Reply to comments from referee #1

R. Rüfenacht, K. Hocke, N. Kämpfer

February 25, 2016

- blue: referee's comments
- green: author's replies

• **Comment on cross-referencing:** references to figures in the manuscript are named "Fig." whereas reference to figures attached to this document are named "Figure". The figure numbering is usually based on the original manuscript and Supplement, except in the case of citations from the reviewed version and new figures included during the review process.

The paper describes the oscillating modes of the middle atmospheric flow as measured with the ground based radiometer WIRA at different latitudes. Such observations are important since the instrument is sensitive to the altitude range 5 hPa to 0.03 hPa where few observations exist and none on a routinely basis. To my knowledge, WIRA is the first ground-based microwave radiometer designed for wind measurements and provide good quality data described in previous papers. It is the complement to the upper atmospheric observations derived from radar systems. The analysis presented in this manuscript shows the detection of well known atmospheric oscillation modes with periods near 5, 10, 16, and 25-50 days. The quasi-2day oscillations and the tidal oscillations are not detected because of the data daily sampling used in the spectral analysis. The results are a good demonstration of what can be done with this new system.

The manuscript presents important results that should be published but I think the discussion is too short to match ACP journal requirements. Therefore, I would recommend minor changes before publication. My main concerns are:

1) There are extensive theoretical and experimental studies related to the observed oscillations and their connections with atmospheric waves or atmospheric states. The reference to previous works is not enough. The main oscillation characteristics derived from the WIRA observations (latitudinal and seasonal variations, period variability, life time) should be compared with those from previous studies. I can not really figure out if WIRA observations are in agreement with what it is supposed to be known. Also they are some features in the plots that are not mentioned.
We agree that our discussion was a bit short and substantially extended it. We also added 10 new references. Moreover, many more comparisons to the outcomes of the studies in already cited or new references were incorporated to the

manuscript. As WIRA is the first instrument which is continuously measuring wind at these altitudes we had to rely on studies based on model data, on observations of wind at other altitudes (mainly mesopause region) or observations of middle-atmospheric temperature, geopotential height or the concentration of trace gases. Further theoretical literature about atmospheric dynamics has been added. For more details, please refer to the "Specific Comments" and the new version of the manuscript with marked-up differences to the discussion paper.

2) The impacts of the characteristics of the measurements and of the periodogram (spectral features broadening, time resolution of the periods, measurement vertical resolution, possible spectral artifacts) are not sufficiently taken into account in the discussion. - The spectral features seen in the periodogram are broadened by the analysis because of the limited lifetime of the oscillations ($\sim$ 30 days?) and of the spectral window (3T). For instance, the spectral broadening for a long-period oscillation ($T > 20$ days) should be large ($\Delta_T > 10$ days, FWHM). - The vertical wavelengths of the waves associated with some of the stratospheric oscillations are similar to the retrieval vertical resolution. The latter may have a significant impact on the results. - I believe that some spectral features discussed in the manuscript can be artifacts. If I am right, their interpretation has to be presented with more cautions.
The interpretation of the results has been revisited. Along with this task a more thorough assessment of the properties of the spectral method (peak broadening, artefacts, etc.) was carried out and comments added in the manuscript. Details are given in the "Specific Comments" section.

I think these comments are minor since they are simply a demand for more information and do not require any modifications of the data analysis presented in the manuscript. The details are given in the specific comments section herebelow.
Thank you very much for all the very interesting and constructive comments.

Specific Comments:

P35038, L11: Is the vertical resolution derived from the FWHM of the averaging kernels as explained in Rüfenacht2014? If yes I would expect such estimation to underestimate the actual vertical resolution because of the strong asymmetric shape of the averaging kernels and the presence of negative lobs. Should a better estimation of the retrieval vertical resolution be used?
Yes, we used the definition given in Rüfenacht et al. 2014. This is the most common definition of altitude resolution in microwave radiometry and is broadly accepted (e.g. see the textbook by Rodgers 2000 and numerous papers such as Forkman et al. 2003, Straub et al. 2010, Palm et al. 2010 and many more). From our point of view the averaging kernels are not particularly asymmetric in the altitude range judged as trustworthy (see definition in the manuscript). The slight overshooting to negative values is a common feature of averaging kernels from midcrowave radiometry (e.g. see previously cited references). Its influence on the width of the averaging kernel is judged to be small, therefore we do not see a need for defining another estimator for the altitude resolution.

The wind averaging kernels depends on the O3 abundance and tropospheric conditions. I am wondering if the change of the averaging kernels due to the seasonal change of these parameters may have enough impact on the retrieved wind profiles to make a spectral signature in the results?
It is correct that ozone abundance and tropospheric opacity have some effect on the wind averaging kernels. It can especially decrease the measurement response (i.e. the area under the averaging kernel) at high and low altitudes. Therefore data at these altitudes may reach the threshold to be judged untrustworthy and will therefore be removed from the spectral analysis. In this way, a temporal oscillation of O3 or the tropospheric water content may introduce time dependent data gaps at very high or low altitudes. However, as the spectral method can handle such data gaps this would not lead to oscillation artefacts in the retrieved wind field.
The effect of ozone or tropospheric conditions is not responsible for a biasing of the wind field as demonstrated in Rüfenacht et al. 2014. The impact on the vertical width of the averaging kernels (i.e. the vertical resolution of the measurement) is minimal so that additional contribution of the wind field of other altitudes can be neglected. Thus oscillations in O3 abundance or tropospheric conditions do not propagate to the wind field as an effect of changing averaging kernels.

P35039, L15: Why the authors use percentage to express the differences? I think it is better to express the differences between ECMWF and WIRA in term of velocity (m/s). For instance, the differences between the observations and ECMWF are expected to be larger in the Tropics (Reunion) than at higher latitudes (other stations) though the stratospheric wind mean velocity is smaller above la Reunion. Also it is interesting to compare the differences with the measurement errors which do not depend on the wind velocity.
AND: Is the statement "mesospheric zonal wind overestimated by the model ... " derived from Fig18 in Rüfenacht et al., 2014? If yes, it should be indicated that it is applicable to only mid/high latitudes sites and not for La Reunion (not given in Fig18). Note that wind measurements with JEM/SMILES (Baron et al., 2013, cited in the Supplements) clearly show a large underestimation of ECMWF forecast in the Tropical mesosphere. The data also shows the overestimation at higher latitudes such as that reported in Rüfenacht et al., 2014.
We have modified this part of the manuscript by omitting percentage indications and relating the agreement to the measurement error. We also restrict the statement of higher ECMWF wind speeds to mid and high latitudes: "A previous study revealed agreement within the measurement error between ECMWF's Operational Analysis and WIRA's wind measurements in the stratosphere, but demonstrated that the mesospheric zonal wind speed is generally significantly larger in the model for mid and high latitude stations (Rüfenacht et al. 2014)."

P35040, L1: Why a width of 3T? How does the width of the window compare to the expected lifetime of the oscillations? The spectral broadening of the spectral features induced by to the size of the window and of the oscillation life time should be discussed. I think it is relatively large (periods of 30 days are spread over a 10-20 days period-range depending on the oscillation lifetime) and should be taken into account in the discussion of the results. (see the supplement file uploaded with my report)

Most oscillations are short-lived and do rarely persist for more than 3 periods as can be inferred from Fig. 4 in the discussion paper. We have also added some numeric values for the longest lifetimes of the observed oscillations to the manuscript in reply to one of your comments below (for the extra long period oscillation 80 days in zonal wind over Bern, 50 days over La Réunion, and 30 days in meridional wind over La Réunion; for the quasi-16-day oscillation over La Réunion 16 days in zonal wind and 16 days in meridional wind). Therefore when observing one specific occurrence of an oscillation a longer time window is not adequate as it would yield lower oscillation amplitudes than the actual oscillation has because periods where the oscillation is not present would contribute to the average. On the other hand a short window increases the frequency uncertainty of the oscillation peaks (broadening). In our eyes a window of three periods is a good tradeoff between accurate estimation of the amplitudes of short-lived oscillations and acceptable broadening of the peaks.

P35040, L10: add "s" to "more detail"
Modified in this sense

P35042, L09: The Figures S2 and S3 should be added to the main manuscript. They should be used to discussed the impacts of the retrieval vertical resolution and missing data in the periodogram. For instance, the 5 days oscillation in the Meridional wind above Provence (Fig 3, mid-stratosphere) is strongly reduced in the unaltered ECMWF data (S2). Is the Fig3 spectral feature an artifact due to missing data? If yes, this should also be the case of the measured one (Fig2)? The mesospheric 10day oscillation in the Provence meridional wind (S2) vanishes in Fig3. Is it due to the measurement vertical resolution? I am surprised to see that in general upper stratosphere and mesospheric oscillations are much stronger in Fig3 than in S2. Altering the data should decrease the oscillation amplitude?
Thank you for pointing this out. We agree and have included figures S2 and S3 to the main article and provided some comments for the interpretations of the figures for "WIRA", "ECMWF at WIRA" and "ECMWF": "The analysis for the scenario ECMWF at WIRA shown in Fig. 3 should yield identical results as presented in Fig. 2 if the measruements are error-free and the atmosphere is realistically represented by the model. In this case WIRA and ECMWF would agree that the periodograms of the real atmosphere correspond to Fig. 4." (p. 3043, l.23). We also provided a new figure showing the temporal evolution of the oscillations based on unaltered ECMWF data in the mesosphere at 0.05 hPa (Fig. S12 in the Supplement) which can also help in the interpretation of the differences between Figure 3 and S2 of the original submission.
For example, a strong 10-day oscillation features appears in the meridional wind at 0.03 hPa over Provence in December 2012, right before the onset of the major SSW in January 2013. It is clear that this oscillation causes a relatively large 10-day signal in the temporal average (of the unaltered time series). However, from Fig. 1 one can infer that meridional WIRA data are very rare at this altitude in December. Consequently also "ECMWF at WIRA" contains data gaps for this time where the strong oscillation is present. Therefore, in contrast to the unaltered ECMWF data, one cannot see a strong 10-day oscillation in the upper mesosphere in the temporal average of "ECMWF at WIRA". We have clarified the properties of the scenario "ECMWF at WIRA" in the manuscript

in reply to your next comment and a request by referee #2 (please see below). Vertical resolution does not play a role here. The limited vertical resolution of WIRA can, however, reduce the amplitude of oscillations with a vertical extension in the range of or smaller than the vertical resolution.
The 5-day oscillation in stratospheric meridional wind for WIRA might be an artefact triggered by the small data gap at the beginning of January 2013 as it is visible for the altered ECMWF time series whereas it is not present for the original. The limited altitude resolution cannot be made responsible for the appearance of this feature as there is no oscillation signal at other altitudes which could contribute to the weighted average described by the averaging kernels. We are sorry that we did not comment on this fact in the interpretation. We would like to point out that the 5-day oscillation visible in Fig. 2 (WIRA) in the other data sets, except meridional wind in Provence, does not seem to be an artefact of the measurement setup as it is absent in both Fig. S2 and Fig. 3. Therefore these occurrences seem to be real differences between WIRA observations and ECMWF model data. We added information about the 5-day wave to the manuscript at P35043, L13-15 (see below)
The fact that mesospheric oscillations are generally stronger in Fig. 3 when compared with Fig S2 is due to the seasonality in the tropospheric opacity (due to the water content). The consequence is that during the phases of low opacity (in winter) the better measurement conditions cause the altitude range of trustworthy data to extend to higher altitudes. Therefore the temporal averages at high altitudes is strongly influenced by winter data and only very weakly by summer data (because data gaps are introduced at times and altitudes where the measurements are judged untrustworthy). As in the scenario "ECMWF at WIRA" data gaps are added to ECMWF at the same altitude/time points the same is true for Fig. 3. Winter is also the season with enhanced oscillation activity (also in the mesosphere as seen from the new Fig. S12 in the supplement). Therefore, an average that runs mainly over winter data (Fig. 3) yields a higher amplitude than an average which also considers summer data (Fig. S2). The statement at p.35042, l.12 on the seasonality of WIRA's altitude range has been clarified (see reply to your next comment).
Please note that introducing data gaps will not necessarily reduce the oscillation signal as our method does not interpolate the gaps but rather treats them as missing values. Moreover, the limited altitude resolution might indeed increase mesospheric oscillation amplitudes rather than weakening them because the usually stronger stratospheric oscillation signal might be averaged into the mesosphere.

P35042,L16: "seasonal averages" means that all seasons are averaged which is not the case since the mean periodogram is more representative of winter conditions.
This part of the manuscript has been adapted in order to also satisfy the request for more detail by referee #2. The term seasonal average is not used anymore: "From Fig. 1 one can identify levels where trustworthy measurement data are predominantly present during winter, because the generally wetter summer troposphere alters the signal-to-noise ratio of the observation setup as a consequence of a stronger attenuation of the middle-atmospheric radiation. At these altitudes the oscillation amplitudes should thus not be interpreted as averages over the entire duration of the campaign."

P35042,L21: The 50day period is also a systematic feature in the results. I would expand the period range to 20–50 days and indicate that 50 days is the upper limit of the period estimation.
We have modified the manuscript in this sense.

