

Abstract

During winter, the latitude belt at 60°S is one of the most intense hotspots of stratospheric gravity wave (GW) activity. However, producing accurate representations of GW dynamics in this region in numerical models has proved exceptionally challenging. One reason for this is that questions remain regarding the relative contributions of different orographic and non-orographic sources of GWs here.

We use 3-D satellite GW observations from the Atmospheric InfraRed Sounder (AIRS) from winter 2012 in combination with the Gravity-wave Regional Or Global Ray Tracer (GROGRAT) to backwards ray trace GWs to their sources. We trace over 14.2 million rays, which allows us to investigate GW propagation and to produce systematic estimates of the relative contribution of orographic and non-orographic sources to the total observed stratospheric GW momentum flux in this region.

We find that in winter 56% of momentum flux (MF) traces back to the ocean and 44% to land, despite land representing less than a quarter of the region's area. This demonstrates that, while orographic sources contribute much more momentum flux per unit area, the large spatial extent of non-orographic sources leads to a higher overall contribution. The small islands of Kerguelen and South Georgia specifically contribute up to 1.6% and 0.7% of average monthly stratospheric MF, and the intermittency of these sources suggests that their short-timescale contribution is even higher. These results provide the important insights needed to significantly advance our knowledge of the atmospheric momentum budget in the Southern polar region.

Plain Language Summary

Just like the ocean, our atmosphere contains waves which transport energy and momentum. These atmospheric waves, known as gravity waves (GWs), strongly influence large-scale wind patterns but are hard to represent in weather and climate models. The Southern Hemispheric stratosphere has some of the strongest GW activity on our planet and accurately representing this region in models has proved exceptionally challenging. Further, the exact contributions of GWs from different sources, such as flow over mountains, convection in storms and weather systems, and instabilities in the atmospheric flow, are large unknowns that can lead to major model biases.

Here, we use satellite observations of stratospheric GWs and, using new methods, separate GW observations from noise and measure GW amplitudes, wavelengths and directions. We then use these observations in combination with a ray tracing model to track observed GWs back to their sources near the ground. We trace more than 14.2 million observed GW events. This approach means that for the first time we are able to produce systematic estimates of the relative contribution of different wave sources to the observed stratospheric activity in this region.

1 Introduction

Gravity waves (GWs) are small-scale buoyancy waves in the atmosphere for which gravity/buoyancy acts as a restoring force. These waves play a major role in the vertical coupling of the atmosphere, transporting momentum and driving the circulation at high altitudes, in particular the overarching mesospheric circulation branch (Fritts & Alexander, 2003). Misrepresentation of GWs in General Circulation Models (GCMs) can lead to major circulation biases.

During winter, the southern hemispheric polar stratosphere is the world's strongest region of GW activity (Hoffmann et al. (2013); Hindley et al. (2020, 2015); Wright et al. (2016); Bacmeister and Schoeberl (1989); Alexander et al. (2010); Hertzog et al. (2012) and many others). Here, maps of GW activity are dominated by orographic waves from

69 the Southern Andes and Antarctic Peninsula, where strong surface winds flow perpen-
70 dicularly over tall mountains, forcing air upwards and generating the highest-amplitude
71 stratospheric GWs on Earth. Small islands such as South Georgia (Hindley et al., 2020)
72 and Kerguelen (Alexander & Grimsdell, 2013) spread across the Southern Ocean also
73 act as strong local sources (Hoffmann et al., 2016), generating GW tails which stretch
74 hundreds of kilometres downstream (Alexander et al., 2009). Additionally, intense GW
75 activity is found all around the 60°S belt over open ocean and is believed to be gener-
76 ated by non-orographic sources such as storms, frontogenesis and jet adjustment processes
77 around the edge of the polar vortex (Wu & Eckermann, 2008; Holt et al., 2017, 2023; Hen-
78 dricks et al., 2014; Plougonven et al., 2017; Hindley et al., 2015; Strube et al., 2021). Con-
79 sistent strong wind conditions that increase with altitude during winter allow GWs gener-
80 ated in the lower atmosphere to propagate upwards through the stratosphere, where
81 their momentum deposition can have a major impact on the global general circulation
82 by decelerating the background winds.

83 Most weather and climate models use simplified representations of GWs, and this
84 can have significant and negative consequences. For example, it is widely hypothesised
85 that missing GW drag in models is a leading-order mechanism underlying the ‘cold pole’
86 bias (McLandress et al., 2011; Holt et al., 2023; Alexander & Grimsdell, 2013), whereby
87 the Southern Hemisphere polar stratosphere is too cold in winter and the polar strato-
88 spheric vortex breaks down too late in spring relative to observations. Supporting this
89 hypothesis, models persistently show a significant local reduction in stratospheric GW
90 momentum flux (MF) at 60°S in disagreement with observations (Holt et al., 2023; Geller
91 et al., 2013).

92 While the community agrees that the cold pole problem bias is primarily due to
93 missing GW drag, the source of the GWs that produce this drag remains a topic of ma-
94 jor debate. Previous studies suggest that at least a proportion of the missing flux can
95 be explained by the lateral convergence of GWs from sources poleward and equatorward
96 of 60°S. This has been demonstrated in model ray-tracing experiments by Sato et al. (2011);
97 Rhode et al. (2023) and shown to be consistent observed directional GW properties by
98 Wright et al. (2017), Hindley et al. (2015) and Moffat-Griffin et al. (2020).

99 Other work, meanwhile, highlights underrepresented orographic MF from small is-
100 lands in the Southern Ocean as a possible source. In NASA’s Goddard Earth Observ-
101 ing System Chemistry Climate Model (GEOS CCM), Garfinkel and Oman (2018) increased
102 the orographic wave drag over three small islands in the Southern Ocean to near observed
103 levels and found a reduction in the cold pole bias. Observationally, meanwhile, Hoffmann
104 et al. (2016) explored GW activity from 18 hotspots including small islands in the South-
105 ern Ocean using AIRS satellite data, and concluded that mountain waves at these hotspots
106 contribute significantly to overall observed MF. MF from these small islands is often vastly
107 underestimated in models as the island size is much smaller than the model grid cell (Alexander
108 et al., 2009). Finally, research has highlighted the importance of non-orographic GWs,
109 which can be generated across the large spatial area of the Southern Ocean and may hence
110 integrate to make a large overall contribution to total MF at these latitudes (Plougonven
111 et al., 2013; Hertzog et al., 2008; Jewtoukoff et al., 2015; Plougonven et al., 2020).

112 Garcia et al. (2017) explored the modification of the Whole Atmosphere Commu-
113 nity Climate Model (WACCM)’s GW parametrisation and noted that increasing orographic
114 GW forcing reduced the cold pole bias, but that other approaches to enhance GW ac-
115 tivity can also reduce the bias. For example, recently, Eichinger et al. (2023) found a re-
116 duction in model biases by implementing a parametrisation that included lateral prop-
117 agation. This highlights the need for observational work to determine the specific be-
118 haviour of the real atmosphere. Untangling the sources of GWs in this region, their re-
119 lative importance and their propagation behaviour could provide a key way to address
120 this knowledge gap. This would in turn help advance weather and climate modelling,

121 reduce the cold pole bias and simultaneously address many other problems arising in this
 122 region from the poor simulation of GW effects.

