A Spectral Rotary Analysis of Gravity Waves: An Application during one of the SOUTHTRAC Flights

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Abstract

To understand the main orographic and non-orographic sources of gravity waves (GWs) over South America during an Experiment (Rapp et al, 2021, https://doi.org/10.1175/BAMS-D-20-0034.1), we propose the application of a rotational spectral analysis based on methods originally developed for oceanographic studies. This approach is deployed in a complex scenario of large-amplitude GWs by applying it to reanalysis data. We divide the atmospheric region of interest into two height intervals. The simulations are compared with lidar measurements during one of the flights. From the degree of polarization and the total energy of the GWs, the contribution of the upward and downward wave packets is described as a function of their vertical wavenumbers. At low levels, a larger downward energy flux is observed in a few significant harmonics, suggesting inertial GWs radiated at polar night jet levels, and below, near to a cold front. In contrast, the upward GW energy flux, per unit area, is larger than the downward flux, as expected over mountainous areas. The main sub-regions of upward GW energy flux are located above Patagonia, the Antarctic Peninsula and only some oceanic sectors. Above the sea, there are alternating sub-regions dominated by linearly polarized GWs and sectors of downward GWs. At the upper levels, the total available GW energy per unit mass is higher than at the lower levels. Regions with different degrees of polarization are distributed in elongated bands. A satisfactory comparison is made with an analysis based on the phase difference between temperature and vertical wind disturbances.

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Key Points:

- A rotary spectral analysis is proposed to classify possible sources of gravity waves according to their degree of polarization.

- From reanalysis data, the method is applied at a selected position during one of the flights of the SOUTHTRAC-GWExperiment.

- Upward and downward gravity wave structures from orographic and non-orographic origin with different degrees of polarization are observed.

22 **Abstract**

23 To understand the main orographic and non-orographic sources of gravity waves (GWs) over

24 South America during an Experiment (Rapp et al, 2021, https://doi.org/10.1175/BAMS-D-20-

25 0034.1), we propose the application of a rotational spectral analysis based on methods originally

26 developed for oceanographic studies. This approach is deployed in a complex scenario of large-

27 amplitude GWs by applying it to reanalysis data. We divide the atmospheric region of interest

28 into two height intervals. The simulations are compared with lidar measurements during one of

29 the flights. From the degree of polarization and the total energy of the GWs, the contribution of

30 the upward and downward wave packets is described as a function of their vertical

31 wavenumbers. At low levels, a larger downward energy flux is observed in a few significant

32 harmonics, suggesting inertial GWs radiated at polar night jet levels, and below, near to a cold

33 front. In contrast, the upward GW energy flux, per unit area, is larger than the downward flux, as

34 expected over mountainous areas. The main sub-regions of upward GW energy flux are located

35 above Patagonia, the Antarctic Peninsula and only some oceanic sectors. Above the sea, there are

36 alternating sub-regions dominated by linearly polarized GWs and sectors of downward GWs. At

37 the upper levels, the total available GW energy per unit mass is higher than at the lower levels.

38 Regions with different degrees of polarization are distributed in elongated bands. A satisfactory

39 comparison is made with an analysis based on the phase difference between temperature and

40 vertical wind disturbances.

41 **Plain Language Summary**

42 Atmospheric gravity waves (GWs) are of great importance in the transport of energy and

43 momentum through the atmosphere. Their sources can be broadly classified as stationary and

44 non-stationary. The southern tip of South America represents one of the most important natural

45 laboratories for detecting the coexistence of large-amplitude GWs. We present a spectral method

46 to establish a semi-quantitative classification of the different groups of GWs and their main

47 vertical direction of propagation. We apply the method on the basis of global model data.We

48 divide the lower and middle atmosphere into two vertical intervals and compare the model with

49 data from one of the instruments deployed during the experiment. From the degree of

50 polarization of the GWs, we describe the net contribution of the upward and downward wave

51 packets as a function of their spectral harmonics. The main subregions of upward gravity wave

52 energy flux alternate with subregions dominated by linearly polarized GWs and downward

53 gravity wave sectors mainly above the ocean. At the upper levels, the total available GW energy

54 per unit mass is higher than at the lower levels. A comparison is made between these results and

55 an independent analysis based on the known polarization relations for GWs.

56 **1 Introduction**

57 The complex structure inherent to frequently observed atmospheric gravity wave (GW)

58 ensembles constitutes a challenge that remains difficult to address (e.g., P. Alexander et al.,

59 2015a, b; de la Torre et al., 2019; Fritts & M.J. Alexander, 2003; Wickert et al., 2020). This is

60 mainly due to the time and space constraints imposed by the observational windows and by the

61 complexity of the atmospheric wave structures and other present phenomena (M.J. Alexander,

62 1998; Wu et al., 2006). The following basic classification of the main GW sources are: the flow

63 of the air forced by the orography (called mountain waves (MWs)), atmospheric convection, and

64 the spontaneous emission after geostrophic adjustment of the flow in the vicinity of jets and

65 fronts (Fritts & M.J. Alexander, 2003; Plougonven& Zhang, 2014; Zhang et al., 2004). In

66 particular, the usual assumption describes a scenario with dominant monochromatic linear GWs,

67 which would explain the transport of large fractions of the wave energy and momentum flux

68 through different atmospheric levels and synoptic conditions.

69 In a relatively simple GW scenario, the hodographic technique (see e.g.,Gubenko et al., 2020;

70 Vincent, 1984) requires a single coherent wave leading to the fluctuations that perturb the

71 horizontal velocity profile. For a single, linear, steady, non-dissipating, elliptically polarized

72 wave in a region with negligible vertical shear in the background wind (Eckermann, 1996), the

73 intrinsic frequency of the GWs can be obtained by the axial ratio of the ellipse (Cot& Barat,

74 1986), its horizontal propagation axis by the orientation of the ellipse major axis (Vincent

75 &Fritts, 1987) and the direction of the GWs vertical group velocity by the sense of ellipse

76 rotation with height (Hirota& Niki,1985). However, Eckermann & Hocking (1989) demonstrated

77 that hodographic analyses of profiles that contained a large number of GWs sometimes yielded

78 results that reflected the statistical properties of random incoherent fluctuations, rather than the

79 polarization characteristics. Nevertheless, the isolation and characterization of GWs when the

80 wave field consists mainly of a few monochromatic waves are quite straightforward.

81   From another perspective, spectral techniques allow searching for coherent waves within various

82   traceable wavelength bands. These methods are especially useful when the distribution of GW

83   energy is broadly assigned to wave packets with very different wavelengths, frequencies and

84   amplitudes (e.g., Hines, 1991). This may be a typical scenario in the geographic region

85   considered in this study. The analysis of the polarization characteristics of the GW spectrum may

86   provide a valuable semi-quantitative characterization of the GW ensemble (Eckermann, 1996;

87   Gonella, 1972; Leaman & Sanford, 1975; Mooers, 1973), specifically their dominant intrinsic

88   frequencies or wavelengths, vertical propagation direction of GW and GW energy and

89   momentum fluxes. This approach has been applied in the past to oceanic GWs (e.g., Leaman &

90   Sanford, 1975).

91   A classification of GWs by their sources is proposed: orographic (linearly polarized (LP)) or

92   non-orographic (elliptically polarized (EP)). This classification is based on their degree of

93   polarization. As is well known, the degree of polarization also corresponds to non-hydrostatic,

94   hydrostatic non-rotating or rotating GWs, following their intrinsic frequency regimes (e.g. Gill,

95   1982, Section 8.8). From For the polarization relations for the complex amplitudes of the zonal

96   and meridional perturbation velocity components (Vadas, 2013 –equation (B3); P. Alexander et

97   al., 2022 –equation (1)), it may be seen that an ellipse links both horizontal velocity components,

98   whereby the eccentricity equals the ratio of GW inertial to intrinsic frequency. As the

99   eccentricity lies between 0 and 1, a value close to 1 indicates a wave linearly polarized, which

100   corresponds to an intrinsic frequency close to the buoyancy frequency, within the non-

101   hydrostatic regime. An alternative to this proposal may be to rely on their time dependence

102   (stationary or non-stationary, respectively). In the present analysis, we will illustratively apply

103   the method considering model simulations with high spatial resolution at a fixed time. We leave

104   the time dependence classification based on mesoscale simulations for a future contribution.

105   The geographic region considered in this study includes the southern Andes, Patagonia, the

106   Antarctic Peninsula and the surrounding oceanic areas. It exhibits the world's strongest hotspots

107   of GW activity, taking place mainly during austral winter and early spring (e.g., P. Alexander et

108   al., 2010; de la Torre et al., 2012; Fritts et al., 2016; Hoffmann et al., 2013; Llamedo et al.,

109   2019; Rapp et al., 2021). An intense MW activity was observed by other studies above and to

110   the lee of the mountains, given the prevailing strong tropospheric westerly winds. Strong GW

111 activity is observed in the middle to upper stratosphere along 60°S, from the Drake Passage to

112 the South Pacific (see, e.g., Ern et al., 2006; Hindley et al., 2015; M. J. Alexander et al., 2010].

113 This circumpolar belt of almost zonally symmetric GW activity is related to strong momentum

114 fluxes and is sometimes referred to as the GW belt.

115 A precursory experiment to the one referred in this study, also performed in the southern

116 hemisphere in winter, was the Deep Propagating GW Experiment (DEEPWAVE) (Fritts et al.,

117 2016). It was conducted by several research flights with two aircraft from Christchurch, New

118 Zealand, involving various ground-based instruments, satellite datasets, and a variety of

119 numerical models (Bramberger et al., 2017; Fritts et al., 2016; Gisinger et al., 2017; Portele et al.,

120 2018; Smith et al., 2016).The Southern Hemisphere Transport, Dynamics, and Chemistry–

121 Gravity Waves (SOUTHTRAC-GW) mission, performed in September 2019, was based on a

122 synchronized multiple experimental platform. During this experiment, the complexity of the

123 interacting ensemble of GW activity below the mesopause, at extratropical southern latitudes

124 was again observed, as expected (Rapp et al. 2021).The experiment consisted in deploying three

125 main instruments dedicated to the measurement of GW signatures. In particular, the Airborne

126 Lidar for Middle Atmosphere research (ALIMA), a compact upward-pointing Rayleigh lidar

127 using a pulsed neodymium-doped yttrium aluminum garnet laser (Kaifler et al., 2020). The

128 campaign objectives are described in Rapp et al (2021).SOUTHTRAC-GW was the first airborne

129 field campaign devoted to GW dynamics in the atmosphere from the troposphere up to the

130 mesopause (5 to 80 km altitude) in the region considered here (Rapp et al., 2021). During the

131 experiment, 7 successful flights spanning a total of 60 hr were completed. The campaign period

132 coincided with the occurrence of a sudden stratospheric warming which created critical level

133 conditions at about 40 km altitude (Dörnbrack et al, 2020). Among many parameters,

134 measurements from temperature (T) and zonal (u), meridional (v) and vertical (w) wind

135 components were obtained. A preliminary analysis of the measurements and model results

136 revealed strong evidence for MW excitation over the Andes and subsequent vertical as well as

137 horizontal propagation, including refraction and downwind advection into the polar night jet and

138 along the GW belt (Rapp et al., 2021).

139 In order to interpret the observations, the sources of GWs and their propagation direction is very

140 important. Our main aim, after describing a rotary spectral method capable of detecting the

141 spatial distribution of dominant up- and down going GW energy, is to apply it to a

142 SOUTHTRAC case study. We selected one of the first flights, identified as ST08, performed

143 from 11 September at 23:05:36 UTC to 12 September 2019 at 07:21:14 UTC (Rapp et al., 2021).

144 The The method is based on the determination of the dominant degree of polarization of the GW

145 ensemble, as a function of the vertical wavenumber, height interval and geographic sector,

146 above the southern Patagonia, Drake Passage and Antarctic Peninsula. Stationary waves are

147 expected to be mostly linearly polarized (LP) and are included in the analysis. The method is

148 illustrated for a fixed time selected after the beginning of one of the HALO flights, when the

149 reanalysis data are available. ST08 was the flight with the best conditions for excitation and deep

150 mountain wave propagation and we chose the time when HALO crossed the highest mountains

151 for our reanalysis. The selected altitude ranges include the tropospheric and stratospheric

152 regions.