P35042,L23: The limitations due to the spectral analysis and measurement characteristics should be taken into account in the discussion of the quasi 30day oscillations. For instance separate modes such as 30day and 50day periods may overlap because of the spectral broadening and be seen as single "blob" with period ranging from 20 to above 50 days (except for the zonal wind above Provence).
We have tested the spectral broadening of the oscillation peaks by our method. Results for monochromatic input signals are shown in Figure 1. 30 and 50-day oscillations could indeed overlap with this method as seen in the left panel of Figure 3. At the risk of generating stronger artefacts due to the sharp cutoff at the window edges we have also used our method with a rectangular window instead of a hamming window. Rectangular windowing has the effect to reduce spectral broadening as shown in Figure 2 because data points away from the centre of the window are considered with full instead of reduced weight. Rectangular windowing allows to separate peaks at 30 and 50 days as shown in the right panel of Figure 3. We also applied the rectangular window method to the data set of wind observations. However, this did not lead to a separation of oscillation peaks at 30 and 50 days or other peaks. We therefore conclude that the extra-long period oscillation is not generally originating from two different oscillation peaks with periods differing by more than 20 days.
We also added a comment on the limited vertical resolution and its effect on the altitude-dependent periodograms to section 4.1 of the manuscript (where the new discussion about the altitude dependence of the periodogram was introduced, see reply to your comment concerning P35043, L16): "In the interpretation of Fig. 2 we should keep in mind that the limited vertical resolution of WIRA, which lies around 12 km (i.e. 0.75 pressure decades) at these altitudes, may vertically smear out the oscillation peaks."

P35043,L5: The discussion about the long oscillations is too short. There are clear features in Fig2 that are not mentioned. Mid-latitude oscillations between 20-35 days seems to expand from the mid-stratosphere to the top of the retrieval range (mid/upper mesosphere) while the oscillations larger than 35/40 m/s are blocked at 0.02 hPa. At high latitudes, the oscillation is predominant in the lower mesosphere with a period very close to 27 days but it is not seen in the stratosphere. Are these behaviors compatible with what it is expected? More references about studies on 27day oscillation and more generally those describing periods between 20 and 50 days should be provided (the one provided in the manuscript is not enough). (e.g, Huang et al., observational evidence of quasi-27-day oscillation propagating from the lower atmosphere to the mesosphere over 20N, Ann. Geophys., 33, 1321-1330, 20, 2015, Fedulina et al., Seasonal, interannual and short-term variability of planetary waves in Met Office stratospheric assimilated fields, Q. J. R. Meteorol. Soc., 2004).
Please note that the aim of this publication was not to give a comprehensive analysis of the sources and mechanisms of any individual wave and oscillation

in the period range between 5 and 50 days. It is rather a first paper showing what kind of studies can be made with data obtained from the novel technology of wind radiometry and how the observations compare to ECMWF to get a first idea of the quality of the middle-atmospheric wind field in ECMWF (and of the wind measurements). It would be well beyond the scope of this study to investigate details of the forcing of the extra-long period oscillation because, as mentioned in the manuscript and confirmed by other studies, the influence of the solar rotation on extra-long period oscillations is not direct and might depend on many other factors.
Thank you for the hints towards additional literature (the paper by Huang et al. was published (30 October 2015) only after our manuscript had been submitted to ACPD (6 August 2015)). We have now integrated these two studies and extended the discussion of extra-long periods: "... are often discussed in the context of the modulation of the solar forcing with the rotational period of the sun (e.g. Fedulina et al., 2004; Huang et al., 2015)" and further "Huang et al. (2015) indicate that their observed extra-long period oscillation might be an atmospheric normal mode and that it may be indirectly introduced by the modulation of tropospheric convective activity with the solar rotation period. Fedulina et al. (2004) report a modulation of the 5-day wave amplitude with a period of 25 to 35 days but point out that a correlation with solar activity might appear by coincidence regarding the considered time scales."
We have to be careful not to conclude from one special case to generality. For example, when considering Supplementary Figs. S5 or S6 one can see that also periodicities larger than 35 days can extend over a large range of altitudes. From Figs. S4 and S6 it is obvious that also at high latitudes the oscillation period is not always close to 27 days. We included one more link to the manuscript (p. 35043, l.20) to these supplementary figures to prevent the reader from drawing conclusions too rapidly: " This hypothesis is supported by Figs. S4 to S7 showing ECMWF data for more extended time intervals at the campaign sites."

P35043, L13-15: The 5-day oscillation of the meridional wind above la Reunion is more significant (alpha near 0.01, white contour) than above Provence (alpha > 0.1, grey contour). Is alpha > 0.1 a reliable value? Can we trust a large peak but with low significance?
There is a confusion between Provence and La Réunion in our manuscript. We are extremely sorry for that and thank you very much for pointing it out! We intended to write that the 5-day oscillation was present in La Réunion meridional wind and that it might be present also for Provence but with low significance. We are convinced that α is the better indication for a reliable oscillation detection than the amplitude. In Provence the 5-day oscillation occurs close to the sudden stratospheric major warming event, when the variability in the atmosphere is high. A strong oscillation peak overlaid to a "noisy" background can be less significant than a weaker oscillation overlaid to a almost constant background wind field. Therefore the peak on La Réunion is more significant. We have more trust in a peak with a lower alpha value and rather than in a peak with high amplitude but higher alpha. As discussed in reply to a previous comment the 5-day oscillation in the Provence meridional wind is believed to be an artefact from data gaps at an unfortunate moment.
The manuscirpt has been modified to: "A quasi 5-day wave is observed in WIRA's zonal wind measurements for Bern and Sodankylä, and for the zonal

and meridional winds on La Réunion. The 5-day signal in the meridional wind in Provence has lower significance and seems to be an artifact of the measurement situation as it is also present in Fig. 3 showing "ECMWF at WIRA" data but not in the periodogram of the unaltered ECMWF data in Fig. 4. It might originate from the small data gap at the beginning of January 2013 (see Figs. 5 and 6) at a time of high variability due to a major sudden stratospheric warming."

P35043, L16: Over la Reunion, the zonal wind oscillations with periods larger than 10 days vanished in the mesosphere. Is it expected based on other radar and satellite measurements or is it a lack of measurement sensitivity/resolution that could explain the oscillations decrease?
Lower oscillation amplitudes in the mesosphere can indeed be expected from theory and observations. We added the following sentences to the manuscript at p. 35043, l. 20: "The reduced wave activity in the mesosphere, particularly above 0.1 hPa, may be explained by planetary wave breaking in the stratosphere (e.g. McIntyre and Palmer, 1983; Brasseur and Solomon, 2005). Interestingly this consideration also applies to the extra-long period oscillations what is in line with the periodograms of geopotential heights from MLS at mid-latitudes presented by Studer et al. (2012). In the interpretation of Fig. 2 we should keep in mind that the limited vertical resolution of WIRA, which is around 12 km (i.e. 0.75 pressure decades) at these altitudes, may vertically smear out the oscillation peaks.
The only major exception to the quiet mesosphere in Fig. 2 is the 27-day peak around 0.1 hPa in the periodogram for Sodankylä. This oscillation can probably be regarded as a special case as it occurs in the vicinity of the major sudden stratospheric warming event of January 2012 as seen from supplementary Fig. S12 which displays the oscillation activity at 0.05 hPa"

Similarly, Day et al. 2012 (cited in the manuscript) clearly shows a 16-day signal in winter mid-latitude at high altitudes. In Fig.2, above Bern and Provence, the 16day oscillation signal strongly decreases at 0.1 hPa and increase slightly again at the top of the retrieval range. I have the same questions as previously for La Reunion site.
After the adaptations to the previous comment the following statement has been added to the manuscript: "Although based on very few data points, the slight increase near the 16-day periodicity at the very top of the retrieval range might be understood as an influence of the strengthening of this signal in the MLT region reported by other observational studies (e.g. Williams and Avery, 1992; Day et al., 2012)." (The abbreviation MLT is explained in the introduction)

My general feeling on this section is that the behaviors of the 5/10/16day periods should be described in more detailed and, their main characteristics should be compared with previous studies in the middle and upper atmosphere.
We extended the discussions in the subsections 4.1 and 4.2 and added comparisons to previous studies (altitude dependence, duration of the oscillations, seasonality, SSW's . . .) at various places in the text. Please see the version of the manuscript with marked up modifications uploaded along with this document.

P35043, L24: This result is compatible with other measurements and theoretical studies. Previous works should be cited. (e.g., Fedulina et al., Seasonal, interannual and short-term variability of planetary waves in Met Office stratospheric assimilated fields, Q. J. R. Meteorol. Soc., 2004, ...).
The following sentence has been added: "It (the hypothesis of seasonality) also confirms previous studies based on observations or assimilated model data (Hirota and Hirooka, 1984; Hirooka and Hirota, 1985; Day et al., 2011; Fedulina et al., 2004)"

P35044, L6-10: As already mentioned, the comparison with results from other observations should be improved.
We extended the discussion in subsection 4.1 (and 4.2) and added comparisons to several other studies. Please refer to the new version of the manuscript with marked-up differences to the discussion paper.

P35045, L20: The interpretation of the spectral features is too fast (I don't say wrong). The period variation (35-25 days) is in the same order that the spectral broadening (period resolution (FWHM) is $\sim 10-20$ days for a period of 30 days). The effect has to be taken into account in the discussion.
We have investigated the broadening of oscillation peaks in reply to your comment to P35042, L23 (please see above for details). The period variation is indeed in the range of the spectral broadening. The period variation, however, does not seem to be a random feature as it monotonically decreases over three oscillation cycles. A similar decrease in the oscillation period could also be seen in the analysis with rectangular windowing (please also refer to the comment on P35042, L23). We have modified the manuscript to: "... between the different campaigns. It can even vary within a single occurrence of the oscillation as seen in the example of Bern where the period decreases from 35 to 25 days between December 2010 and March 2011. A 10 days period change is at the limit of the spectral resolution of our analysis method for this long periodicities. Nevertheless it may be interpreted as a real signal, not only due to the monotony of the decrease, but also in accordance with an additional check using our spectral method with rectangular instead of Hamming windowing in order to improve the spectral resolution (not shown)."

P35045, L24: The 16day period is too quickly attributed to atmospheric wave. The period resolution has to be taken into account (as stated in my previous comment). Also the 16day oscillation signature can be reproduced as an artifact at the beginning and the end of a long-period monochromatic oscillation event. The authors should check if such artifacts can explain the spectral signature seen in their observations. (see the supplement file I uploaded with my report).
We assumed that the long period oscillation builds up and vanishes smoothly. In this case no strong 16-day artefact should be produced. In your simulation the sharp edges at the start of the oscillation (around day 70 in column c) or at the termination of the oscillation (around day 100 in column d) trigger a strong 16-day feature but the smooth termination in column c and the smooth initiation in column d do cause not cause significant artefacts. That an increase of randomly distributed data gaps generally increases noise at short periodicities is clear to us. But this should happen independently of the presence of a 30-day oscillation. Moreover the assumption of 20% randomly distributed data gaps

does not correspond to the reality at stratopause level as seen in Fig. 1 of the manuscript.
If, however, the atmospheric 30 day oscillation is abruptly initiated or terminated an artefactic feature at 16-days cannot be excluded. We commented on this possibility in the manuscript: "... the strongest 16-day amplitudes are observed near the initiation and the termination of the extra-long period oscillation. However, it should be noted that if the extra-long period oscillation is abruptly initiated or terminated, the 16-day signal could be produced as an artifact of the used spectral method as simulations showed. Whether a real 16-day wave is present and whether the two oscillations are linked in some way will have to be verified in further studies." Thank you for drawing our attention to this possibility.

P35046, L1: Note that if the 16day spectral features are artifacts, they are still a good indication of the beginning and termination of the long-period oscillation event. A value of the measured oscillation lifetime should be provided for Bern and La Reunion (it is difficult to infer it from the plots) and compared with other studies.
The first part of your comment has been treated in the previous reply. For the second part, we added lifetimes for the 30 and 16 day periodicity: "In the Bern and the La Réunion time series the strongest 16-day amplitudes (lasting for about 1 period) are observed near the initiation and the termination of the persistent extra-long period oscillation with a duration of 80 and 50 days, respectively. The duration of the presence of these oscillations is comparable to the results for mesopause wind presented by Luo et al. (2001)."

P35046, L21-26: "... extra long period (20-40 days)" → (20-50 days)
Modified.

P35046, L26: The 16day spectral feature might be described with cautions if the authors agree with my comment in the previous section.
We have modified our statement: "Enhanced quasi 16-day oscillation activity has sometimes been detected in the vicinity of strong extra-long period oscillations. A more extended study would however be needed to establish the origin of this signal and to uncover a potential link between the quasi 16-day wave and the extra-long periodicities. In addition to the extra-long period oscillations, normal modes with periods near 5, 10 and 16 days are present in our observations."

Supplement TextS1, second paragraph: HRDI has also measured wind in the stratosphere over a long period ($\sim$ 10 years). The observations started from $\sim$ 30 km (e.g., Ortland D. A, Rossby wave propagation into the tropical stratosphere observed by the High Resolution Doppler Image, GRL, 24, 16, 1997)
Thank you for pointing this out. We modified the sentence on HRDI: "Previously, mesospheric observations down to 65 km and stratospheric daylight wind observations up to 40 km had been performed by HRDI on UARS (Hays et al., 1993; Ortland et al., 1996)." We used another reference here, focussing more on the instrument.

