Response to Referee #1

“Orographic and convective gravity waves above the Alps and Andes mountains during GPS radio occultation events — a case study” by Rodrigo Hierro et al.

We acknowledge very much the detailed comments and suggestions made by Referee 1.

General Comment
In my AMTD access review several major concerns were raised which showed that a major rewriting and refocusing of the manuscript would be required, probably exceeding the time usually allotted for revisions of a paper under review. Therefore my recommendation at this stage was to reject the paper. Since then, only minor changes were made. This is why this recommendation is repeated. Of course, having a collocation database between RO events and convection over orographic regions is a valuable contribution, same as the detailed discussion of two cases of WRF simulations. The comparison of RO events and WRF simulations, however, which is the core part of the paper, is incomplete and based on wrong assumptions. Still, I think that the two selected cases are good examples for discussing several important aspects that have to be considered when comparing high resolution simulations with real observations. Therefore resubmission of a revised manuscript is encouraged. If the manuscript were to be revised and resubmitted, several major issues have to be addressed.

Major Concerns
(I) Firstly, it is obvious that for both detailed comparisons, the Alps and Andes cases, the waves simulated with WRF are not seen in the corresponding RO soundings. Following Alexander et al. (2008), the amplitude attenuation factor E can be calculated.
For the Alps case, E is <10^{-11}
For the Andes case, E is <0.03
Amplitudes in the RO soundings are 2K, sometimes more. For explaining these amplitudes with the WRF simulations, simulated amplitudes would have to be >60K. This is physically not reasonable. In the Andes case the tangent points do not even hit the region of simulated wave trains. Further, the simulated wave trains are quite fuzzy, suggesting that amplitude attenuation should be even stronger. Details on the calculation of E are given below in a separate section.

Our revised manuscript, as it may be appreciated in the attached, lengthy new version “with track changes”, has been completely rewritten. Old figures 4, 5, 8 and 9 were eliminated and replaced by the new figures 2, 5, 7, 8, 9 (new version). Old Figure 2 was enlarged in two plates (new figure 3). Many additional paragraphs are now included. The discussion regarding the expected wavelengths distortion was separately explained in an Appendix. New calculations and simulations regarding the 2 case studies, now including simultaneously WRF simulations, reanalysis data and RO measurements are included.

In particular, in base of this last reviewer’s comment, a detailed calculation of the attenuation factor has been made. This factor has been obtained for the two case studies, based on the mathematical details provided in our paper Alexander et al. (2008). We analyzed the possibility of RO detection of 4 clearly different structures, at tropospheric
and stratospheric altitudes, during both case studies. These were not completely reported in our previous version. The results are shown in Table 1, now included. As it may be appreciated, 3 structures are expected to be, at least partially, detected. This is not possible for the fourth structure. For example, in the Andes case study, we found that different segments of the same profile exhibit GW belonging to different sources.

Please notice that the new simulations and our new interpretations of the corresponding GW lead to different attenuation values, as aspect ratios and angles between LOS and GW fronts have now changed.

(II) This clearly shows that the WRF simulations alone are not sufficient to explain the observations. In some cases they may be sufficient, but generally they are not. The simplest explanation is that horizontal wavelengths of the observed waves are usually much longer than those of the simulated waves. This possibility and its consequences are not discussed and completely ignored. The wavelet analysis even stops at 120km, which is at the verge of the range of waves that can be seen by GPS RO. One explanation could be mountain waves and convective waves of longer scales that are not captured by the WRF simulations, but co-exist with the simulated short scale wave modes.

The analysis now includes ERA Interim reanalyses data and an extensive discussion is given about the need to consider this information to perform a reliable study of the observed GW structures, mainly for the Alps case study (Sec 3.1.1. to 3.1.3. and 3.2.1.) The wavelet analysis is now applied only to the RO $\delta T$ profiles at both regions (3.1.2. and 3.2.1.)

Another explanation could be gravity waves emitted from jets and fronts. Surprisingly, this third major source of gravity waves has been completely disregarded in the manuscript. Just as an example, in the beginning of the abstract only orography and convection are listed as major wave sources. Usually gravity waves emitted from jets and fronts are of larger scale and could co-exist with the small scale waves that occur in the WRF simulations. Since the Alps case is in the winter season when gravity waves emitted from jets and fronts are quite abundant, ignoring this wave source is not possible.

We completely agree with this comment. Here, we carefully selected our case studies, taking into account the convenience of considering only scenarios in the absence of jets and fronts. In doing so, we would expectedly filter out GW from at least one or two of these major sources, thus avoiding an extremely intricate analysis, perhaps not possible at all.

(III) Thirdly, since the WRF simulations are insufficient to describe the observed waves, meteorological data sets, such as ECMWF analyses, could be investigated whether larger scale wave patterns are found that can explain the RO observations. GPS RO measures temperatures. Therefore analysis of temperature fluctuations is preferable to the analysis of vertical wind $w'$, also in the WRF simulations. Focusing too much on $w'$ will bias any analysis towards high-frequency waves that are difficult for GPS RO to observe. Moreover, a direct comparison of amplitudes is not possible.
In the new version, in addition to the included reanalyses data, we restricted ourselves to show vertical velocity simulations only in relation with mountain waves. The inclusion of $\delta T$ from simulations and reanalysis data is now considered and shown in all the new figures and results.

(IV) Fourthly, including a detailed discussion of vertical wavelength biases in the manuscript will distract the readers. For the examples given, observed and simulated waves are obviously different and wavelengths extracted from the simulations cannot be assumed for the observations. Therefore it is not clear whether these sampling biases apply.

Two of our main changes in the manuscript are the inclusion of the expected amplitude attenuation and wavelength distortion during the collocated RO measured profiles. This last discussion is now moved to the Appendix. We feel that now it will not distract from the main objectives of the manuscript.
Response to Referee #2

“Orographic and convective gravity waves above the Alps and Andes mountains during GPS radio occultation events — a case study” by Rodrigo Hierro et al.

We acknowledge very much the detailed comments and suggestions made by Referee 2.

Summary: This paper analyzed the collocated GPS radio occultation profiles near the convective systems identified from ISCCP over two orographic regions of Alps and Andes. Out of a total of 10 collocated RO profiles, one RO sounding (bending angle and temperature profiles) from each region was analyzed. The convective cloud top height was identified. Gravity wave (GW) analysis over both selected regions were also carried out. The gravity wave signature from the two case studies were derived base on the WRF simulation and the RO vertical profiles. The GWs with horizontal wavelengths of 20 km and 40 km (two mode) and vertical wavelengths (15 km or 20-25 km) were identified from the WRF simulation over the two regions. The vertical propagating GWs with “apparent” vertical wavelength of ~4 km over Alps, or ~4.5 km over Andes were also identified from GPS RO soundings. The so-called distortion factor was also investigated, which measures the discrepancy between the “apparent” (or measured) and the “real” vertical wavelength affected by the RO observation geometry reference to the GWs propagation direction. Overall, the paper use the case study to demonstrate the GPS RO capable of detecting the vertically transporting GW over the orographic regions, where mountain waves persistent as seen in the WRF simulations. The high vertical resolution GPS RO sounding has the advantage of detecting the fine vertical scale GWs but less capable of identify the GW with fine horizontal wavelength (e.g., Wu et al., 2006). The paper seems trying to synergize the GPS RO observation with the WRF simulation to present a more complete picture of the GW morphology, which has the merit for publication. However, it is not clearly stated in both the introduction and conclusion of the paper. I would recommend publication of the paper after “major revision” with my comments below:

Major comments:

1. The paper writing need some significant improvement to better describe the research work, including the grammar and sentence structures.
   a. Many super long sentences should be split into shorter sentences.
   b. The author(s) intend to use the “first” person throughout the paper. Generally the scientific paper should be written with third person.