153 Section 2 introduces the spectral rotary method. In Section 3, the model and experimental data,

154 the expected limitations derived from the observational windows and the available time and

155 space resolution are described. The synoptic conditions and a validation of the simulated T

156 profile against the lidar data are performed at the fixed selected time. In section 4, the rotary

157 spectra method is applied to reanalysis data at a representative HALO position during one of the

158 SOUTHTRAC-GW flights. We separate the region considered into two non-overlapping tropo-

159 stratospheric and strato-mesospheric altitude intervals. The flight considered in this study reveals

160 an unusually deep propagation of stationary GWs up to mesospheric levels. In section 5, a

161 comparison is made with an independent method consisting in the calculation of the phase

162 differences between T and wperturbations (T' and w') and from there, the associated vertical

163 horizontal momentum flux. Section 6 provides a discussion and some conclusions that should

164 also be taken into account in future analyses and remaining case studies of the SOUTHTRAC-

165 GW Experiment.

166 **2 Spectral rotary analysis (SRA)**

167 As pointed out by Eckermann (1999), three statistical approaches may be used to characterize the

168 polarization ellipses defined from horizontal wind velocity perturbation data: the hodographic

169 method analysis (e.g., Cadet &Teitelbaum, 1979; Cot & Barat 1986; Vincent, 1984; Vincent &

170 M. J. Alexander, 2020), the cross-spectral analysis (e.g., Cho, 1995), and the spectral rotary

171   analysis (e.g., Eckermann & Vincent, 1989). As stated by Eckermann (1999), all three methods

172   are in some sense equivalent. The appropriate choice will probably depend on the scenario.

173   One particularly general form of the hodographic method is a description in terms of the so-

174   called Stokes parameters (e.g., Vincent & Fritts, 1987). This is an analysis technique derived

175   from the electromagnetic waves theory and is well described in many standard textbooks (e.g.,

176   Mishchenko, 2014). According to this method, any partially polarized wave motion can be

177   described completely and uniquely in terms of its Stokes parameters. Vincent & Fritts (1987)

178   applied such parameters in GW studies. The method assumes that any vertical profile of

179   horizontal wind velocity perturbations contains a partially polarized coherent wave field

180   embedded in an unpolarized, isotropic, noise-like background velocity field. The latter is

181   characterized by a variance equal to the sum of the average of u' and v' variances and a phase

182   accounting for the elliptical nature of the wave. If this phase is 0° or 180°, it implies a linear

183   polarization, 90° or 270° implies a circular polarization and any value in between implies an

184   elliptical polarization. The perturbation velocity vector will rotate anticyclonically with time and

185   space as one moves in a direction opposite to the phase velocity (Gill, 1982; Placke et al., 2013).

186   In the southern hemisphere, this means that upgoing waves (downward phase progression)

187   account for a wind vector that rotates anticlockwise with increasing height, while with

188   downgoing waves, a clockwise rotation is expected (Vincent, 1984). For atmospheric scenarios

189   with undeniably complex distributions of coexisting wavepackets, a spectral approach should be

190   undertaken, in order to recognize the statistically meaningful processes lying within.

191   In the process, a rotary-vector analysis method may be developed based on the assembly of a

192   complex vector consisting of 2 components of the velocity vector along perpendicular axes, in

193   particular, the zonal and meridional wind components (e.g., Gonella, 1972; Mooers, 1973).

194   Below, we adapted the mentioned developments to our purpose. After a Fourier transform of the

195   horizontal zonal and meridional residual wind components u' and v':

196     $$u'(z) = \frac{\pi}{2} \int_{0}^{\infty} [B_1(m) \cos(mz) + B_2(m) \sin(mz)] \, dm \qquad (1)$$

197   and

198 $\quad v'(z) = \dfrac{\pi}{2} \displaystyle\int_0^\infty [B_3(m)\cos(mz) + B_4(m)\sin(mz)]\, dm$ (2)

199 the spectral method gives the decomposition of the total available wave energy in terms of the

200 so-called clockwise and anticlockwise spectra, as a function of the vertical wavenumber (m). In

201 the present analysis, we choose the vertical z coordinate increasing downwards, following a

202 convention in the above mentioned previous spectral analyses in the ocean. That is, z = 0 at the

203 highest point of each of the two altitude ranges selected below. If one considers the horizontal

204 velocity vector to be u + iv, where u is the east (real) part of the horizontal velocity and v is the

205 north (imaginary) part, then, at each m, we can represent the above helix simply by:

206 $\quad u_m + iv_m = u_+ e^{imz} + u_- e^{-imz}$ (3)

207 with complex constants u_+ and u_-.

208 Then, it may be shown that (e.g., Gonella, 1972):

209 $\quad |u_+| = \dfrac{1}{2}[(B_4 + B_1)^2 + (B_3 - B_2)^2]^{1/2}$ (4)

210 and

211 $\quad |u_-| = \dfrac{1}{2}[(B_4 - B_1)^2 + (B_3 + B_2)^2]^{1/2}$ (5)

212 The anticlockwise and clockwise components of the energy per unit mass spectrum are given by:

213 $\quad S_+ = \dfrac{1}{2}(u_+^* u_+)$ (6)

214 and

215 $\quad S_- = \dfrac{1}{2}(u_-^* u_-)$ (7)

216 The integration over m under S_+ and S_- shows the relative contribution of each energy

217 component. It provides the partition of the total energy. However, it must be stressed that this is

218 an overestimation of the energy associated with the upgoing and downgoing waves. Low-

219 frequency GWs are not exactly circularly polarized except near the inertial frequency, but

220   elliptically polarized. Since an elliptically polarized wave can always be resolved into clockwise

221   and anticlockwise circularly polarized components, even a purely upgoing or downgoing wave

222   will contribute to both the clockwise and the anticlockwise spectra. In this sense, this analysis

223   must not be considered as strictly quantitative. Nevertheless, useful statistical information

224   regarding the prevailing up- or down-propagating GW packets may be obtained and, based only

225   on the nature of their polarization, their probable sources can be identified.

226   For the present analysis, we define the total rotational energy as

227    $E_T = S_- + S_+$ (8)

228   In turn, the difference

229    $C_R = S_- - S_+$ (9)

230   will be defined here as the 'rotary coefficient'. It is proportional to the average surface of the

231   ellipse. Its sign indicates the dominant polarization of the ellipse: positive for clockwise,

232   negative for anticlockwise. Then, a positive/negative C_R value means

233   clockwise/counterclockwise rotation with increasing z (namely, counterclockwise/clockwise

234   with increasing altitude).

235   Additionally, sometimes it is convenient to define the 'normalized rotary coefficient', as it is

236   bounded in the interval [-1, 1]:

237    $NC_R = (S_- - S_+)/(S_- + S_+)$ (10)

238   In effect, its magnitude will be +/- 1 for pure rotary motion and zero for unidirectional (linearly

239   polarized) motion. To set this out, we write $S_+ = p\,S_-$, with p real and ≥ 0, $NC_R = (S_- - p\,S_-) / (S_- +$

240    $p\,S_-) = (1 - p)/(1 + p)$.

241   Next, we calculate and plot C_R and NC_R, as they provide complementary information. For

242   example, for a given vertical wavenumber m and altitude interval, a latitude-longitude sector

243   with positive/negative C_R will reveal dominant up-/down-propagating GWs. Besides, if C_R is

244   close to zero, this may indicate two possible structures: i) the presence of linearly polarized

245   orographic GWs ($S_- \approx S_+$) or ii) a low total GW energy, where any polarization is possible.

246   Accordingly, for i), NC_R will be close to but different from zero and if ii), any NC_R value may be
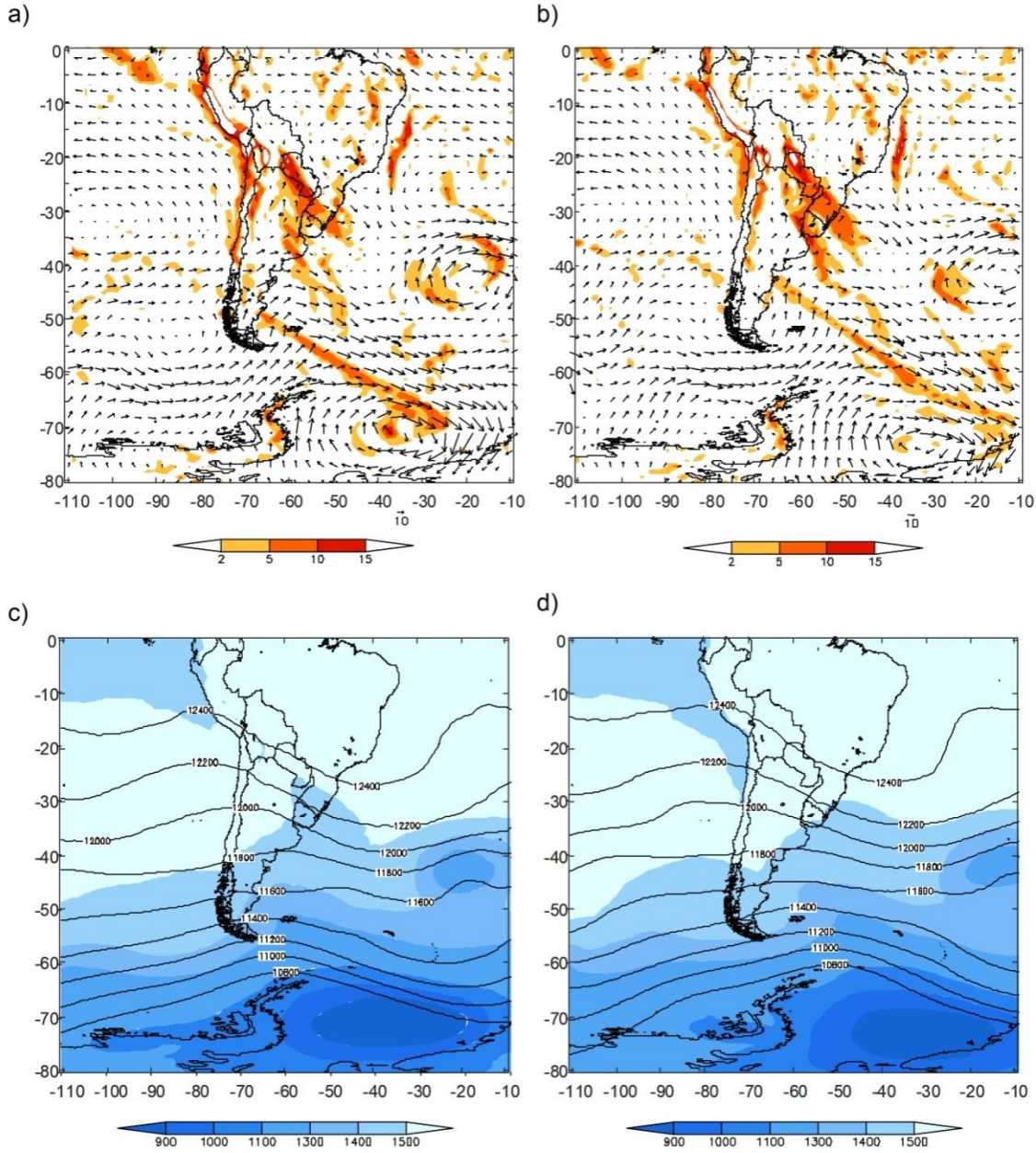
247   expected.

248   3 **IFS model reanalysis and experimental data: a case study**

249   The Integrated Forecasting System (IFS) of the European Centre for Medium-Range Weather

250   Forecasts (ECMWF) is a global, hydrostatic, semi-implicit, semi-Lagrangian model for

251   numerical weather prediction (horizontal resolution: 0.1°x0.1° (e.g., Polichtchouk et al., 2021).

252   Perturbations of temperature, zonal, meridional and vertical wind velocity were inferred by

253   subtraction from vertical profiles of T, u, v, w with a low pass cutoff at 15 km. GWs are

254   considered to be well represented in IFS analyses up to an altitude of 55 km (Ehard et al., 2015).

255   At higher altitudes, the simulated wave activity is damped within the model's sponge layer for

256   numerical reasons.

