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. They are 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 measure atmospheric tides only in the

5 temperature field and continuous measurements of the tides in the wind field of the stratosphere and lower mesosphere are not available. 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 between measurements and reanalysis with the most important features of the diurnal tides represented in both data sets. When looking

10 at shorter timescales, we find an intermittency of the diurnal tide that is not represented in the MERRA-2 reanalysis data. 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 provide additional insight to middle atmospheric dynamics that is complementary to temperature observations and reanalysis data.

1 Introduction

15 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

20 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 $80\,\mathrm{km}$ to $400\,\mathrm{km}$. 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.

5   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

10 location and thus sample the diurnal cycle of a specific location with only $12\,\mathrm{h}$ resolution. The global coverage nevertheless enables tidal studies also for instruments on these satellites.

    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

15 in the wind fields (Portnyagin et al., 1993, 2004; Merzlyakov et al., 2009; Jacobi, 2012; Wilhelm et al., 2019).

    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.

20   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 and measurements are evident above approximately 40 km altitude and the spread between them is quite large in the lower mesosphere.

25   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)

30 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 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 these observations with reanalysis data to investigate the phase relations of temperature and

35 wind tides. However, lidar observations require cloud free conditions, which usually limits the continuity of such time series.

The microwave Doppler wind radiometer WIRA-C 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) in the stratosphere and mesosphere. 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. 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. 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 GHz ozone rotational emission line with a high spectral resolution of 12.5 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 wind speed. The pressure broadening effect allows the retrieval of altitude resolved wind profiles in an altitude range from 30 km to 75 km on a 3 km vertical grid with 12 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 GHz. Despite the low noise, integration times of

12 hours to 24 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
5   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.

10   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.

15   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

20 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 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
25 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
30 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. 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 measure-
5 ments of the same time of day over multiple days. Typically we use a window of 7 or 13 days and aggregate by time of day with a 2 hour resolution. This gives a total integration time of 14 and 26 hours respectively, centered around a central day. We refer to this aggregation scheme by $(\Delta D, \Delta H)$ where ΔD indicates the number of days and ΔH the number of hours for the integration kernel. The schemes used in this study are denoted as $(13, 2)$ and $(7, 2)$. For example, we collect all measurements taken between midnight and 02h00 over 13 days and integrate them together.

10 After integration we run the wind retrieval for the WIRA-C instrument. For MERRA-2 reanalysis data we apply the same integration kernel 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 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
15 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
20 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 respectively. 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.

Once we have retrieved the wind profiles (or extracted them from the reanalysis data), we fit a simple tidal model to extract
25 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 $k = 1, 2, 3, ...$ are
30 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

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

$$\phi_1 = \arctan 2\,(a_1, b_1) \ \in (-\pi, \pi]. \tag{4}$$

Since we average over 13 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.

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 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 distribution of the parameters. This captures 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 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 $3.7\,\text{hours}$. For the arctic campaign at $15.7°$ longitude, the offset of local mean solar time to UT is $1\,\text{hour}$.

4.1 Results for the tropical campaign

For the tropical campaign, we selected the 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 WIRA-C measurements and MERRA-2 reanalysis. The zonal and meridional winds indicate some variability at temporal scales of a few days. Characteristic for the zonal winds are westward winds below $40\,\text{km}$ altitude and a strong zonal eastward stratospheric jet from $45\,\text{km}$ to $70\,\text{km}$ 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 $60\,\text{km}$.

Figure 2 shows the retrieved meridional wind speed from WIRA-C with $2\,\text{hour}$ temporal resolution together with MERRA-2 reanalysis data for the $50\,\text{hPa}$ altitude level (approx. $53\,\text{km}$) for 7 days in April 2017. The mean value of the reanalysis and the measurement are close to $0\,\text{m\,s}^{-1}$. 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 in Fig. 3. The upper two panels (Fig. 3a and 3b) show the WIRA-C retrievals. The lower two panels (Fig. 3c and 3d) are obtained by running the analysis on the MERRA-2 reanalysis. The WIRA-C diurnal tidal amplitudes reach a maximum at the beginning of the campaign of about $16\,\text{m\,s}^{-1}$ to $20\,\text{m\,s}^{-1}$ for both components. During the second phase of the campaign we observe smaller tidal amplitudes of approximately $4\,\text{m\,s}^{-1}$ to $12\,\text{m\,s}^{-1}$. 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 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 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 data.

The agreement between MERRA-2 and the WIRA-C wind retrievals with respect to the mean behaviour can be assessed in Fig. 4. The left panel (Fig. 4a) 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 4b 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

5 and reanalysis are in agreement with respect to the amplitudes and phases up to an altitude of $55\,\mathrm{km}$ 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 $55\,\mathrm{km}$ 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. 4b indicates a vertical wavelength of $30\,\mathrm{km}$.

10 Approximately the same vertical wavelength is found in the reanalysis. In both data sets, the vertical wavelength increases drastically above $55\,\mathrm{km}$ altitude, and the phase eventually becomes constant with altitude. Evidently, the tide seen by WIRA-C lags behind the tide represented in the reanalysis by $5\,\mathrm{hours}$ at the lower most altitude levels. Currently, we cannot explain this offset.