123 Ray-tracing methods provide an ideal tool for tackling this problem and have con-
 124 sequently been employed previously in various GW studies. Ray-tracing is a technique
 125 whereby GWs with specified initial conditions are propagated through a background at-
 126 mosphere in time. Previous forward-tracing work has used model-derived (for instance
 127 Preusse et al., 2014; Sato et al., 2011; Vosper, 2015), observationally determined (Preusse
 128 et al., 2009; Krasauskas et al., 2023; Pramitha et al., 2020) or idealised (Alexander, 1998;
 129 Q. Jiang et al., 2019; Preusse et al., 2002) GW properties to launch GW from locations
 130 on the surface and explore their propagation through model/reanalysis background fields.
 131 Backwards ray-tracing, where GW properties are defined later in the GW’s lifecycle, such
 132 as from observations, allows for the determination of GW sources. Pulido et al. (2013)
 133 backwards ray-traced radiosonde observations from a case study over the Andes and Wrasse
 134 et al. (2006) backwards ray-traced airglow observations from four mid-latitude sites. Krisch
 135 et al. (2017) used observations of a gravity wave event over Iceland from the aircraft based
 136 Gimballing Limb Observer for Radiance Imaging of the Atmosphere (GLORIA) and traced
 137 the waves forwards and backwards from 11.5 km altitude. More recently, Perrett et al.
 138 (2020) backwards traced a single month of AIRS observations in the Southern Hemisphere,
 139 providing a proof of concept we expand upon in this study.

140 Backwards tracing stratospheric AIRS observations is a particularly powerful method
 141 for untangling GW source mechanisms in this region. The observed 3-D wave vector is
 142 fully characterised by using a 3-D AIRS retrieval and the recently developed 3-D spec-
 143 tral analysis technique which allows for full 3-D inputs for ray-tracing. Additionally, our
 144 use of satellite data as the input for back-tracing allows for spatial coverage that ground-
 145 based or radiosonde observations cannot achieve. This specifically allows us to explore
 146 (i) convergence of GWs to 60°S, (ii) downstream propagation of orographic GWs, (iii)
 147 spatial distribution of MF from orographic and non-orographic sources, (iv) quantify-
 148 ing MF originating from different source regions across the southern polar region.

149 We present the Data in Section 2, Section 3 describes the methods used to obtain
 150 GW properties and perform the ray tracing. Results are presented and discussed in Sec-
 151 tion 4 and we conclude our work in Section 5.

152 **2 Data**

153 **2.1 3-D gravity wave observations from AIRS**

154 We use stratospheric GW observations made in polar winter from May to Septem-
 155 ber 2012 by the Atmospheric InfraRed Sounder (AIRS) onboard the National Aeronau-
 156 tics and Space Administration’s (NASA) Aqua satellite (Aumann et al., 2003; Chahine
 157 et al., 2006). Aqua was launched in 2002 and is still operating. We chose 2012 for this
 158 work as it was a non-extreme year for the Quasi-biennial Oscillation (QBO) and the El
 159 Niño Southern Oscillation (ENSO), and as such we expect it to be a broadly represen-
 160 tative year.

161 Aqua follows a near-polar orbit with a period of ≈ 100 minutes. AIRS is a hyper-
 162 spectral imager and measures atmospheric radiances in a cross-track sampling geome-
 163 try. The data have a swath width of 1780 km with a resolution of 13.5 km (across-track)
 164 x 18 km (along-track) at the nadir, which reduces towards the edges of the swath (Hoffmann
 165 et al., 2014). We use the 3-D temperature retrieval of Hoffmann and Alexander (2009);
 166 this retrieval covers a height range of 20 to 60 km and uses the instrument’s full sam-
 167 pling resolution to enhance the horizontal resolution by a factor of three compared to
 168 the operational retrieval.

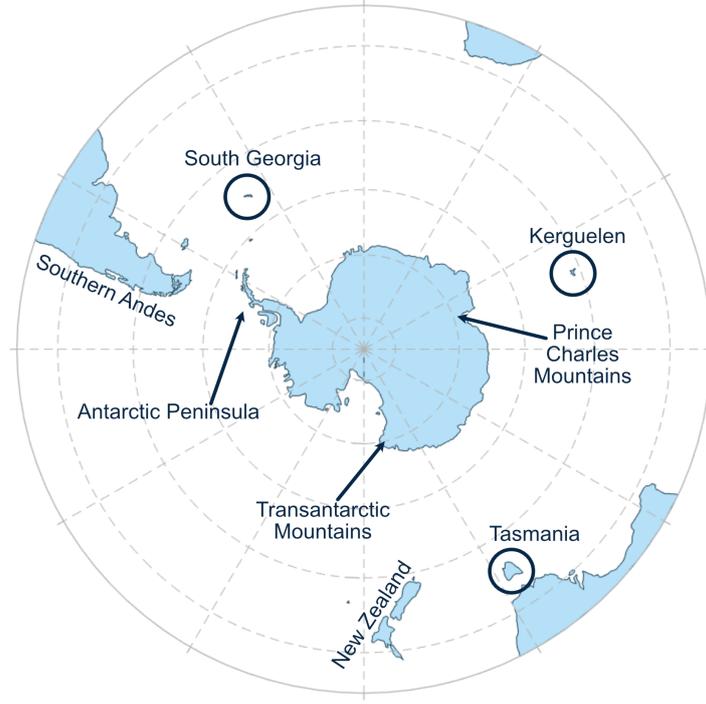


Figure 1. The Southern Hemisphere study region

169 No single measurement technique can observe the full spectrum of GWs, and obser-
 170 vations will be sensitive to specific scales depending on observational and methodolog-
 171 ical characteristics; this issue is known as the observational filter. The observational fil-
 172 ter of different observational techniques for measuring GWs is described in more detail
 173 by Alexander et al. (2010) and Wright et al. (2016). Hindley et al. (2019) investigated
 174 the observational filter of AIRS by characterising the sensitivity of the Hoffmann and
 175 Alexander (2009) retrieval. The retrieval was found to be almost 100% sensitive to GWs
 176 with vertical wavelengths between 35-45km and horizontal wavelengths less than 500km.
 177 However, this sensitivity fell with decreasing vertical wavelength and increasing horizon-
 178 tal wavelength. For example, wavelengths < 17 km in the vertical and > 1000 km in the
 179 horizontal are less than 50% sensitive, see Figure 2c of Hindley et al. (2019). GWs with
 180 short horizontal and long vertical wavelengths carry the majority of GW momentum flux,
 181 making AIRS observations suitable for characterising MF (Wright et al., 2021). The noise
 182 of this retrieval was quantified by Hindley et al. (2019) and is ~ 1.5 K for the southern
 183 hemisphere winter. The study region is presented in Figure 1 with labels for the key re-
 184 gions we discuss in this paper.