257   The ALIMA lidar system was located onboard the German research aircraft HALO. It yields

258   atmospheric density profiles in the altitude range from 20 to 90 km. T between 20 and 80 km

259   altitude is obtained with varying degrees of accuracy. From 20-60 km, 60-70 km and 70-80 km,

260   the corresponding error is 0.9, 2.9, and 6.5 K respectively. To separate GW induced temperature

261   perturbations from atmospheric background temperatures, a 30 min running mean is applied.
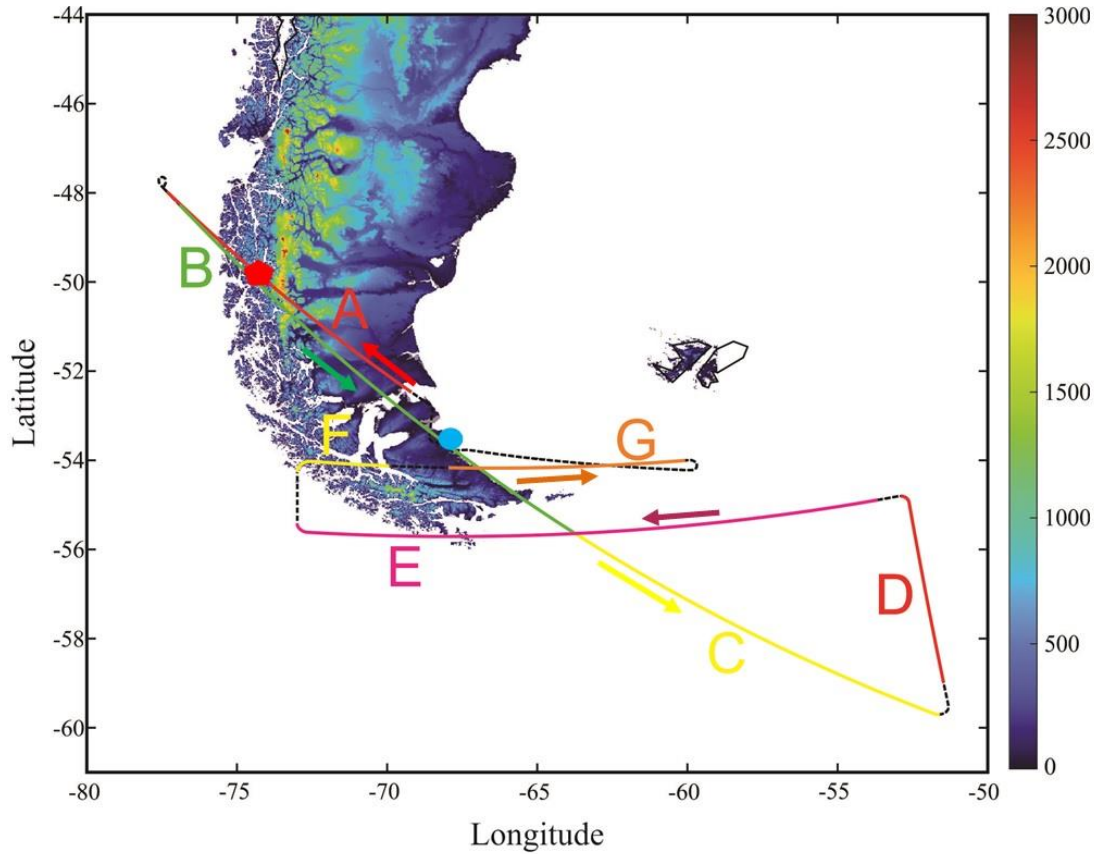
262   The seven HALO flights designed for the study of GW dynamics took off from Río Grande.

263   Each of them travelled along a trajectory typically around 7000 km.

264   The synoptic conditions for Flight 08 were dominated by a sudden stratospheric warming (SSW)

265   that was present during September 2019, as described by Dörnbrack et al (2020). Although it

266   was a weak event (Rapp et al., 2021), it affected the propagation conditions for MWs. In Figure

267   1a, the equivalent potential temperature shows a cold front at 850 hPa around 45-50°S. After 12

268   hours (Figure 1b), the air mass has been displaced to the north leaving the continent at lower

269   levels. At 200 hPa, the streamlines field shows a deepening of the 850 trough with an almost in-

270   phase N-S axis (Figure 1c) with a displacement to the east of the axis of the trough and an almost

271   divergent flow over southern Patagonia (Figure 1d).

Figure 1. Synoptic conditions from NCEP on September 12, 2019. Equivalent potential temperature [K] at a) 00 UTC and b) 12 UTC. Geopotential height [m] at c) 00 UTC and d) 12 UTC. Isolines correspond to 200 hPa and colorbar to 850 hPa.

The trajectory followed by HALO during this flight is shown in Figure 2. Taking into account the takeoff time and duration of this flight, below we will consider IFS simulations available within this interval, on 12 September, 00UTC. Six segments (or legs) from this flight may be identified, on the basis of their lengths and constant direction and pressure levels. The latitude-longitude coordinates corresponding to the extremities of each leg are provided in Table 1.

281

Figure 2. Trajectory of HALO flight ST08 during SOUTHTRAC-GW Mission performed on 11/12 September 2019. The position of the aircraft at 00:00 UTC on 12 September is indicated by the red pentagon. Seven segments (named from A to G - Table 1), correspond to seven constant pressure altitude legs followed by HALO. The orographic height is indicated in the colorbar [m]. HALO's takeoff location at Río Grande is shown by the blue circle.

L eg	Initiallati tude	Final latitude	Initiallongi tude	Final longitude	Staticpres sure [hPa]	Pressure altitude [Giez et al 2017] [m]	Beginning (min)	End (min)
A	52.47° S	47.99° S	69.20° W	77.31° W	238.3	10670	0	59
B	48.27° S	55.62° S	76.91° W	63.78° W	178.2	12510	69	149
C	55.62° S	59.70° S	63.78° W	51.63° W	178.2	12510	149	201

D	58.97° S	54.80° S	51.47° W	52.85° W	161.7	13130	208	245
E	54.89° S	55.42° S	53.66° W	73.00° W	147.1	13740	250	355
F	54.26° S	54.12° S	73.00° W	69.97° W	147.1	13740	363	376
G	54.17° S	54.01° S	67.96° W	60.12° W	133.6	14340	384	415

Table 1. Parameters defining the six constant pressure legs. Leg names A – G are as in Figure 1. Time intervals (in min) correspond to each leg in Figure 2, counting from the beginning of leg A.

The comparison between ALIMA data (resolution 0.9 km) and ECMWF IFS reanalysis on 12 September 00UTC is shown in Figure 3. It shows T as a function of altitude and time as retrieved from ALIMA during the full flight. The observed general variability mimics the latitude sectors and synoptic conditions cut across by HALO. The ALIMA T profile at 00UTC exhibits an intense wave structure up to the mesopause (Figure 3b). A relative agreement is observed in the stratosphere. The model progressively fails to solve the wavelike structure above 55 km. Note that experimental vertical profiles of horizontal or vertical wind are not available from this campaign.
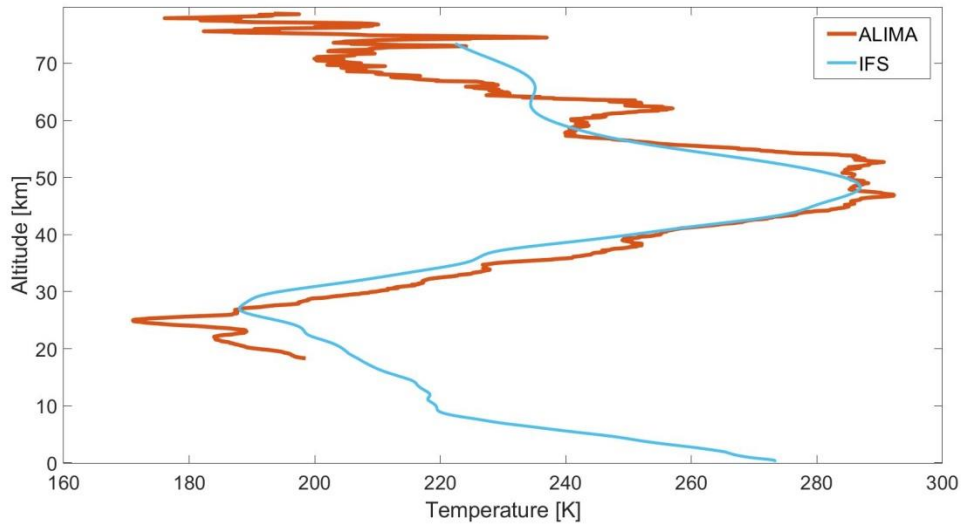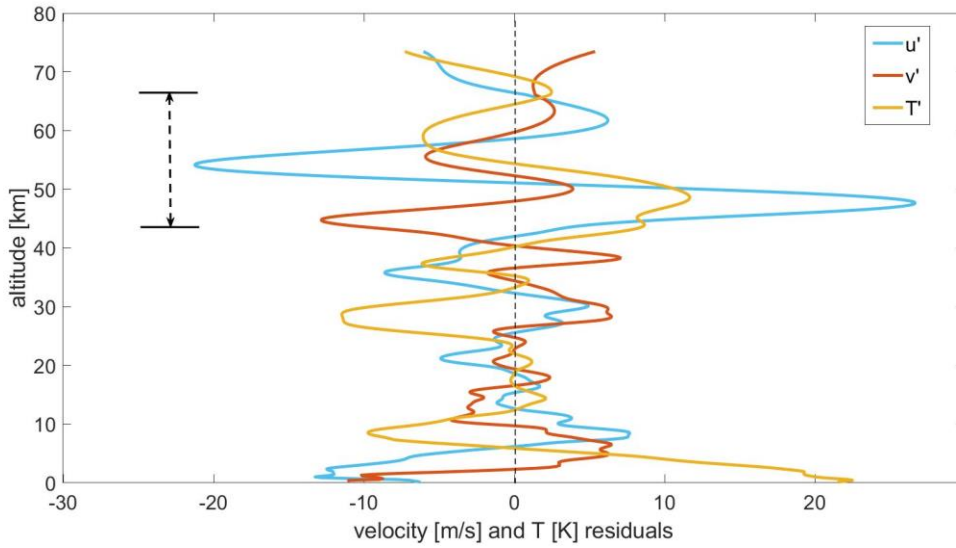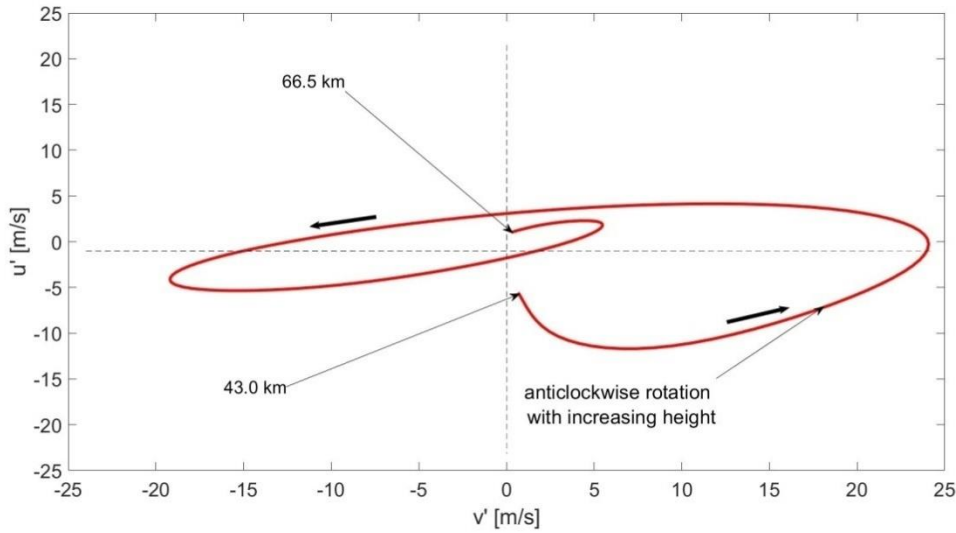
a)

b)

301

Figure 3. (a) Time-altitude section of temperature retrieved by the ALIMA lidar during flight ST08 along the flight track covering different regions and containng sharp turns as shown in Fig. 2. The dashed white line marks 0 UT on September 2019 when HALO crossed the highest peak of the southern Andes at 50.01 S and 74.97 E and for which we use IFS reanalysis. (b) IFS and ALIMA T for this time are compared.