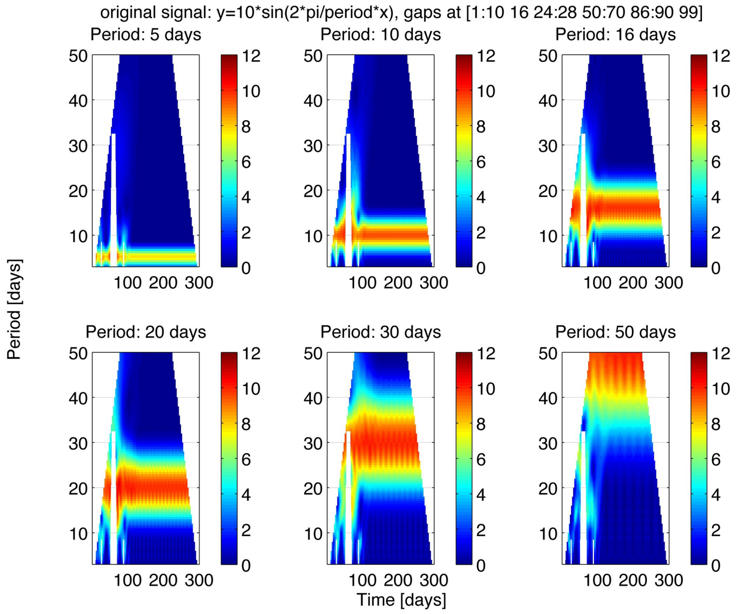

Figure 1: Reconstruction of synthetic monochromatic oscillation signals with the spectral method used for the analysis published in the manuscript (Lomb-Scargle with Hamming windowing, window width 3 periods).

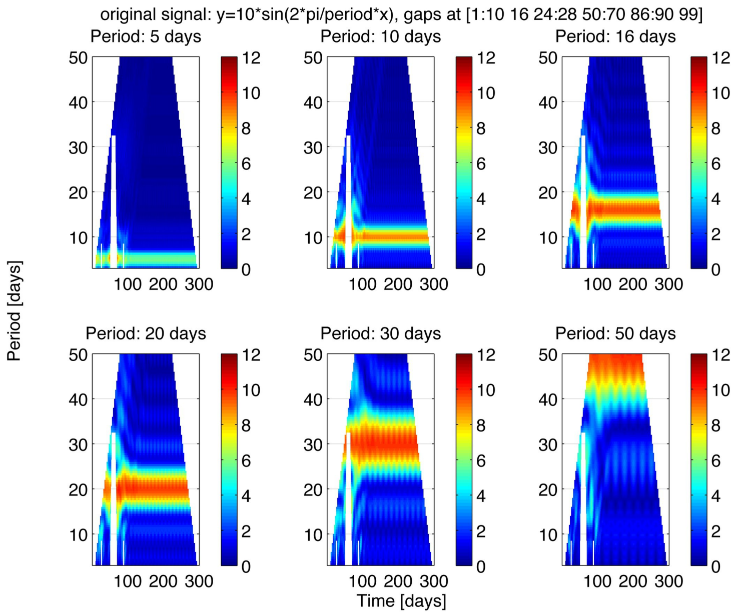

Figure 2: As Figure 1 but with rectangular windowing instead of Hamming windowing.

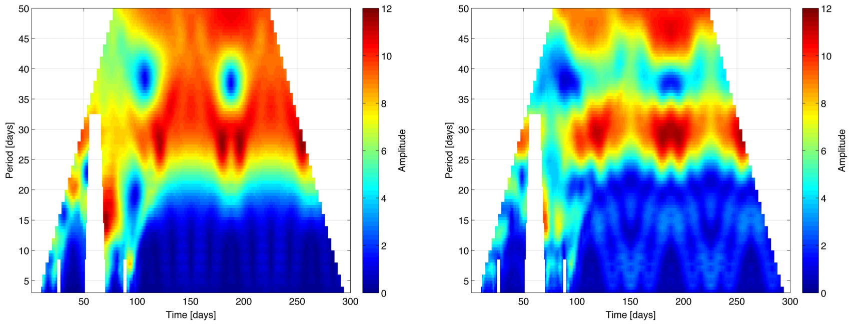

Figure 3: As Figures 1 and 2 but for the reconstruction of a superposition of a 30 and 50-day oscillation both with oscillation amplitude 10. Left panel: reconstruction with the method as used in the paper (Hamming windowing); right panel: reconstruction using a rectangular window function.

Reply to comments from referee #2

R. Rüfenacht, K. Hocke, N. Kämpfer

February 25, 2016

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This paper outlines the first science results from an opportunitistc network of novel ground-based Doppler radiometers. The potential to record continuous wind measurements in the upper stratosphere and mesosphere is quite unique to this instrument type and could well complement the existing ground-based, air-borne/in situ and satellite observing networks, where direct wind measurements are limited to balloons, airplanes, lidar and meteor radar. The authors do well to analyze (admittedly) short time series from the small number sites operating this instrument and report evidence for planetary waves and middle atmosphere wind seasonality. The paper highlights good agreement with ECMWF Operational Analyses within the stratosphere but with important differences above the stratopause. The latter is thought to be due to the paucity of observations assimilated by ECMWF during the times of the WIRA campaign. This is a good first science paper but does suffer from the short WIRA record. Nonetheless it would appear to highlight the potential for a wider use of these profilers which would also benefit centres such as the ECMWF in producing more accurate weather and climate products of the upper atmosphere. Pending due consideration of the comments below, I would recommend publication.

Comments:
The authors make use of the Lomb-Scargle method to reconstruct periodograms used in the analysis of wave-types. As seen in the Supplementary Text, the unaltered ECMWF OA periodograms seem to show weaker spectral power in the mesosphere as compared to the data which is sampled as WIRA (i.e. excluding data poor times). The weaker signals are more like the WIRA data. The authors cite previously published deficiencies in the ECMWF data to explain this bias, but does sampling play a role here too. Can one use a resampling procedure (with replacement) to reconstruct confidence intervals in the ECMWF data, sampled as WIRA. The existing ECMWF data seems overly, "significant", so it might be worthwhile to check against a non-parametric approach like this.
The unaltered ECMWF periodograms in the Supplement (now moved to the main article in as required by referee #1) indeed feature lower amplitudes in the mesosphere. Missing data play a role here, however not in the way you siggest. The dominant effect is the seasonality of the data (i.e. much more mesospheric data recorded during winter months due to the lower tropospheric

water content). The effect of the data gaps as such on the periodogram is small as seen from the simulation shown in Figure 1 attached to the present document. This effect of the seasonality in sampling is mentioned in the manuscript (p. 35042 l. 12). To make the statement easier to understand some more details have been provided as suggested in one of your comments below: "From Fig. 1 one can identify levels where trustworthy measurement data are predominantly present during winter, because the generally wetter summer troposphere alters the signal-to-noise ratio of the observation setup as a consequence of a stronger attenuation of the middle-atmospheric radiation. At these altitudes the oscillation amplitudes should thus not be interpreted as averages over the entire duration of the campaign. This is especially the case for the upper altitude data from Sodankylä (above approx. 0.2 hPa) but to a lesser extent also applies to the other stations."

For the comparisons between measurements and model one should definitely use "ECMWF at WIRA". Comparisons of the observations to this data exclude the effect of gaps (as they are located at the same days and altitudes for "WIRA" and "ECMWF at WIRA") as well as the effect of the limited vertical resolution of the instrument (as for "ECMWF at WIRA" the ECMWF data are convolved with the averaging kernels of WIRA). If the periodograms with unaltered ECMWF data look more like the ones for the WIRA data it is simply by coincidence. There is no physical reason why one should directly compare unaltered model data with the measurements. In short, if ECMWF were a perfect representation of the atmosphere and the WIRA observation and retrieval setup were free of any errors the periodograms for "WIRA" and "ECMWF at WIRA" should exactly match although there may be differences to the periodograms for unaltered ECMWF data. In this case the WIRA observations would confirm that unaltered ECMWF data exactly match the true state of the atmosphere.

The effect that peaks in the periodograms of ECMWF data are generally more significant is due to the fact that the WIRA data contain measurement noise in contrast to the more smooth behaviour of an assimilated general circulation model.

Specific Comments:

I leave it to the discretion of the editor and authors just show many of the suggested grammatical corrections are adopted. However, the authors would do well to address the use of language throughout the text.

Thank you very much for the many editorial comments. As non-native English speakers we appreciate your help and have gladly incorporated your suggestions to improve the manuscript.

(Title) I would replace "strato-/mesospheric" with "stratosphere-mesosphere" or even "middle atmosphere"

We tried to avoid the term "middle atmosphere" as it seems to be less precise to some readers. We also think that compactness is an asset of our title in comparison to "First continuous ground-based observations of long period oscillations in wind profiles of the stratosphere and mesosphere"

(35036, L5) "...measurements of tracers..." → "...tracer measurements..."

Modified in this sense.

(L11) suggesting removing the word "model"
Removed.

(L15) suggest removing "A shown by current research", i.e. "An accurate representation of middle atmosphere dynamics can..."
Modified in this sense.

(L17) What is meant by long time scales in this context? Seasonal?
This was indeed an unclear formulation. It was modified to "... especially on time scales beyond one week".

(L18) "validation"
Modified to: "Therefore validation of these models is needed...".

(L20) The last sentence does not make sense, please rephrase.
To make our point more clear the following clause has been appended to this sentence "... as such oscillations play an important role in the dynamics of the middle atmosphere."

(L24) Suggest, "For studying long period oscillations long and continuous measurements are required."
Modified to "... long time series of continuous measurements are required"

(35037, L1) "non-existent" and remove "so far"
Modified in this sense.

(L5) Suggest, "...have been previously used to retrieve vertical profiles of horizontal wind...of providing long and continuous measurements for the analysis..."
Modified to: "... have been used to retrieve vertical profiles of horizontal wind throughout the stratosphere and mesosphere. However the novel ground-based microwave wind radiometer WIRA (Rüfenacht et al., 2012; Rüfenacht et al., 2014) is the only instrument capable of providing wind observations between 35 and 70 km altitude (5 to 0.04 hPa) with time series satisfying the requirement of long term continuity. "

(L10) "Presently available lidar data are too short for long-period spectral analysis, whereas" (L13) "Wind data from rocket soundings..."
Modified to: "Presently, the published wind lidar data sets are too short for long period spectral analyses. The coarse time resolution of rocket ..."

(L16) "Horizontal wind oscillations..."; remove "region"; "...have been extensively studied..."; "In the upper stratosphere and lower mesosphere, analyses of long period oscillations in trace gas concentrations, such as ozone and water vapour, have been reported..."
Corrected.

(35038, L3) "The Doppler Wind...is a novel ground-based...used for continuous observation of horizontal wind profiles, which is a unique strength of this instrument."
changed to "The Doppler WInd RAdiometer WIRA is a novel ground-based

passive heterodyne receiver designed for the observation of horizontal wind profiles from the mid-stratosphere (5 hPa) to the mesopause (0.02 hPa) where no other application provides continuous time series of wind measurements."

(L12) "However, as indicated by Rodgers (2000), features vertically spaced..."
Modified in this sense.

(L17) "A strength of microwave radiometers is their ability to take measurements day and night and under overcast conditions. This strength, compared with low operation costs, allows for the generation of long and continuous time series."
Modified to "This strength, combined with low operation costs, allows for the recording of long continuous time series."

(L26) "...comprise both zonal and meridional components."; "untrustable" → "untrustworthy" perhaps (also Figure 1 caption).
Modified in this sense.

(35039, L1) It is stated that a strength of the instrument is that it can "see" through overcast conditions, but it is nonetheless adversely affected by tropospheric water. Can the authors expand a little more on this. Also, "The altitude range sensitivity largely depends on the signal-to-noise ratio of the receiver as well as on the tropospheric conditions, especially the water content. The sensitivity was significantly improved by an instrument upgrade in autumn 2012."
Modified to: "The sensitive altitude range largely depends on the signal-to-noise ratio of the receiver, which was significantly improved by an instrumental upgrade in autumn 2012. Moreover the strength of the radiation signal reaching the receiver depends on tropospheric conditions. While ice clouds are fully transparent to microwave radiation near 142 GHz, attenuation by liquid and gaseous water can negatively impact the signal-to-noise ratio, although observations remain possible even in the presence of non-precipitating liquid water clouds or fog."

(L6...) How about, "The European Centre for Medium-Range Weather Forecasts (ECMWF) is a major service provider of weather and climate data products. The Operational Analysis used in this study combines meteorological data from a variety of different observing platforms with a continually updated climate model". I am not sure the 6-hourly output is relevant here. You might like another sentence describing how the Operational Analyses differ from reanalyses (i.e. underscore the model is receiving updates in the former and not the latter), and also what observations are being assimilated at the heights relevant for WIRA. That is are you effectively comparing against a model (i.e. very few observations are being assimilated)?
Modified in this sense except using the the term "general circulation model" instead of "climate model" to avoid confusion. Moreover we have added a sentence why we use Operational Analysis rather than the re-analysis: "The Operational Analysis data used in this study combines meteorological data from a variety of different observing platforms with a continually updated general circulation model. The observations assimilated in a 4-D-Var assimilations window of 12 h mainly originate from the troposphere and lower stratosphere (e.g. Dee et al.

2011; ECMWF, 2016). Operational Analysis is preferred over the re-analysis, i.e. ERA-Interim, principally because of the higher model top (0.01 hPa compared to 0.1 hPa). For the research presented here data from model versions ..."

(L8) "measurement data" → "observations"
Modified in this sense.

(L23-25) "...with periods ranging from 5-50 days are intermittent, showing little phase preference"
Modified in this sense.

(35040, L3) "and the use of a Hamming windowing function to help minimise spectral leakage."
Modified in this sense.