Further, in Fig. 4b it can be seen that the meridional tide leads the zonal tide by approximately $6\,\mathrm{hours}$ ($90°$ phase angle) in

15 the measurements as well as in the reanalysis as is expected for the southern hemisphere.

Figure 5 shows a comparison of the time series between WIRA-C and the MERRA-2 reanalysis at an altitude of $55\,\mathrm{km}$. The shaded area represents the statistical uncertainties of the estimated diurnal tidal amplitudes. 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

20 diurnal tidal amplitudes are. This intermittency of the tide is only partly seen in the reanalysis.

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 expand this period to

25 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 $45\,\mathrm{km}$ to $55\,\mathrm{km}$ altitude, which evolves into a typical polar vortex until November covering nearly all observed altitudes from $40\,\mathrm{km}$ to $70\,\mathrm{km}$. Meridional winds are dominated by a southward flow at the beginning of the

30 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 extracted amplitudes and phases of the diurnal tide for the arctic campaign over time and altitude. The panels on the left (Fig. 7a and 7c) show the diurnal tidal amplitude A_1 for the WIRA-C measurements and the MERRA-2 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 $15\,\mathrm{m\,s^{-1}}$.

5 This is different for the reanalysis data, where amplitudes are generally lower than $10\,\mathrm{m\,s^{-1}}$.

The extracted diurnal tidal phase Φ_1 is shown in Fig. 7b and Fig. 7d 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 is in strong contrast to the measurements, where the diurnal tidal phase is highly variable with time and

10 altitude on the presented timescales. The measurements do not indicate a stable phase but suggest a more intermittent behavior compared to the reanalysis data.

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 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

15 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 stable situation with infinite vertical wavelength above $45\,\mathrm{km}$. The maximum of the diurnal tide is around noon and 18h local time for the zonal and meridional component respectively. Below $45\,\mathrm{km}$, the phase of the zonal component starts to deviate in the measurements and matches the meridional

20 phase at approximately $40\,\mathrm{km}$ altitude. Above $45\,\mathrm{km}$, the phase difference between zonal and meridional component is about $6\,\mathrm{hours}$ ($90°$ phase angle) and the zonal component leads the meridional component, as expected for the northern hemisphere.

Figure 9 shows the time series for one specific altitude level ($53\,\mathrm{km}$) and additionally shows the amplitudes of the original reanalysis data, that has not been averaged with our integration kernel. 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,

25 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.

30 ## 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 ($30\,\mathrm{km}$ to $70\,\mathrm{km}$) with ground based instruments. In contrast to the standard time series retrievals applied in previous studies, we apply a time-of-day aggregation over several days that is well suited for tidal studies. This aggregation 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 $6\,\mathrm{hours}$ ($90°$ 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) 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.

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 the reanalysis model.

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.

Ground-based microwave radiometers are capable to measure continuously over decades and can be deployed in tropical and arctic latitudes with minimal maintenance and deployment effort. This makes these instruments very valuable to observe dynamics in the atmosphere, especially from $30\,\mathrm{km}$ to $70\,\mathrm{km}$ 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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5 and helped to discuss the method and the results. NK is PI of the project.

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References

Baray, J.-L., Courcoux, Y., Keckhut, P., Portafaix, T., Tulet, P., Cammas, J.-P., Hauchecorne, A., Godin Beekmann, S., De Mazière, M., Hermans, C., Desmet, F., Sellegri, K., Colomb, A., Ramonet, M., Sciare, J., Vuillemin, C., Hoareau, C., Dionisi, D., Duflot, V., Vérèmes, H., Porteneuve, J., Gabarrot, F., Gaudo, T., Metzger, J.-M., Payen, G., Leclair de Bellevue, J., Barthe, C., Posny, F., Ricaud, P., Abchiche, A., and Delmas, R.: Maïdo observatory: a new high-altitude station facility at Reunion Island (21° S, 55° E) for long-term atmospheric remote sensing and in situ measurements, Atmospheric Measurement Techniques, 6, 2865–2877, https://doi.org/10.5194/amt-6-2865-2013, https://www.atmos-meas-tech.net/6/2865/2013/, 2013.

Baumgarten, K. and Stober, G.: On the Evaluation of the Phase Relation between Temperature and Wind Tides Based on Ground-Based Measurements and Reanalysis Data in the Middle Atmosphere, Annales Geophysicae Discussions, pp. 1–29, https://doi.org/10.5194/angeo-2019-25, 2019.

Buehler, S. A., Mendrok, J., Eriksson, P., Perrin, A., Larsson, R., and Lemke, O.: ARTS, the Atmospheric Radiative Transfer Simulator – version 2.2, the planetary toolbox edition, Geoscientific Model Development, 11, 1537–1556, https://doi.org/10.5194/gmd-11-1537-2018, https://www.geosci-model-dev.net/11/1537/2018/, 2018.

Forbes, J. M. and Wu, D.: Solar Tides as Revealed by Measurements of Mesosphere Temperature by the MLS Experiment on *UARS*, Journal of the Atmospheric Sciences, 63, 1776–1797, https://doi.org/10.1175/JAS3724.1, 2006.