Figure 4a show the IFS u', v' and T' residuals at the 00UTC HALO position at 50.01 S and 73.97 E. A highpass runing mean filter was applied to keep vertical wavelengths below a cutoff of 15 km in order to retain in the profiles mainly GWs, filtering out possible and non negligible planetary wave and tide contributions. A general more intense GW activity is observed in the strato-mesosphere regions compared to lower levels. Note the large amplitude oscillation in the selected vertical interval. Despite partially exceeding our imposed limit where the sponge begins at 55 km, the vertical interval between 43.0 and 66.5 km allows to illustrate the classic hodographic method. In Figure 4b, an anticlockwise rotation of the horizontal velocity perturbation with increasing altitude is observed in the selected interval. This indicates a dominant upgoing and probably non-orographic inertia GWpossibly generated close to jet levels, where the GW amplitude was observed to be considerably smaller.
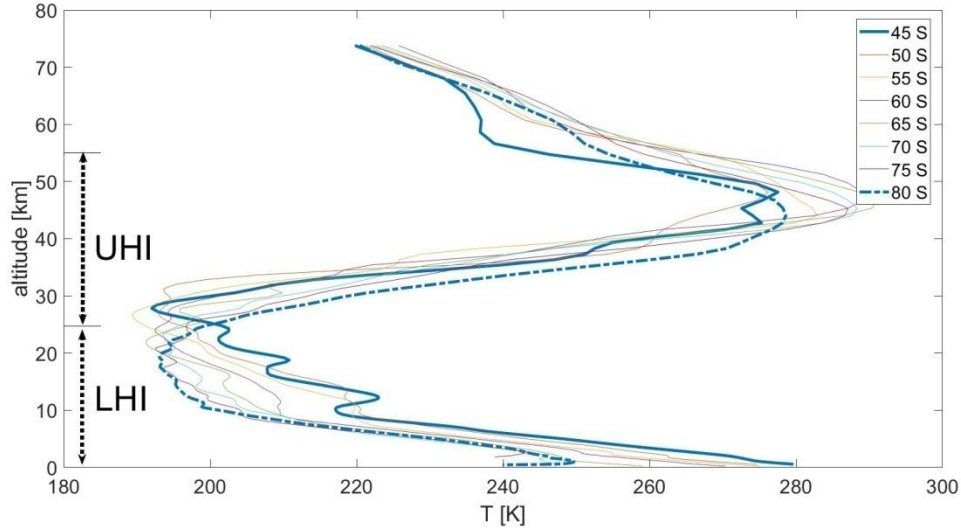
a)

319

b)

321

Figure 4. a) Zonal and meridional wind and temperature residuals at 00UTC HALO position (latitude/longitude = -50.01/-73.97), during ST08 flight on September 12, 2019. A highpass filter for vertical wavelengths below 15 km was applied. A selected highlighted vertical interval (43.0-66.5 km) is shown. b) Hodograph corresponding to the vertical interval highlighted in a), showing the anticlockwise rotation with increasing height.

From IFS simulations, the detected average coldest height is situated at ~25 km (26 hPa). Here, the lapse rate changes sign (also in conjunction with the position of the polar night jet core -see next section-). Then we divide the overall altitude interval below the IFS sponge layer into two sectors: [0, 25] km and [25, 55] km, namely, lower and upper height intervals (LHI and UHI),

330   respectively. Figure 5 illustrates vertical T profiles from IFS data, at an arbitrary longitude

331   (70°W), every 5° between 45°S and 80°S. The profiles exhibit typical lapse rates above and

332   below the ACH in the region considered in this study. The ACH is substantially higher than the

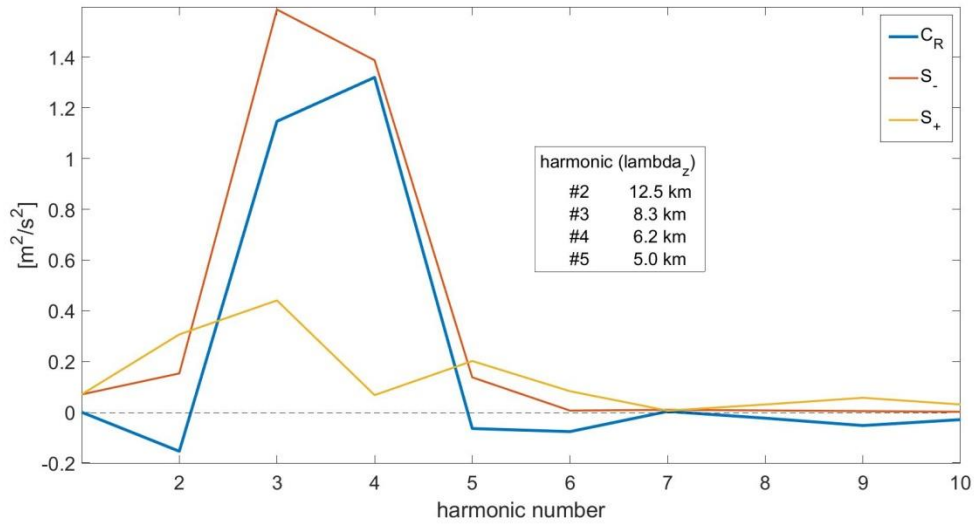333   average thermal tropopause, according to the frequent multiple tropopauses structure.

334

335   **Figure 5.** Vertical T profiles from IFS data at 70°W, every 5° between 45°S and 80°S, exhibiting the typical lapse

336   rates above and below the ACH in the region considered in this study.

337   **4 SRA at 00UTC on September 12, 2019**

338   **4.1 LHI (Lower Height Interval)**

339   After an interpolation in log-pressure vertical coordinates, a Hanning taper to reduce the spectral

340   leakage is applied to u' and v'. Following the spectral transformation described in section 2 (eq.

341   (4) to (10)) C_R, E_T and NC_R are obtained in the position HALO was at 00UTC, 12 September

342   (flight 08). An altitude column between 0 and 25 km is considered here. C_R (see Figure 6), E_T (=

343   S_- + S_+) and NC_R (not shown) exhibit relevant amplitudes only at the first harmonics.

344

Figure 6. Rotary, counterclockwise and clockwise energy coefficient (C_R, S_- and S_+, respectively) corresponding to the first 10 harmonics obtained in LHI (between 0 and 25 km height), at the 00UTC HALO position (lat/lon= -50.01/-73.97) on September 12, 2019, during ST08 flight.

Significant rotational energy is distributed between harmonics #2 and #5, which correspond to vertical wavelengths(λ_z) between 12.5 and 5 km, revealing a clear dominant net upwards flux. For harmonics larger than #5 ($\lambda_z < 5.0$ km), the remaining rotational energy suddenly decreases to negligible values. The HALO flight position at the lat/lon pixel corresponding to this figure lies immediately west of the mountains, not strictly above them. Accordingly, modes with C_R different from 0 (not LP) suggest a significant GW contribution possibly originated in non-orographic sources. We may wonder under what conditions the GW energy at any pixel can be adequately described by only a few modes. The concept of a possible dominant quasi-monochromatic GW packet at any geographical position seems questionable, at least in the complex region considered here.

We extend the analysis illustrated in a single column (pixel) to the overall latitude-longitude region, made up by 1001x351=351,351 independent (0.1°x0.1°) pixels. In doing so, we delimit our geographic area of interest: [45S-80S, 120E-20E].
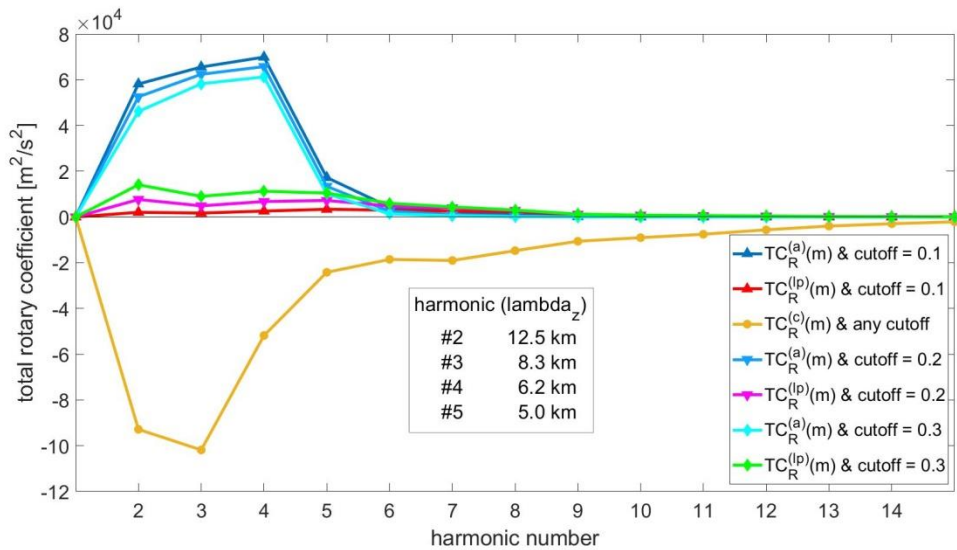
We define, for each harmonic, two quantities:

1) The total rotary coefficient, $TC_R^{(i)}(m)$, equal to the sum of $C_R(m)$ over all the p_i-pixels. Here, i = (a) anticlockwise, (lp) linearly polarized or (c) clockwise and $p_a(m) + p_n(m) + p_c(m) = 351,351$

364   pixels, for each m. $TC_R^{(i)}(m)$ may be interpreted as the total up- and downgoingGW energy, as a

365   function of each vertical wavelength.

366   2) The average rotary coefficient, $AC_R^{(i)}(m) = TC_R^{(i)}(m) / p_i(m)$, that is to say, $TC_R^{(i)}(m)$

367   normalized over the total number of p_i-pixels. $AC_R^{(i)}(m)$ may be interpreted as the distribution of

368   GW energy density at each p_i subsector, within the overall geographic domain. For example, we

369   expect to observe enhanced upgoingGW energy flux concentrated around mountain areas. If we

370   select any different geographic region, this will modify both $TC_R^{(i)}(m)$ and $AC_R^{(i)}(m)$.

371   According to the criteria we use to distinguish between orographic from non-orographic GWs,

372   those pixels with $C_R(m)$ lying close to 0 are identified as LP. The "closeness" of $C_R(m)$ to 0 for a

373   given m is, of course, arbitrary. To isolate LP GWs, we may choose, for example, upper and

374   lower C_R thresholds as $[-\alpha, +\alpha]$ m^2/s^2, where $0 < \alpha \ll 1$. However, GWs from orographic origin

375   are expected to be LP and, in addition, upgoing. Then, we propose that C_R must be > 0 and we

376   set the upper and lower thresholds: $[0, +\alpha]$ m^2/s^2. To illustrate the variability arising from these

377   constraints, in Figure 7 we show $TC_R^{(i)}(m)$ for the first 15 harmonics and three arbitrary upper
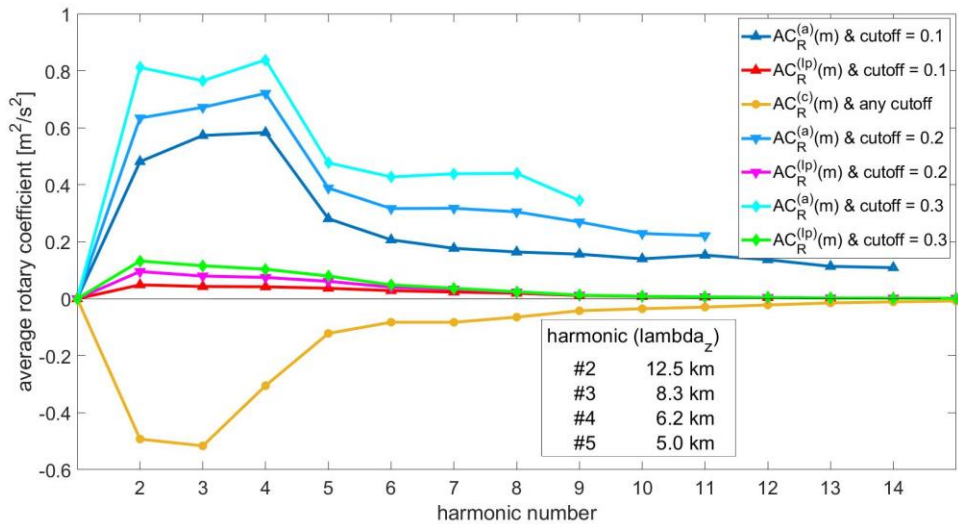
378   thresholds: $\alpha = 0.1, 0.2$ and 0.3.

379

380   **Figure 7.** Total rotary coefficient, $TC_R^{(i)}$, calculated in the overall latitude-longitude region, made up by

381   1001x351=351,351 (0.1°x0.1°) pixels. i = (a) anticlockwise, (lp) linearly polarized or (c) clockwise GW rotation.

382   Three cutoffs defined to distinguish between GWs of orographic and non orographic sources are arbitrarily chosen

383   to show the variability of each upgoing contribution to the overall energy flux. According to our definition, different

384   upper cutoffs do not affect downgoing GWs.