185 2.2 ERA5 reanalysis

186 We use data from the ERA5 reanalysis (Hersbach et al., 2020) to provide large scale
 187 winds for context and background fields for ray-tracing. ERA5 is a widely-used reanal-
 188 ysis product provided by the European Centre for Medium-Range Weather Forecasting
 189 (ECMWF). For the ray-tracing we require inputs of the background atmospheric state
 190 and the wave properties. We use zonal and meridional wind, surface pressure, geopoten-
 191 tial and temperature at three-hourly time resolution. We remove small-scale perturba-
 192 tions using the separation of scales method i.e. by applying a spectral cutoff at zonal wavenum-
 193 ber 18 described by Strube et al. (2021) and smooth in the meridional and vertical di-
 194 rections. We then interpolate this background onto a $1^\circ \times 1^\circ$ latitude-longitude grid, with

195 a 0.5 km vertical resolution between 2-39 km altitude. Due to the high topography of the
 196 Southern Andes and parts of Antarctica we do not trace rays below 2 km altitude, and
 197 consider this to represent ground level.

198 3 Method

199 3.1 Deriving gravity wave properties from AIRS data

200 We remove the large-scale dynamics from AIRS observations by subtracting a fourth-
 201 order polynomial in the cross-track direction at each height (e.g. Wu, 2004; Alexander
 202 & Barnet, 2007; Hoffmann et al., 2016; Wright et al., 2017; Hindley et al., 2019). We next
 203 re-grid the data onto a regular distance grid and perform spectral analysis to derive GW
 204 properties.

205 We use a three dimensional spectral analysis method known as the 2D+1 S-transform
 206 (ST) method and described by Wright et al. (2021). This method uses a 2D-ST in the
 207 horizontal in combination with vertical phase shift estimation to compute horizontal and
 208 vertical wavelengths and corresponding amplitudes. Unlike a Fourier transform, the ST
 209 lets us spatially locate GW frequency peaks, and is commonly used in GW analysis (e.g.
 210 Fritts et al., 1998; Alexander et al., 2008; McDonald, 2012; Wright & Gille, 2013). The
 211 2D+1 method builds upon the 1D method originally applied to AIRS data by (Alexander
 212 & Barnet, 2007), the subsequent 2D method developed by Hindley et al. (2016), and is
 213 a refinement of the 3-D method described in (Hindley et al., 2019) and first applied in
 214 Wright et al. (2017). Once we obtain the spectral properties, we identify GWs in the data
 215 by locating regions of consistent horizontal wavelength. This relies on the premise that
 216 GWs have approximately consistent horizontal wavelengths across their extent, whilst
 217 background noise leads to random wavelength measurements for each pixel with no re-
 218 lation to their neighbours. The method produces a binary mask identifying whether or
 219 not a wave is present for each pixel of AIRS data.

220 We use the 39 km altitude data level, which lies at the centre of AIRS’s useful re-
 221 trieval height range and thus provides the most reliable determination of GWs’ verti-
 222 cal wavelengths by avoiding truncation effects. This level also exhibits low noise rela-
 223 tive to other heights (Hindley et al., 2019).

Finally, following Ern et al. (2004), we calculate absolute vertical flux of horizon-
 tal pseudo-MF (hereafter simply ‘absolute MF’) at the observation height as,

$$|\text{MF}| = \sqrt{\text{MF}_x^2 + \text{MF}_y^2}$$

$$(\text{MF}_x, \text{MF}_y) = \frac{\rho}{2m} \left[\frac{g}{N} \right]^2 \left[\frac{T'}{\bar{T}} \right]^2 (k, l),$$

224 where MF_x and MF_y are the zonal and meridional MF respectively. k and l represent
 225 the horizontal wavenumbers in the zonal and meridional directions, and m in the ver-
 226 tical; g is acceleration due to gravity, N is the Brunt Väisälä frequency, which we assume
 227 to be 0.02 s^{-1} , and T' and \bar{T} are the wave amplitude and background temperature re-
 228 spectively. ρ is the atmospheric density.

229 3.2 Backwards ray-tracing

We use the Gravity wave Regional Or Global RAY Tracer (GROGRAT), originally
 introduced in Marks and Eckermann (1995). GROGRAT is based on the GW disper-
 sion relation and wave tracing equations of Lighthill (1967), which describe position and
 wavenumber along the ray path as,

$$\frac{d\mathbf{x}}{dt} = \frac{\partial\omega}{\partial\mathbf{k}}, \quad \frac{d\mathbf{k}}{dt} = -\frac{\partial\omega}{\partial\mathbf{x}}.$$

Where \mathbf{x} and \mathbf{k} are vectors denoting the wave’s spherical position and wavenumbers respectively, and ω is the wave’s ground-based frequency. We use a modified version of GROGRAT which incorporates the great-circle correction described by Hasha et al. (2008).

GROGRAT was initially designed to trace waves forward in time, i.e. to determine wave propagation from a specified source and properties. A later update to GROGRAT (Eckermann & Marks, 1997) allowed for backwards ray-tracing of waves, and we use this approach.

Each pixel of AIRS data that is identified as a wave is used to initialise a separate ray. We calculate the intrinsic frequency ($\hat{\omega}^2$) as

$$\hat{\omega}^2 = \frac{N^2 (k^2 + l^2) + f^2 (m^2 + \frac{1}{4H^2})}{k^2 + l^2 + m^2 + \frac{1}{4H^2}} \quad (1)$$

and use the ERA5 background winds to convert this to ground-based frequency (ω^2),

$$\omega^2 = \hat{\omega}^2 + ku + lv. \quad (2)$$

Finally, we calculate the wind wave amplitude, \hat{u} , from the AIRS observed temperature amplitude using the polarisation relation,

$$\hat{u} = \frac{g}{N} \frac{T'}{T} [1 - (f/\omega)^2]^{-1/2} \quad (3)$$

Where N is the Brunt-Väisälä frequency. k , l and m are wavenumbers in the zonal, meridional and vertical. $f = 2\Omega \sin \phi$ is the Coriolis parameter at latitude ϕ and H is the scale height. u and v are the ERA5 background zonal and meridional winds.

We output the ray location (i.e. latitude and longitude) at 1 km altitude increments, tracing the ray downwards from 39 km until the ray terminates. Typically, GROGRAT terminates rays because (i) the ray has reached the bottom of the prescribed atmosphere, (ii) the ray has reached a critical level and stalls vertically (i.e. has a vertical velocity $< 0.01 \text{ ms}^{-1}$) and a small minority of rays terminate due to (iii) vertical reflection which is not supported by GROGRAT. This means that waves will sometimes terminate at their source, but can also be traced backwards through the source without terminating. Unfortunately, this means that rays can travel to the ground whilst the real source of the wave could lie somewhere along the ray path (Preusse et al., 2014). In our results, we find that 61% of all rays terminate because they have reached the ground; this percentage will be a combination of correctly traced orographic waves as well as rays that have been back-traced through non-orographic sources and continued downwards to the ground. The height at which the ray terminates is referred to as the lowest traceable altitude (LTA). Finally, it is important to note that this method is not perfect. Rays may be mis-traced, meaning that the path the ray takes deviates from the real path of the GW. This can happen for several reasons, including instrument noise/errors in the observation of GWs, method errors in determining GW properties, or inaccuracy of ERA5 background wind fields.

