Detailed reply to comments from the two anonymous referees of manuscript “Gravity-wave effects on tracer gases and stratospheric aerosol concentrations during the 2013 ChArMEx campaign” (acp-2015-889)

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First, we thank the anonymous reviewers for their helpful detailed comments and suggestions on our manuscript.
In the following, comments of the reviewers are fully addressed and modifications have been made in the revised manuscript accordingly.
Responses to comments of referee #2 are highlighted in red; those of referee #3 in blue as well as revised sentences and paragraph in the updated manuscript. A new version of the manuscript is attached as supplement.

Yours sincerely,
Fabrice Chane Ming

<u>Referee 2:</u>

Major comments:

1.) The reviewer suggests that the GW patterns in the ECMWF analyses look like concentric. This observation is unclear and the authors think that we should be cautious about interpreting ECMWF analyses as true representation of GW patterns. However, the authors are planning to use a mesoscale model (WRF model) to assess the wave process and investigate complexity of a jet-front system as a source of GWs.

2.) This part has been modified as the other reviewer suggested. The explanation of the calculation is described in five lines and therefore it does not need to be moved to an appendix (refer to comment P5).

3.) The conclusion has been modified accordingly.

4.) The language has been improved by a native English speaker. Some additional introductory or explanatory sentences have been included in the text.

5.) We have modified the conclusion to address the reviewer's comment.

6.) The authors hope that the figure quality is now satisfactory for the reviewer. For a better quality, the Fig. 9 is provided. In addition all high quality figures can be provided separately.

6b) We have made consistency of the maps.
For Fig. 6a, we can not extend the latitude range at -20°E because it is beyond the size of the image.

Specific comments:
P7L11
We have specified " Background temperature and horizontal wind profiles". P7L18

P9L1
GPS-RO measurements have vertical resolution varying from about 0.5 km in the lower stratosphere (LS) to 1.4 km at 40 km heights in the middle atmosphere (refer to P6L2). So GWs with vertical wavelengths of 2-4 km can be observed. Indeed Fig. 6b shows evidence of a variability of GW energy from a vertical wavelength of 1.5 km in GPS RO profiles.

P9L28
The authors agree with the reviewer. We have reformulated the sentence.
Change P10L9: "The validity of the Wentzel-Kramers-Brillouin (WKB) approximation based on the slow variation of the vertical wavenumber with height ensures the integration of the ray equations. Previous studies have shown that GROGRAT is an efficient tool to identify GW sources (Guest et al., 2000, 2002; Pramitha et al., 2015) and to simulate GW-background interactions such as GW effects, wave filtering, space and time variability of GW activity and characteristics (Wei and Zhang, 2015)."

P11L9
The modification has been done.

P11L13
The modification has been done.

P11LL29/Figure2:
We have described more clearly the use of such charts.
Change P12L10: "Ucellini and Koch (1987) and Koch and O'Handley (1997) produced similar charts to depict synoptic environment of jet streak typifying occurences of mesoscale GWs at the exit region of the upper-level jet streak."
P12L15 " Maximum wind speeds at 300 hPa visualize the jet core at west of Portugal. In addition wind speeds >50 ms^{-1} from 1200 UTC indicate the presence of a significant jet streak."

Figure 4:
Figures have been redrawn to address the reviewer's comments.

P14L6
We have specified what is precisely in quadrature. Hodographs of u' and v' is based on the phase quadrature between u' and v' and they have been intensively used to visualize and to extract elliptical structures. These structures are characteristic of GWs independently on the orientation of the wave vector.
The orientation of the ellipse provides the direction of the wave vector (± π).
Change P14L22: " RS horizontal wind perturbations (u' and v')"

P14LL20 and Fig 5b:
In the present version, we have focused on GWs with horizontal wavelengths <1200 km observed at latitudes between 42° and 48°N (refer to new figures 5) for which the horizontal wavelengths can be correctly estimated and are clearly visible on the data series. The previous Fig 5b has been removed as

redundant. Revised Figure 5 provides the main information: location of wavelike structures and presence of waves with horizontal wavelengths of 400-800 km. Indeed, some small-scale perturbations with long wavelengths could be a noise in ECMWF data.