385   Some features may be noted:

- The main energy flux is concentrated in the lower harmonics. A fast decrease in $TC_R^{(a)}$ with increasing m reveals an accumulation of GW energy only in this spectral range. A net larger downgoing energy flux is observed above the overall geographic sector considered here. At first glance, this result may be somehow unanticipated, if we do not take into account that most of the region is covered by oceanic areas, in comparison to mountain regions.

- $TC_R^{(c)}$ corresponding to downgoing GW rotational energy flux, in turn, diminishes with m considerably slower. This energy is spread into additional shorter vertical wavelengths than $TC_R^{(a)}$. It is unaffected by the variability in the upper cutoff.

- Downwards GW energy flux distribution among larger m values suggest a possible relevance of inertia GWs, generated after geostrophic imbalance close to or at polar night jet levels. In addition, reflection effects may be significant.

- $TC_R^{(a)}(TC_R^{(lp)})$ decreases(increases) with increasing(decreasing) upper cutoff. We remind that these two parameters share the total available upgoing energy flux.

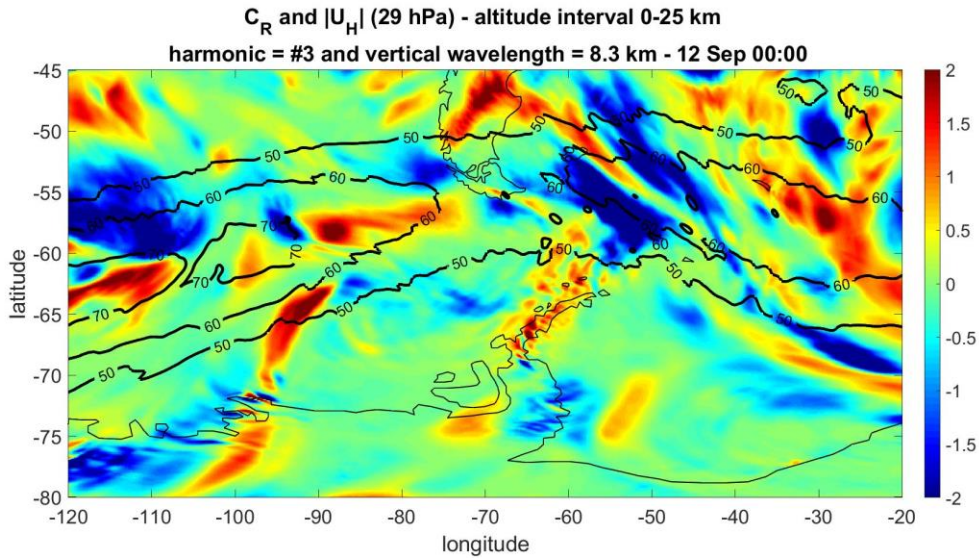400   In Figure 8, we show the $AC_R^{(i)}$ distribution.

Figure 8. Average rotary coefficient, $AC_R^{(i)}$, calculated in the latitude-longitude region as in Figure 7.

403   The following features can be observed:

404   •   The relative relevance of upgoing as compared to downgoing GW energy per unit area is

405   now evident. Clearly, it is concentrated in limited subregions, mostly corresponding to

406   mountain areas. These are defined by a considerably lower pixels number than those

407   corresponding to downgoingGWs.

408   • $AC_R^{(a)}$ is here always larger than $AC_R^{(c)}$ and increases with increasing upper cutoff,

409   inversely to what is observed when comparing $TC_R^{(a)}$ and $TC_R^{(c)}$. $AC_R^{(lp)}$ increases with

410   increasing upper cutoff, similarly to what happens with $TC_R^{(lp)}$.

411   •   As the cutoff is set to larger values, p_a is equal to zero beyond a given harmonic and

412          $AC_R^{(a)}$ is obviously not defined. For these higher cutoffs, the total available upgoingGW

413   energy flux seems to be shared only between a few harmonics.

414   •   The enhance of $AC_R^{(lp)}$ with increasing cutoff, also observed in $TC_R^{(lp)}$, suggests that the

415   number of pixels defining the total area with LP GWs seems not to expand significantly.

416   These are are concentrated in reduced areas.

417   In Figure 9 we analyze the geographic distribution of $C_R(m)$, now in a latitude-longitude plot.

418   For illustrative purposes, we first perform an approximation of the general characteristics that

419   can be extracted from this parameter. We select one representative dominant harmonic (#3),

420   based on the results in Figure 8. This harmonic corresponds to $\lambda_Z = 8.3$ km. The plot was

421   obtained at 00UTC, on 12 September 2019.

C_R and $|U_H|$ (29 hPa) - altitude interval 0-25 km
harmonic = #3 and vertical wavelength = 8.3 km - 12 Sep 00:00
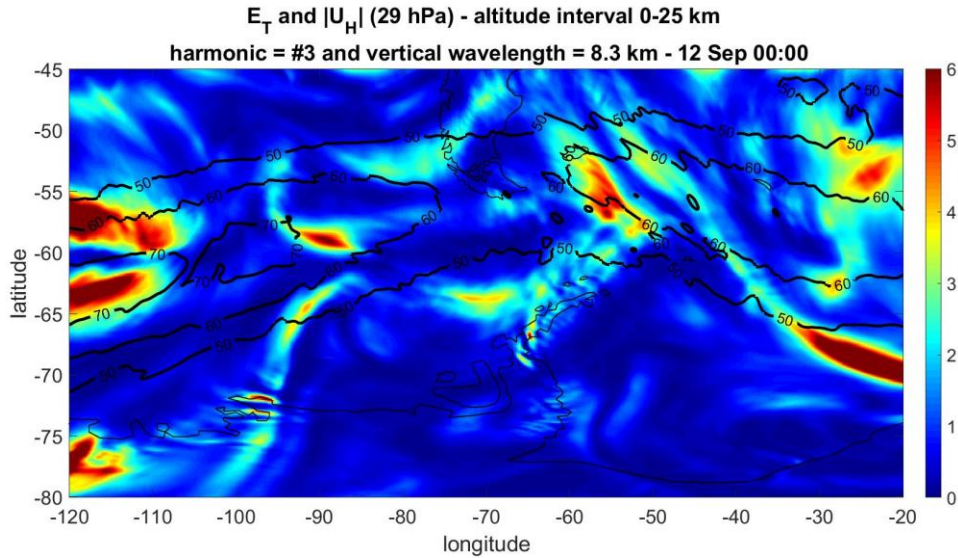
422

423   **Figure 9.** Rotary coefficient for harmonic #3 in $[m^2/s^2]$, corresponding to $\lambda_Z = 8.3$ km. The black isolines show the
424   absolute value of the horizontal wind in [m/s] at 29 hPa, where the core of the polar night jet is found.

425   We interpret the different pixel regions as follows. Positive(negative) C_R values correspond to
426   GW packets with dominant anticlockwise(clockwise) rotation with increasing height. This is
427   what is expected from upwards(downwards) energy propagation in the southern hemisphere.
428   Pixels with C_R bounded between 0 and α with $\alpha << 1$ indicate subregions where one of two
429   possible characteristics prevails: dominant LP, as expected from typical MWs (as explained
430   before, we consider only $\alpha > 0$), or with negligible GW activity. This uncertainty may be
431   removed by plotting E_T (m) for the same #3 harmonic (see below). The position of the jet core
432   (black contours) is situated above oceanic and continental areas at 25 km height (26 hPa). Some
433   features can be identified from this figure, bearing in mind that it corresponds only to a single
434   harmonic:

435   •   Two subregions with upwards propagating GW energy above continental areas over
436   central Patagonia and the Antarctic Peninsula show different degrees of elliptic
437   polarization.
438   •   Above southern Patagonia and Tierra del Fuego Island, there is a predominance of LP
439   GWs, suggesting their orographic origin.
440   •   Above the remaining oceanic areas, there is a broad distribution of up- and downgoing
441   energy flux. In particular, at and near to the jet and the jet streak position. As mentioned
442   before, possible sources for this variability may be found in departures from geostrophic
443   equilibrium near to the jet and the proximity to the cold front.
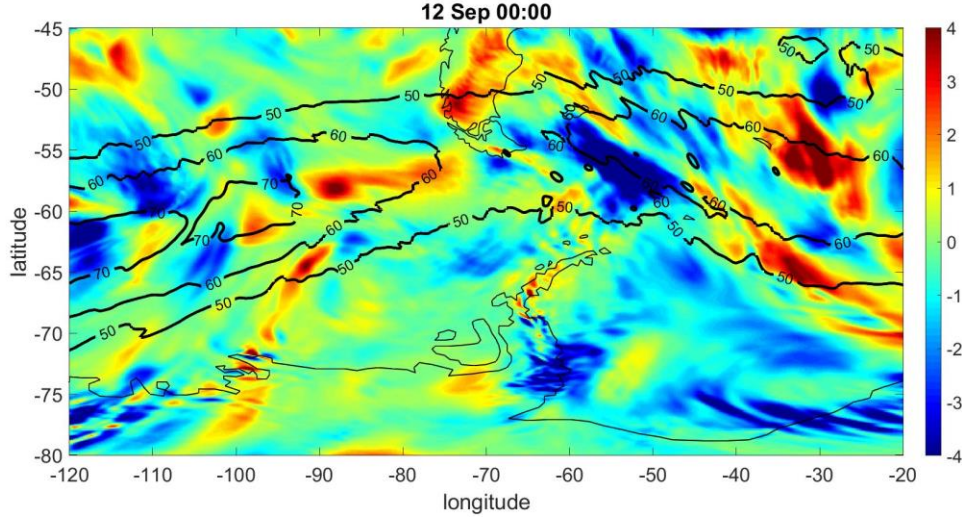
444   In Figure 10 we show E_T, also for #3:

Figure 10. Total rotary energy for harmonic #3 in [m²/s²], corresponding to $\lambda_Z = 8.3$ km. The black isolines show the absolute value of the horizontal wind in [m/s] at 29 hPa, where the core of the polar night jet is found.

The following features are observed:

- A geographic correspondence between subregions where E_T is enhanced and extreme C_R values (Figure 9). This is seen mostly near to the jet (Figure 10).

- This feature also applies to central Patagonia and the Antarctic Peninsula, although with less intense E_T values than near the jet stream. Taking into account that the characteristics observed in figures 9 and 10 are very different for any different m, in videos 1 and 2 we extend the description of figures 9 and 10 respectively,as a function of m between #2 and #6. The distributions of C_R and E_T are shown. Equal scales were preserved within each video, for comparison. There is a general increasing variability with increasing m of the up- and downgoing structures. This provides an insight of the complex GW ensemble to be expected in the region considered here.

- The geographic distribution of the enhanced $C_R$subregions is different for each harmonic. The same is observed for subregions where LP GWs are expected.

- The opportunity of isolating geographic sub-regions where monochromatic waves would dominate seems unrealistic.

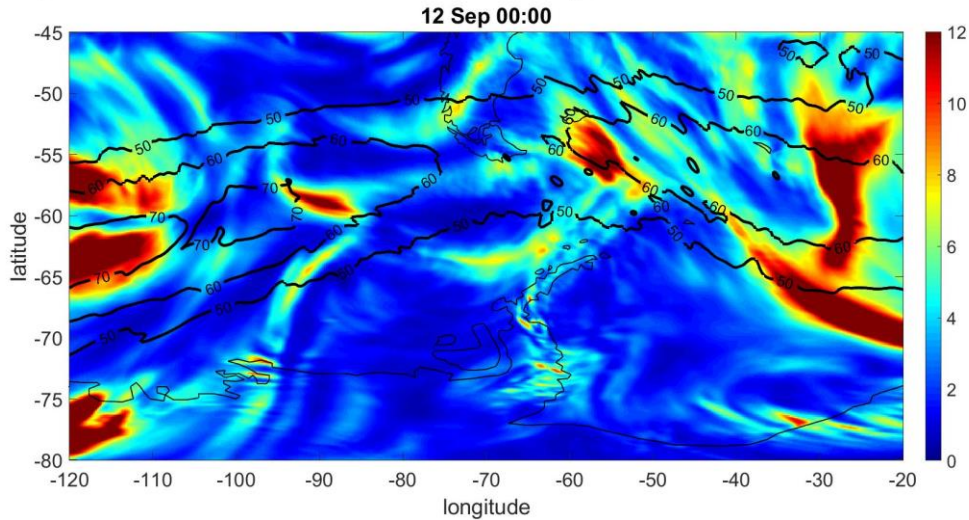- The overall amplitude of C_R decreases with increasing m, as expected from the features in Figure 7.