Our revised manuscript, as it may be appreciated in the attached, lengthy new version “with track changes”, has been completely rewritten. Along these track changes, the general reduction of sentences as well as the use of third person may be appreciated. The grammar was revised by an expert. Old figures 4, 5, 8 and 9 were eliminated and replaced by the new figures 2, 5, 7, 8, 9 (new version). Old Figure 2 was enlarged (new figure 3). Many additional paragraphs are now included. The discussion regarding the
expected wavelengths distortion was separately explained in an Appendix. New calculations and simulations regarding the 2 case studies, now including simultaneously WRF simulations, reanalyses data and RO measurements are included.

(2) The motivation and key contribution of this paper need to clearly stated in the introduction. The authors add a short paragraph (L102-108) in the introduction, which was the details of work of the paper, but not “Why” to carry out such work. The motivation should be the science or technical questions that haven’t been addressed, or what is new in this paper that advances the field of study.

We now feel that all of these comments and suggestions have been fulfilled in our new version (please see Sec 1).

(3) Only 5 collocated cases from each regions (Alps and Andes) were identified between GPS RO and ISCCP. And only one RO case for each region were used for the case studies. It is hard to believe that one single RO case is representative of such a large region, especially hard to believe the single cloud-top-height identified from the bending/temperature anomaly method will be representative over such a large study domain.

a. The author’s response shows 294 collocations over Alps but only 50 collocation over Andes within 3-hr and 100 km of the ISCCP convective systems, which should be included in the manuscript. The selection of the 10 case need to be justified.

b. Should consider demonstrate these RO soundings in statistical sense that they can detect consistently the gravity waves with vertical wavelength of 4-4.5 km, instead of randomly pick one out of 5 cases.

As we now explain in the text (line 186-7): “In the present study, a GW climatology from the available limited number of collocated cases is not intended”. The response to these two comments (a. and b.), as well as the pre-selection and later selection of case studies are detailed and discussed in lines 187-197.

c. Also ISCCP website shows the DX (B3) data are available 07/01/1983 - 12/31/2009.

This point is now explained in several segments of text between lines 140-171

d. More robust analysis of the GW from more collocated GPS RO soundings near convective systems will strengthen the selection of the “representative” case for further WRF simulation study and improve the paper quality.

Our final objective in this paper was only a detailed analysis of two cases study, however we fully agree with this comment.

(4) Some technical details are missing and need to be added,

a. What exact parameters from ISCCP were used?

The parameters extracted from ISCCP data, are: time of occurrence, center (mass center) and radius of the storm. The COSMIC mission started in June 2006.
b. How ISCCP identify the convective system? Any uncertainty related to the usage of infrared CTT to identify the convective system, especially over cold surface?

A discussion detailing all the information available for us regarding the used cloud data is provided in Sec. 2. We used time of occurrence, the center of the storm (mass center) and radius of the storm. We don’t have access to ISCCP methodology so we just used their database.

c. How to detect the CTH from the anomaly method (Biondi et al, 2012)? What threshold etc. used to identify the CTH in Fig. 1a,b? Can’t just cite the paper. The basic details are still needed to be included in the paper.

Here we are just able to answer in a similar way as before, regarding ISCCP. We don’t have access to the methodology used in Biondi et al. (2012). On the other hand, in the mentioned paper, details of the procedure used by the authors to detect CTH, are available.

d. Discussion on the result out of CWT is missing for both Fig. 5 and Fig. 9. What exactly plotted (e.g., parameters) need to be detailed described in the manuscript, and should be after the discussion of Fig. 4. The author(s) sometimes jump the discussion without following the orders of the figures.

We agree with this observation. The original text has been fully rewritten and we feel that a new order is given to the description of parameters, figures and hypotheses. Previous (some of them modified) and new results may be now appreciated. In particular, the CWT analysis is now limited only to both GPS RO $\delta T$ profiles.

e. Section 2: missing information of the duration of RO data used in this paper, e.g., what years data were used, are they same for different RO missions?

This information is now included in the text.

f. L156: need description of the reference climatology profile, e.g., how many year average, horizontal, vertical sampling interval, how to do average etc.

g. L159: WRF model description needed, e.g., version, horizontal, vertical resolution, citation.

Please see lines 172-186

(5) Figures need to be improved:

a. Fig. 1: The four cases in smaller inlet are hardly legible.
   i. Might consider combine all five (or more cases) into one statistical plot plus the one individual plot in the middle panel.
   ii. RO profiles from which RO mission should be indicated in plot or the manuscript.

b. Fig. 8&9 should be consistent with Fig. 4&5, respectively
   i. Why Fig. 8 only has three UTC time but Fig. 4 shows four UTC time?
ii. Why adding temperature wavelet analysis result in Fig. 9d but not in Fig. 5?

As mentioned above, old figures 4, 5, 8 and 9 were eliminated and replaced by the new figures 2, 5, 7, 8, 9. The plates in the new figure 3 are enlarged. We feel that the results are more clear and consistent now.

c. Fig. 10:
i. The distortion factor could explain the discrepancy of the GW vertical wavelength seen in GPS RO (4 – 4.5 km, L322, ) as compared to the WRF simulation (~15 km, L288, ~20-25km, L421). But why the two “green circle” at those certain locations were not discussed. Will the plot different for other region, e.g., over Alps?

Now, part of the distortion discussion was moved to an appendix. Other reviewer suggested to not distract the reader with these considerations too much. Nevertheless, the two geen circles, suggesting possible under- and/or overestimations for a given set of parameters is included for illustration only.

(6) Most of the figure captions did not describe what is plotted and need to be updated.
a. The reader should be able to understand the figure without the need to consult the text. It might be worth consulting the paper by de la Torre A. et al. (2006) or others on caption writing.
b. All the color bars do not have “UNITs” either on plot or in the caption.

All of these points have been carefully taken into account in the preparation of the new version. We hope that the descriptions are more clear now.

c. Fig. 3: There are no description on what is plotted in Figure 3, variance?? You can’t simply say it is “GW” structure.

The GW perturbation to the vertical velocity is explicitly written in the caption and in the text.

d. Same for Fig. 5, 6c, 7,8, 9c. The details in each panel need to be clearly described in caption succinctly.

Here we apply the same comment as the two before.

Technical comments:
L40: “Vertical profiles … (Kursinski and Gebhardt, 2014). Need to be rewritten to be parallel statement.
Done.

L42: “0.1-0.3 g kg-1 ”
Done.

L48: “troposphere and lower stratosphere
Done.
L72: “storms”
Done.

L74: “strongly affects”
Done.

L83: “Fovel et al., …, generating high-frequency???” Sentence is not complete.
Done.

L102 -108: Not a motivation, need to be rewritten.
Done.

L109: “Section 2…”
Done.

L125: RO data duration should be added
Done.

L130: Figure 1 caption should include what is plotted. E.g., the elevation map, Alps over Europe and Andes in South America...
Done.

L143: According
Done.

L146: “interval” à “difference”
Done.