(L9...) I would suggest simply referring to a single reference, such as Press et al ("Numerical Recipes") for the Lomb(-Scargle) description, only referring in text to departures from the standard treatment or to the particular application of the statistical tests used here.
The references to Scargle 1982 and Lomb 1976 have been given to make clear that the Lomb-Scargle approach was not developed by Press et al. 2001.

(35042, L1) "Spectral analyses have been performed on daily-averaged wind data from WIRA and ECMWF Operational Analysis."
Modified to: "Spectral analyses have been performed on daily average wind profiles by WIRA and ECMWF Operational Analysis." Moreover "operational analysis" has been changed to "Operational Analysis" in the entire document.

(L8) Remove the words "The results for the", i.e. "Analysis of the unaltered ECMWF time series is shown in Figs. S2 and S3 of the Supplement Material."
The statement has been removed from the manuscript in a modification requested by referee #1.

(L14) "cause trustable" - not a good phrase. How about "less significant" or some other.
For a better understanding the sentence has been modified, split in two and some more information about the seasonality of the altitude coverage has been added: "From Fig. 1 one can identify levels where trustworthy measurement data are predominantly present during winter, because the generally wetter summer troposphere alters the signal-to-noise ratio of the observation setup as a consequence of a stronger attenuation of the middle-atmospheric radiation."

(L16) I think "seasonal averages" is not the right phrase to use here. The profile-spectra simply apply to a time window having length 7 or > 12 months, depending on data set used. Also altitude dependent temporally averaged periodogram does not sound right either, how about profile-time periodograms? Just a thought.
The statement has been clarified by avoiding the word "seasonal": "At these altitudes the oscillation amplitudes should thus not be interpreted as averages over the entire duration of the campaign."

(L18) "lower" → "lesser"
Modified in this sense.

(L20) Perhaps the authors can comment on the phase of the solar cycle during the measurement campaigns (i.e. during solar max there is a conspicuous 27-day rotation period which is largely absent at other times). Also, in the stratosphere, at least, conspicuous 20-30 days oscillations can be seen in annular mode (AM) data, and has been linked with the shouldering of AM autocorrelation function in tropospaheric and stratospheric data (e.g. Ambaum and Hoskins, 2002).
All observations were made during solar cycle 24, mostly during its maximum phase (WIRA observations between September 2010 and February 2015). It should be noted that solar cycle 24 is a comparatively weak cycle. We have also added the information about the solar cycle to the manuscript: "From this fact and from the obvious seasonality (see Sect. 4.2) of these wind oscillations observed during the maximum phase of solar cycle 24 we infer that the influences of the variations in the solar forcing ..."

(35043, L1), "if existing" → "if present" or "at best"
We do not see a problem in using the word "existing" in this context.

(L8) "measured average periodogram": can the authors think about rephrasing instances of this throughout the text please.
Modified to "average periodograms of WIRA measurements". We did not find other occurrences of this inaccurate language use ("measured/observed periodograms" or similar) throughout the manuscript.

(L10) Presumably the authors refer to the Nyquist limit for diagnosing the 2-day (planetary) wave in the "daily averaged" data? Also use 2-day, 5-day notation for describing these particular planetary wave types.
As this seems to be unclear the manuscript has been modified: "According to the Nyquist theorem, measurements of…". The notation has been modified to "x-day wave" throughout the text.

(L11) I do not see the 5-day feature the authors refer to in the text. Well perhaps so in the Provence data, but not so in Sodankyla nor Bern.
We are speaking here about Fig. 2 (WIRA data) not Fig. 3 (ECMWF data). In Fig. 2 the quasi 5-day (periodicities approx. 4-6 days) feature is present in all panels except the lower left for zonal wind in Provence where this oscillation is not significant. For Sodankylä it is significantly present only up to slightly above the stratopause.

(L14) "Oscillations". Also probably start next sentence with "Evidence for the 16-day wave...", as no independent evidence has been provided that the wave should be seen here.
Modified to: "Oscillations with periods around 10 days…" and "A quasi 16-day variation..."

(L20) High wind speeds can also be seen in figure 1. The authors need to weaken their statements of high interannual variability inferred from data covering ef-

fectively 2 winter seasons and different monitoring equipment and locations. Please simply reference an independent paper here (there are plenty!).
AND: Also, please relax statements about seasonality in the text. Features seen in figures 4 and 5 may very well be due to seasonal differences in variability, but the length of your time series are not long enough to show this. However, if you were to add the caveat of looking at an extended time series of ECMWF OA data, statements to this effect could be added.
We would like to clarify that all observations were made with the same radiometer (which received instrumental upgrades between the campaigns) which traveled to the different campaign sites. The data used in this study cover a total of 44 months, split between 4 different stations.
Plots of the temporal evolution of the periodograms for ECMWF Operational Analysis data for all campaign periods, i.e. 44 months, at each campaign site have been included to the Supplement (Fig. S8 to S11) in addition to the already existing plots of the temporally averaged periodograms of ECMWF (Fig. S4 to S7). That means, there is a coverage of 5 summer and winter periods at each site so that we judge that this makes it reasonable to comment on the seasonality. We also added references to several studies investigating the seasonality of the oscillations and compared them with our results.
We modified, extended and clarified our statement concerning seasonality in the manuscript: "A clear seasonality is apparent for all observations and model data with oscillation activities being much stronger in the winter half year for all oscillation periods covered by the present study. The seasonality is also visible for other years at the campaign sites as shown by ECMWF data (Figs. S8 to S11 of the Supplement) and is in accordance with other observational studies of stratopause level oscillations (Hirooka and Hirota, 1985; Day et al., 2011; Studer et al., 2012) and especially with the climatological periodogram of zonal wind at 58 km in Fig. 5 of Luo et al. (2001). As in the mentioned climatology, no quasi 5-day wave signature could be found in the summer data from WIRA, in contrast to the results of Hirota and Hirooka (1984) and Fedulina et al. (2004) which indicate the frequent presence of such a wave at the summer stratopause. The same pattern of seasonality as for the high and mid latitude stations is observed on La Réunion although it is located in the southern tropics (21°04′ S). One can infer that the station is substantially influenced by mid-latitude dynamics."

(L28) "Analysis of the ECMWF data which has been similarly sampled to that of the WIRA data...". The remainder of the sentence should be rephrased: you are validating the WIRA data against the ECMWF Operational Analysis data not the other way around! To reiterate from a previous comment: it will be good to know what observations are being assimilated by the ECMWF OA (are you seeing model or observations?). One might also check to see if the ECMWF forward model, used in the development cycles mentioned, employ a (spectral) gravity wave parameterisation suitable for the upper stratosphere and mesosphere. If they do not, and there are little to no observations at upper levels, this would be consistent with the overly strong winds seen in the analysis data.
We have modified our statements related to ECMWF. There are strong indications for the correctness of WIRA's observations (good agreement with ECMWF in the stratosphere where the model representation is surely more elaborate than in the mesosphere and where there is much more effect from assimilated data,

TIDI suggesting lower wind speeds slightly above the upper altitude limits of WIRA's observations and others, see Rüfenacht et al. 2014). However, we indeed have to consider that we could not yet validate against other wind observations in the middle atmosphere as there is currently only one other wind instrument worldwide covering altitudes between 35 and 70 km (the ALOMAR wind lidar in Andenes, where an extensive intercomparison campaign with the wind radiometer is planned for 2016/17). Thus, despite the strong indications for the correctness, we are not completely beyond missing an unknown influence on wind radiometer measurements in the mesosphere. For these reasons we rephrased all statements about the comparisons between ECMWF and WIRA by neutrally speaking of differences instead of using formulations like "the model overestimates". Such statements are expected to become defensible after the planned 2016/2017 intercomparison campaign between WIRA and the ALOMAR wind lidar.
Yes, the used ECMWF cycles rely on a spectral gravity wave parametrisation. For us as non-modelers it is hard to judge on the quality of the details of the parametrisation.

(35044, L10...) Re: previous comment, you indirectly mention the issues I raise, but specific details of mesospheric observations and gravity wave parameterisations would be good to include here.
This question has been addressed in the reply to your previous comment. The mesospheric data assimilation has been treated in answer to your comment about (p. 35039, l. 6…).

(35045, L2) "Atmospheric waves can be intermittent in nature (i.e. wave-packets). Accordingly, the temporal evolution of the oscillations was examined."
Modified to "Atmospheric waves and oscillations can be intermittent in nature (i.e. wave-packets) and seasonality might be present. Accordingly, the temporal evolution of waves were examined."

(L9...) "...and is consistent with the absence of measurement noise."
Modified to "… what is consistent with the absence of measurement noise."

Also, please relax statements about seasonality in the text. Features seen in figures 4 and 5 may very well be due to seasonal differences in variability, but the length of your time series are not long enough to show this. However, if you were to add the caveat of looking at an extended time series of ECMWF OA data, statements to this effect could be added.
This comment has been addressed together with your comment to p. 35043, l. 20. Please see above.

(35046, L22...) "...with the wave features showing pronounced temporal intermittency"
Modified to "… with the features showing pronounced temporal intermittency and the period being subject to temporal variations."

The analysis and comment here about signatures for a solar signal is not very strong, as the data length is small (even for the 27-day rotational period) and there are no hypotheses about how the forcing might manifest within the short time record of winds ("...however solar forcing might influence the atmospheric wave pattern in an indirect way.").

We are well aware that our records are rather short for a thorough investigation of the influence of the 27-day solar rotation signal. For this reason we do not make a strong statement about the absence or presence of the solar influence. Nevertheless time series between 6 (Provence) and > 30 (La Réunion) times longer than the period of the considered oscillation justifies to make some statement in our eyes. It would be beyond the scope of this paper to investigate possible mechanisms of the solar 27-day influence on middle-atmospheric wind. Such a research effort would justify a publication on its own.

We extended the manuscript with references to other studies: " Huang et al. (2015) indicate that their observed extra-long period oscillation might be an atmospheric normal mode and that it may be indirectly introduced by the modulation of tropospheric convective activity with the solar rotation period. Fedulina et al. (2004) report a modulation of the 5-day wave amplitude with a period of 25 to 35 days but point out that a correlation with solar activity might appear by coincidence regarding the considered time scales."

Sentence starting, "An augmented presence..." does not read well and should be rephrased.

Rephrased to: "Enhanced quasi 16-day oscillation activity has sometimes been observed in the vicinity of strong extra-long period oscillations."

Sentence following this one describes the low frequency variability as a wave. It has not been established whether this longer period variability (20-50 days) is wave-like and not just part of a broader spectrum of variability.

We totally agree. The sentence has been modified to "... uncover a potential link between the quasi 16-day wave and the extra-long periodicities"

Care must me taken in making overly assertive statements of strong seasonality. Two of the stations are close to one another, one is in a sub-tropical location and there is 5 months to a about a years worth of data between the separate radars. Seasonality is to be expected, but please first place this in the broader literature.

There might be some confusion here. The present paper is not based on radar observations but rather by measurements of one single ground-based microwave radiometer, i.e. a passive measurement technique. No other radiometers with wind capacity existed during the WIRA campaigns. The radiometer has travelled to different locations for subsequent campaigns, so we do not have simultaneous measurements but 4 subsequent time series covering the time period September 2010 to February 2015 (with a few months between the campaigns for transportation and refurbishing of the instrument and upgrades and testing of the hardware). The following modifications were made in reply to your comment to p. 35043 l. 20 (please see above for details): Plots of the temporal evolution of the periodograms for ECMWF Operational Analysis data for all campaign periods at each campaign site have been added to the Supplement, so that there is a coverage of 5 summer and winter periods. We also put our observations on the seasonality of atmospheric oscillations in context with other studies.

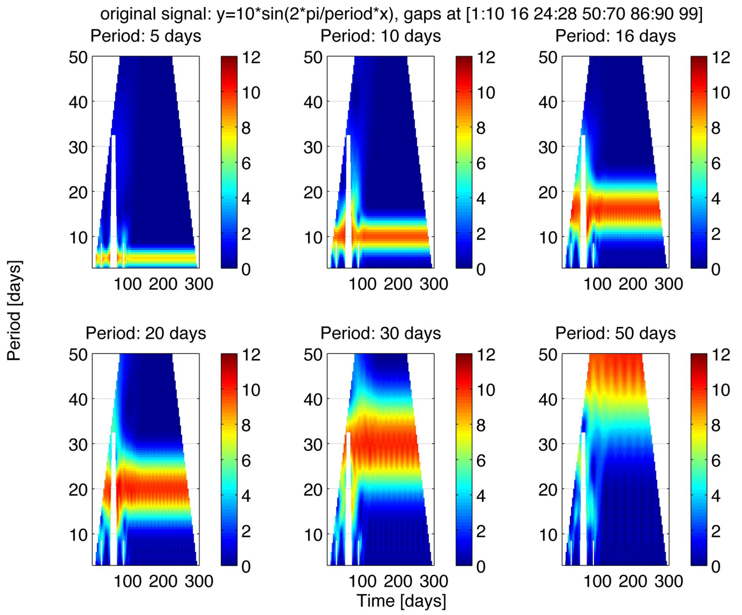

Figure 1: Reconstruction of synthetic monochromatic oscillation signals containing data gaps (at the locations specified in the heading) with the spectral method used for the analysis published in the manuscript.

(35047, L7) How about, "In addition, the ECMWF Operational Analysis data shows reduced variability (< 10 days) as compared with the WIRA data."
Modified to: "In addition, ECMWF Operational Analysis data shows reduced variability at periods below 10 days as compared with the measurements by WIRA."