Fig 5d:
The new Fig 5c reveals a continuous spectrum of GWs with horizontal wavelengths of about 400-800 km. We can observe several peaks at latitude of 46.5° with a dominant one at about 400 km. Thus, we do not discuss subharmonics.

Change P14L1-9:
" Spectral density of vertical velocities is calculated for longitudes of 10°W-20°E at latitudes between 42° and 48°N. In particular, the energy of mesoscale wavelike structures with horizontal wavelengths in the east-west direction λ_x<500 km is well-localized at the latitude of 46 °N which corresponds to the latitude of the exit region of the jet streak. Figure 5b displays the energy distribution of dominant wavelike structures at latitudes of 42-48°N for horizontal wavelengths λ_x<1200 km. In particular, it highlights a continuous spectrum of GWs with horizontal wavelengths λ_x of 400-800 km with a dominant mode of 400 km at latitudes of about 46°N. The spectral densities at latitudes of 42-48°N and 46°N confirm that the mode of 400 km is dominant at 46°N within the wavelength range of 400-800 km (Fig. 5c). "

Figure 6a:
The map has been redrawn to keep consistency of maps (refer to major comment 6b)

P15 The first paragraph has been revised to address the reviewer's suggestion.
Change P14L12-19: "The waves from this event can be identified in GPS-RO soundings as well. Figure 6a shows an overview of the GPS-RO soundings over western Europe for the days 26 to 29 July, 2013. We selected profiles for longitudes of 2.5°-6° E and latitudes of 40-50° N for spectral analysis of the altitude range of 10-20 km. The results are shown in Figure 6b. The individual spectra are labeled by the day and UTC of the measurement (e.g. 2605 for 26 July; 05 UTC) and marked also accordingly in Figure 6a. As one can see from results for consecutive days, GWs are enhanced starting from 27 July, peak at 28 July and are still active on 29 July. Spectral density peaks are found for wavelengths 2-3.5 km"

Table 1:
The methods used to obtain parameters provide characteristics of dominant GWs, e.g., peaks of wave parameter distributions. For example, at heights of 3-7 km, we have reported three values of horizontal wavelengths because the hodograph analysis provides three peaks in the ω/f distribution.
Change P32: "Characteristics of dominant GWs on 27 July at 2303 UTC above Ile du Levant using a hodograph analysis and combined conventional methods (grey cells) on observed and simulated (marked by *) profiles. Values are derived from peaks of wave parameter distributions."

P16LL12
The text about possible reasons for phase shift uncertainty has been removed because effects are supposed to be minor or difficult to quantify. Indeed, previously published papers on retrieval of horizontal wavelengths from GPS RO phase shift were not focused on such uncertainties and therefore in this paper we also do not discuss such uncertainties.
In addition the part about phase shift has been modified according to comments of another reviewer. In the present study, time variation is taken into account because the value of ω has been previously estimated.
The details of the analysis based on five concise lines do not need to be moved into an appendix.

Change:
refer to P16L28- P17L12 for modification about the computation of the phase shift in taking into account time variation.

We have added an explanation, as suggested by the reviewer P17L12:
"The estimate is somewhat lower but compatible with the value of 0.05 m^2s^{-2} derived from the radiosonde measurements"

Page 18L1:
The modification has been done.

P18 first paragraph:
Few rays break near the tropopause in particular for large horizontal wavelengths (450-550 km). If we extend the range of ω/f and horizontal wavelengths we can observe a wider dispersion in the termination altitude, time and location.
The authors have verified the termination condition at the altitude of the jet core. It is not simply because of the tropopause because the tropopause is located at about 15 km heights and rays are traced back to 10 km heights.
Thus, in this paper we only present the results for which we can provide explanations. In our future research, a more detailed description of the wave process will be investigated using a mesoscale model (WRF).
Change P18L26: "Because rays pass over a convective region when the front system moves eastward, some GWs produced by convective sources might also be captured."

Referee 3:

Major Comments

(MC1) The whole manuscript has been checked for clarity and consistency about discussion on multiple waves as it is supported by the spread of parameters in table 1 (horizontal wavelengths and ω/f) .
Indeed, our methods of analysis of GW characteristics (Table 1) are focused on dominant GWs among wave packets.
Modifications in the text are presented in our responses to specific comments.