L156: Missing description of the reference climatology profile, e.g., how many year average, horizontal, vertical sampling interval, how to do average etc.
We used the data from the climatology, as provided by the Wegener Center. Nevertheless, some details regarding how it was obtained were not available for us.

L172: The total number of collocations (e.g, 294 over Alps, 50 over Andes) should be mentioned, and better to show the statistical results of the analysis instead of the handpick of the 5 cases. Or justification of the representativeness of the selected cases are required.
An detailed explanation about this comment is included in the text now.

L180: Fig.1 need to be updated. Hardly legible.
Done.

L183: Caption should describe/mention each panel. Very hard to understand and need to be rewritten.
This was considered in all the new and old figures.

L195: 3.1. Case study over the Alps region
Done.

L205: What is plotted in Fig. 3 need to be clearly stated.
They reach again… after a partial… à They reach large amplitudes again in stratosphere after … tropopause at around 11km.

New figures, corresponding captions and discussions in the text are now included.

in red for altitude reference. (CWT) corresponding to Figs. 4a, b, and d, …, Why missing Fig. 4c??

This figure is now removed.

“perfect” band-pass, What does that mean?

A comment is included at lines 284-285.

Fig. 6c caption should describe what is plotted, basically what is the results after CWT, plus the unit of the color bar.

A text is now included in the figure caption.

“This method has two steps: …, …, and to force a zero mean.” Super long sentence and need to be broken up into smaller pieces.

We keep in mind that à Note that.

prevent us to (from) observing

3.2. Case study over the Andes region

What does “[7;-3]” mean? It was shown in many places.

The horizontal mean wind components, now explained in the text.

caption need to describe what is plotted, plus the unit.

Figure now removed.

Missing detailed description and discussion of Fig. 9.

This discussion was moved to an Appendix and partially referred to a very recent accepted paper, following a suggestion of another reviewer.

Fig. 8, Zonal variation of w in WRF simulation at ??altitude in three UTC times (13, 17, and 21 UTC) over the Andes region. The GPS RO took place at 16:56 UTC with mean LTP at ….

This figure is now removed.

Similar to Fig. 6, but for the RO case study from Fig. 1b over the Andes region.

Equation (1): should cot(a) be cos(a) instead?
It is correct as it is written (please see A18).

**L465:** please describe why the two green circles at the specific “propagation angle”.
Because the $\alpha$ value represent the inclination of the LTP respect to the horizontal plane.

**L474:** were $\rightarrow$ where
Done.
Orographic and convective gravity waves above the Alps and Andes mountains during GPS radio occultation events – a case study

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Abstract. Gravity waves (GW) and convective systems play a fundamental role in atmospheric circulation, weather, and climate. Two usual main sources of GW are orographic effects triggering mountain waves and convective activity. In addition, GW generation by fronts and geostrophic adjustment must be considered too. The utility of Global Positioning System (GPS) radio occultation (RO) observations for the detection of convective systems is tested. A collocation database between RO events and convective systems over sub-tropical to mid-latitude mountain regions, close to the Alps and Andes is built. From the observation of large amplitude GW structures and the absence of jets and fronts, subsets of RO profiles are sampled. A representative case study among those considered at each region is selected and analyzed. The case studies are investigated using mesoscale WRF simulations, ERA Interim reanalyses data and the measured RO T profiles. The absence of fronts or jets during both case studies reveals similar relevant GW features (main parameters, generation and propagation). Orographic and convective activity generates the observed GW. Mountain waves above the Alps reach higher altitudes than close to the Andes. In this last case a critical layer prevents for the propagation of GW packets up to stratospheric heights. The case studies are selected also because they illustrate how the observational window for GW observations through RO profiles admits a misleading interpretation of structures at different altitude ranges. From recent results, the distortion introduced in the measured atmospheric vertical wavelengths by one of the RO events is illustratively discussed. In the analysis, both the elevation angle of the sounding path (line of tangent points) and the gravity wave aspect ratio estimated from the simulations and the line of sight, are taken into account.
both case studies, a considerable distortion, over- and underestimation of the vertical wavelengths measured by RO may be expected.

1. Introduction

The Global Positioning System (GPS) radio occultation (RO) technique has been proven to be a powerful tool to analyze meteorological tropospheric features with a moderate/high spatial and temporal resolution in essentially any meteorological condition. Its ability to penetrate clouds allows to retrieve temperature ($T$) and water vapor pressure ($e$), amongst several other atmospheric variables with high vertical resolution close to the near surface. Vertical profiles of $T$ are provided with an accuracy of less than 1 K (e.g., Kursinski et al., 1997; Steiner and Kirchengast, 2005; Scherlin-Pirsch et al., 2011; 2017) in the troposphere to lower stratosphere and specific humidity with an accuracy of about 0.3 g kg$^{-1}$ to 0.1 g kg$^{-1}$ in the lower to middle troposphere (Kursinski and Gebhardt, 2014). Although measurements are taken irregularly in time and space, they provide a global coverage. Data are available from several missions such as the CHAllenging Minisatellite Payload (CHAMP), Satélite de Aplicaciones Científicas-C (SAC-C), Gravity Recovery and Climate Experiment (GRACE), or the Formosa Satellite mission-3/Constellation Observing System for Meteorology, Ionosphere, and Climate mission (hereafter referred to as COSMIC), and found to be of high quality and consistency in the troposphere and lower stratosphere (e.g., Steiner et al., 2011; 2013; Angerer et al., 2017, this AMT special issue).

Biondi et al. (2011) recognized double tropopause events using bending angle (BA) anomalies derived from GPS RO measurements from different missions. Later, Biondi et al. (2014) found that the GPS RO technique is useful for understanding the thermal structure of tropical cyclones and possible overshootings into the stratosphere. The complexity of the relationship between deep convection and flow convergence over mountains has been widely studied. Demko et al. (2009) showed that during days with deep convection, the convergence over mountains is weaker than on days when deep convection does not occur.

Over the Alps, considering the kinematic and dynamic features of divergence, flow splitting or mesoscale vortices, it is possible to find regions which initiate or intensify the storms (Bica et al., 2007). Thermally driven flows over the Alps are associated to convergence caused by large-scale topographic heat flow (Langhans et al., 2011). These flows supply moisture from source regions close to the surface, which stimulates the initiation of deep convection (e.g. Barthlott et al., 2006). Gladich et al. (2011) mentioned that southward oriented reliefs receive more solar radiation, resulting in a warmer atmosphere in comparison with flat terrain. Also, the orography presents a negative energetic balance as compared to flat regions.

Extratropical regions in the Southern Hemisphere show strong wave activity close to the Andes and to the Antarctic Peninsula (e.g., Eckermann and Preusse, 1999; de la Torre et al., 2012; Hierro et al., 2013). The eastern side of the Andes at mid-latitudes, between the subtropical and polar jets (Houze, 2012), is a natural laboratory for gravity waves (GW), in particular mountain waves (MW). The dynamic processes
involved in convection over this region have been analysed, e.g., by de la Torre et al. (2004), who found
that anabatic winds act as triggering mechanism in the presence of moist enthalpy under unstable
75 conditions. A relationship between MW and the development of deep convection was found by de la
Torre et al. (2011). Through the design of several non-dimensional numbers related to storms
development and MW energy, Hierro et al. (2013) found that MW are able to provide the necessary
energy to overcome a surface stable layer. Vertically propagating short-period GW strongly affect the
general circulation as well as the structure of the middle atmosphere (e.g., Dutta et al., 2009).