(L11) Is there a better reference to use for the EU ARISE project?
Unfortunately there does not yet exist a review paper of the ARISE project. However, we modified the reference to a conference contribution describing the project (Blanc, E., Charlton-Perez, A., Keckhut, P., Evers, L., Heinrich, P., Le Pichon, A., and Hauchecorne, A.: The ARISE project: dynamics of the atmosphere and climat, Our Common Future Un- der Climate Change, International Scientific Coference, https://hal-insu.archives-ouvertes.fr/ insu-01183228, poster, 2015).

(L16) "...used in WIRA's retrieval algorithm as described in Rüfenacht et al. (2014)"
Modified in this sense.

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First continuous ground-based observations of long period oscillations in strato-/mesospheric wind profiles

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Abstract

Direct measurements of middle-atmospheric wind oscillations with periods between 5 and 50 days in the altitude range between mid-stratosphere (5 hPa) and upper mesosphere (0.02 hPa) have been made using a novel ground-based Doppler wind radiometer. The oscillations were not inferred from ~~measurements of tracers~~tracer measurements, as the radiometer offers the unique capability of near-continuous horizontal wind profile measurements. Observations from four campaigns at high, mid and low latitudes with an average duration of 10 months have been analyzed. The dominant oscillation has mostly been found to lie in the extra-long period range (~~20–40~~20–50 days), while the well-known atmospheric normal modes around 5, 10 and 16 days have also been observed. Comparisons of our results with ECMWF ~~operational analysis model~~ Operational Analysis data revealed remarkably good agreement below 0.3 hPa but discrepancies above.

1 Introduction

The dynamics of the middle atmosphere is characterized by waves and oscillations with distinct periods. ~~As shown by current research, an~~ An accurate representation of the middle-atmospheric dynamics can improve the forecast skills of numerical weather prediction models, especially on ~~longer time scales~~ time scales beyond one week (e.g. Baldwin et al., 2003b, a; Charlton et al., 2004; Hardiman et al., 2011; Sigmond et al., 2013). Therefore ~~validations~~ validation of these models ~~are~~ is needed also in the stratosphere and mesosphere in addition to tropospheric analyses. Thereby not only the correctness of the absolute values of the atmospheric parameters, but also the correct representation of their natural oscillations should be studied as such oscillations play an important role in the dynamics of the middle atmosphere.

Measurements of zonal and meridional wind are the most direct way to observe atmospheric dynamics. For studying long period oscillations ~~continuous long-term measurement time series~~ long time series of continuous measurements are required. However, wind observations in the upper stratosphere and lower mesosphere are practically ~~inexistent so far~~ non-existent and the few measurements available are not present on a continuous basis (see Supplement Text S1).

Rocket soundings (e.g. National Research Council, 1966; Müllemann and Lübken, 2005) and the Doppler wind lidar at ALOMAR (Hildebrand et al., 2012; Baumgarten, 2010) have been ~~reported to be able to measure the wind profile~~used to retrieve vertical profiles of horizontal wind throughout the stratosphere and mesosphere. However the ~~broadly validated time series measured by the~~ novel ground-based microwave wind radiometer WIRA (Rüfenacht et al., 2012, 2014) is the only instrument capable of providing wind observations between 35 and 70 km altitude (5 to 0.04 hPa) ~~and~~ with time series satisfying the requirement of long term continuity~~necessary for the analysis of long period oscillations. The published time series of the wind lidar~~ . Presently, the published wind lidar data sets are too short for long period spectral analyses~~whereas the~~ . The coarse time resolution of rocket soundings seems inadequate for the investigation of oscillations with periods shorter than approximatively 20 days. A rocket-sensed wind data set with 1–2 profiles per week has, however, been used by Keckhut (1995) in a study investigating the effect of the ~~27~~27-day solar rotation period on middle atmospheric dynamics.

Oscillations of horizontal wind in the (upper) mesosphere/lower thermosphere ~~region~~ (MLT) have ~~extensively been~~ been extensively studied using radar observations (e.g. Araújo et al., 2014; Day et al., 2012; Guharay et al., 2014; Luo et al., 2001, 2002). In the upper stratosphere and lower mesosphere region analyses of long period oscillations in the concentration of trace gases, such as ozone and water vapor, have been reported based on microwave radiometry (e.g. Hocke et al., 2013; Scheiben et al., 2014).

Here we present an analysis of oscillations in upper stratospheric and mesospheric horizontal wind profiles with periods between 5 and 50 days. We also compare results obtained from wind radiometer measurements to the ~~operational analysis~~ Operational Analysis data from the European Centre for Medium-Range Weather Forecast model (ECMWF).

2 Data sets

2.1 Wind radiometer data

The ~~novel~~ Doppler WInd RAdiometer WIRA is a novel ground-based passive heterodyne receiver designed for the observation of horizontal wind profiles from the mid-stratosphere (5 hPa) to the mesopause (0.02 hPa) where no other application provides continuous time series of wind measurements. Wind profiles are determined by measuring Doppler shifts of the pressure broadened emission line of ozone at 142 GHz. The retrieval from the raw data is based on an optimal estimation inversion (Rodgers, 2000) of an atmospheric radiative transfer model implemented in the ARTS/QPACK software (Eriksson et al., 2011, 2005). Typical measurement uncertainties and vertical resolutions of the daily average wind profiles used in this study range from 10 to 20 $m\,s^{-1}$ and from 10 to 16 km, respectively. However, as ~~also~~ indicated by Rodgers (2000), ~~it should be noted that~~ features vertically spaced by less than 10 km can in many cases be recognized as individual peaks in the retrieved data, although their amplitudes are not independent. Detailed descriptions of the instrument and retrieval characteristics of WIRA have already been published (Rüfenacht et al., 2012, 2014).

A strength of microwave radiometers is ~~the possibility to measure also~~ their ability to take measurements during day and night and under overcast conditions~~and independently of daylight situation. Paired~~. This strength, combined with low operation costs~~this allows the sampling~~, allows for the recording of long continuous time series. The present study is based on measurements taken by WIRA at four different locations at high, mid and low latitudes: Sodankylä (67°22′ N/26°38′ E, October 2011–July 2012), Bern (46°57′ N/7°26′ E, September 2010–July 2011), Observatoire de Haute-Provence (43°56′ N/5°43′ E, November 2012–May 2013) and Observatoire du Maïdo on La Réunion (21°04′ S/55°23′ E, September 2013–February 2015). The data series from these campaigns are plotted in Fig. 1. At Sodankylä and Bern only zonal wind was measured, whereas the observations from Provence and La Réunion comprise ~~the~~ both zonal and meridional ~~component~~components. The gray areas in Fig. 1 correspond to data points judged untrustable untrustworthy (measurement response < 0.8, altitude resolution > 20 km or altitude accuracy > 4 km, see Rüfenacht et al., 2014, for details). The sensitive altitude range largely depends on the signal-to-noise ratio of the receiver, which was significantly improved by an instrumental upgrade in autumn 2012, as well as on the tropospheric conditions, especially on the water content2012. Moreover the strength of the radiation signal reaching the receiver depends on tropospheric conditions. While ice clouds are fully transparent to microwave radiation near 142 GHz, attenuation by liquid and gaseous water can negatively impact the signal-to-noise ratio, although observations remain possible even in the presence of non-precipitating liquid water clouds or fog.

2.2 ECMWF model data

The European Centre for Medium-Range Weather Forecast Forecasts (ECMWF) provides Europe's major assimilated numerical weather prediction model for global medium-range weather forecasts with 6hourly output. The measurement data is a major service provider of weather and climate data products. The Operational Analysis used in this study combines meteorological data from a variety of different observing platforms with a continually updated general circulation model. The observations assimilated in a 4-D-Var assimilations window of 12 h mainly originate from the troposphere and lower stratosphere (e.g. Dee et al., 2011) . (e.g. Dee et al., 2011; ECMWF, 2016) . Operational Analysis is preferred over the re-analysis, i.e. ERA-Interim, principally because of the higher model top (0.01 hPa compared to 0.1 hPa). For the research presented here operational analysis data from data from model versions 36r2 (September to November 2010), 36r4 (November 2010 to May 2011), 37r2 (May to November 2011), 37r3 (November 2011 to June 2012), 38r1 (June 2012 to June 2013), 38r2 (June to November 2013) and 40r1 (November 2013 to February 2015) with a spectral resolution of T1279 have been used (ECMWF, 2015). A previous study revealed good agreement (within 10) agreement within the measurement error between ECMWF's operational analysis Operational Analysis and WIRA's wind measurements in the stratosphere, but demonstrated that the mesospheric zonal wind speed is generally overestimated by the model with discrepancies increasing with altitude to reach up to 50in the upper mesosphere significantly larger in the model for mid and high latitude stations (Rüfenacht et al., 2014). In contrast, comparisons between a limited data set of WIRA and the MERRA re-analysis from NASA's GEOS-5 model (Rienecker et al., 2011) revealed good agreement also in the mesosphere (Le Pichon et al., 2015).

3 Data analysis

It is known from earlier research that atmospheric waves in the range of periods considered here (with periods ranging from 5–50 days) are present on intermittentbasis only (e.g. Araújo et al., 2014; Day et al., 2012) . The different occurrences might also be out of phase. are intermittent, showing little phase preference (e.g. Araújo et al., 2014; Day et al., 2012) . Therefore we perform the spectral analyses in sliding Hamming windows encompassing three oscillation periods T. The window width matching an integer multiple of the searched period and the use of a Hamming window function avoid windowing function help to minimize spectral leakage. Data gaps in the measured time series can be large at some times and altitudes, therefore gaps were not interpolated as done in other studies, because this would artificially alter the oscillation signal (damping it in case of linear interpolation). They were rather treated as missing values and the Lomb–Scargle spectral approach for irregularly spaced data was applied (Press et al., 2001; Scargle, 1982; Lomb, 1976).

The spectral method used in the present study will be described in some more detail details in the following: For each altitude level a wind time series $\boldsymbol{x}$ is sampled at equally spaced times $t_j = k \cdot \delta t$ with $x_j = \boldsymbol{x}(t_j)$ and $k \in \mathbb{N}$. However, for some t_j no reliable measurement data x_j exist at the respective altitude. Such pairs of (t_j, x_j) will be excluded from the following analysis leading to an unequally spaced time series. We define $\bar{x}_j$ and σ_j as the mean and standard deviation of $\boldsymbol{x}$ in the index range $(j-n)\dots(j+n)$, i.e. within a window of length $(2n+1) \approx 3T/\delta t$. The Lomb–Scargle transform $\mathcal{L}$ is applied to the windowed time series to obtain a normalized periodogram P_j for each point in time:

$$P_j = \mathcal{L}_{i\in\mathcal{B}_j}\{t_{j+i}, h_i \cdot (x_{j+i} - \bar{x}_j)\} \tag{1}$$

with the indices i in the range

$$\mathcal{B}_j = \{m \,|\, m \in \{-n, -n+1, \ldots, 0, \ldots, n\} \wedge \exists x_{j+m}\} \tag{2}$$

and with h_i being the coefficient of a Hamming window of length $(2n+1)$ centered around index 0. Let us also define:

$$\mathcal{C}_j = \{m \,|\, m \in \mathcal{B}_j \wedge |m| \cdot \delta t \le T/2\}, \tag{3}$$

i.e. $\mathcal{C}_j$ denotes the central third of $\mathcal{B}_j$. P_j's calculated from windows with an insufficient amount of relevant data points, i.e. when

$$\#\mathcal{B}_j < \frac{T}{\delta t} \quad \vee \quad \#\mathcal{C}_j < \frac{T}{3\delta t} \tag{4}$$

are rejected from the analysis. The entire procedure is repeated for all searched oscillation periods T, for all times t_j and for all altitude levels.

The normalized periodogram P_j is readily transformed to the amplitude spectrum (e.g. by combining Eq. 6 from Hocke, 1998, and Eq. 15 from Harris, 1978):

$$A_j(T) = 2\sigma_j \sqrt{\frac{\sum_{i\in\mathcal{B}_j} h_i^2}{\left(\sum_{i\in\mathcal{B}_j} h_i\right)^2} P_j(T)}\,. \tag{5}$$

P_j also contains the information about the significance α of an oscillation peak at a distinct frequency

$$\alpha_j(T) = 1 - [1 - \exp(-P_j(T))]^M\,. \tag{6}$$

In our case M is a factor close to the window width (for details see Press et al., 2001). The variable α might also be referred to as “false alarm probability of the detection”, a small α value indicates a highly significant oscillation.

For comparison, the pseudo-wavelet approach used by Studer et al. (2012) and Scheiben et al. (2014) has been modified in order not to rely on interpolation. The difference between the results obtained with the modified pseudo-wavelet method shown in Figs. ~~S8 and S9~~ S2 and S3 in the Supplement and the outcomes of the Lomb–Scargle method (Figs. 2 and 5) was found to be small. Moreover, the different spectral methods with and without interpolation and with different windowing functions have been tested for their ability of retrieving synthetic oscillation signals containing data gaps correctly. The Lomb–Scargle method used with a Hamming window applied in the analyses presented in this paper was most successful and produced only marginal differences between the retrieved and the initial signal, but the pseudo-wavelet approach without interpolation of the data gaps used for Figs. ~~S8 and S9~~ S2 and S3 also provided satisfying results.