(MC2) This part has been modified. The phase shift is now computed between RS2723 and RO2802 for which time variation and the distance are 1.8h and 179.14 km respectively. Because time variation is > 15 minutes, our calculation of phase shift takes into account the time variation using the estimated ω (Table 1). The authors think that it is important to report the estimation of wave parameter from GPS RO measurements because they also support observations of GWs (refer to comment 5 for more details).

Specific Comments

Comment (1 & 2):
Response: The text has been modified as suggested by the reviewer.
Change P2L31:
Thanks to recent progress in computer technologies, current operational numerical weather prediction models have sufficient spatial and temporal resolution to resolve the portion of GW wave spectrum with horizontal wavelengths of 100-1000 km (Shutts and Vosper, 2011). However, global climate models as well as numerical weather prediction models still need a set of GW parameterizations with a large number of tunable parameters for a realistic representation of the middle atmosphere (Preusse et al., 2014). By comparison with observations, it has been shown that the resolved GWs are usually under-represented (Schroeder et al., 2009).

Comment (3):

Response: The authors have compared GPS-RO dry and wet temperature profiles used in this study. They are similar above the altitude of 10 km. We mentioned that our study is focused on heights of 10-20 km because GW fluctuations in both wet and dry temperatures might be biased below 10 km heights.

Change P6L4: We have removed 'wet' from the text and included the following sentence "Because GW fluctuations in both wet and dry temperature profiles would be biased by the effect of water vapor at heights below 10 km, the study is focused on heights above 10 km.

Comment (4):
Response: The authors have removed the last sentence at the end of Sect.3.3 and modified the text
Change P9L3: "At a given altitude, the horizontal wavelength can be deduced from adjacent vertical profiles of temperature close in time and space in order to observe the same GW packet. Thus, the time variation in the phase difference can be neglected (refer to equation 5 in Wang and Alexander (2010)) and the phase shift divided by the distance provides the horizontal wavenumber projected along the line connecting the two profiles. Ern et al. (2004) introduced this method to estimate horizontal wavelength of GWs and global absolute values of vertical flux of horizontal momentum at 25 km altitude from adjacent temperature profiles from Cryogenic Infrared Spectrometers and Telescopes for the Atmosphere (CRISTA). The method is adapted to pairs and triads of RO temperature profiles using the S-transform and CWT in the altitude range of 17.5–22.5 km with temporal windows of 4 h and 2 h (Wang and Alexander, 2010; Faber et al., 2013). To better constrain estimated horizontal wavelengths and momentum fluxes, Schmidt et al. (2016) used temporal and spatial windows of 250 km and 15 minutes."

Comment (5):
Response: The authors have modified the text and only compute the phase shift between RS2723 and RO2802 at the altitude of 17 km for which time difference is 1.8 h because of the ascent time of the RS. In addition, the calculation of the horizontal wavelength takes into account the time variation by using the value of period and the uncertainty of the direction of horizontal propagation (Phi) reported in Table 1. Fig. 7d has been removed. Scalograms of RO2802 and RO2812 have been preserved because they complete Fig6b. Indeed they support the presence of GWs with 2-3 km vertical wavelength in the troposphere and the lower stratosphere on 28 July like observations on RS2723.

Change P16L28: the text has been modified as follows:
"Figure 7a visualizes temperature profiles from RS at 2303 UTC (hereafter called RS2723) on 27 July above Ile du Levant and RO at 0200 UTC (hereafter called RO2802) and 1200 UTC (hereafter called RO2812) on 28 July. As observed on the RS2723 temperature profile, GPS RO temperature profiles also show evidence of small-scale perturbations in the troposphere and the lower stratosphere. Scalograms of RO2802 and RO2812 temperature perturbations support the presence of dominant GW structures with vertical wavelengths of 2.5-3 km at heights of 10-18 km on 28 July (Fig. 7b, c). By assuming that the same GW packet is observed on RS2723 and RO2802 profiles in the LS, the phase shift (Φ) between perturbation profiles is calculated at the altitude of 17 km taking into account of the time variation (refer to section 3.3) using a GW period of 12 h at heights of 15-20 km and a time difference of 1.8 h at the altitude of 17 km between RS and RO measurements. Using a distance of 179.14 km between temperature profiles, the phase shifts (Φ) of 1.67 radians provide an horizontal wavelength of 673.6 km. The estimated horizontal wavelength is larger than the 'real' value by a factor 1/cos α, where α is the angle between the connecting line of the two profiles and the real horizontal wave vector (Preusse et al., 2002). Thus the 'real' horizontal wavelength is ranged between 396 and 674 km (Phi=200±29°). The result is consistent with values of horizontal wavelengths derived from applying conventional methods on RS2723 profiles at heights of 13-20 km."