Convective activity is one of the most important sources of GW through the release of latent heat,
contributing to the interaction between waves and mean flow in the middle atmosphere (e.g., Alexander,
1995; Pandya and Alexander, 1999). When a convective cloud reaches the mean flow, waves which
propagate upstream are generated (Beres et al., 2002 and references therein). Convective instability, in
turn, yields oscillatory movements, which give place to GW that propagate vertically as a harmonic
oscillator (e.g., Fritts and Alexander, 2003). Several authors have analyzed the main mechanisms which
describe the possible sources of gravity waves generated by convection. In the “obstacle effect”, the
background finds a barrier given by the convective flow (Clarke et al., 1986). Fovell et al. (1992),
proposed a mechanism where updrafts and downdrafts reach the tropopause, generating high-frequency
GW. Röttger (1991) studied penetrating cumulus convection which generates GW by transferring kinetic
energy from the troposphere to the lower stratosphere.

Evan et al. (2012) determined that the Weather Research and Forecasting (WRF) mesoscale model
(Skamarock et al., 2008) is able to simulate stratospheric GW, when it is run under actual boundary
95 conditions. It was also possible to resolve GW generated by convection in the tropics. Stephan
Alexander (2014), in turn, showed that WRF physics parameterizations are not decisive to get good
results from GW simulations. From WRF simulations above the Southern Andes, de la Torre et al. (2012)
detected systematic large-amplitude, stationary, nonhydrostatic GW structures, forced by the mountains
up to the lower stratosphere and persisting for several hours. Their dominant modes were characterized by
90 horizontal wavelengths ($\lambda_H$) of around 50 km. The vertical wavelengths ($\lambda_Z$) were estimated to be
between 2 km and 11 km. Over the Andes region, de la Torre et al. (2011) detected two main modes of
mountain waves with large amplitude and high intrinsic frequency. Over the same region, Hierro et al.
(2013) found stationary modes with $\lambda_H$ between 40 km and 160 km and $\lambda_Z$ of around 7 km. de la Torre et
al. (2015), analyzing storms in the presence of MW, distinguished two different structures in vertical
wind simulations. Both of them seem to be fixed to the mountains, defining systematic updraft and
downdraft sectors. GW parameters were analyzed from band-pass and wavelet analysis, indicating for the
cases analyzed the presence of short $\lambda_H$ and long $\lambda_Z$, as expected for high intrinsic period GW.

The motivation of the present work is two folded: First, to find a set of collocations among GPS RO
105 profiles and mesoscale sub-tropical convective systems under reasonable conditions of proximity in
space and time occurrence over orographic regions (Alps and Andes). We use this dataset to test the
utility of Global Positioning System (GPS) radio occultation (RO) observations for the detection of
convective systems. To detect the cloud top altitude from the RO profiles, we apply a technique
based in the anomay in the BA. Secondly, the GW structures are analyzed and discussed for two
selected case studies detected in the absence of jets and fronts, from high resolution mesoscale model simulations and reanalysis data. The possible determination or misleading interpretation of GW parameters from GPS RO is discussed in detail for these case studies. Sect. 2 outlines the RO data used and the methodology applied and describes the two subsets of RO events retrieved during convective activity close to Alps and Andes ranges. In Sect. 3, one case study at each region is selected and relevant GW features are analyzed from the simulation, the reanalysis data and the measurement of both RO events. In Sect. 4, conclusions are given.

2. Data and methodology

The utility of RO observations for the investigation of convective systems (Biondi et al, 2012; 2015b) and GW over orographic regions in Europe and South America (Alps and Andes mountains) is tested. It is known that a sharp spike in RO BA is highly correlated to the top of the cloud, corresponding to anomalously cold temperatures within the cloud. Above the cloud, the temperature returns to background conditions, and a strong inversion appears above the cloud top. For usual tropospheric cloud tops, the $T$ lapse rate within the cloud often approaches a moist adiabat, consistent with rapid undiluted ascent within the convective systems.

We built a collocation database between RO observations and mesoscale convective systems over subtropical to mid-latitude mountain regions. The selected regions for the Alps and Andes are [40°N to 55°N, 0°E to 20°E] and [20°S to 40°S, 60°W to 74°W], respectively (Fig. 1). We use RO data processed at the Wegener Center for Climate and Global Change (WEGC) with the Occultation Processing System (OPS) version 5.6 (Schwärz et al., 2016), based on excess phase and orbit data version 2010.2640 from the University Corporation for Atmospheric Research (UCAR) from the CHAMP, SAC-C, GRACE, and COSMIC missions. We analyse $BA$ and $T$ profiles which are available from near surface up to 40 km altitude with 100 m vertical sampling.
Figure 1: The Alps (right) and Andes (left) regions selected to build a collocation database between RO data and cloud data over sub-tropical to mid-latitude mountain regions. Convective systems are located in time and space using the global deep convective tracking database of the International Satellite Cloud Climatology Project (ISCCP) (Rossow et al., 1996), from January 2006 to July 2008. This period was chosen due to the constraints and limitations imposed by the ISCCP database and the COSMIC data. The first source, available between 1983 and 2008, is currently incomplete and being reprocessed. The global ISCCP data set, with a horizontal grid resolution of 30 km and a nominal time resolution of 3 h, is based on brightness temperatures from geostationary satellite measurements. It provides information on the location and extent of mesoscale deep convective cloud systems and their properties. The parameters extracted from ISCCP data, are: time of occurrence, center (mass center) and radius of the storm. The COSMIC mission started in June 2006.

The selection criterion applied in the present work considers the position of the RO observation with respect to the center of the storm, thus providing 294 and 50 collocations at the Alps and Andes regions respectively. According to this criterion, it is observed whether the latitude and longitude corresponding to the mean tangent point (TP) belonging to each RO profile is located within a radius of 100 km with respect to the center of the storm, as provided by ISCCP. A maximum time interval of 3 h was allowed between each RO event and the data from ISCCP. The collocated events were selected using cloud data from geostationary satellites METEOSAT (Europe) and GOES (South America) (Fig. 2).

![Figure 2. Collocated events between GPS RO profiles and convective systems. The latitude and longitude corresponding to the mean tangent point belonging to each RO is located within a radius of 100 km respect to the center of the storm. It is detected in a time interval less than 3 hours. The Alps region (-left- 294 collocations). The Andes region (-right- 50 collocations).](image)

The collocated RO BA and T profiles were further used to determine the vertical structures of sub-tropical convective systems over orographic regions. In order to detect the cloud top altitude with RO, we applied the anomaly technique developed by Biondi et al. (2013) for anomalous atmospheric profile and cloud top detection of convective systems. Each BA and T profile collocated with a storm was referenced against a RO background reference climatology profile, which was extracted for the same location and the same
month from the global RO BA and T reference climatology, respectively (for details see Biondi et al. (2017)). We then subtracted the collocated RO reference climatology profile from the individual RO profile. BA was normalized with respect to the reference climatology profile in order to obtain a fractional anomaly profile. The cloud top altitude is represented as a pronounced spike in the vertical BA anomaly structure and correspondingly, in the T anomaly profile.

