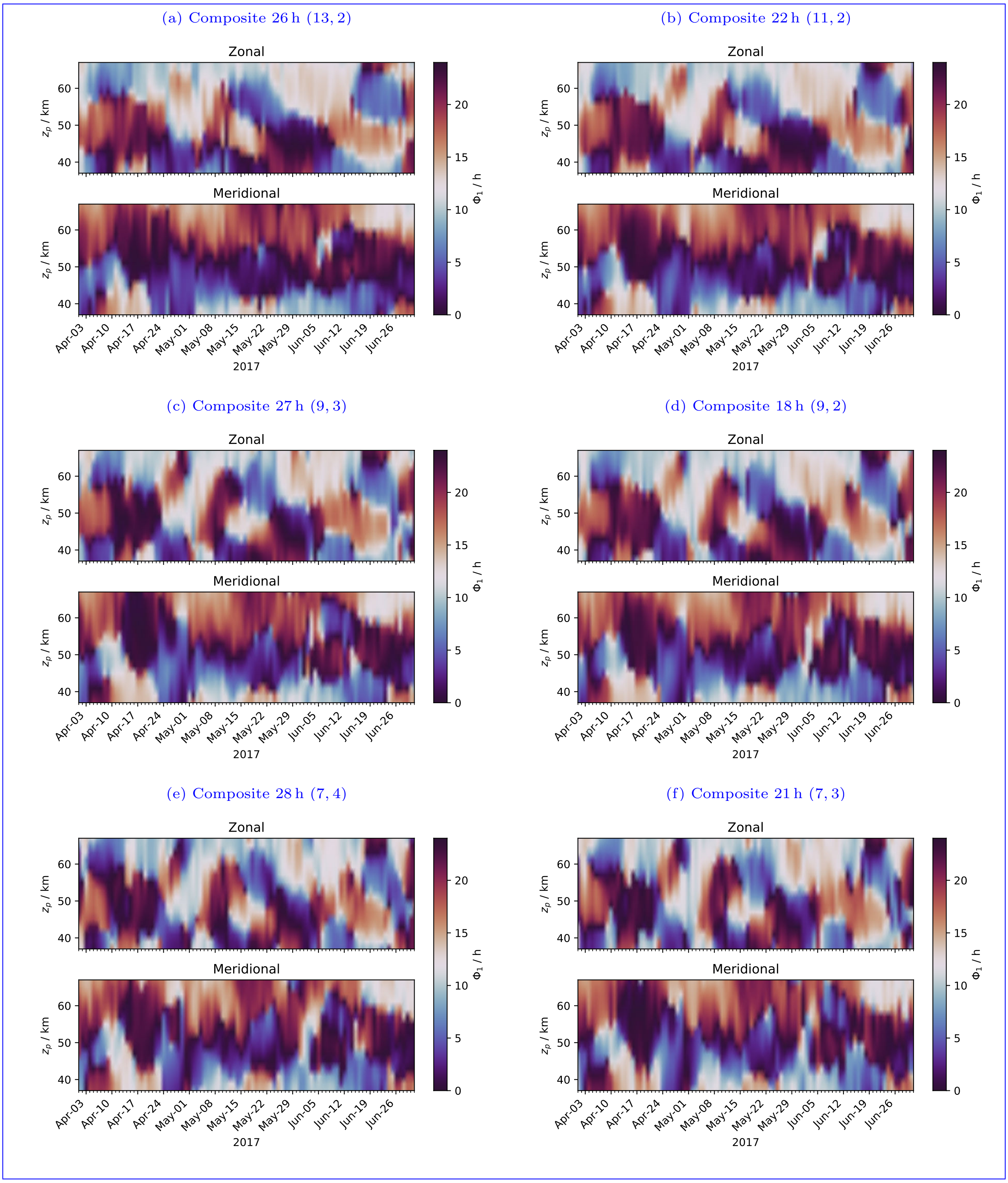


Figure A2. Tropical campaign: Phase of the diurnal tide for six different composites with a similar total integration time of 21 h to 28 h ordered by window length.