Comment (6):
Response: Here we discuss multiple waves characterized by a dominant wavelike structure (peak of intensity). The word "both" has been removed.

Comment (7):
Response: We have done the modification "°C^2 km^{-1}"

Comment (8):
Response: Modifications have been done.
Change P15L27: "In particular, the hodograph analysis reveals the presence of mesoscale inertia GWs"

Comment (9):
Response: We have included suggestions of the reviewer concerning comparison with previous studies in summer mid latitudes.
Change P16L5:
"Our computed value of vertical flux of horizontal momentum (about 8 mPa) is well beyond values of 1 mPa and 0.02 $m^{-2}s^{-2}$ observed in the LS in summer midlatitudes respectively by Ern and Preusse (2012) over Europe from High Resolution Dynamics Limb Sounder (HIRDLS) observations and Zhang et al. (2014) from radiosondes over North America. Thus the value of vertical flux of horizontal momentum supports our statement that the case on 27 July 2013 represents a stronger GW event."

Comment (10):
Response: We have added some explanation about the expected range of p and modified our statement.
Change P16L10:" The ratio between kinetic and potential energy of GWs provides a spectral index (p) of about 2.6-2.9 which is larger than the theoretical values of p (about 5/3). However, Hertzog et al. (2002) find values of p in the range 1.5-2.2 for high-frequency GWs from superpressure balloon measurements in the stratosphere. They suggest that values greater than 5 could be caused by enhancements of the velocity spectrum near the inertial frequency."

Comment (11):
Response: Refer to our response to comment (5). We provided a reference on paper of Schmidt and Alexander (2016) at the end of section 3.3.

Comment (12)
Response: The authors agree with the reviewer that our approach is simplified and it does not take into account all possible GWs at heights from the ground to 26 km. However, our objectives are to produce simplified synthetic profiles of the dominant mesoscale GW at heights of 13-20 km in agreement with mean spectral characteristics of observed mesoscale GWs, the intensity of observed GW perturbations, phase relationships as well as energy densities and horizontal phase speed. Analyses of wave parameters from simulated profiles of perturbations and comparison between observed and simulated profiles support that the simplified synthetic profiles contain the main information about the dominant mesoscale GW at heights of 13-20 km which is useful in the next section to interpret the impact of GWs on stratospheric tracers and aerosols.
The discussion about the variation of Brunt Vaisala frequency with height and the horizontal wavelength has been removed.
The text of section 5.3 has been revised to mention clearly our assumptions and objectives.
Change: refer to P17L26-P18L13

Comment (13)
The authors believe that change in wavelength mean as a function of time provides information about the time evolution of GW distribution. They agree with the reviewer’s comment that a given combination of wave parameters could preferentially be observed as a function of altitude and time depending on the background wind field.
Change P18L31:
“A given combination of wave parameters might preferentially be observed depending on the background wind field.”

at the end of 5.3:

P19L6 "In conclusion, the GROGRAT simulation indicates that mesoscale GWs with a whole range of parameters around the mean parameter could be excited by the front and propagate to the location of Ile du Levant at heights of 13-20 km."

Comment (14)
We have modified the sentence to discuss multiple waves instead of a single wave.
Change P21L22 : “The methodology is illustrated on a case study on 27 July 2013 when mesoscale inertia GWs produced by the jet-front system were identified during a jet-streak event”

Other comments: all suggested modifications have been incorporated into the revised text (refer to the modifications highlighted in blue).