4 Results

~~The spectral~~ Spectral analyses have been performed ~~for the daily averages of the wind measurements~~ on daily average wind profiles by WIRA and ~~of the model data from the ECMWF operational analysis~~ECMWF Operational Analysis. In order to allow direct comparisons between measurements and model, the ECMWF data were convolved with WIRA’s averaging kernels to account for the limited vertical resolution of the radiometer and data gaps were added at the times t_j where the measurement did not provide reliable data. In the following, the model data treated in this way are referred to as “ECMWF at WIRA”. ~~The results for the analysis of the unaltered ECMWF time series are displayed in Figs. S2 and S3 in the Supplement.~~

4.1 Altitude dependence of the periodograms

The altitude dependent temporally averaged periodograms of the horizontal wind measurements by WIRA are shown in Fig. 2. The temporal average runs over all oscillation amplitude data existing at a certain altitude for the respective campaign. From Fig. 1 one can identify levels where atmospheric conditions cause trustable measurement data to be present predominantly in winter, so that oscillation amplitudes at these altitudes should be understood as seasonal averages rather than averages trustworthy measurement data are predominantly present during winter, because the generally wetter summer troposphere alters the signal-to-noise ratio of the observation setup as a consequence of a stronger attenuation of the middle-atmospheric radiation. At these altitudes the oscillation amplitudes should thus not be interpreted as averages over the entire duration of the campaign. This is especially the case for the upper altitude data from Sodankylä (above approx. 0.2 hPa) but to a lower lesser extent also applies to the other stations.

Figure 2 indicates that the dominant oscillations in horizontal wind occur in the extra-long period range (20–4020–50 days) at all stations. Atmospheric oscillations with periods around 27 days are often discussed in the context of the modulation of the solar forcing with the rotational period of the sun (e.g. Fedulina et al., 2004; Huang et al., 2015) . However, cross-correlation analyses of WIRA's wind measurements with solar UV irradiance data revealed that the phase difference between wind and irradiance time series varies significantly for the different measurement campaigns. From this fact and from the obvious seasonality of these wind oscillations (see Sect. 4.2) of these wind oscillations observed during the maximum phase of solar cycle 24 we infer that the influences of the variations in the solar forcing on middle atmospheric horizontal winds must be indirect, if existing. Similar conclusions were drawn by a study with the WACCM model to be presented in a separate publication where it is demonstrated that periods around 27 days can also be produced inherently by the atmosphere and that oscillations in the solar irradiance can manifest themselves in the atmospheric wind periodograms at frequencies differing from the variations in solar forcing (Ansgar Schanz, personal communication, 2015). Huang et al. (2015) indicate that their observed extra-long period oscillation might be an atmospheric normal mode and that it may be indirectly introduced by the modulation of tropospheric convective activity with the solar rotation period. Fedulina et al. (2004) report a modulation of the 5-day wave amplitude with a period of 25 to 35 days but point out that a correlation with solar activity might appear by coincidence regarding the considered time scales.

Normal modes in the atmosphere are known to have oscillation periods around 2, 5, 10 and 16 days (Salby, 1981a, b) which can also be observed in the measured average periodograms average periodograms of WIRA measurements for the different campaigns. Measurements According to the Nyquist theorem, measurements of daily average wind profiles do not allow to draw meaningful conclusions regarding the behavior of the quasi two-day 2-day periodicity. A quasi 55-day wave is observed in WIRA's zonal wind measurements for Bern , and Sodankylä, and for the zonal and meridional winds on La Réunionand . The 5-day signal in the meridional wind measurements from Provence . It might also be present in the meridional wind on La Réunion, but the significance of this signal is low.in Provence has lower significance and seems to be an artifact of the measurement situation as it is also present in Fig. 3 showing "ECMWF at WIRA" data but not in the periodogram of the unaltered ECMWF data in Fig. 4. It might originate from the small data gap at the beginning of January 2013 (see Figs. 5 and 6) at a time of high variability due to a major sudden stratospheric warming. Oscillation Oscillations with periods around 10 days are clearly visible in the zonal wind in Sodankylä and the zonal and meridional wind in Provence. The quasi 16A quasi 16-day variation is weakly recognizable in the zonal wind measurements from La Réunion.

The highest wave amplitudes are usually detected around the stratopause which is also the region where the highest absolute wind speeds are generally observed (e.g. Rüfenacht et al., 2014) . Despite the fact that high High interannual variability has to be expected (e.g. compare the results from the Bern and the Provence campaign which were sampled at very close geographical locations)one might also conclude . Despite this variability, one might conclude from the WIRA data that zonal wind oscillations tend to be strongest at mid latitudes, and that meridional wind oscillations are weaker in the tropics than at mid-latitudes. This hypothesis is supported by model data from ECMWF for the time periods of WIRA's measurement campaigns analyzed at all four locations investigated in the present study (see Figs. Figs. S4 to S7 in the Supplement). S7 showing ECMWF data for more extended time intervals at the campaign sites. It also confirms previous studies based on observations or assimilated model data (Hirota and Hirooka, 1984; Hirooka and Hirota, 1985; Day et al., 2011; Fedulina et al., 2004) . The highest oscillation amplitudes are usually detected around the stratopause which is also the region where the highest absolute wind speeds are generally observed (e.g. Rüfenacht et al., 2014) . The reduced wave activity in the mesosphere, particularly above 0.1 hPa, may be explained by planetary wave breaking in the stratosphere (e.g. McIntyre and Palmer, 1983; Brasseur and Solomon, 2005) . Interestingly this consideration also applies to the extra-long period oscillations what is in line with the periodograms of geopotential heights from MLS at mid-latitudes presented by Studer et al. (2012) . In the interpretation of Fig. 2 we should keep in mind that the limited vertical resolution of WIRA, which is around 12 km (i.e. 0.75 pressure decades) at these altitudes, may vertically smear out the oscillation peaks.

The only major exception to the quiet mesosphere in Fig. 2 is the 27-day peak around 0.1 hPa in the periodogram for Sodankylä. This oscillation can probably be regarded as a special case as it occurs in the vicinity of the major sudden stratospheric warming event of January 2012 as seen from supplementary Fig. S12 which displays the oscillation activity at 0.05 hPa. Although based on very few data points, the slight increase near the 16-day periodicity at the very top of the retrieval range might be understood as an influence of the strengthening of this signal in the MLT region reported by other observational studies (e.g. Williams and Avery, 1992; Day et al., 2012) .

The analysis for the scenario ECMWF at WIRA shown in Fig. 3 should yield similar identical results as presented in Fig. 2 if the measruements are error-free and the atmosphere is realistically represented by the model. In this case WIRA and ECMWF would agree that the periodograms of the real atmosphere correspond to Fig. 4. The qualitative and quantitative agreement between measurements and model is remarakbly remarkably good below 0.3 hPa. The only notable discrepancies occur at periods larger than 45 days, for the 55-day wave which is mostly absent in ECMWF and for the 1010-day periodicity. The last one is present in ECMWF with amplitudes comparable to WIRA only for the meridional wind during the Provence campaign.

Above 0.3 hPa ECMWF tends to overestimate the oscillation amplitudes produce higher oscillation amplitudes than WIRA. Wind oscillation amplitudes observed in the MLT region (e.g. Araújo et al., 2014; Luo et al., 2001, 2002) better match with the uppermost observations from WIRA than with the high amplitudes in the ECMWF model.

A previous study (Rüfenacht et al., 2014) has shown thatECMWF generally overestimates mesospheric zonal wind speeds , in comparison with WIRA, ECMWF generally features stronger mesospheric zonal winds with discrepancies increasing for higher altitudes. When normalizing the oscillation amplitudes by dividing by the mean wind profile of the measurement campaign at the respective altitude the differences between WIRA and ECMWF were highly diminished (Fig. S10 S13 in the Supplement). This shows that the oscillation amplitude discrepancy behaves similarly to the absolute wind speed discrepancy, i.e. increases by the same factor with increasing altitude. Knowing that the ECMWF model is constrained by the assimilation of tropospheric and stratospheric data but is mainly free-running in the mesosphere (Orr et al., 2010; ECMWF, 2015) (Orr et al., 2010; ECMWF, 2016) , one might conclude that some of ECMWF's model physics are not accurate enough to reproduce the dynamics of the mesosphere to detail. An overestimation of the upward momentum transport or an underestimation of some damping mechanisms in the mesosphere are possible causes of this effect. Another explanation might be that the model contains assumptions on the balance between the wind and temperature fields which are not accurate in the mesosphere. As noted by Shepherd et al. (2000) and Koshyk et al. (1999) the unbalanced component of the flow increases with altitude. However, the exact reason for the concomitant mesospheric overestimation of the discrepancies between ECMWF's and WIRA's absolute wind speeds and the oscillation amplitudes in ECMWF oscillation amplitudes remain unclear.

4.2 Temporal evolution of the periodograms

Long period atmospheric oscillations usually manifest themselves on intermittent basis, therefore also the temporal distribution of their appearance was studiedAtmospheric waves and oscillations can be intermittent in nature (i.e. wave-packets) and seasonality might be present. Accordingly, the temporal evolution of the oscillations was examined. Figures 5and 6 , 6 and 7 display the results for WIRAand , ECMWF at WIRA and unaltered ECMWF data, respectively, at stratopause level where the highest amplitudes have generally been observed. Contours indicating the significance levels of the oscillation peaks according to Eq. (6) are overlaid to the amplitude plots. Again, Fig. 7 would show the behavior of the real atmosphere represented by the measurements of WIRA in case Figs. 5 and 6 exactly match.It

From the analyses it becomes obvious that the dominant oscillation in the extra-long period range is always highly significant. The oscillation peaks for ECMWF data are slightly more significant due to what is consistent with the absence of measurement noise.

A clear seasonality is apparent for all observations and model data with wave oscillation activities being much stronger in the winter half year for all oscillation periods covered by the present study. This pattern is also The seasonality is also visible for other years at the campaign sites as shown by ECMWF data (Figs. S8 to S11 of the Supplement) and is in accordance with other observational studies of stratopause level oscillations (Hirooka and Hirota, 1985; Day et al., 2011; Studer et al., 2012) and especially with the climatological periodogram of zonal wind at 58 km in Fig. 5 of Luo et al. (2001) . As in the mentioned climatology, no quasi 5-day wave signature could be found in the summer data from WIRA, in contrast to the results of Hirota and Hirooka (1984) and Fedulina et al. (2004) which indicate the frequent presence of such a wave at the summer stratopause.

The same pattern of seasonality as for the high and mid latitude stations is observed on La Réunion which, although although it is located in the tropics, features high oscillation amplitudes in austral winter and low activity in summer what might suggest southern tropics

(21°04′ S). One can infer that the station is substantially influenced by mid-latitude dynamics. This influence is also recognizable in the time series of the observed zonal wind (Fig. 1) where the mid-latitudinal annual variation mostly dominates over tropical semi-annual variation, although the latter one is still clearly visible.

During WIRA's measurement campaigns in the northern hemisphere two major sudden stratospheric warmings occurred in mid January 2012 and at the beginning of January 2013. Previous studies (e.g. Alexander and Shepherd, 2010; Day et al., 2011; Scheiben et al., 2014) reported a strong decrease in planetary wave activity in the days and weeks following the onset of major warmings. This feature can nicely be seen in WIRA and ECMWF data for the Provence campaign, but the effect is absent from both data sets for the Sodankylä campaign.

The period of the extra-long period oscillations is not constant between the different campaigns. ~~The period~~ It can even vary within a single occurrence of the ~~wave~~ oscillation as seen in the example of Bern where the period decreases from 35 to 25 days between December 2010 and March 2011. A 10 days period change is at the limit of the spectral resolution of our analysis method for this long periodicities. Nevertheless it may be interpreted as a real signal, not only due to the monotony of the decrease, but also to an additional check using our spectral method with rectangular instead of Hamming windowing in order to improve the spectral resolution (not shown). A similar feature has simultaneously been observed at three different sites from high to lower mid-latitudes in the mesopause region by Luo et al. (2001). This study also noted that the extra-long period oscillation often appears in combination with a quasi ~~16~~16-day wave. The occurrence of this ~~wave~~ periodicity has not been obvious from Figs. 2 and 3 because it had been masked by other oscillation signals in the temporal average. In contrast, it is clearly identifiable as independent periodicity in Figs. 5 and 6. ~~An interesting fact is that in~~ In the Bern and the La Réunion time series the strongest ~~16wave amplitudes~~ 16-day amplitudes (lasting for about 1 period) are observed near the initiation and the termination of the persistent extra-long period oscillation ~~. Whether~~ with a duration of 80 and 50 days, respectively. The duration of the presence of these oscillations is comparable to the results for mesopause wind presented by Luo et al. (2001) . However, it should be noted that if the extra-long period oscillation is abruptly initiated or terminated, the 16-day signal could be produced as an artifact of the used spectral method as simulations showed. Whether a real 16-day wave is present and whether the two oscillations are linked in some way will have to be verified in a study including more long term observationsfurther studies.

In general the agreement between WIRA and ECMWF at stratopause level is very good in terms of timing, amplitude and frequency. The extra-long oscillations in zonal wind at the two mid latitude stations of Bern and Provence are slightly stronger in the WIRA time series and the amplitude of the quasi 1616-day wave in the zonal wind is slightly enhanced for the measurements. However, the most notable difference between WIRA and ECMWF appears at shorter periods. Although mostly not statistically significant, ECMWF seems to underestimate variablities with periods shorter than 10 days for all measurement campaigns. A similar feature has been found for the comparison of middle-atmospheric temperature lidar observations from Observatoire de Haute Provence and Table Mountain (34°24′ N, 117°42′ W) with ECMWF model data (Le Pichon et al., 2015).