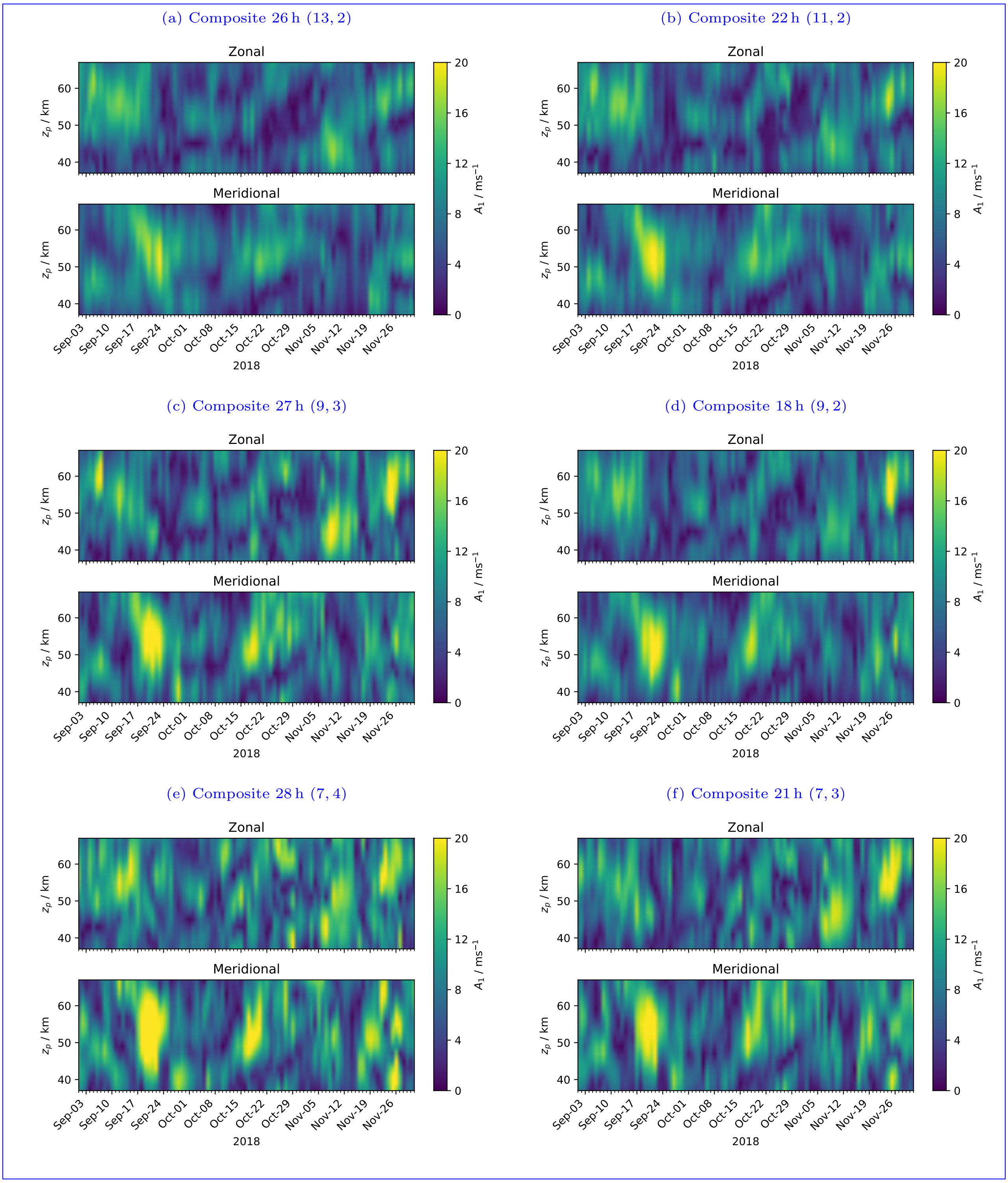


Figure A3. Arctic campaign: Amplitude of the diurnal tide for six different composites with a similar total integration time of 21 h to 28 h ordered by window length.