Global Modeling and Assimilation Office (GMAO): MERRA-2 inst3_3d_asm_Np: 3d,3-Hourly,Instantaneous,Pressure-Level,Assimilation,Assimilated Meteorological Fields V5.12.4, Goddard Earth Sciences Data and Information Services Center (GES DISC), Greenbelt, MD, USA, https://doi.org/10.5067/QBZ6MG944HW0, 2015.

Hagan, M. E., Burrage, M. D., Forbes, J. M., Hackney, J., Randel, W. J., and Zhang, X.: GSWM-98: Results for Migrating Solar Tides, Journal of Geophysical Research: Space Physics, 104, 6813–6827, https://doi.org/10.1029/1998JA900125, 1999.

Hagen, J.: Wind fields from aggregated retrievals from the WIRA-C Doppler wind radiometer in tropical and arctic lattitudes, https://doi.org/10.5281/zenodo.3468900, 2019.

Hagen, J., Murk, A., Rüfenacht, R., Khaykin, S., Hauchecorne, A., and Kämpfer, N.: WIRA-C: A Compact 142-GHz-Radiometer for Continuous Middle-Atmospheric Wind Measurements, Atmospheric Measurement Techniques Discussions, pp. 1–30, https://doi.org/10.5194/amt-2018-69, 2018.

Häusler, K., Lühr, H., Hagan, M. E., Maute, A., and Roble, R. G.: Comparison of CHAMP and TIME-GCM nonmigrating tidal signals in the thermospheric zonal wind, Journal of Geophysical Research: Atmospheres, 115, https://doi.org/10.1029/2009JD012394, https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2009JD012394, 2010.

Jacobi, C.: 6 year mean prevailing winds and tides measured by VHF meteor radar over Collm (51.3°N, 13.0°E), Journal of Atmospheric and Solar-Terrestrial Physics, 78-79, 8 – 18, https://doi.org/https://doi.org/10.1016/j.jastp.2011.04.010, http://www.sciencedirect.com/science/article/pii/S1364682611001210, structure and Dynamics of Mesosphere and Lower Thermosphere, 2012.

Kopp, M., Gerding, M., Höffner, J., and Lübken, F.-J.: Tidal signatures in temperatures derived from daylight lidar soundings above Kühlungsborn (54°N, 12°E), Journal of Atmospheric and Solar-Terrestrial Physics, 127, 37 – 50, https://doi.org/https://doi.org/10.1016/j.jastp.2014.09.002, http://www.sciencedirect.com/science/article/pii/S1364682614002077, layered Phenomena in the Mesopause Region, 2015.

Lindzen, R. S.: Tides and Gravity Waves in the Upper Atmosphere, in: Mesospheric Models and Related Experiments, edited by Fiocco, G., vol. 25, pp. 122–130, Springer Netherlands, Dordrecht, https://doi.org/10.1007/978-94-010-3114-1_8, 1971.

Lindzen, R. S. and Chapman, S.: Atmospheric Tides, Space Science Reviews, 10, 3–188, https://doi.org/10.1007/BF00171584, 1969.

Liu, H.-L.: Variability and predictability of the space environment as related to lower atmosphere forcing, Space Weather, 14, 634–658, https://doi.org/10.1002/2016SW001450, https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2016SW001450, 2016.

Liu, H.-L., Bardeen, C. G., Foster, B. T., Lauritzen, P., Liu, J., Lu, G., Marsh, D. R., Maute, A., McInerney, J. M., Pedatella, N. M., Qian, L., Richmond, A. D., Roble, R. G., Solomon, S. C., Vitt, F. M., and Wang, W.: Development and Validation of the Whole Atmosphere Community Climate Model With Thermosphere and Ionosphere Extension (WACCM-X 2.0), Journal of Advances in Modeling Earth Systems, 10, 381–402, https://doi.org/10.1002/2017MS001232, https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2017MS001232, 2018.

McCormack, J., Hoppel, K., Kuhl, D., de Wit, R., Stober, G., Espy, P., Baker, N., Brown, P., Fritts, D., Jacobi, C., Janches, D., Mitchell, N., Ruston, B., Swadley, S., Viner, K., Whitcomb, T., and Hibbins, R.: Comparison of mesospheric winds from a high-altitude meteorological analysis system and meteor radar observations during the boreal winters of 2009–2010 and 2012–2013, Journal of Atmospheric and Solar-Terrestrial Physics, 154, 132 – 166, https://doi.org/https://doi.org/10.1016/j.jastp.2016.12.007, http://www.sciencedirect.com/science/article/pii/S1364682616303182, 2017.

McLandress, C., Shepherd, G. G., and Solheim, B. H.: Satellite Observations of Thermospheric Tides: Results from the Wind Imaging Interferometer on UARS, Journal of Geophysical Research: Atmospheres, 101, 4093–4114, https://doi.org/10.1029/95JD03359, 1996.