5 Conclusions

Long and extra-long period oscillations in the horizontal wind have been observed by the novel ground-based Doppler wind radiometer WIRA in the altitude range between mid-stratosphere (5 hPa) and upper mesosphere (0.02 hPa) at low, mid and high latitudes. In this altitude range wind observations are extremely sparse and the measurement time series from WIRA are the only ones satisfying the necessary conditions for the study of this type of oscillations.

The dominant oscillations were found to lie in the extra-long period band (20–4020–50 days) with the features showing pronounced temporal intermittency and the period being subject to temporal variations. A direct link between the solar forcing and this wave these atmospheric periodicities could not be established, however solar forcing might influence the atmospheric wave pattern in an indirect way. ~~An augmented presence of the quasi 16wave~~ Enhanced quasi 16-day oscillation activity has sometimes been ~~observed~~ detected in the vicinity of strong extra-long period oscillations. A more extended study ~~with more data would~~ would however be needed to establish the origin of this signal and to uncover a potential link between ~~those two waves~~the quasi 16-day wave and the extra-long periodicities. In addition to the ~~quasi 16wave, also~~ extra-long period oscillations, normal modes with periods near 5~~and~~ , 10 and 16 days are present in our observations. All observed oscillations manifest a strong seasonality with amplitudes being much higher during the winter half year. The strongest oscillation amplitudes were usually found around the stratopause.

WIRA observations and ECMWF model data agree remarkably well below 0.3 hPa. At higher altitudes ECMWF ~~tends to overestimate the oscillation amplitudes in a similar way as it~~ features higher oscillation amplitudes than the observations, a discrepancy behaving similarly to what has been noted for the discrepancy in absolute wind speeds in a previous study. In addition~~ECMWF seems to lack of~~ , ECMWF Operational Analysis data shows reduced variability at periods below 10 days as compared with the measurements by WIRA. More detailed validations of numerical weather prediction models such as ECMWF in the middle-atmosphere will be an important task for the near future and shall among others be addressed in the framework of the ARISE project ~~(**?**)~~ (Blanc et al., 2015) . Wind radiometer data could provide a valuable contribution to such research.

Data availability

We acknowledge ECMWF for the ~~operational analysis~~ Operational Analysis data (www.ecmwf.int) as well as NASA for the Aura MLS temperature profiles (http://disc.gsfc.nasa.gov/acdisc) used in WIRA's retrieval algorithm in the way described in Rüfenacht et al. (2014). The WIRA data presented in this manuscript can be made available on request.

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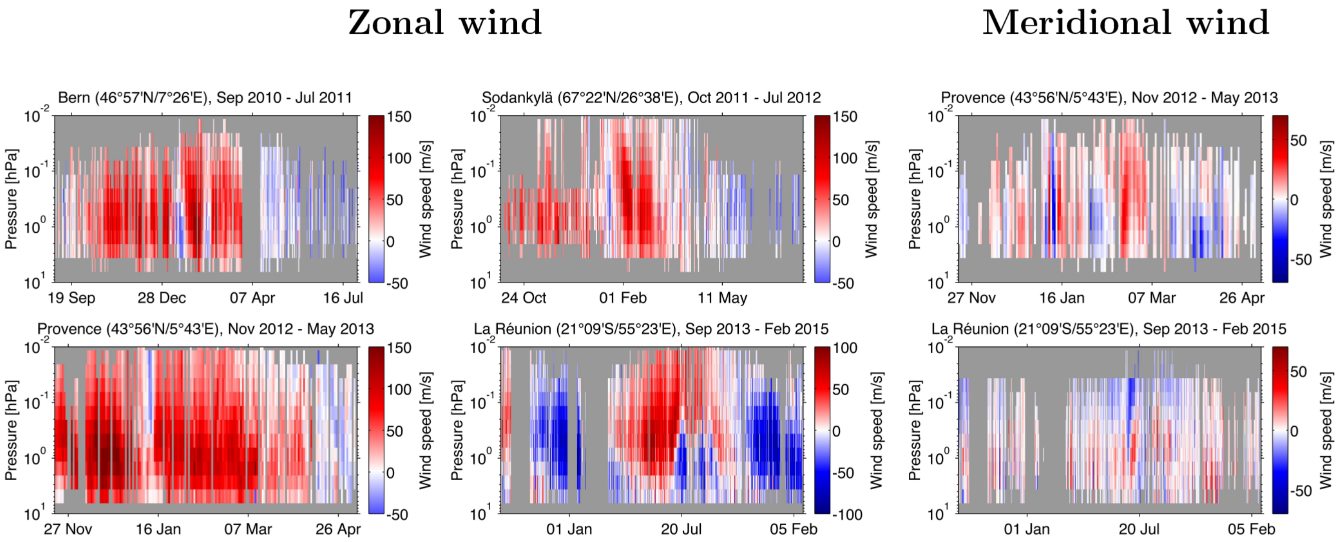

Figure 1. The zonal and meridional wind time series measured by WIRA during four different measurement campaigns analyzed in the present study. The gray areas correspond to data points judged ~~untrustable~~ untrustworthy according to the conditions indicated in the text. Please note the different color scale for zonal and meridional wind.

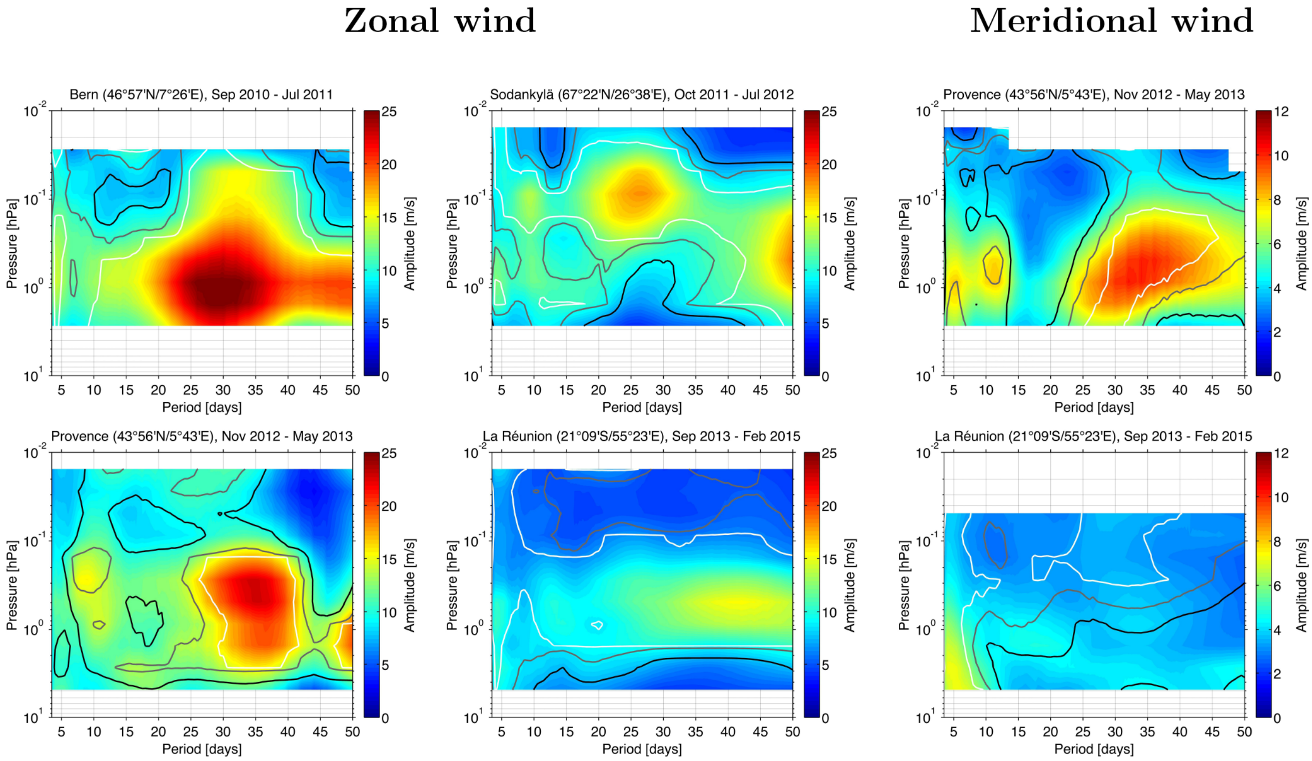

Figure 2. Temporally averaged periodograms of zonal and meridional wind profiles measured by WIRA. The black, gray and white contour lines mark $\alpha = 0.5$, 0.1 and 0.01, where the lowest value, i.e. the white contour, corresponds to the highest significance. The values of α were calculated from Eqs. (5) and (6) based on the average oscillation amplitude and the noise of the entire wind measurement time series determined using the Allan standard deviation (detrended version of the standard deviation e.g. Allan, 1966). The white areas represent altitudes and periods (i.e. window widths) for which the conditions of Eq. (3) are not satisfied, i.e. for which WIRA cannot provide reliable information due to an insufficient number of data points.

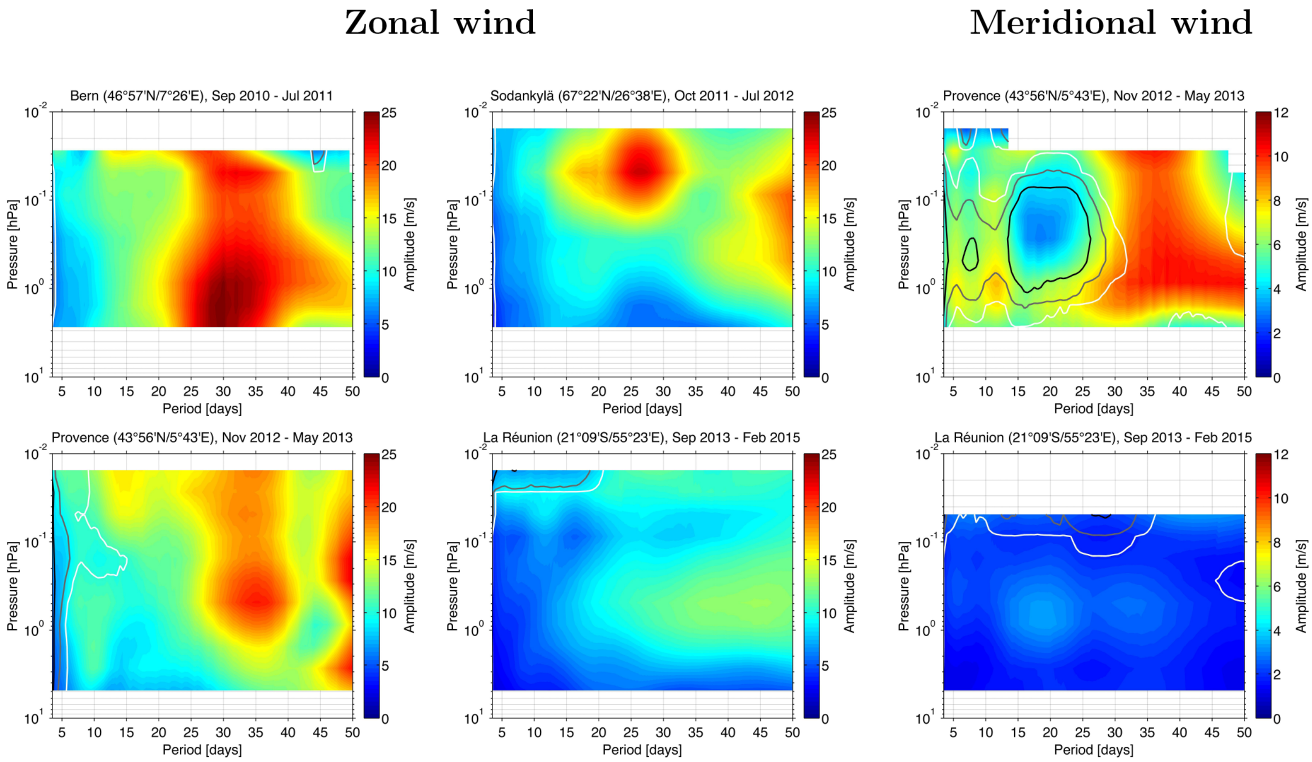

Figure 3. As Fig. 2 but for the scenario ECMWF at WIRA, i.e. for ECMWF profiles convolved with WIRA's averaging kernels and with data gaps introduced where WIRA did not provide reliable measurements.