465 • As in the case of C_R, the geographical distribution of sub-regions of enhanced E_T is

466 different for each m. An overall decrease in E_T with increasing m is also evident. To

467 better appreciate the cumulative effect through m of C_R and E_T, in Figures 11 and 12

468 these parameters are addedover the whole set of harmonics, namely, $C_{R\ (INT)}$ and $E_{T\ (INT)}$,

469 respectively. Note that these figures were rescaled with respect to Figures 9 and 10.

470

471 **Figure 11.** $C_{R\ (INT)}$, in [m²/s²], obtained by adding all the harmonics C_R (m).

472

473 **Figure 12.** $E_{T\ (INT)}$, in [m²/s²], obtained by adding all the harmonics E_T (m).

474   In addition to the general characteristics already described, near the jet, a high concentration of

475   GW energy with a significant degree of non-linear polarization is evident, especially over

476   oceanic areas.

477   In Figure 13, we classify the distributions from Figures 11 and 12 in four groups as follows: GW

478   packets with i) negligible total wave energy, ii) anticlockwise rotation, iii) mainly LP and iv)

479   clockwise rotation.We label each of these 4 groups with an index "0", "1", "2" or "3"

480   respectively. Sub-regions where the total wave energy remains below an arbitrarily cutoff $C = 1$

481   m^2/s^2 (group i), we assign an index "0". If the energy is greater than C, we assign an index "1"

482   or "3", for C_R negative or positive, respectively. Finally, we assign "2" if C_R lies within the

483   interval [0, +r] (after Figures 7 and 8, for brevity we only illustrate with $r = 0.3$ m^2/s^2). We

484   interpret this last group as containing the dominant LP GW packets.

485

Figure 13. The four areas with different up- and downgoing dominated GWs. Labels "0", "1", "2" and "3", indicate,
respectively, C_R values with negligible total rotational energy, downgoing dominated GW energy flux, LP and
upgoing. Here $C = 1$ m^2/s^2 and $r = 0.3$ m^2/s^2.

489   The following features may be noted:

490   • UpgoingGW energy flux subregions ("3") (or pixel groups) are mostly situated above

491   Patagonia, Antarctic Peninsula and several oceanic sectors. The latter alternate with

492   subregions dominated by LP GWs ("2").
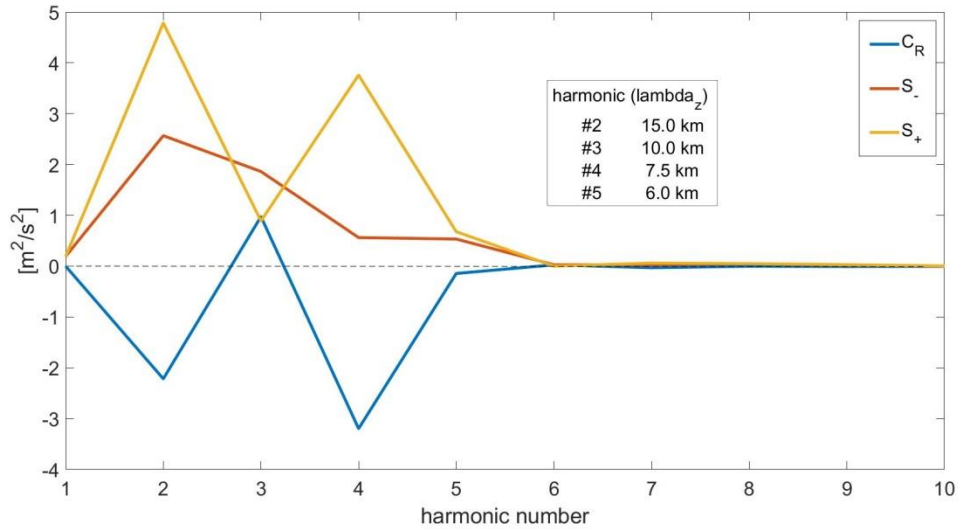
493   •   The downstream GW sectors ("1") only appear above the sea. As mentioned above, they

494   represent the main contribution in terms of relative areas (but not in terms of relative

495   energy flux contribution, as explained after Figure 8) of the overall region under

496   consideration.

497   •   For any value of C, the relative coverage of zones "2" and "3" obviously still depends on

498   r, although, the sum of the two remains unchanged. For example, if we set r = 0.1 (figure

499   8), region "2" will decrease considerably and "1" will increase. If C is modified, the

500   relative distribution of the 4 regions will also change.

501 In video 3, we show the evolution through successive m values of the normalized rotary

502 coefficient (NC_R). Clearly, the horizontal spatial scale of variability of this relative

503 dimensionless coefficient, which is bounded by -1 and +1, considerably increases with m. The

504 complex structure of the different wave packets becomes more evident here than in C_R and E_T. It

505 must be remarked that the information available from the 3 coefficients, C_R, E_T and NC_R is, in

506 some sense, complementary. For example, let us consider extreme values: if NC_R is 1 or -1 we

507 do not know whether the upward or downward rotational energy flux is large or small. This

508 knowledge is provided by C_R or E_T. On the other hand, if NC_R is close to 0, from C_R alone no

509 information about E_T is available. However, in this case from NC_R we infer that the energy flux

510 associated to the presumed LP mountain waves is significant. In video 3, this occurs in the

511 transition zones between red and blue sectors. Nevertheless, it must be remarked that the

512 conclusions drawn from each image are valid only for its corresponding harmonic.

513 **4.2. UHI (Upper Height Interval)**

514 Following the procedure applied in section 4.1, we now consider the interval [25, 55] km. Note

515 that instead of the simple separation proposed here between LHI and UHI, other spectral

516 intervals could also reveal significant features and possible sources, e.g. a sliding vertical

517 window or non overlapping vertical intervals with different lengths. We expect that the coercive

518 presence of the jet may provide a "turning point" in the net vertical energy flux. Regions where

519 geostrophic unbalance exists near to the jet may constitute a non negligible GWs source. In the

520 absence of critical layers, orographic GWs may also be able to propagate high in the

521 stratosphere; hence, we expect that the two main sources of upgoing GWs are the same as in

522 LHI. Figures 14 to 21 represent, respectively, the counterparts of Figures 6 to 13 in UHI.
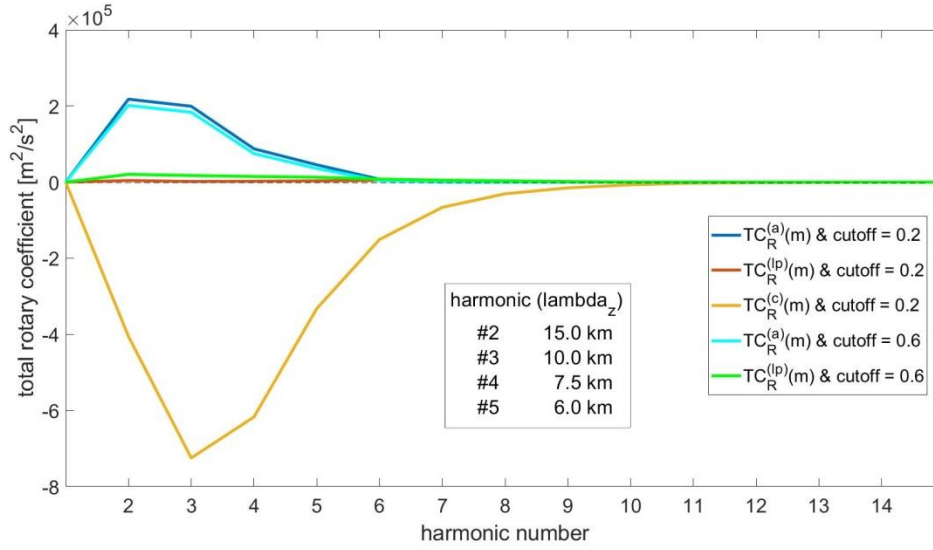
523 On the basis of the description already made in the previous section, in UHI, the relevant

524 similarities with and differences from the lower levels are detailed below each figure.

525

526 **Figure 14.** As in Figure 6, rotary, counterclockwise and clockwise energy coefficient corresponding to the first 10

527 harmonics obtained in UHI (between 25 and 55 km height), at the 00UTC HALO position.
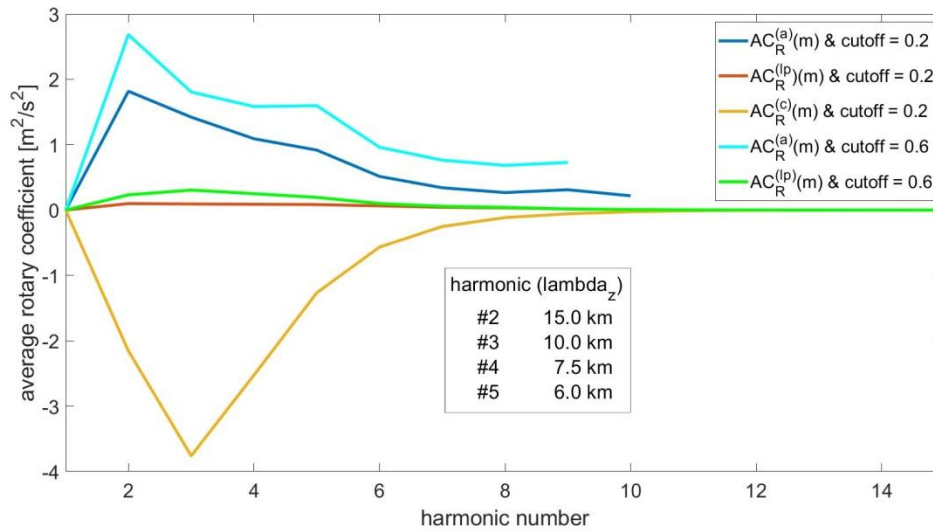
528 In Figure 14, the significant rotational energy in UHI at the single pixel corresponding to the

529 00UTC HALO position (lat/lon = -50.01/-73.97) on September 12, 2019, during ST08 flight is

530 shown. It is distributed within the first harmonics, mainly #2 and #4. These correspond to λ_z

531 equal to 15.0 and 7.5 km, but, in UHI, they reveal a net downwards flux. For harmonics larger

532 than #5, the remaining rotational energy decreases to negligible amplitudes. As in LHI, C_R

533 different from 0, suggests that a significant GW contribution originated in non-orographic

534 sources or that reflection occurred. For #3 ($\lambda_z = 10.0$ km) C_R close to 0 may correspond to an

535 orographic mode.

536 In Figure 15, identical remarks to those after Figure 7 can be made. The effect of only two

537 arbitrary cutoffs in the energy flux distribution is shown for illustration.
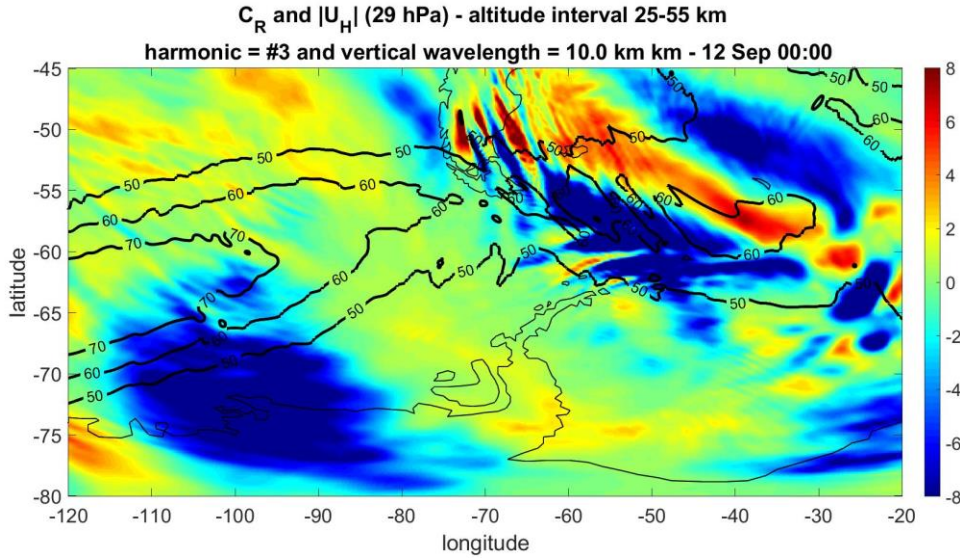
Figure 15. As in Figure 7, $TC_R^{(i)}$ is shown in the overall latitude-longitude region, between 25 and 55 km height. Here, the effect of two cutoffs is shown.