Taking into account the wave signatures observed in the RO T profiles (see below), GW were analyzed from two different data sources: mesoscale model simulations and ERA Interim reanalyses data. The WRF simulations (Skamarock et al., 2008) were performed using 1°×1° National Center of Environmental Prediction (NCEP) Global Final Analysis (FNL), as boundary conditions. They are conducted in four nested domains (27 km, 9 km, 3 km, and 1 km respectively) with 60 vertical levels. A sponge layer was applied in the upper 3 km. The size of the inner domain in the Alps region is about 300 km x 200 km and that of the Andes region about 300 km x 300 km. For each domain, the microphysical schemes used were the following: WRF Single Moment-6 class (WSM6; Hong et al., 2004); Yonsei University (YSU; Hong et al., 2006) to represent the planetary boundary-layer (PBL) physics; Rapid Radiative Transfer Model Longwave (RRTM; Mlawer et al., 1997) and MM5 Dudhia Shortwave (Dudhia scheme; Dudhia, 1989) for radiation processes; the Noah land surface model (developed jointly by NCAR and NCEP; Skamarock et al., 2008) and Monin–Obukhov scheme; (Monin and Obukhov, 1954) for surface physics and thermal diffusion processes respectively. The cumulus parameterization used was the New Grell scheme (Grell3; (Grell and Devenyi, 2002)) for the first two domains, while no-cumulus parameterization was selected for the two inner one.

In the present study, a GW climatology from the available limited number of collocated cases is not intended. Instead, by focusing on selected large amplitude RO T profiles, wave features at both mountain subtropical regions are compared. In doing so, five collocations were pre-selected in each region (central panels in Fig. 3a-b). All of the pre-selected collocations show some spikes in the BA profile, from which one is correlated with the cloud top of the corresponding convective structure. Large amplitude oscillations that may be associated to hydrostatic and/or non-hydrostatic GW structures are evident. The analysis is further conducted on two peculiar case studies (central frames in Fig. 3a-b), defined by the simultaneous absence of jets and fronts. When these last GW sources (e.g. Fritts and Alexander, 2003) coexist with other sources, the analyses is expectedly more intricate.

In the present case studies, GW structures are conceivably limited to orographic and/or convective sources. The RO case studies exhibit attractive oscillatory features and correspond, in the Alps region, to 02 Feb 2008, 17:24 UTC (47.29°N, 12.02°W) and in the Andes region to 19 Dec 2006, 16:56 UTC (25.35°S, 67.37°W).
Figure 3: Pre-selected collocations between GPS RO profiles and convective developments in a) the Alps region and b) the Andes region. Shown are absolute profiles and anomaly profiles for bending angle.
(green) and temperature (red) and the respective climatology profile (dotted). The cloud top height is indicated by a blue star. **The collocations pre-selected for case studies are based on observed large amplitude wave features in the RO $T$ profiles. The two selected case studies are based on the simultaneous absence of GW sources given by jets and fronts.**

3. **WRF model simulations, ERA Interim reanalyses data and GPS RO observations**

The GW in the two selected study cases at the Alps and Andes region are investigated from WRF numerical simulations, ERA Interim reanalyses data and the collocated GPS RO observed profiles.

3.1. **Case study at the Alps region**

3.1.1. **Numerical simulations of GW structures**

At the Alps region, the dynamic and thermodynamic parameters are simulated. In Fig. 4 the vertical air velocity ($\delta w$) in the considered area is shown. Two altitude levels (8 km and 12.5 km) are chosen, above and below the cloud tops (situated at 9.8 km height) at 17:00 UTC. The $\delta w$ field is represented a few minutes before the RO event (17:24 UTC).
Figure 4: Simulated high resolution (inner WRF domain) $\delta w$ structures at the Alps region (defined in Fig. 1). Two altitude levels, a) above and b) below the clouds top are shown. The line of tangent points (LTP) corresponding to the collocated RO event is indicated in both panels from lower (3 km) to upper (40 km) points (solid black line). The line of sight (LOS, dotted black line) at both levels is also indicated.

The mesoscale outputs were obtained every 60 min. It is generally accepted that $\delta w$ adequately highlights the main GW amplitudes and wavelengths characteristic of MW. These, usually belong to high and medium intrinsic frequency regimes. In Fig. 4, coherent, mostly bi-dimensional GW structures with constant phase surfaces are seen. They are mainly oriented along S-N direction and slightly tilted to N-E with increasing latitude. The mean horizontal wind is directed from NW to SE at 700 hPa, causing the apparent forcing of MW. It is equal to $[U,V] = [3; -3]$ m/s at 18 UTC. Prevailing amplitudes and $\lambda_H$ ranging between 1-2 m s$^{-1}$ and 20-60 km respectively are distinguished. Two main features may be remarked at both levels. GW amplitudes are weaker below than above the
cloud tops and two different structures are visible. One structure is stationary and the other is not stationary. The last one is zonally and meridionally displaced when observed at 1-hour intervals during the evolution of convection (not shown). The GW sources seem to be orographic forcing and associated to the clouds development respectively. $\delta v$ amplitude values up to 2 m s$^{-1}$ correspond to MW with short horizontal wavelength. These $\delta v$ perturbations exhibit, as expected, the presence of MW more clearly than $\delta T$. (Fig 5a). Contrarily, the non stationary GW with longer $\lambda_H$ and amplitude values above 2 K are more evident in $\delta T$ than in $\delta v$, as a function of longitude and latitude (Fig 5b and 5c). Systematic $\lambda_Z$ values $\sim$ 8 km, associated to these longer $\lambda_H$ are appreciated. In these figures, the vertical line indicates the position of the RO mean TP. The orographic amplitudes are more significant early in the morning, exhibiting a general decrease with increasing local time (not shown). They reach large amplitudes at stratospheric heights beyond the tropopause, located at 11 km. No critical levels for MW or reflection effects are observed (Fig 5d). The strongest orographic structures are observed until the early afternoon. On the other hand, the non-stationary GW packets are generated between 12 km and 17 km height, during the convection development after mid-afternoon and radiated above the cloud tops. The longer $\lambda_H$ values are not well defined, suggesting the coexistence of two or more non-stationary modes.

Figure 5. Simulated high resolution GW structures at the Alps region, showing a) $\delta v$ and $\delta T$ signatures as a function of b) longitude and c) latitude. Non-stationary/stationary GW with longer/shorter horizontal wavelength are more clearly seen in $\delta T$ / $\delta v$. d) Zonal and meridional mean wind. The dotted line indicates the position of the TP.

3.1.2. Analysis of gravity waves in the RO observation
The wavelike structure of the RO T profile, retrieved at the Alps region is analyzed. This profile is shown in the central panels of Fig 3a. Its horizontally projected line of tangent points (LTP) is seen in Fig. 4.

Figure 6: a) Retrieved RO T vertical profile (black line) and its corresponding low-pass background component TB (red line) at the Alps region. b) Remaining oscillation (black), isolated after applying a band-pass filter (red) and a double filtering process to the background (black dotted) profile. c) Continuous wavelet transform (CWT) applied to the perturbation T structure, as a function of the vertical wavelength. The RO event took place at 17:24 UTC.