Figure 2 demonstrates our method as applied to an example swath of AIRS data, recorded on the 4th June 2010 at $\sim 04:00$ UTC. Panel (a) shows temperature perturbations at 39 km altitude, and panel (b) shows the areas identified by our masking technique as GWs. Panel (c) shows the rays we trace backwards from this wave; the rays are shown as green lines, and one has been initialised from each pixel of AIRS data at 39 km.

In this example, most rays terminate because they reach the bottom of the specified background (2 km altitude): one group of rays travels almost directly downwards towards the Antarctic Peninsula (approximately 65°W , 65°S), whilst another traces back to the Southern Andes, possibly due to refraction in the jet (Dunkerton, 1984; Sato et al., 2011; Wright et al., 2017). The ray path towards large mountain ranges and all the way down to 2 km suggests that the orography is the likely source of these GWs.

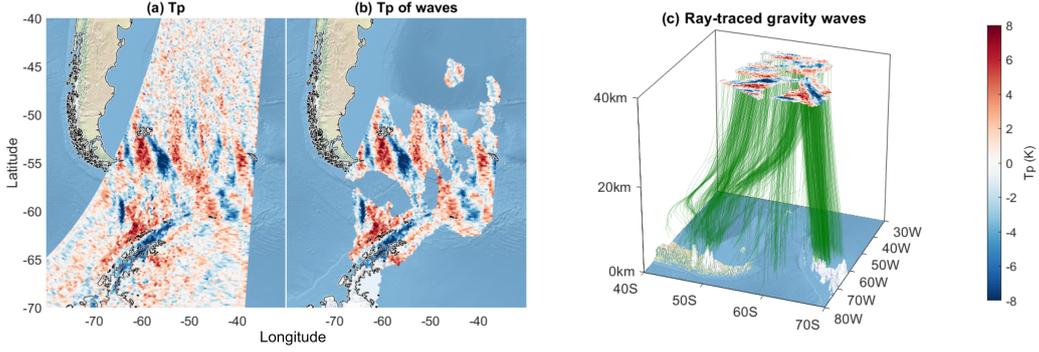


Figure 2. An example of a ray-traced overpass from AIRS from 4th June 2010 at approximately 04:00 UTC. Panel (a) shows the temperature perturbations at 39 km from AIRS. Panel (b) shows the temperature perturbations of pixels that are identified as GWs. Panel (c) shows the ray-tracing. The original masked GWs are shown at the top with rays coloured in green descending back towards the Southern Andes and Antarctic Peninsula mountain ranges. Each pixel of AIRS data is used to initialise a ray at 39 km.

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3.3 Post processing of traced rays

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Backwards ray-tracing five months of detected waves from all AIRS data from May - September 2012 results in 14.2 million rays which we then analyse in a number of different ways. We first investigate the meridional propagation of GWs by considering the difference between their observed latitude (i.e. the latitude at which they are observed by AIRS at 39 km altitude and where a ray is initialised) and the latitude the ray is then traced back to lower in the atmosphere. This provides an estimate of the meridional propagation distance of the waves to where they are observed in the stratosphere by AIRS.

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Secondly, we investigate the propagation of GWs from specific orographic sources: the Southern Andes, Antarctic Peninsula, Prince Charles Mountains, Transantarctic Mountains, South Georgia and Kerguelen (Figure 1). To do this, we consider all the rays that are traced back to chosen regions with a lowest traceable altitude of <5 km and explore how far away these waves are observed in the stratosphere by AIRS.

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Thirdly, we divide waves that are traced to land and ocean and present the observation location and respective momentum fluxes from these two classes. This quantifies the proportion of momentum flux traced to land and ocean, providing an estimate of the split between orographic and non-orographic GW activity to the observed stratospheric momentum flux in this region. This is an upper estimate of orographic activity as sources over land may also be non-orographic. We note that due to AIRS' polar orbit, we have more observations and hence initialise more rays at high latitudes. To compensate for this effect, in this work we consider daily mean results of MF as almost the whole area poleward of 30° S is observed by AIRS at least once per day.

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Finally, we further divide the geographical regions (including small islands) and quantify GWs traced back to different areas and weighted by their daily mean observed stratospheric momentum flux. This quantifies the proportion of observed MF in the stratosphere that is traced back to each region. A key point here is that we do not claim this represents all MF originating from each region: we explicitly only trace rays that are observed by AIRS in the stratosphere, and hence these waves must have been able to propagate up to these altitudes without dissipating or being critical level filtered and in addition must be observable to AIRS.

4 Results

4.1 AIRS observations and background winds

Figure 3 shows AIRS observations of GWs and ERA5 zonal winds at 39 km altitude. The left column shows the total number of GWs observed each month. In the middle column, we scale these totals by the number of AIRS overpasses to give an occurrence frequency. We note that all regions in our study area are observed by AIRS at least once every 12 hours.

Both GW metrics show localised hotspots, as well as general activity over the ocean and Antarctic continent extending northwards to $\sim 20^\circ\text{S}$. Overall, GW activity increases from May until mid-winter (July and August) before tailing off. This seasonal peak agrees with and is likely to be related to the background wind structure, which also peaks in strength in mid-winter. It is well-known that the Southern Andes act as the largest individual source of GW activity in this region and arguably the whole Earth system, as first identified by (Eckermann & Preusse, 1999), confirmed with AIRS (Hoffmann et al., 2013; Hindley et al., 2020), GPS-RO (Hindley et al., 2015), the SABER, MLS and HIRDLS limb sounders (Alexander et al., 2008; Wright & Gille, 2013; Geller et al., 2013; Wright et al., 2016; Ern et al., 2018; Wu & Eckermann, 2008), and the Aeolus Doppler wind profiler (Banyard et al., 2021). Other orographic GW hotspots of GWs can also be seen in our data, including the Antarctic Peninsula, South Georgia, Kerguelen, the Prince Charles Mountains, the Transantarctic mountains, Tasmania and New Zealand. We see ‘tails’ of GW activity downstream of orographic sources, particularly from the Southern Andes and Antarctic Peninsula extending into the Drake Passage. We also see GW activity over the open ocean away from clear orographic sources. The exact sources of these GWs remain unclear and difficult to attribute. Finally, the observed GW activity clearly shares key morphological features with the zonal wind field at the same height, presented in the right column. The polar night jet sits above the Southern Ocean during all five months, maximising in strength at $\sim 80\text{ ms}^{-1}$ in July. Observed GW activity follows the jet centre, and a stronger jet correlates spatially and temporally with stronger GW activity. This is due to (1) refraction to longer vertical wavelengths which increases visibility to AIRS and (2) actual geophysical lateral propagation of GWs into the center of the jet, which has been shown in observations e.g. (Hindley et al., 2015; Wright et al., 2017; Hindley et al., 2020) and is discussed in the next section below.