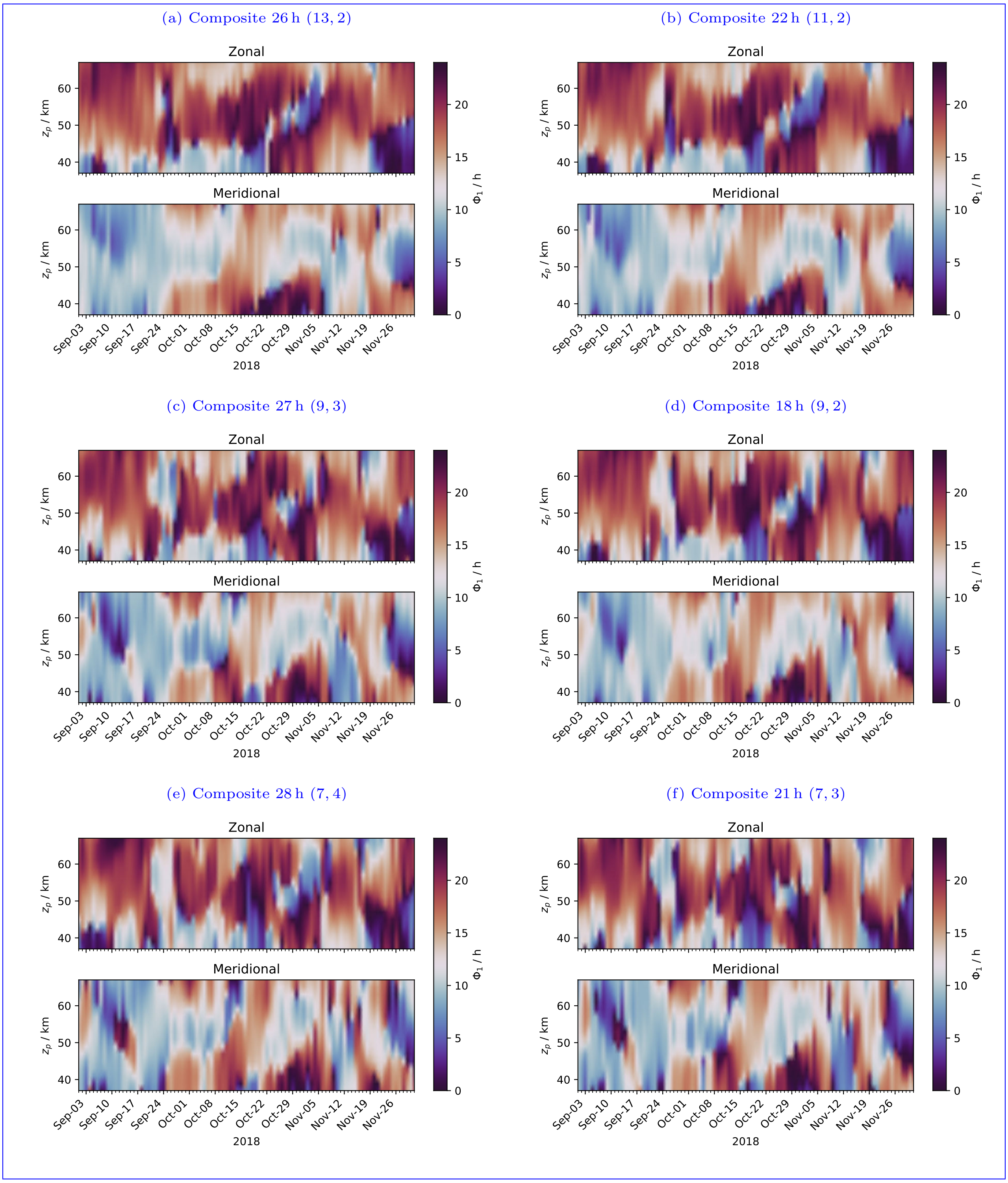


Figure A4. Arctic campaign: Phase of the diurnal tide for six different composites with a similar total integration time of 21 h to 28 h ordered by window length.