In Figure 16, we now show the $AC_R^{(i)}$ distribution. It can be observed that, contrary to what happens in LHI, the average upgoing GW energy flux is weaker than the downgoing flux, even though it is probably concentrated in limited mountainous regions.

Figure 16. Average rotary coefficient, $AC_R^{(i)}$, calculated in the latitude-longitude region as before. The effect of two cutoffs is shown.

548   In Figure 17, we analyze the geographic distribution of $C_R(m)$ in a latitude-longitude plot,

549   selecting one representative dominant harmonic (#3), as in Figure 9. This harmonic corresponds

550   to λ_Z equal to 8.3 km. The plot was rescaled, taking into account that C_R (and E_T below in Figure

551   18) are in units of energy per unit mass. These magnitudes are expected to increase in the

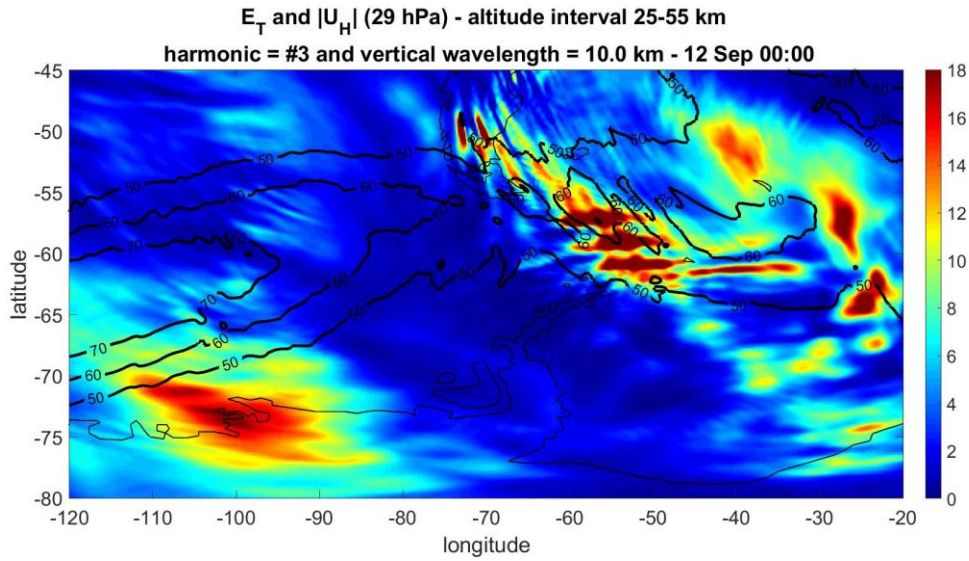552   stratospheric altitudes due to the decrease in air density.

553

554   **Figure 17.** Rotary coefficient for harmonic #3 in $[m^2/s^2]$, corresponding to $\lambda_Z = 10.0$ km. The black isolines show

555   the absolute value of the horizontal wind in [m/s] at 29 hPa, where the core of the polar night jet is found.

556   Following the general considerations stated above for Figure 9, we interpret the different regions

557   in Figure 17 as follows: positive(negative) C_R values correspond to GW packets with dominant

558   anticlockwise(clockwise) rotation with increasing height. This is what is expected from

559   upwards(downwards) energy propagation in the southern hemisphere. Pixels with $0 < C_R < \alpha \ll 1$

560   indicate subregions where one of two possible characteristics prevails: dominant LP, as expected

561   from typical MWs (as explained before, we consider only $\alpha > 0$), or with negligible GW activity.

562   This uncertainty may be removed by plotting $E_T(m)$ for the same #3 harmonic (Figure 18). The

563   position of the jet core (black contours) is situated above oceanic and continental areas at 25 km

564   height (26 hPa). From this figure:

565   • Two subregions with upwards propagating GW energy above continental areas of central

566   Patagonia and the Antarctic Peninsula, showing different degrees of elliptic polarization.
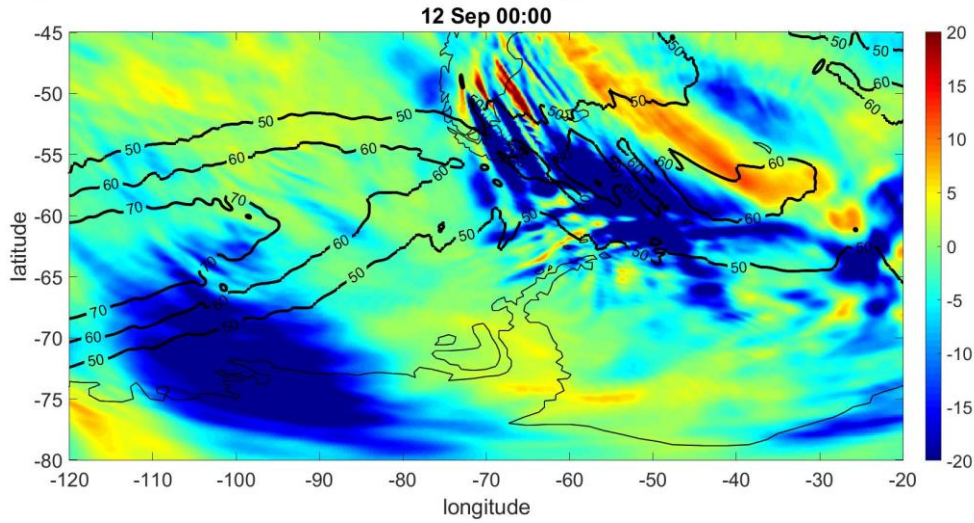
567   •   Above southern Patagonia and Tierra del Fuego Island, a predominance of LP GWs is

568   clear, suggesting an orographic origin.

569   •   Above the remaining oceanic areas, there is a broad distribution of up- and downgoing

570   energy flux, in particular at and near to the jet and the jet streak position. As mentioned

571   before, possible sources for this variability may be found in departures from geostrophic

572   equilibrium near to the jet.

573

574

575 **Figure 18.** Total rotary energy for harmonic #3 in $[m^2/s^2]$, corresponding to $\lambda_Z = 10.0$ km. The black isolines show

576 the absolute value of the horizontal wind in [m/s] at 29 hPa, where the core of the polar night jet is found.

577 The cumulative effect through m, of C_R and E_T in UHI ($C_{R\,(INT)}$ and $E_{T\,(INT)}$) is shown in Figures

578 19 and 20. The regions where upward and downward flows with significant departures from

579 linear polarization are observed to the east of 70W meridian and in the South Pacific. This is also

580 observed in E_T.

581

Figure 19. $C_{R\,(INT)}$, in [m²/s²], obtained by adding all the harmonics C_R (m).

583 In Figure 20,it may be observed that in UHI, the total available GW energy per unit mass is, on

584 average, around five times larger than in LHI.

585

Figure 20. $E_{T\,(INT)}$, in [m²/s²], obtained by adding all the harmonics E_T (m).

587 In Figure 21, thresholds $C = 10.0$ m²/s² and $r = 4.0$ m²/s² are adapted to the energy distribution

588 now observed in UHI.

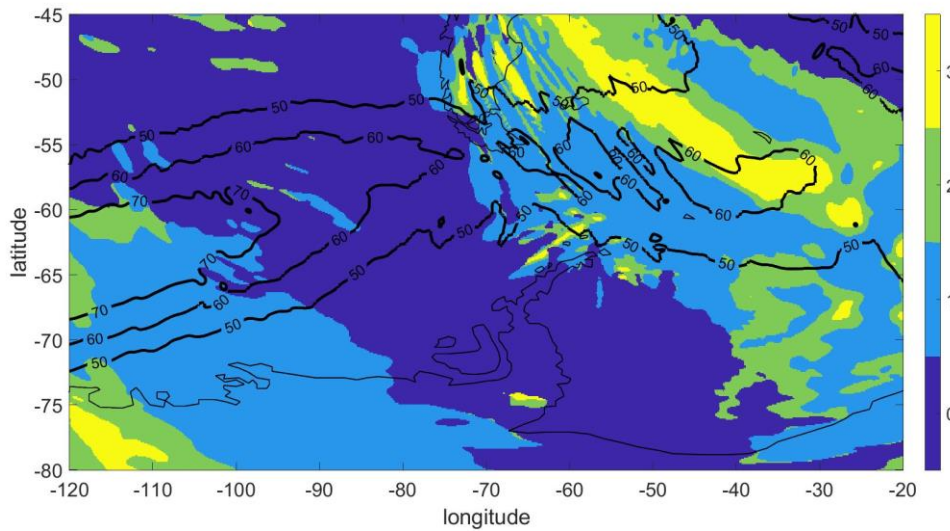**Figure 21.** As in Figure 13, the four areas with different up- and downgoing dominated GWs. Labels "0", "1", "2" and "3", indicate, respectively, C_R values with negligible total rotational energy, downgoing dominated GW energy flux, LP and upgoing. Here C = 10.0 m^2/s^2 and r = 4.0 m^2/s^2.

We can observe sub-regions with different degrees of polarization where downward flows dominate, systematically distributed in elongated bands. These are of different widths and have a predominantly NW-SE direction. Their relative distribution depends, as in LHI, on the arbitrary choice of r and C cutoffs.

Finally, for completeness, we include videos 4 to 6, which are respectively UHI counterparts of videos 1 to 3. We recall that the characteristics and conclusions drawn from each image shown in each of the videos 1 to 6 are valid only for the corresponding harmonic and are notably different for the rest of the harmonics.

5 A comparison with a GW temperature-vertical wind phase difference based analysis

We corroborate our rotational analysis with an independent technique that also allows us to investigate the upward or downward direction of wave energy propagation. This alternative analysis was based on the same ECMWF IFS operational analysis data for 12 September 2019, 00:00 UTC, as the rotational analysis introduced above. A brief description of the alternative technique is given below.

ECMWF data was processed using small-volume few-wave decomposition method S3D (Lehmann et al., 2012), currently implemented as part of the JUWAVE package for GW analysis

609   developed in ForschungszentrumJülich. S3D uses least-squares fitting to determine the

610   amplitude, 3-D wave vector and phase of several highest amplitude waves in a relatively small

611   rectangular box (boxes measured 300 km by 300 km in horizontal and 6 km in the vertical

612   direction in this study). S3D was used to independently find waves (harmonic disturbances) in

613   temperature and vertical wind data. If both temperature and wind disturbances were indeed a

614   consequence of GW activity, their phases and amplitudes must satisfy certain conditions that can

615   be derived from linear GW theory. Following, for example, Section 2.1 of Fritts & Alexander

616   (2003), one can describe GWs as linear disturbances on a hydrostatic main state satisfying WKB

617   (Gill, 1982) conditions. Temperature and vertical wind disturbances with amplitudes and phases

618   T_A, Φ_T and w_A, Φ_w can then be written as

619
$$T = T_A e^{z/2H} \cos(kx + ly + zm - \omega t + \Phi_T) \tag{11}$$

620
$$w = w_A e^{z/2H} \cos(kx + ly + zm - \omega t + \Phi_w) \tag{12}$$

621   where (k, l, m) is the 3-D wave vector, t is time, ω is the wave frequency and H is the scale

622   height. We also assume that speed of sound is very large, to eliminate acoustic waves from the

623   analysis. Then, it follows from equation (18) in Fritts & Alexander that $\Phi_T - \Phi_w$ is $\pi/2$ for

624   upward propagating waves, $-\pi/2$ for downward propagating waves and

625
$$\frac{T_A}{w_A} = \frac{T_0 N^2}{g\omega} \tag{13}$$

626   where T_0 is the undisturbed air temperature, N is the Brunt-Väisälä frequency, g is gravitational

627   acceleration and ω is the intrinsic frequency of the wave (it can be obtained from the GW

628   polarization relations knowing k, l, m from wave fit). These relations were used to determine

629   whether each S3D fitting box contained GWs and whether they were propagating upwards or

630   downwards. In particular, box was said to contain a GW if either $| \Phi_T - \Phi_w - \pi/2| < 0.2$ (upward

631   propagating wave) or $| \Phi_T - \Phi_w + \pi/2| < 0.2$ (downward propagating wave) and

632
$$\frac{T_0 N^2}{2g\omega} < \frac{T_A}{w_A} < 2\frac{T_0 N^2}{g\omega} \tag{14}$$

633   i.e. T_A / w_A was between half and twice the theoretically predicted value.