Merzlyakov, E., Jacobi, C., Portnyagin, Y., and Solovjova, T.: Structural changes in trend parameters of the MLT winds based on wind measurements at Obninsk ($55°$N, $37°$E) and Collm ($52°$N, $15°$E), J. of Atmospheric and Solar-Terrestrial Physics, 71, 1547–1557, https://doi.org/https://doi.org/10.1016/j.jastp.2009.05.013, http://www.sciencedirect.com/science/article/pii/S1364682609001461, long-Term Changes and Trends in the Atmosphere-Ionosphere System, 2009.

Oberheide, J., Forbes, J. M., Häusler, K., Wu, Q., and Bruinsma, S. L.: Tropospheric tides from 80 to 400 km: Propagation, interannual variability, and solar cycle effects, Journal of Geophysical Research: Atmospheres, 114, https://doi.org/10.1029/2009JD012388, https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2009JD012388, 2009.

Oberheide, J., Forbes, J. M., Zhang, X., and Bruinsma, S. L.: Climatology of upward propagating diurnal and semidiurnal tides in the thermosphere, Journal of Geophysical Research: Space Physics, 116, https://doi.org/10.1029/2011JA016784, https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2011JA016784, 2011.

Pancheva, D. and Mukhtarov, P.: Atmospheric Tides and Planetary Waves: Recent Progress Based on SABER/TIMED Temperature Measurements (2002–2007), pp. 19–56, Springer Netherlands, Dordrecht, https://doi.org/10.1007/978-94-007-0326-1_2, https://doi.org/10.1007/978-94-007-0326-1_2, 2011.

Pancheva, D., Miyoshi, Y., Mukhtarov, P., Jin, H., Shinagawa, H., and Fujiwara, H.: Global response of the ionosphere to atmospheric tides forced from below: Comparison between COSMIC measurements and simulations by atmosphere-ionosphere coupled model GAIA, Journal of Geophysical Research: Space Physics, 117, https://doi.org/10.1029/2011JA017452, https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2011JA017452, 2012.

Portnyagin, Y., Forbes, J., Fraser, G., Vlncent, R., Avery, S., Lysenko, I., and Makarov, N.: Dynamics of the Antarctic and Arctic mesosphere and lower thermosphere regions II. The semidiurnal tide, J. of Atmospheric and Terrestrial Physics, 55, 843–855, https://doi.org/https://doi.org/10.1016/0021-9169(93)90025-T, http://www.sciencedirect.com/science/article/pii/002191699390025T, 1993.

Portnyagin, Y. I., Solovjova, T. V., Makarov, N. A., Merzlyakov, E. G., Manson, A. H., Meek, C. E., Hocking, W., Mitchell, N., Pancheva, D., Hoffmann, P., Singer, W., Murayama, Y., Igarashi, K., Forbes, J. M., Palo, S., Hall, C., and Nozawa, S.: Monthly mean

climatology of the prevailing winds and tides in the Arctic mesosphere/lower thermosphere, Annales Geophysicae, 22, 3395–3410, https://doi.org/10.5194/angeo-22-3395-2004, https://www.ann-geophys.net/22/3395/2004/, 2004.

Rodgers, C. D.: Inverse Methods for Atmospheric Sounding - Theory and Practice, vol. 2, https://doi.org/10.1142/9789812813718, 2000.

Rogers, A. E., Erickson, P. J., Goncharenko, L. P., Alam, O. B., Noto, J., Kerr, R. B., and Kapali, S.: Seasonal and Local Solar Time
   Variation of the Meridional Wind at 95km from Observations of the 11.072-GHz Ozone Line and the 557.7-Nm Oxygen Line, Journal of
   Atmospheric and Oceanic Technology, 33, 1355–1361, https://doi.org/10.1175/JTECH-D-15-0247.1, 2016.

Rüfenacht, R., Murk, A., Kämpfer, N., Eriksson, P., and Buehler, S. A.: Middle-atmospheric zonal and meridional wind profiles from polar,
   tropical and midlatitudes with the ground-based microwave Doppler wind radiometer WIRA, Atmospheric Measurement Techniques, 7,
   4491–4505, https://doi.org/10.5194/amt-7-4491-2014, https://www.atmos-meas-tech.net/7/4491/2014/, 2014.

Rüfenacht, R., Hocke, K., and Kämpfer, N.: First Continuous Ground-Based Observations of Long Period Oscillations in the
   Vertically Resolved Wind Field of the Stratosphere and Mesosphere, Atmospheric Chemistry and Physics, 16, 4915–4925,
   https://doi.org/10.5194/acp-16-4915-2016, 2016.

Rüfenacht, R., Baumgarten, G., Hildebrand, J., Schranz, F., Matthias, V., Stober, G., Lübken, F.-J., and Kämpfer, N.: Inter-
   comparison of middle-atmospheric wind in observations and models, Atmospheric Measurement Techniques, 11, 1971–1987,
   https://doi.org/10.5194/amt-11-1971-2018, https://www.atmos-meas-tech.net/11/1971/2018/, 2018.

Sakazaki, T., Fujiwara, M., Zhang, X., Hagan, M. E., and Forbes, J. M.: Diurnal Tides from the Troposphere to the Lower Mesosphere as
   Deduced from TIMED/SABER Satellite Data and Six Global Reanalysis Data Sets, Journal of Geophysical Research: Atmospheres, 117,
   https://doi.org/10.1029/2011JD017117, 2012.