4.2 Convergence of gravity waves to 60°S

Numerous studies have hypothesised that a significant proportion of the “missing” MF at 60°S in chemistry-climate models reaches 60°S via meridional convergence (McLandress et al., 2012; Strube et al., 2021; Moffat-Griffin et al., 2020; Hindley et al., 2015; Wright et al., 2017; Geller et al., 2013, and others). In particular, persuasive evidence has been shown of orographic waves from the Southern Andes and Antarctic Peninsula converging in this way: in a numerical modelling study, Sato et al. (2011) used the high vertical resolution Kanto model (Watanabe et al., 2008) to show that rays launched from the surface of the Andes and Peninsula would be expected to exhibit this convergence, while observationally, Hindley et al. (2015) demonstrated that GW potential energies derived from Global Positioning System Radio Occultation (GPS-RO) measurements showed evidence of this convergence southwards from the Southern Andes, but did not find evidence for northward propagation from the Peninsula using 2010 data. Wright et al. (2017), meanwhile, used instantaneous AIRS-observed group speeds over the Drake passage to infer convergence from both the Andes and the Peninsular based on observed wave orientation. They found that the orientation of the waves turn in the wind, demonstrating that the refraction of the waves in the background winds plays a role in their lateral propagation.

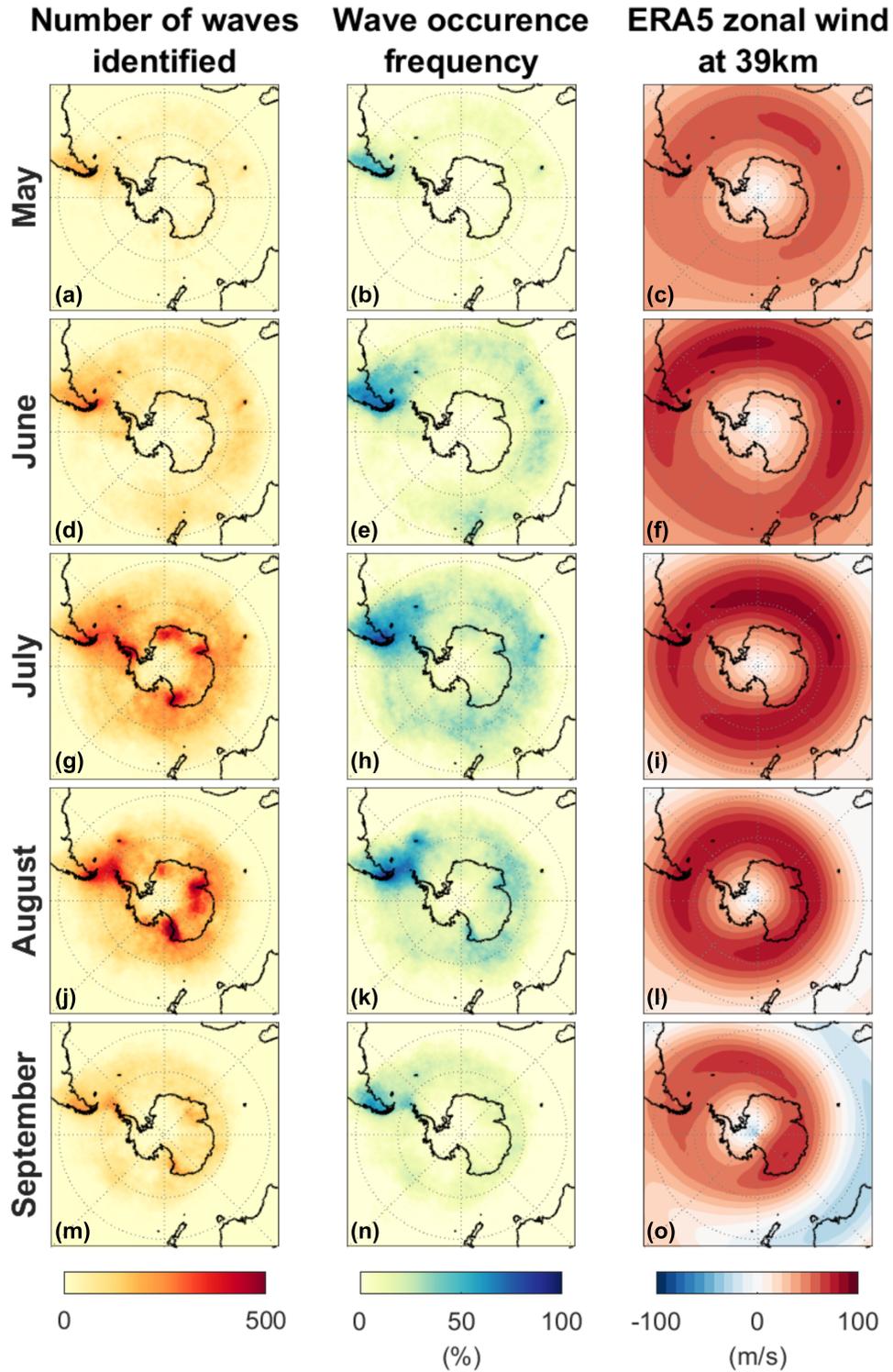


Figure 3. AIRS observed GWs and ERA5 background winds. Left column, the total number of GW observations at 39 km altitude from AIRS. Middle column, GW occurrence frequency at 39 km from AIRS calculated from number of waves identified per overpass. Right column, ERA5 zonal winds at 39 km.

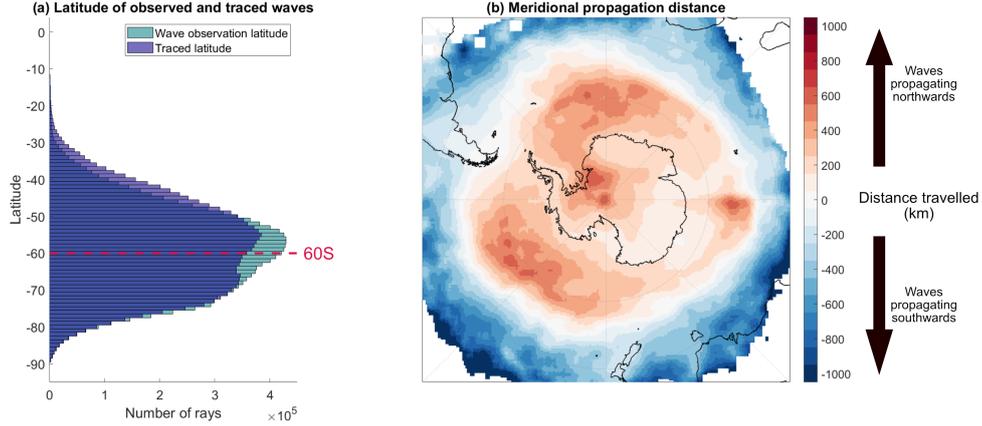


Figure 4. Meridional propagation of rays. Panel (a) shows a histogram of the observation and traced latitude of the waves. We define the GW “observation” latitude as the latitude that AIRS observes at the GW at 39 km, and the “traced” altitude as the lower-altitude latitude which the ray traces back to. (b) shows the average meridional distance travelled by the rays in km positioned by the traced position of the ray (i.e. the source location of the GW).

