# Reply to comments from referee #2

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

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.

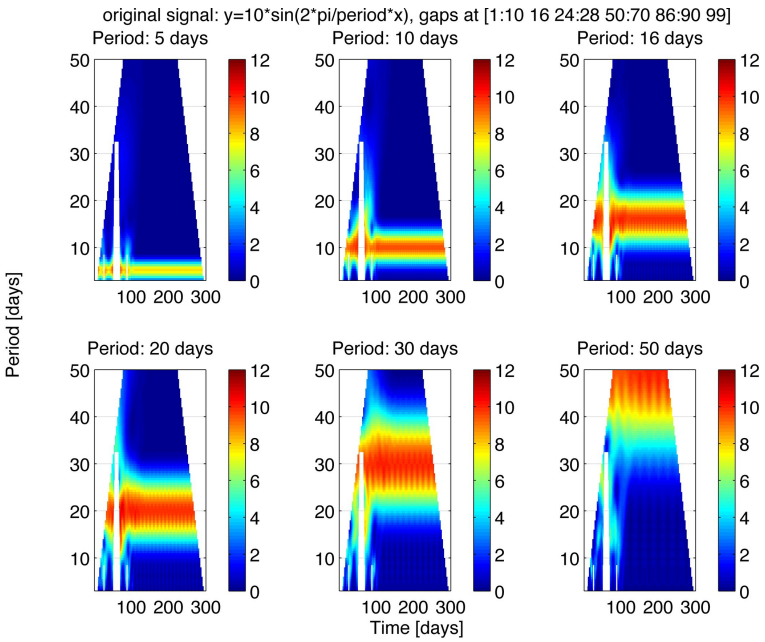


Figure 1: Reconstruction of synthetic monochromatic oscillation signals containing data gaps (at the locations specified in the heading) with the spectral method used for the analysis published in the manuscript.

(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.