Sakazaki, T., Fujiwara, M., and Shiotani, M.: Representation of Solar Tides in the Stratosphere and Lower Mesosphere in State-of-the-Art
   Reanalyses and in Satellite Observations, Atmospheric Chemistry and Physics, 18, 1437–1456, https://doi.org/10.5194/acp-18-1437-2018,
   2018.

Schranz, F. et al.: Small-scale gradients of stratospheric ozone during the SSW 2018/2019 observed at Ny-Ålesund, Svalbard; in preparation,
   2019.

Stober, G., Jacobi, C., Fröhlich, K., and Oberheide, J.: Meteor radar temperatures over Collm (51.3°N, 13°E), Advances in Space Research,
   42, 1253 – 1258, https://doi.org/http://dx.doi.org/10.1016/j.asr.2007.10.018, 2008.

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

Wang, H., Boyd, J. P., and Akmaev, R. A.: On computation of Hough functions, Geoscientific Model Development, 9, 1477–1488,
   https://doi.org/10.5194/gmd-9-1477-2016, https://www.geosci-model-dev.net/9/1477/2016/, 2016.

Wilhelm, S., Stober, G., and Brown, P.: Climatologies and long-term changes of mesospheric wind and wave measurements based on radar
   observations at high and mid-latitudes, Annales Geophysicae Discussions, 2019, 1–37, https://doi.org/10.5194/angeo-2019-51, https://
   www.ann-geophys-discuss.net/angeo-2019-51/, 2019.

Woolnough, S. J., Slingo, J. M., and Hoskins, B. J.: The Diurnal Cycle of Convection and Atmospheric Tides in an Aquaplanet GCM, Journal
   of the Atmospheric Sciences, 61, 2559–2573, https://doi.org/10.1175/JAS3290.1, 2004.

Yiğit, E., Knížová, P. K., Georgieva, K., and Ward, W.: A review of vertical coupling in the Atmosphere–Ionosphere system: Effects of
   waves, sudden stratospheric warmings, space weather, and of solar activity, Journal of Atmospheric and Solar-Terrestrial Physics, 141,