354 Ray-tracing allows us to investigate this. To do so, we first compare the start and
 355 end locations of our 14.2 million rays as a function of latitude. Figure 4a shows the re-
 356 sults of this analysis as a pair of overlaid histograms. For clarity of discussion, we de-
 357 fine the GW “observation” latitude as the latitude that AIRS observes at the GW at 39 km,
 358 and the “traced” altitude as the lower-altitude latitude which the ray traces back to. The
 359 observation-level distribution of waves, shown in cyan, forms a near-Gaussian distribu-
 360 tion centred around 55°S, consistent with Figure 3. The traced latitude (dark blue), how-
 361 ever, produces a bimodal distribution, with a local minimum at ~60-65°S. This suggests
 362 that the GWs seen by AIRS around 60°S are largely generated by sources significantly
 363 north and south of where they are observed in the stratosphere. The peak centred at 55°S
 364 is larger than the peak centred at 70°S, suggesting that sources to the north play a slightly
 365 larger role in the observational-level peak near 60°S.

366 Figure 4b characterises how far these rays propagate meridionally. Specifically, we
 367 show the difference between the observation latitude and the traced latitude. Positive
 368 values (red) indicate that on average waves have propagated northwards from their source
 369 to the observation altitude, while negative (blue) values indicate that waves have prop-
 370 agated southwards. We see northwards propagation over the Antarctic continent and near-
 371 continental regions of the Southern Ocean and southward propagation from more equa-
 372 torward regions of our map. We find local minimum over and near orographic sources
 373 of gravity waves (the Southern Andes, the Antarctic Peninsula, South Georgia, Kergulen
 374 and New Zealand) this is likely due to the high frequency of wave events. Equally, re-
 375 gions which show a local maximum of lateral propagation are typically have lower grav-
 376 ity wave activity.

377 Over Antarctica, waves generally propagate ~200-600 km northwards, travelling
 378 outwards over the Southern Ocean into the jet core. Over the ocean itself, meanwhile,
 379 meridional wave propagation averages out between north and south; this is because of
 380 the shifting jet-centre location, and hence represents a shifting focus. Further north, our
 381 results suggest that waves can propagate meridional distances as large as 1000 km from

382 source to observation; however, in practice the number of waves seen here is small and
 383 hence inaccurate traces may contribute significantly to this mean.

384 This result is the first time convergence to 60°S has been demonstrated across all
 385 longitudes of the Southern Ocean by backwards ray-tracing observations, providing a vi-
 386 tal quantitative constraint on the average distance travelled by these waves. This sug-
 387 gests that all GWs, both orographic and non-orographic, converge towards 60°S and hence
 388 that both may contribute significantly to the missing MF at 60°S. The significance of
 389 this result is that it expands on previous conclusions of the modelling study of McLandress
 390 et al. (2012), who focused on orographic waves but concluded that a significant non-orographic
 391 contribution was unlikely. It does however, agree with the observational work of Hindley
 392 et al. (2016) and Holt et al. (2017), who used AIRS observations and found that direc-
 393 tional MF (in Hindley et al., 2016) and wave propagation direction (in Holt et al., 2017)
 394 visible to AIRS converged towards 60°S at all longitudes.

395 Our results apply only to GWs in the observational filter range of AIRS. However,
 396 we can make inferences about other parts of the observational filter from work using other
 397 datasets. Specifically, Moffat-Griffin et al. (2020) carried out a comprehensive study of
 398 GWs observed by radiosondes launched from 11 different sites in Antarctica, the South-
 399 ern Andes and from small islands in the Southern Ocean. They calculated the angular
 400 distribution of momentum flux for 12-30 km altitude and found that for sites poleward
 401 of 60°S, the momentum flux was northwards and for sites at lower latitudes, the momen-
 402 tum flux was southwards. This again suggests a convergence of gravity waves towards
 403 60°S. The observational filter of radiosondes and AIRS observations do not overlap (Alexander
 404 et al., 2010; Wright et al., 2016), yet we also see suggested convergence to 60°S all around
 405 the Southern Ocean, not just over the Drake Passage. This suggests that our results may
 406 generalise across the GW spectrum. This radiosonde dataset may also cover some of the
 407 same waves we trace from AIRS at 39 km however at lower wind velocities at lower al-
 408 titudes.

409 **4.3 Lateral propagation of orographic gravity waves**

410 We next explore the horizontal propagation of GWs from orographic sources. We
 411 do this by considering all rays that trace back to defined regions over orography and which
 412 terminate at altitudes less than 5 km. This is shown in Figures 5-7; here, colours show
 413 the number of rays traced back to each region, with the ERA5 westwards wind at 39 km
 414 shown in greyscale. Figure 5 shows the Southern Andes (blue), Figure 6 shows the Antarc-
 415 tic Peninsula (blue), the Prince Charles Mountains (red) and the Transantarctic Moun-
 416 tains (green), and Figure 7 shows South Georgia (blue), Kerguelen (green) and New Zealand
 417 (red). These regions were selected from the hotspots found in Figure 3.

418 In Figures 5-7, we see that the overwhelming majority of waves are observed di-
 419 rectly above the region that they trace back to. This suggests that the majority of the
 420 AIRS-observed waves travel almost directly upwards. AIRS is particularly sensitive to
 421 long-vertical-wavelength waves, which tend to have fast vertical phase speeds and thus
 422 are expected to behave in this way. Despite this, in all cases we see trails of waves prop-
 423 agating downstream from each orographic region. This is particularly clear for the South-
 424 ern Andes (Figure 5), where GWs observed hundreds of kilometres downstream can be
 425 traced back to < 5 km altitude here. This is consistent with Sato et al. (2011), their Fig-
 426 ure 5, who launched waves from the Southern Andes and Antarctic Peninsula with hor-
 427 izontal wavelengths of 300 km and a ground-based phase speed of zero through idealised
 428 background conditions. These rays propagated laterally up to 50° eastwards before reach-
 429 ing 40 km in altitude. The SOUTHTRAC-GW campaign which comprehensively explored
 430 GW dynamics over the Andes (Rapp et al., 2021) with airborne observations and high
 431 resolution modelling found compelling evidence of refraction of gravity waves into the
 432 polar night jey and subsequent eastwards propagation towards 60°S. Recently, Krasauskas