In doing so, the perturbation component of this profile is removed (Fig. 6a). If a simple band-pass filter is applied (e.g., de la Torre et al, 2006), the “tropopause problem” must be faced, as far as RO T profiles are available as a function of altitude. As pointed out by Alexander et al. (2011), even if filters with ideal cut-offs exist, part of the problem would still be there because the tropopause kink usually departs from a sinusoid or any other function that may be used as a basis. Real filters do not yield ideal spectral component isolations (side effects are amplitude reduction for example) and may need some manual fine tuning procedures to optimize their performance. After a “perfect” band-pass is used, there should be no remaining components at wavelengths outside the considered range. The method here applied consists in two steps. (i) A bandpass filtering to isolate the wavelength range of interest to separate the background and eliminate the noise was used. (ii) A
cutoff larger than or equal to the bandpass upper limit was applied. This allows to remove large wavelengths representing background behavior or trends still present and to force a zero mean. The tropopause kink in \( T \) can be viewed as the surrounding of a long sinusoidal peak. In the first step, a bandpass between 1 km and 10 km, and in the second step, a cutoff of 10 km are applied. The resulting filtered \( \delta T \) profile is marked by the solid black line in Fig. 6b. A continuous wavelet transform (CWT) is finally applied to the remaining \( \delta T \) wave structure (Fig. 6c).

The CWT is a useful method to detect the main oscillation modes present in a signal analysis. As it is known, it is a powerful tool for studying multiscale and non-stationary processes occurring over finite spatial and temporal domains (Lau and Weng, 1995). It allows detecting short-period as well as long-period oscillations. The CWT compares the original signal against a set of synthetical signals, which are called mother wavelets, obtaining correlation coefficients. The comparison between signals is carried out through a process of translation and contraction or dilation of the mother wavelet in each signal portion. This process is repeated for all scales of mother wavelets, allowing the location of short life and high-frequency signals like sharp changes, thus obtaining detailed information. In this work, the mother wavelet selected is the Morlet wavelet (Morlet, 1983), which consists of a flat wave modified by a Gaussian envelope. Fig. 6c shows a clear GW signal throughout the tropo-stratospheric region, with prevailing \( \lambda_z \approx 4 \) km. A second considerably weaker mode is also present in the tropospheric region, with \( \lambda_z \approx close to 7 \) km.

To search for a possible correspondence among these two modes and the structures observed in Figs. 4 and 5, the expected amplitude attenuation effects must be considered (P. Alexander et al., 2008). In particular, for this RO event, the LOS stands at each TP almost exactly perpendicular to the GW phase surfaces observed in Fig. 3, at 88° from North direction (dotted lines in Fig. 4). This should prevent the observation of vertical oscillations corresponding to short \( \lambda_H \) structures, as seen in Fig. 4. In this figure, the quasi perpendicular orientation of the constant GW phases relative to the line of sight (LOS) is appreciated. This clearly does not benefit the GW detection during the RO event. The horizontal averaging of RO retrievals produces an amplitude attenuation and phase shift in any plane GW, which may lead to significant discrepancies with respect to the original values (Alexander et al., 2008). The lower and upper altitudes of LTP are 3 km and 40 km, respectively. The observation of GW structures with short \( \lambda_H \) observed in Fig. 4, will expectedly suffer amplitude attenuation and should not be visible by GPS RO events (Preusse et al., 2002; P. Alexander et al., 2008). An estimation of the expected attenuation in the stationary and non-stationary structures during the RO sounding is performed. The amplitude attenuation factor defined as the ratio between derived and original amplitudes is deduced. This factor is a function of the ratio of GW vertical and horizontal wavelengths and the angle on the horizontal plane between the wave fronts and the line of sight (LOS). Ideal conditions that lead to no attenuation are, respectively, a null ratio between vertical and horizontal wavelengths and a null angle between LOS and the fronts. The analyzed case study shows the corresponding values of both parameters and the attenuation factor (range 0-1 covers from null to full output) (Table 1). According to these
results, in the Alps case study a considerable attenuation of mountain waves below the tropopause is expected.

3.1.3. Analysis of GW structures from ERA Interim data.

The resulting estimation of a negligible attenuation factor at both height levels shown in Fig. 4, confirms that the GW cannot be captured there during the RO event. It is clear that the mesoscale simulations are not enough to explain the observed GW structure. To understand the origin of the oscillation observed in the RO $\Delta T$ profile, the possibility that the presence of GW with scale long enough is not able to be captured by mesoscale WRF simulations is analyzed. According to this, the corresponding ERA Interim reanalyses data are observed. In Fig. 7, $\Delta T$ resulting from these data at 22 km height reveals a defined non-stationary oscillation propagating in NW-SE direction, with $\lambda_X$ and $\lambda_Y$ equal to 530 and 650 km respectively. The attenuation factor derived from these values is estimated in 0.90. This value is consistent with a clear oscillation observed at stratospheric heights in the RO profile, with $\lambda_Z$ equal to 4 km (Fig. 6c and Table 1).

![Figure 7. ERA Interim $\Delta T$ data corresponding to the case study at the Alps region. The red point indicates the mean TP](image-url)
vertical/horizontal wavelength ratio | angle between wave fronts and LOS | attenuation factor
---|---|---
Alps above | 0.02 | 48 | 0.90
Alps below | 0.51 | 78 | 1e-49
Andes above | 0.01 | 32 | 0.99
Andes below | 0.35 | 7 | 0.44

Table 1. Attenuation factor as a function of the ratio of GW vertical and horizontal wavelengths and the angle, on the horizontal plane, between the wave fronts and the LOS. Alps and Andes case studies above and below the tropopause level. A considerable/partial attenuation below the tropopause at the Alps/Andes region is expected.

Independently to the expected attenuation, an additional distortion must be considered due to the slanted nature of the sounding. This is introduced in the measured GW $\lambda_H$ and $\lambda_Z$ by atmospheric soundings performed in any other than vertical and horizontal direction. This is the case during GPS RO events or during radiosoundings (e.g., de la Torre and Alexander, 1995; P. Alexander et al., 2008). In the case of RO events, a visibility condition imposed to the line of sight (LOS) described in P. Alexander et al. (2008), must be satisfied. The distortion is more or less significant, depending on the elevation angle of the sounding path and the GW aspect ratio (de la Torre et al., 2018, hereafter referred to as T18). For example, during vertically directed measurements with a single lidar, $\lambda_H$ cannot be detected but $\lambda_Z$ is not distorted. A clear advantage of numerical simulations or reanalyses data is that they are not affected by this systematic error inherent to any slanted atmospheric measurement. According to this, we must distinguish between “apparent” (i.e., RO observations) and “real” $\lambda_H$ and $\lambda_Z$ values. For this reason, the apparent 4 km oscillation observed in Fig. 6c must be carefully observed as a distorted signature, which in fact corresponds to a different real $\lambda_Z$ value (T18). Considerable under- or overestimations are in the general case expected, depending on the aspect ratio of GW and inclination of the LTP (T18 and Appendix).
3.2. Case study at the Andes region

3.2.1. Numerical simulations of GW structures

From the simulated dynamic and thermodynamic parameters, in Fig. 8 we show $\delta w$ at constant height levels for the Andes area, delimited in Fig. 1. Constant altitudes of 10 km, 16 km, below (Fig. 8a) and above (Fig. 8b) the cloud top (situated at 14 km height), respectively, and at 26 km (Fig. 8c), at 17:00 UTC, are selected. The $\delta w$ field is represented a few minutes before the RO event (16:56 UTC).

Figure 8: Simulated high resolution GW structures in the Andes region delimited in Fig. 1. Three constant altitudes, a) at 26 km, b) at 16 km (above) and c) at 10 km (below) the cloud tops (situated at 14 km) are selected. In this case, the mean LTP (black line) is located around 25.5°S and 67.1°W. The TP altitudes. The red point indicates the mean TP. The dotted line indicates the LOS crossing the TP corresponding to each selected altitude.