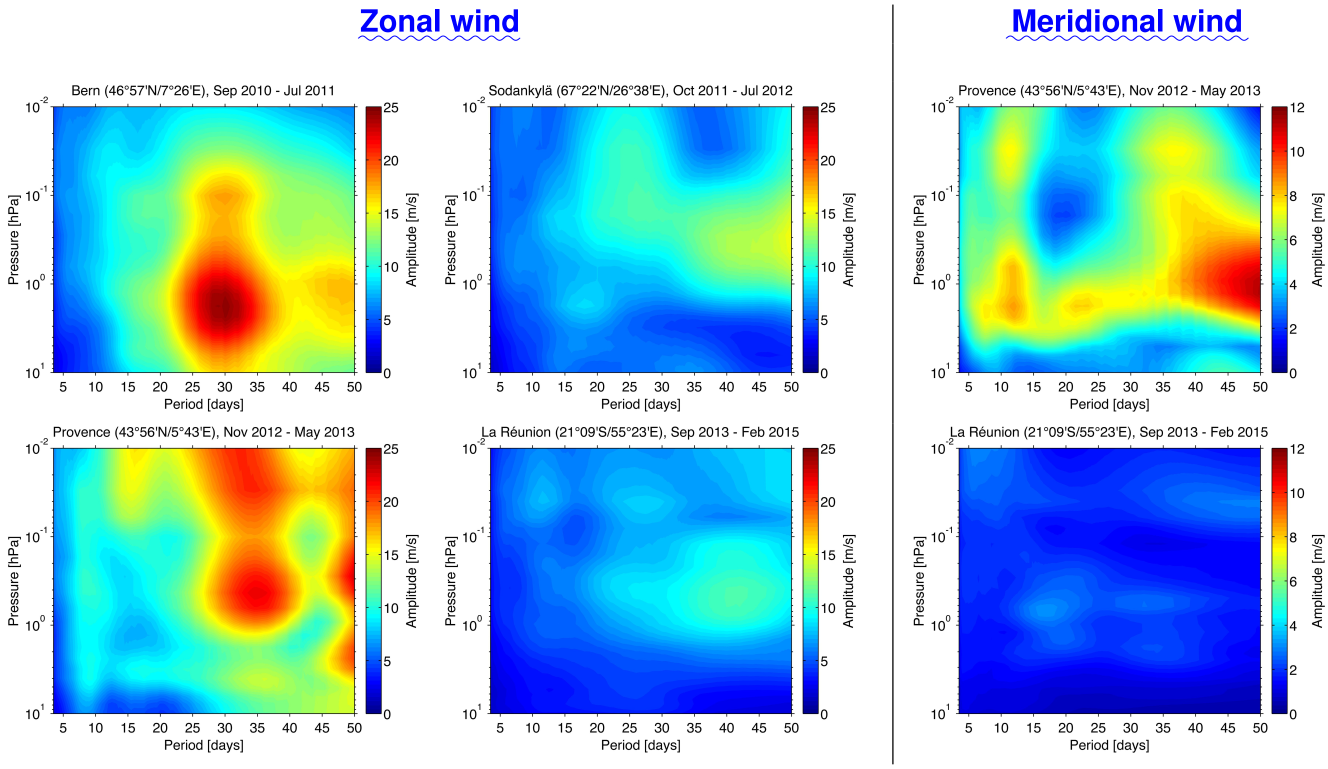

Figure 4. As Fig. 3 but for the unaltered daily average wind data from the ECMWF operational analysis.

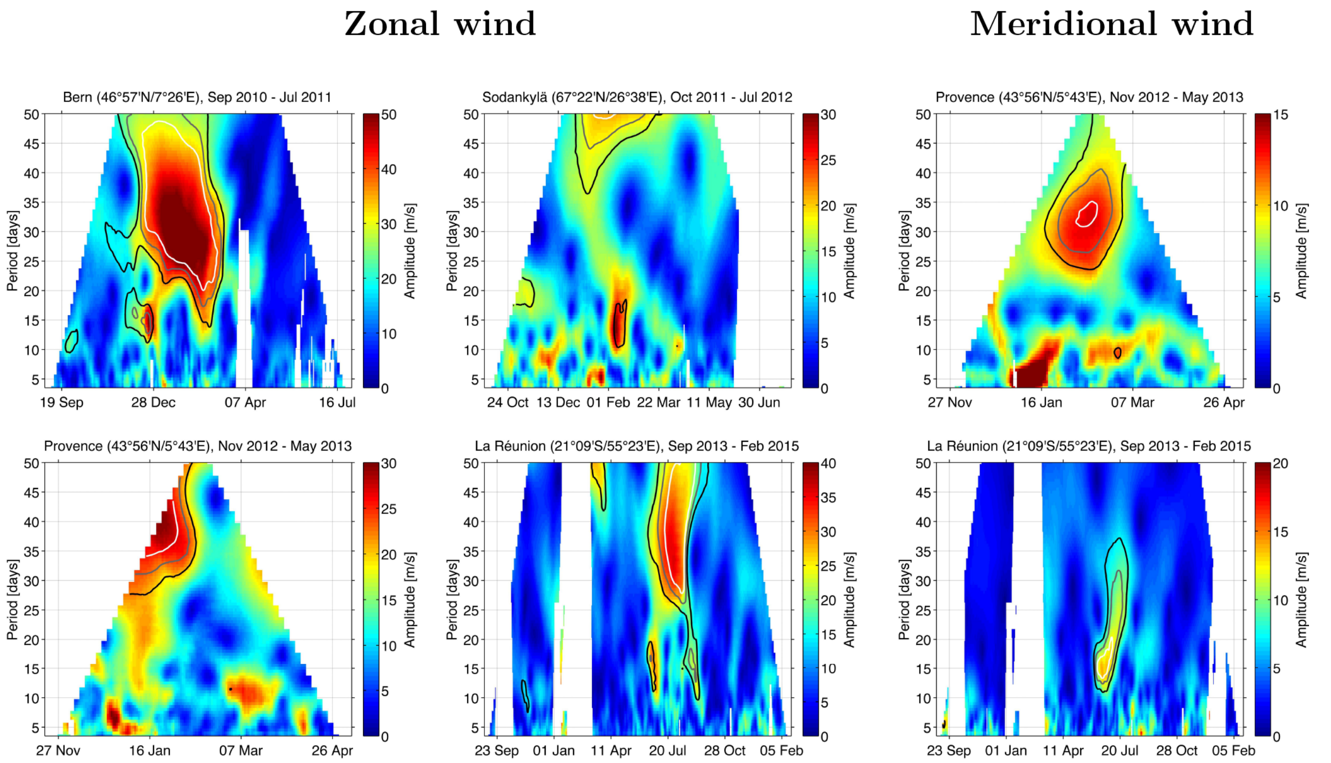

Figure 5. Temporal evolution of the periodogram at stratopause level (0.9 hPa) for wind measurements taken by WIRA. The black, gray and white contour lines mark $\alpha = 0.5$, 0.1 and 0.01 according to Eq. (6). The lowest value, i.e. the white contour, corresponds to highest significance. White areas represent times for which $\mathcal{B}_j$ contains indices before the start date of after the end date of the respective measurement campaign (what entails the trapezoidal shape of the colored area). Other areas are blanked out because the conditions of Eq. (3) are not satisfied, i.e. WIRA cannot provide reliable information due to an insufficient number of data points. Please note the occurrence of ~~16~~16-day oscillations near the onset and the termination of the extra-long period oscillation in zonal wind for Bern and La Réunion.

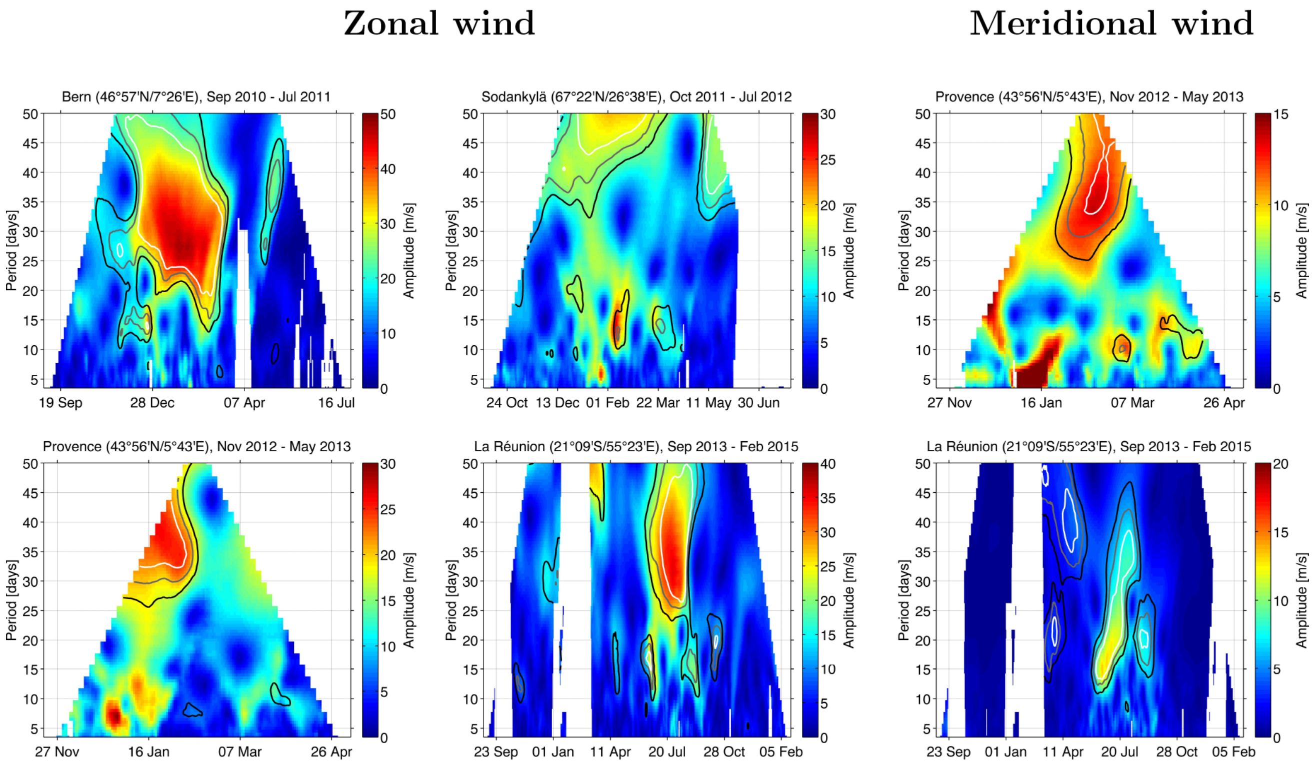

Figure 6. As Fig. 5 but for the scenario ECMWF at WIRA.

Zonal wind | **Meridional wind**

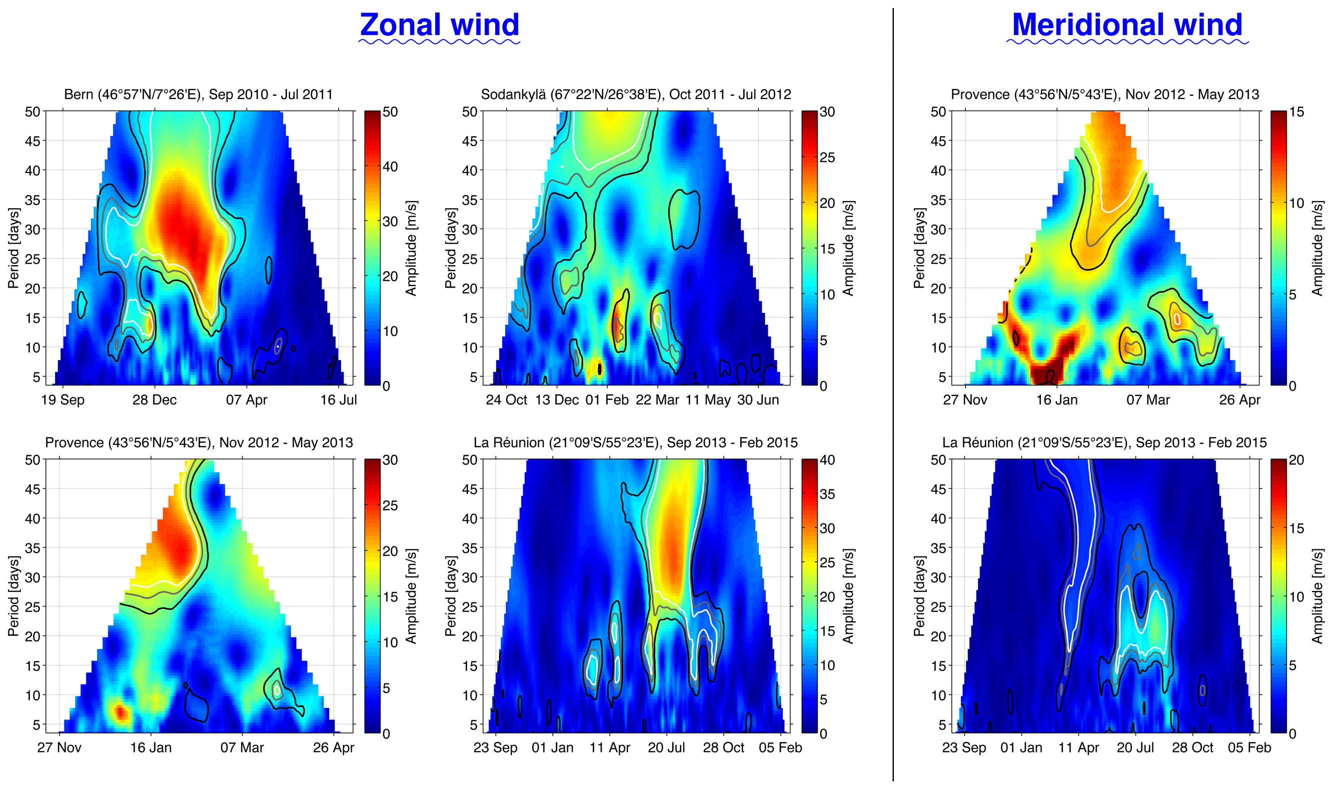

Figure 7. As Fig. 6 but for the unaltered daily average wind data from the ECMWF operational analysis.