1 – 12, https://doi.org/https://doi.org/10.1016/j.jastp.2016.02.011, http://www.sciencedirect.com/science/article/pii/S1364682616300426, sI:Vertical Coupling, 2016.
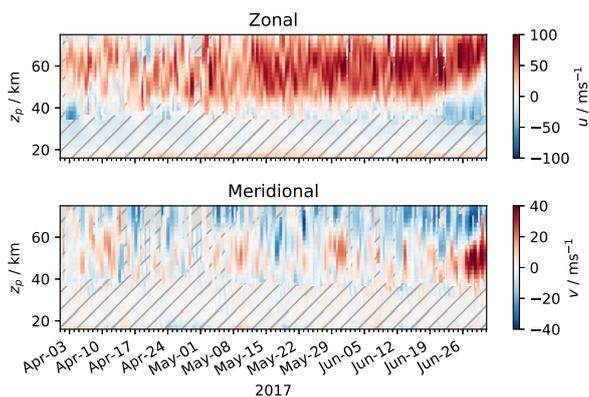
Figure 1. Background wind speed measured by WIRA-C complemented with MERRA-2 reanalysis data (hatched area) for the tropical campaign. Note the different scales for the zonal and meridional component.
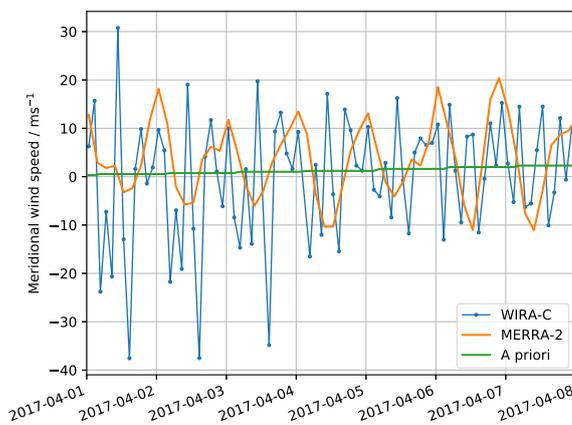
Figure 2. Timeseries of retrieved meridional wind from WIRA-C at 50 hPa (approx. 52 km) for beginning of April 2017 during the tropical campaign. Additionally, MERRA-2 reanalyses data and the a priori data used for the retrieval are shown. Temporal resolution for WIRA-C and MERRA-2 is 2 hours and 3 hours respectively.
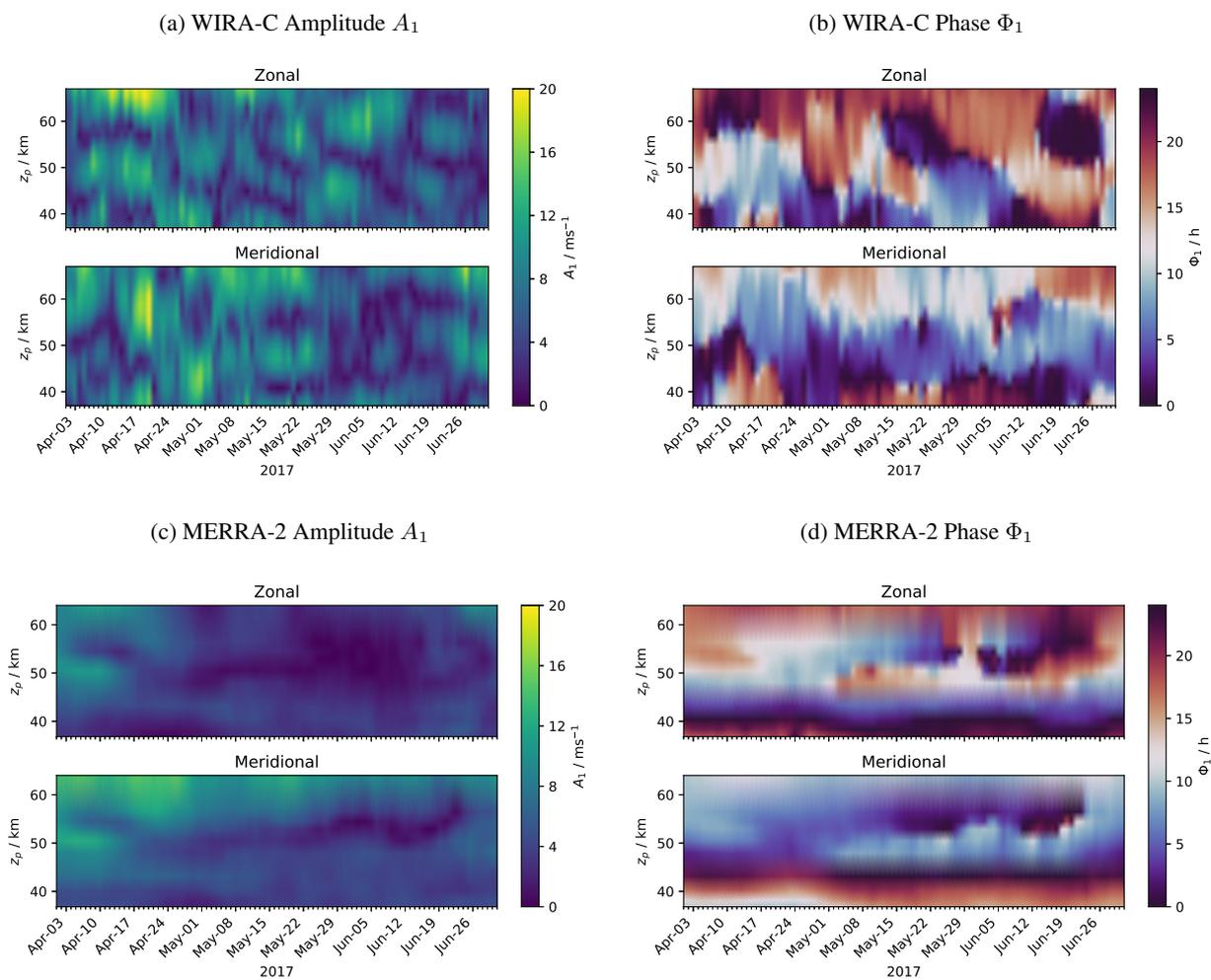
Figure 3. Amplitude and phase of the diurnal tide over three months from WIRA-C measurements (a,b) and smoothed MERRA-2 reanalysis (c,d) during the tropcal campaign at the Maïdo observatory.