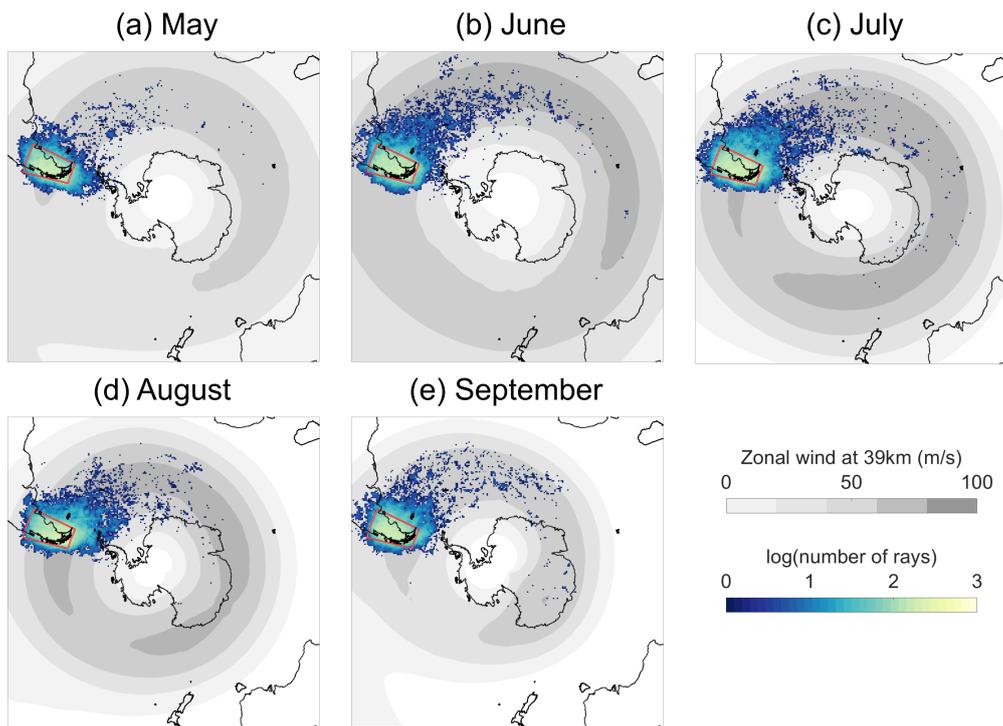


Figure 5. The observation location of all rays traced back to the Southern Andes. Color denotes the number of rays traced back to the red box (log10 scale). Grey contours show the ERA5 westward winds at 39km.

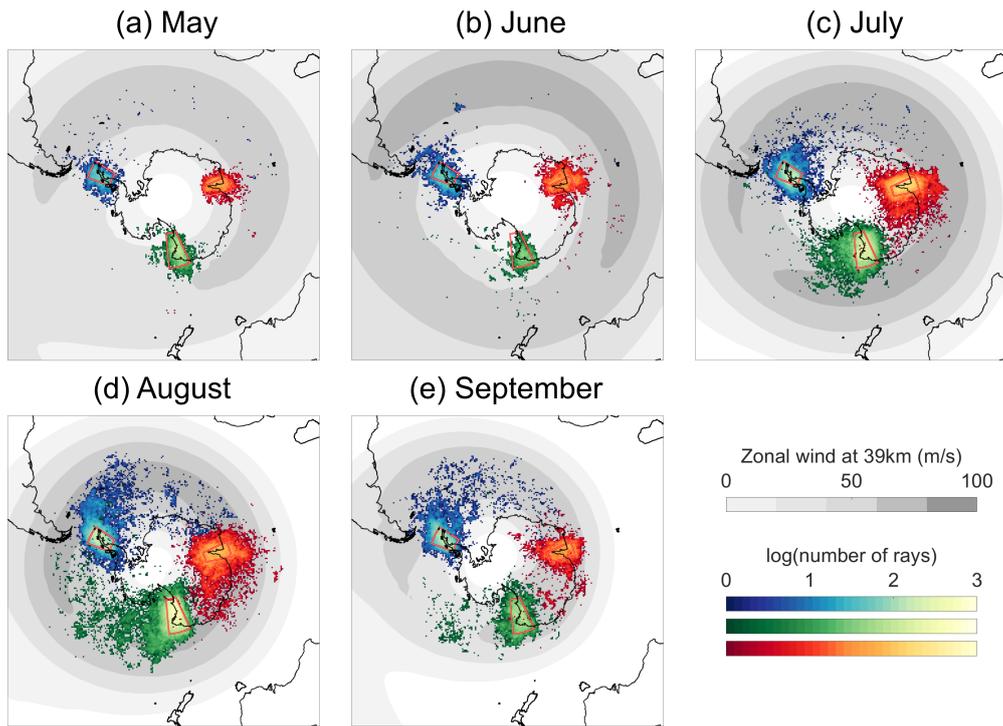


Figure 6. The observation locations of all rays traced back to key orographic source regions on the Antarctic Continent. Colour denotes the number of rays traced back to each red box (log₁₀ scale). The Antarctic Peninsula (blue), Transantarctic Mountains (green) and the Prince Charles Mountains (red). Grey contours show the ERA5 westward winds at 39km.

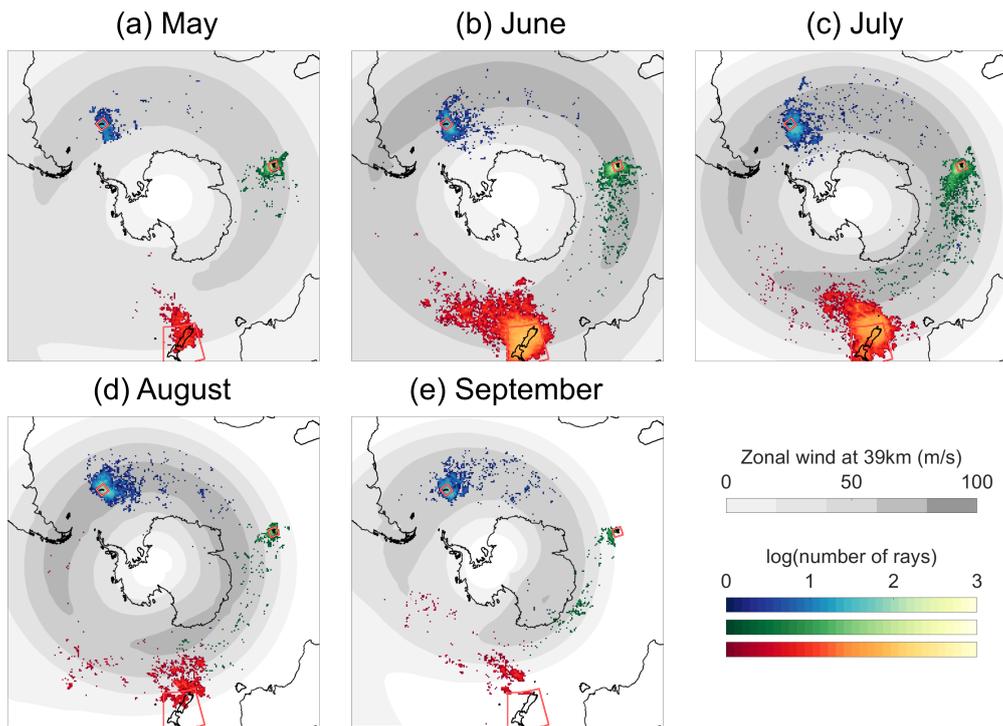


Figure 7. The observation locations of all rays traced back to key island source regions. Colour denotes the number of rays traced back to each red box (log10 scale). South Georgia (blue), Kergulen (green) and New Zealand (red). Grey contours show the ERA5 westward winds at 39km.

et al. (2023) investigated the oblique propagation of gravity waves over the Southern Andes in a multi-instrument case study using GLORIA measurements at 8-15 km altitude and observations from the Airborne Lidar for Middle Atmosphere research (ALIMA) at 20-80 km in height. In a case study in September 2019, they used forwards ray tracing from GLORIA inputs and compared traced ray properties to ALIMA observations. This allowed them to directly observe horizontal refraction of orographic gravity waves in the strong stratospheric winds for the first time.