Coherent bi-dimensional GW structures with constant phase surfaces oriented from SW to NE are seen (Fig 8a and 8b). The mean horizontal wind vector at 700 hPa directed from NW to SE is $[U,V] = [7;-3]$ m/s at 18 UTC. de la Torre et al. (2015) have shown that immediately to the south of Central Andes, close to the mountain tops, two clearly different orographic GW structures are systematically observed at constant pressure levels. One structure type shows highly elongated alternating positive and negative
parallel δν bands, aligned almost in N-S direction. The second type presents a bi-dimensional distribution too, but exhibits alternating fringes of much shorter longitude, mostly in SW–NE direction. The mean wind that forces mountain waves exhibiting the 1D structures of the first type, presents an intense zonal gradient of zonal wind, veering to an increasing westerly mean wind with increasing latitude. The meridional wind component is usually negligible. In the 2D structures of the second type, at and below mountain top levels, a prevailing intense negative meridional wind with less zonal wind contribution is observed. In the case study shown in Fig. 8, the mean wind at 700 hPa with considerable negative meridional component, is associated to the second type. In Fig. 8a to 8c, additional orographic GW structures situated at the NE and SE of the domain are observed. They propagate from low altitudes until at least the upper limit of the simulations. These structures exhibit stationary circularly shaped wave fronts. They penetrate beyond the critical layer for orographic GW, situated at an almost zero wind level, near to 18 km height (Fig. 8a to 8c and 9d).

In Fig. 9a to 9c, as in the Alps case, δν perturbations exhibit the presence of mountain waves more clearly than δT. (Fig 9a). Nevertheless, in Fig 9b and 9c, the presence of two different GW structures, separated by a critical layer at 18 km as a function of longitude and latitude, is identified. The MW propagate upwards and just below the critical layer they increase their amplitude, with decreasing λz in agreement with linear GW theory. Inversely to the Alps case study, the orographic amplitudes at the Andes region are more significant in the afternoon. They exhibit a general increase since sunrise with increasing local time. Above the critical layer, non-stationary GW packets are generated during the convection development after mid-afternoon and radiated above the cloud tops. These longer λH values are well resolved by WRF and shorter from the simulations, than in the Alps case study. In the Andes case, there is almost no spatial coexistence between GW from both GW sources. A clear separation between orographic structures below the critical layer and convective GW above it, is quite evident.
Figure 9. Simulated high resolution GW structures at the Andes region, showing a) $\delta w$ and $\delta T$ signatures as a function of b) longitude and c) latitude. Non-stationary/stationary GW with longer/shorter horizontal wavelength and shorter/longer vertical wavelength, above/below the critical layer are appreciated. d) Zonal and meridional mean wind.

Next, the wavelike structure of the RO $T$ profile, retrieved at the Andes region. This profile is shown in the central panels of Fig 3b. Its horizontally projected LTP is seen in Fig. 8, is analyzed.

3.2.2. Analysis of gravity waves in the RO observation

The procedure is identical to the one applied in case study 1. The utility of the double filter applied is more obvious here than in the Alps case study. Also, the tropopause kink is sharper (Fig. 10b). For this RO event, inversely to the described situation in the Alps case study, the LOS stands at each TP almost aligned to the GW phase surfaces observed in Fig. 8, at 190° from north direction (dotted lines in Fig. 8). This may allow us to detect vertical oscillations in the RO profile corresponding to the short $\lambda_H$ MW structures seen below the critical layer in Fig. 8 and 9.
In Fig. 10c, a clear GW signal appears also in the Andes case, propagating throughout the tropostratospheric region with a prevailing $\lambda_z = 4.5$ km. Here again, attenuation and distortion effects must be considered. The computation of a partial attenuation factor (0.44, Table 1) at the troposphere confirms that the mountain waves at these levels can be captured during the RO event. In this estimation, $\lambda_x$, $\lambda_y$ and $\lambda_z$ values equal to 30, 100 and 10 km respectively are considered. In this case study, the mesoscale simulations are enough to explain the observed GW structure above the critical layer too. Clear signatures of $\lambda_x$, $\lambda_y$ and $\lambda_z$ equal to 350, 400 and 3 km respectively may be seen. These values yield a very high attenuation factor (0.99). To understand the origin of the oscillation observed in the RO $\delta T$ profile, we conclude that below the tropopause, the oscillation is completely due to orographic waves and above, to convective GW. In both cases, mesoscale simulations were able to capture the GW structures. In this case study, like in the Alps case, an expected distortion in the measured $\lambda_z$ value, due to the slanted nature of the sounding must be expected too.

4. Conclusions

From an initial set of collocations between convective systems and GPS RO observations, the applicability of these data sets for the detection and investigation of convective systems and GW over orographic regions is analyzed. In doing so, mountain regions of Europe and South America, over sub-tropical to mid-latitude regions, the Alps and Andes ranges, are selected. A collocation
database was built up. We use RO bending angle and $T$ profiles retrieved at the Wegener Center with processing version OPSv5.6. The storm systems are located in time and space according to the global deep convective tracking database ISCCP. From an initial set of 294 and 50 collocations at Alps and Andes regions respectively, a subset of 10 collocations are pre-selected. This pre-selection is based on the observation of large amplitudes, presumably GW, in the retrieved $T$ RO profiles. Two case studies are finally studied in detail, at the Alps and Andes regions, respectively. The case studies are investigated using mesoscale WRF simulations, ERA Interim reanalysis data and the measured RO $T$ profiles. The case studies considered are selected based on the absence of jets and fronts, in order to be able to filter out two relevant possible sources of GW. Similar GW regimes and dominant vertical and horizontal wavelengths, from convective and orographic origin, are found at both regions.

MW reach above the Alps higher altitudes than close to the Andes. The background mean wind above this last region imposes a critical level for mountain wave propagation, avoiding the propagation of GW packets up to stratospheric heights.

At the Alps, mostly bi-dimensional GW structures with constant phase surfaces are seen. The mean horizontal wind cause the apparent forcing of MW. Prevailing amplitudes and $\lambda_H$ ranging between 1-2 m s$^{-1}$ and 20-60 km respectively are distinguished. GW amplitudes are weaker below than above the cloud tops and two different structures are visible. One structure is stationary and the other is not stationary. The GW sources seem to be orographic forcing and associated to the clouds development respectively. $\delta w$ amplitude values up to 2 m s$^{-1}$ correspond to MW with short horizontal wavelength. These $\delta w$ perturbations exhibit, expectedly, the presence of MW more clearly than $\delta T$. Contrarily, the non-stationary GW with longer $\lambda_H$ and amplitude values above 2 K are more evident in $\delta T$ than in $\delta w$. Systematic $\delta w$ values close to 8 km, associated to these longer $\lambda_H$ are appreciated. The orographic amplitudes are more significant early in the morning, exhibiting a general decrease with increasing local time. They reach large amplitudes at stratospheric heights beyond the tropopause, located at 11 km. No critical levels or reflection effects are observed. The strongest orographic structures are observed until the early afternoon. The non-stationary GW packets are generated during the convection development after mid-afternoon and radiated above the cloud tops. The longer $\lambda_H$ values are not well defined, suggesting the coexistence of two or more non-stationary modes. From the RO profile, the perturbation component is removed, considering the tropopause obstacle to filter out the wavelike structure. A CWT is applied to the remaining $\delta T$. A clear GW signal throughout the tropo-stratospheric region, with prevailing $\lambda_Z = 4$ km is found.