(a) Amplitude A_1 (b) Phase Φ_1
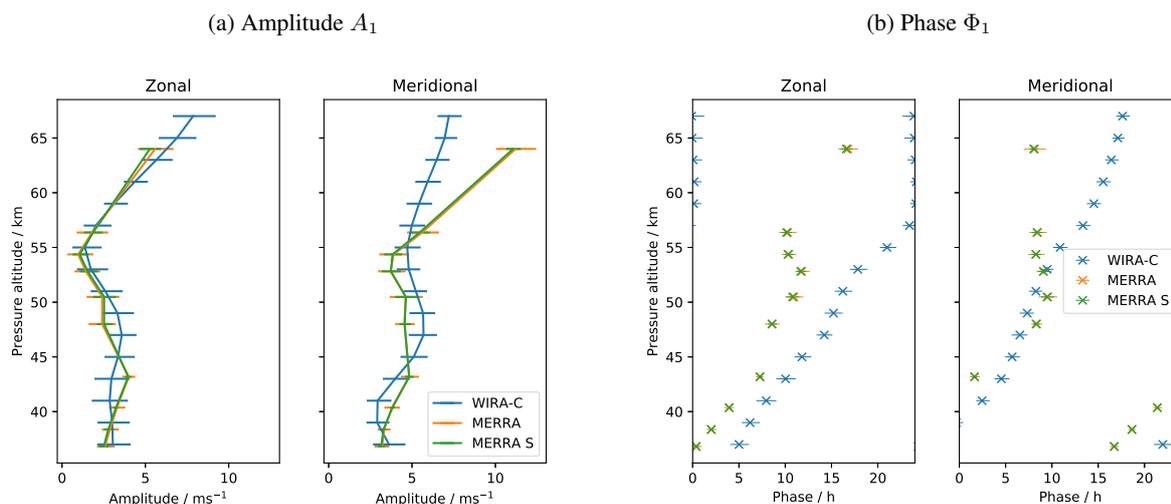
Figure 4. Amplitude and phase of mean daily cycle over three months from MERRA-2 reanalysis (from original and smoothed data) and WIRA-C measurements from the tropical campaign. Error bars indicate 95% confidence limits. Phase is equivalent to solar time of maximum.
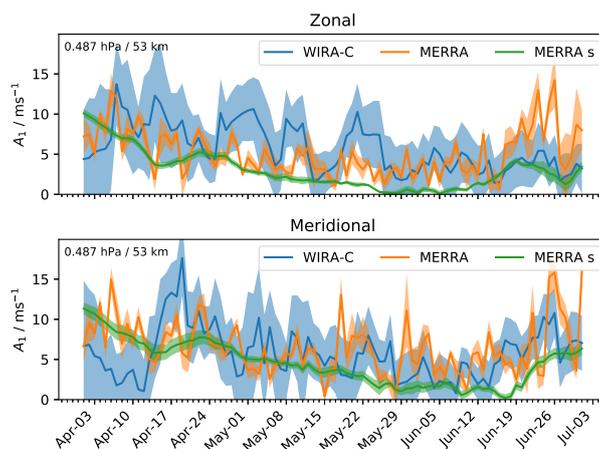
Figure 5. Time series of zonal and meridional diurnal tide amplitudes during the tropical campaign for measurements (WIRA-C), MERRA-2 reanalysis (MERRA) and reanalysis smoothed (MERRA s) at an altitude level of $53\,\mathrm{km}$ with corresponding errors of the model fit as shaded area.
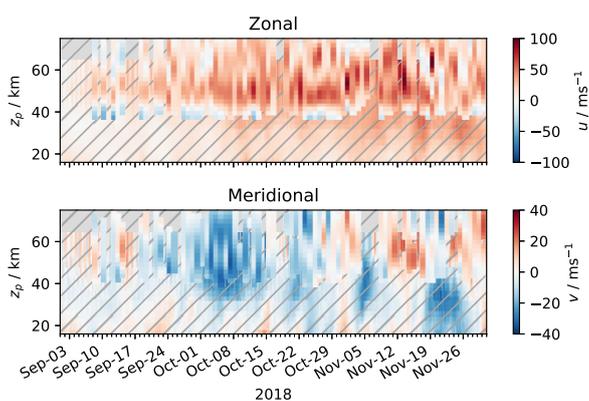
Figure 6. Background wind speed measured by WIRA-C complemented with MERRA-2 reanalysis data (hatched area) for the arctic campaign. Note the different scales for the zonal and meridional component.
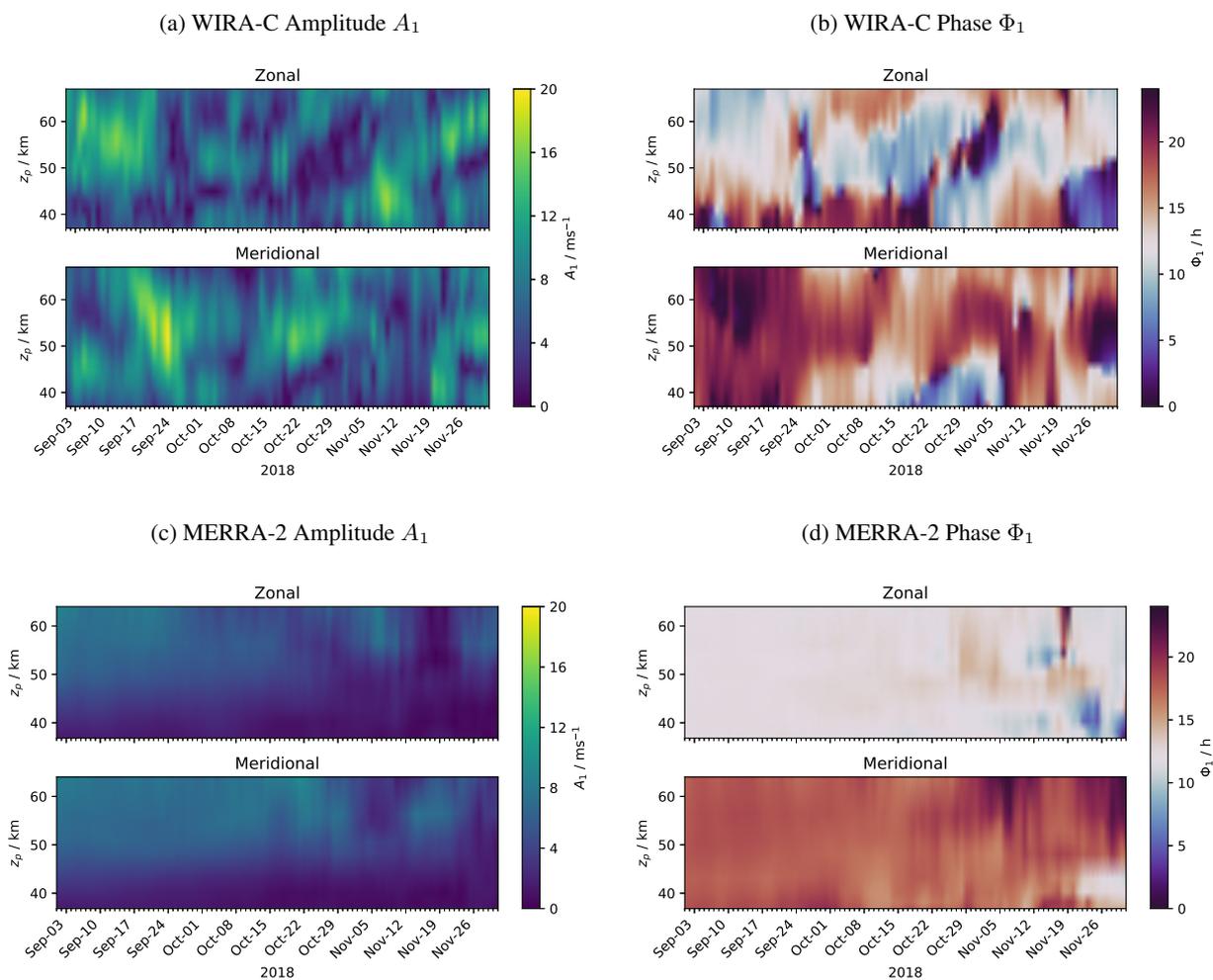
Figure 7. Amplitude and phase of the diurnal tide over three months from WIRA-C measurements (a,b) and smoothed MERRA-2 reanalysis (c,d) during the arctic campaign at the ALOMAR observatory.