634   S3D wave fits are most reliable when horizontal and vertical wavelengths of the detected wave

635   are between about one third of the fitting box size and three fitting box sizes in the respective

636   direction. Therefore, we only considered GWs with horizontal wavelengths between 100 km and

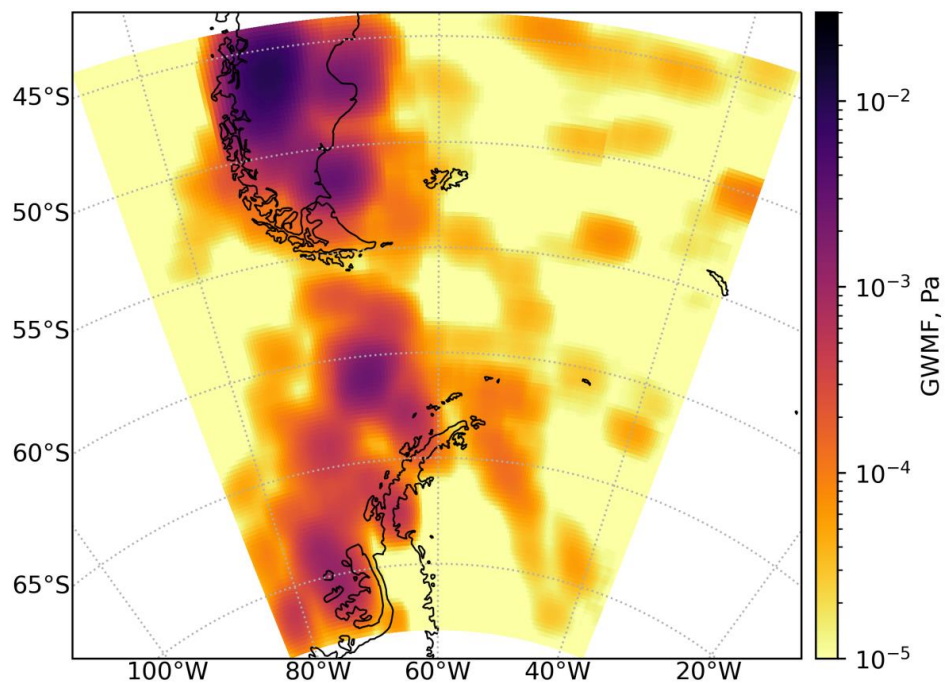637   900 km and vertical wavelengths from 2 km to 18 km.

638   To compare this method to rotational analysis, gravity wave activity in a relatively large altitude

639   range (LHI and UHI intervals) has to be quantified. It is evident from equations (11) and (12)

640   that the amplitudes T_A and w_A grow exponentially with altitude. Hence, calculating mean

641   amplitudes over a tall vertical column would almost entirely represent wave activity at the top of

642   the column. To avoid this problem, we will quantify the amount of wave activity using the

643   density of flux of the horizontal momentum (gravity wave momentum flux; GWMF)

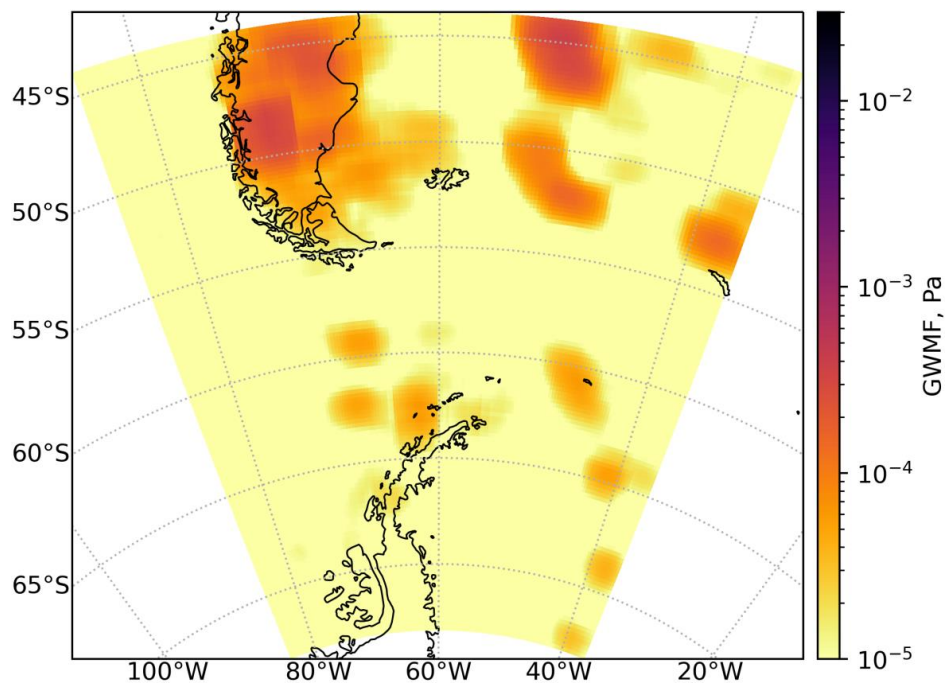644 $$F = \frac{\rho g^2 (k,l)}{2mN^2}\left(\frac{T_A}{T_0}\right)^2 \tag{15}$$

645   where ρ is air density. This quantity is conserved as a wave propagates to higher altitudes (Ern et

646   al., 2015), and hence mean |F| over a vertical column adequately describes the amount of wave

647   activity over the entire column.

648   The results are presented in Figures 22 and 23. For greater data reliability, heavily overlapping

649   S3D boxes were used. Each box measures 300 km by 300 km by 6 km, while box centers lie on a

650   rectangular grid with 0.5 km spacing in the vertical, 0.2° spacing in the meridional direction and

651   0.3° spacing in the zonal direction. To produce Figures 22 and 23, mean |F| for each vertical

652   column of boxes was first computed. Then, every grid point in the Figures was assigned a 300

653   km by 300 km square centered at that point. |F| value for this point was then computed as a mean

654   of all vertical profiles with footprints overlapping the square, weighted by the area of the

655   overlap.

656   A comparison of, for example, Figure 11 against Figures 23 and 23 reveals generally similar

657   results in the most important regions considered here: upward propagating GWs dominate over

658   the South America and Antarctic Peninsula, while areas with more downward propagation can be

659   found over the Atlantic.

660

Figure 22. Mean gravity wave momentum flux of upward propagating waves, in the altitude range from 3 km to 24 km.

663

Figure 23. Mean gravity wave momentum flux of downward propagating waves, in the altitude range from 3 km to 24 km.

666 It is worth recalling that a few years ago, in a study of GWs over Antarctica, Hertzog et al.

667 (2008) observed, from long-duration superpressure balloon flights at stratospheric levels,

668 mountain waves accounting for about two thirds of the total momentum flux. They found zonally

669 averaged fluxes over the ocean similar in magnitude to those above the continent, underlining the

670 importance of non-orographic GWs in the Southern Hemisphere polar and subpolar latitudes.

671 **6 Conclusions**

672 Based on IFS simulations, a rotary spectral, semi-quantitative classification of GWs is proposed

673 according to their sources: orographic or non-orographic. Their degree of polarization is the main

674 factor taken into account, from non-hydrostatic, non-rotating hydrostatic to rotating GWs,

675 following their intrinsic frequency regimes. An alternative analysis may be to look at the time

676 dependence (standing or non-stationary waves). This option can be performed on the basis of

677 mesoscale simulations and is left for a future contribution.

678 In the extremely complex scenario of upward and downward GW packets found during one of

679 the SOUTHTAC flights (Flight 08) above the southern Andes, Patagonia, the Antarctic

680 Peninsula and the surrounding oceanic areas, the rotary-vector analysis method was applied. It is

681 based on the Fourier transformation of a complex vector consisting in the perturbations to zonal

682 and meridional wind components with vertical wavelengths less or equal than 15 km. It should

683 be stressed that low frequency GWs are not exactly circularly polarized, except near the inertia

684 frequency, and that even a purely upward or downward wave contributes to both the clockwise

685 and counter-clockwise spectrum. In this sense, this analysis should be considered useful in a

686 statistical sense. Moreover, based on its polarization nature alone, an identification of its likely

687 sources can be made.

688 After a comparison between IFS simulations and lidar data obtained during one of the flights

689 performed during the Southtrac Experiment, the region under study was divided into 2 disjoint

690 vertical intervals. Here, the expected relevance of the polar night jet core in the radiation of GWs

691 was taken into account.

692 In the lower height interval, the main energy flux is concentrated in the lower harmonics. A net

693 larger downgoing energy flux is observed above the overall geographic sector, taking into

694 account that most of it is covered by oceanic areas. Downward GW energy flux suggests the

695   possible relative relevance of inertia GWs, generated after geostrophic imbalance close to or at

696   polar night jet levels and/or in the presence of a front. Instead, if we compute upward GW energy

697   flux per unit area, this is larger than the downward one, because it is concentrated in limited sub-

698   regions, mostly corresponding to mountain areas. In general, upgoing GW energy flux sub-

699   regions are mostly situated above Patagonia, Antarctic Peninsula and several oceanic sectors

700   where other sources like convection or frontal regions may be relevant enough. The latter

701   alternate with sub-regions dominated by LP GWs. Downstream GW sectors only appear above

702   the sea. As mentioned above, they represent the main contribution in terms of relative areas, but

703   not in terms of relative energy flux contribution of the overall region. The relative coverage of

704   upgoing zones with different degrees of polarization strongly depends on the two thresholds

705   proposed in this paper.

706   In particular, by illustrating the GW activity for harmonic #3, which corresponds to a vertical

707   wavelength of 8.3 km, two sub-regions with upwards propagating GW energy above continental

708   areas in central Patagonia and the Antarctic Peninsula show different degrees of elliptic

709   polarization. Above southern Patagonia and Tierra del Fuego Island, there is a predominance of

710   LP GWs, suggesting their orographic origin. Above the remaining oceanic areas, there is a broad

711   distribution of intense up- and downward energy flux, in particular, at and near to the jet and the

712   jet streak position. As mentioned before, possible sources for this variability may be found in

713   departures from geostrophic equilibrium near to the jet. We summarize the dominant GWs in

714   each sub-region by plotting their latitude-longitude distribution in four areas labeled "0" to "3".

715   The labels "0", "1", "2" and "3" indicate, respectively, CR values with negligible total rotational

716   energy, downward, LP and upward dominant GW energy flux. The relative coverage of each of

717   them depends on the thresholds arbitrarily chosen to define the low-energy and linearly polarized

718   GWs.

719   In the upper height interval, the total available GW energy per unit mass is, on average, five

720   times larger than at lower levels. Also, both the total upward GW energy flux and the upward

721   GW energy flux per unit area are weaker here than the respective downward magnitudes. This is

722   contrary to what is observed in the lower height interval. The cumulative effect on C_R and E_T

723   through the vertical wavenumber indicates upward and downward flows with significant

724   deviations from linear polarization. These are observed east of the 75W meridian and in the

725   South Pacific. This is also observed in E_T. Regions with different degrees of polarization, where

726   downward flows dominate, are systematically distributed in elongated bands. These are of

727   different widths and have a predominantly NW-SE direction. These strips are also clear when

728   labeled in four groups as described above.

729   The information to be extracted from the 3 coefficients, C_R, E_T and NC_R is in some sense,

730   complementary. The features and conclusions drawn from each image shown in each one of the

731   6 attached videos are valid only for the corresponding harmonic and completely different from

732   the remaining harmonics.

733   Finally, using the same IFS simulations, we analyze the phase difference between temperature

734   and vertical wind. In doing so, we determine the vertical propagation direction of GWs in the

735   lower height range based on the phase difference between the temperature and vertical wind

736   disturbances. The relative increase of upward GWs with respect to downward GWs above and

737   near the southern Andes and the Antarctic Peninsula, as well as their geographical distribution, is

738   in agreement with our results in section 4.1.

739   A spectral rotary analysis from mesoscale numerical simulations exhibiting a four-dimensional

740   context for the GWs is left for a future contribution. Recently, a study complementary to the one

741   presented here and based on mesoscale simulations during flight 08 is provided by Alexander et

742   al. (submitted). Version 4.2 of the ARW Weather Research and Forecasting (WRF) model is

743   forced with initial and boundary conditions from the 0.25 x 0.25 degree ERA5 reanalyses

744   provided hourly. Data are available at 137 levels from 1000 to 0.01 hPa. The solution has 150

745   vertical levels and the authors compare the model results with measurements obtained during

746   SOUTHTRAC-GW. In particular, the possible coexistence and interaction of orographic and

747   non-orographic gravity waves is evaluated.

751

752   **Open Research**

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