The correspondence between these two modes and the structures observed in the simulations are investigated. In doing so, the expected amplitude attenuation effects in the RO sounding are considered. It is concluded that the LOS and the wavelength ratio should prevent for the observation of vertical oscillations corresponding to short $\lambda_H$ structures. This clearly does not benefit the GW detection during the RO event. The horizontal averaging of RO retrievals produces an amplitude attenuation and phase shift in any plane GW, which may lead to significant discrepancies with respect to the original values. An estimation of the expected attenuation in the stationary and non stationary structures during the RO sounding is performed. The amplitude
attenuation factor defined as the ratio between derived and original amplitudes is deduced. Ideal conditions that lead to no attenuation are, respectively, a null ratio between vertical and horizontal wavelengths and a null angle between LOS and the fronts. The analyzed case study shows the corresponding values of both parameters and the attenuation factor. In this Alps case study a considerable attenuation of mountain waves below the tropopause is expected. The resulting estimation of a negligible attenuation factor in the troposphere confirms that the GW cannot be captured there during the RO event. As the mesoscale simulations are not enough to capture and explain the observed GW structure the corresponding ERA Interim reanalyses data are observed. From these data at 22 km height, a defined non-stationary oscillation propagating in NW-SE direction with $\lambda_X$ and $\lambda_Y$ equal to 530 and 650 km respectively is observed. This explains the oscillation seen in the RO $\delta T$ profile.

At the Andes, coherent bi-dimensional GW structures with constant phase surfaces oriented from SW to NE, of a type already reported in a previous work, are seen. Additional orographic GW structures situated at the NE and SE of the domain are observed. They propagate from lower altitudes until at least the upper limit of the simulations. These structures, exhibit stationary circular wave fronts and penetrate beyond the critical layer for orographic GW, situated at an almost zero wind level, near to 18 km height. As in the Alps case, $\delta w$ perturbations exhibit the presence of MW more clearly than $\delta T$. The presence of two different GW structures, separated by a critical layer at 18 km is identified. The MW propagate upwards and just below the critical layer they increase their amplitude, decreasing $\lambda_Z$. Inversely to the Alps case study, the orographic amplitudes at the Andes region are, as usually, more significant in the afternoon, exhibiting a general increase with increasing local time. Above the critical layer, non-stationary GW packets are generated during the convection development after mid-afternoon and radiated above the cloud tops. In this case, there is almost no spatial coexistence between GW from both GW sources.

In the retrieved RO $\delta T$ profile a signal appears also propagating throughout the tropo-stratospheric region with a prevailing $\lambda_Z = 4.5$ km. A partial attenuation reveals that at the troposphere, MW can be captured during the RO event. In this estimation, $\lambda_X$, $\lambda_Y$ and $\lambda_Z$ values equal to 30, 100 and 10 km respectively are considered. In this case study, the mesoscale simulations are enough to explain the observed GW structure above the critical layer too. Clear signatures of $\lambda_X$, $\lambda_Y$ and $\lambda_Z$ equal to 350, 400 and 3 km respectively may be seen. These values yield a very high attenuation factor (0.99). It is concluded that below the tropopause, the oscillation is entirely due to orographic waves and above, to convective GW. In both cases, mesoscale simulations were able to capture the GW structures. In this case study like in the Alps case, additionally, an expected distortion in the measured $\lambda_Z$ value must be also forseen. This is due to the slanted nature of the sounding and depends on the GW aspect ratio too.
Appendix

The discrepancy between measured and simulated $\lambda_Z$ (an analogous discussion could be given regarding $\lambda_H$, too—see T17-) may be quantitatively explained as follows. It may be assumed that RO soundings yield $T$ profiles almost instantaneously in such a way that GWs are “frozen” in space during the entire LTP retrieval. The vertical “real” and “apparent” (or measured) wavelengths ($\lambda_e$ and $\lambda_{Z,ap}$, respectively) are related according to the following expression (T18):

$$\frac{\lambda_{Z,ap}}{\lambda_e} = \frac{1}{1 + \cot(\alpha) \cot(\psi)} \quad (A1)$$

where $\alpha$ is the elevation angle, defined by a straight sounding path direction and the horizontal plane, and $\cot(\psi)$ is the ratio between the horizontal wavenumber vector ($k_H$) projected on the vertical plane containing the LTP, and the vertical wavenumber $k_Z$. The ratio $k_H/k_Z = \lambda_Z/\lambda_H$ is also known as the GW aspect ratio = $\tan(\psi)$. It is defined the distortion as the ratio:

$$D = \frac{\lambda_{Z,ap}}{\lambda_e} \quad (A2)$$

and plot this parameter, following Eq. (A1), as a function of $\alpha$ and $\psi$ (red line in Fig. A1). For the LTP shown in Fig. 8, considering that both the horizontal and vertical excursion of LTP, as well as the upper and lower altitudes (40 and 3 km), are known, we infer an average $\alpha = 0.68$ rad. A different curve is obviously expected for different $\alpha$ values, although fitting a similar shape. The divergence at high $D$ values is only suggested by plotting its variability up to $D = 5$. The left green circle qualitatively indicates the $D-\psi$ GPS RO sector encompassing the functional relation among the 3 parameters. The right green circle is included, because an uncertainty between $\alpha$ and $\pi-\alpha$ for our estimated aspect ratio still remains from our previous estimation. The white, light grey and grey backgrounds indicate, for reference purposes, the non-hydrostatic, hydrostatic non-rotating and hydrostatic rotating GW regimes, respectively. Both quadrants are separated by a vertical dashed curve. The horizontal dashed line represents the non-distortion limit, where $\lambda_e$ and $\lambda_{Z,ap}$ should coincide. According to both possibilities (the internal regions defined by any of the green circles), in the case considered (Fig. 10c), there are two possibilities indicating an under- and an overestimation of $\lambda_e$ respectively. This uncertainty can be removed by inspection of Fig. 10 (see T18).
Figure A1: Distortion expected between measured and simulated $\lambda_Z$ (green circles) regarding the GW parameters derived from the GPS RO event above the Andes, as detailed in Figs. 8, 9 and 10. Both green circles illustrate possible combinations of the parameters for under- and overestimation of $\lambda_Z$.

5 Data availability

The WEGC OPSv5.6 RO dataset is available on request from WEGC and will be made publicly available soon. Data on convective systems used in this study are available from the global deep convective tracking database of the International Satellite Cloud Climatology Project (ISCCP) via <https://isccp.giss.nasa.gov/CT/>. Cloud data from METEOSAT are available from the EUMETSAT processing centre via <https://eoportal.eumetsat.int/userMgmt/login.faces> and data from GOES are available from NOAA via <https://www.class.ncdc.noaa.gov/saa/products/welcome>.

Author contributions.

R. Hierro, A. de la Torre, A.K. Steiner, P. Alexander and P. Llamedo made the study design, performed the computational implementation and analysis, performed the numerical modelling, created the figures, and wrote the first draft of the paper.

A.K. Steiner provided guidance on RO data and analysis aspects and contributed to finalizing the manuscript.

P. Cremades provided recommendations and assistance in the WRF simulations.
Competing interests. The authors declare that they have no conflicts of interest.

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