(a) Amplitude A_1 (b) Phase Φ_1
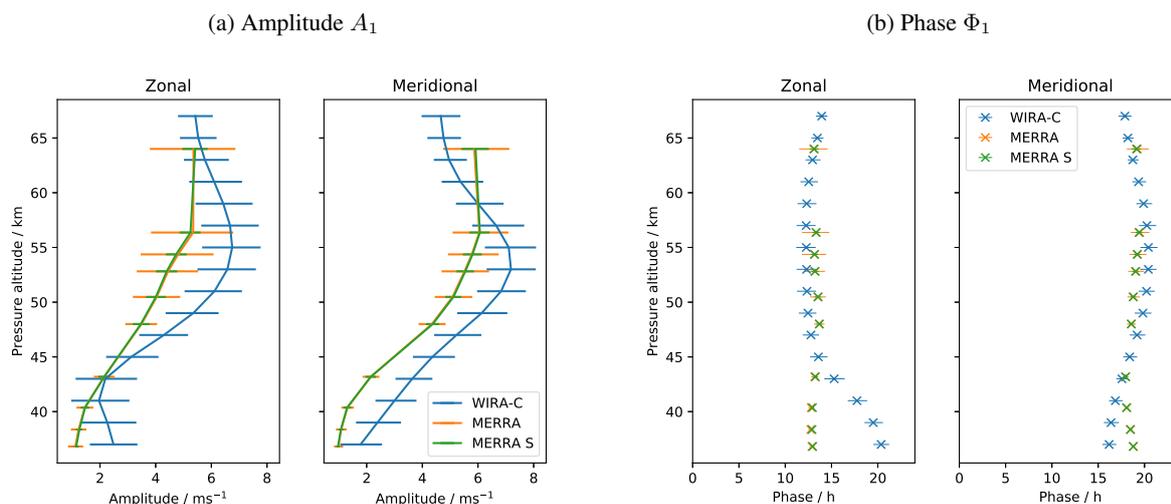
Figure 8. Amplitude and phase of mean daily cycle over three months from MERRA-2 reanalysis (from original and smoothed data) and WIRA-C measurements from the arctic campaign. Error bars indicate 95% confidence limits. Phase is equivalent to solar time of maximum.
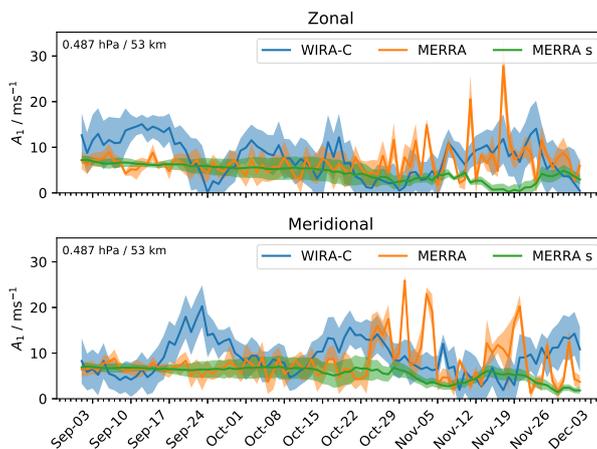
Figure 9. Time series of zonal and meridional diurnal tide amplitudes during the arctic campaign for measurements (WIRA-C), MERRA-2 reanalysis (MERRA) and reanalysis smoothed (MERRA s) at an altitude level of 53 km with corresponding errors of the model fit as shaded area.