Recently, Rhode et al. (2023) devised a mountain wave model for quantifying the horizontal propagation of orographic gravity waves. This model is based on identifying ridges from topography data, determining gravity wave launch parameters then forwards tracing waves from the mountains to predict MF at higher altitudes. Comparison with HIRDLS satellite data showed promising agreement, validating their model. Their predicted gravity wave activity, in particular the downstream propagation patterns agree well with the findings of our study, ‘tails’ of gravity wave activity are found downstream of the Southern Andes, Antarctic Peninsula, Kerguelen, Tasmania and New Zealand of similar shape which also peak throughout June and July. This mountain wave model was implemented in a parametrisation which redistributes GW MF horizontally by Eichinger et al. (2023) and they found a reduction in model biases as a result. This agreement between the mountain wave model (Rhode et al., 2023) and our findings here, as well as an improvement in model biases (Eichinger et al., 2023) shows a promising pathway to improving GW parametrisations.

Throughout all months, in agreement with Figure 4, we also see orographic waves converging towards 60°S. It is especially clear in August, where waves from the Andes propagate south-east (Figure 5d) and waves from the Peninsula north-east (Figure 6d) between surface and the stratosphere. In this month, we also see waves traced back to Kerguelen from south-east of the island (Figure 7d), i.e. propagating into the jet.

The propagation pathways of our traced GWs vary significantly by region and by month, which we attribute primarily to stratospheric background wind variability. The strong jet biases our observations of stratospheric GWs in two ways: (1) the strong westerly winds preferentially allow westward propagating GWs to propagate to observation levels (Hindley et al., 2016) and (2) GWs are refracted to longer vertical wavelengths in the strong winds, making these waves more observable by AIRS (Hindley et al., 2019). The first of these effects acts as a real control on the MF present in the system, however, the second acts on our results as an observational bias. The variation of GW activity with the background wind is consistent with the results of Hoffmann et al. (2016), who correlated AIRS-observed orographic GWs separately with (a) surface winds and (b) stratospheric winds, and found that observation-level winds exhibited a much higher correlation with GW activity, which they attributed to observational filter effects.

We also see that regions of stronger wind correlate with longer “tails” of rays downstream of orographic sources. This is particularly clear over Kerguelen: the GW “tail” here is most prominent in July (Figure 7c), when the jet allows for GW propagation and also refracts them to longer wavelengths. GWs originating over New Zealand also exhibit this effect in May (to some extent), June and July (Figure 7b,c), when the jet reaches further north. The activity of the polar night jet provides a plausible mechanism for the high level of GW intermittency seen over Kerguelen and New Zealand in studies such as Wright et al. (2013).

Waves traced back to South Georgia exhibit a ship wave pattern (Eckermann et al., 2016) with two downstream tails, one to the north-west and another to the south-west. This is because South Georgia lies almost in the centre of the jet, allowing waves to propagate upwards. This was seen previously by Hindley et al. (2021) in snapshots of GW observations by AIRS. Kerguelen is another isolated island and also produces this pattern when the background wind conditions allow it (Figure 7c, for example); how-

485 ever, most of the time, Kerguelen lies north of the jet, and hence we do not observe the
 486 ship wave pattern here.

487 GWs over the Prince Charles mountains and Transantarctic mountains are thought
 488 to be generated by strong katabatic winds flowing off the continent (Watanabe et al.,
 489 2006). Whilst this source has not been extensively studied previously, such katabatic sur-
 490 face winds propagate northwards and hence should result in GWs with phase fronts aligned
 491 parallel to the stratospheric jet. Waves generated over the Southern Andes and Antarc-
 492 tic peninsula, however, have phase fronts perpendicular to the winds of the jet. This dif-
 493 ference may explain why GWs from the Prince Charles mountains and Transantarctic
 494 mountains do not propagate as far downstream.

495 4.4 Orographic and non-orographic sources of gravity waves

496 We next use our traced rays to separate the observed GWs into those that are traced
 497 back to land (defined as land areas plus an extra 200 km coastline) and those that trace
 498 to the ocean. Figure 8 shows the mean number of rays traced to land (left column), sea
 499 (middle column) and total for each month. Figure 9 presents the same division of rays
 500 weighted by the observed stratospheric MF of each ray. We calculate the monthly aver-
 501 age from daily mean values to correct for the polar orbit of AIRS (as all regions pre-
 502 sented are observed at least once every 24 hours). What is perhaps most striking in these
 503 plots is the tails of GW activity found downstream of small islands, in both the num-
 504 ber of rays (Figure 8) and momentum flux (Figure 9). In particular, downstream of Ker-
 505 guelen and Heard island (a small island to the south-west of Kerguelen, 53°S 73°E) in
 506 August we see a large downstream tail of rays with significant momentum flux that traces
 507 back to land (Figures 8j and 9j) and consistent with the results presented in Figures 5
 508 to 7.

509 We previously discussed the propagation and behaviour of orographic GWs in Fig-
 510 ures 5 - 7, so here we focus our discussion on the waves that do not trace back to land
 511 (middle column of Figures 8 and 9). These exhibit some interesting results. Firstly, there
 512 is a surprising peak of GW activity in the Drake passage between the Southern Andes
 513 and the Antarctic Peninsula. This feature is present throughout all months but is per-
 514 haps most evident in mid-winter (Figures 8 and 9 panels e,h,k). This suggests that a sig-
 515 nificant number of waves are observed in the Drake Passage and not traced back to oro-
 516 graphy. Considering the number of rays (Figure 8 panels e,h,k), we see that the Drake
 517 Passage is dominated by a high number of wave observations that are traced back to the
 518 sea. However, in the associated absolute MF of this region (Figure 9 panels e,h,k), we
 519 see a pattern of higher MF only to the south-east of the tip of the South America and
 520 downstream from there, suggesting that the shape of the land plays a role. We have three
 521 possibly hypotheses for the increased wave activity in the Drake Passage which may
 522 all contribute to some extent. (1) high MF orographic GWs from the Southern Andes
 523 and Antarctic Peninsula which have propagated downstream and converge around 60°S
 524 that are mis-traced by the backwards tracing. (2) lower MF waves generated upstream
 525 of the Southern Andes possibly by storms funnelling into the Drake Passage or (3) grav-
 526 ity waves generated by an orographic-jet mechanism. Geldenhuys et al. (2021) presented
 527 the first observational evidence of such orographic-jet generation using GLORIA obser-
 528 vations from a campaign over Greenland. They describe how orography modifies the wind
 529 flow over large scales resulting in an ‘out of balance jet’ which then excites gravity waves.
 530 There are also small hotspots of MF downstream of Kerguelen and South Georgia vis-
 531 ible in the absolute MF of waves, which are traced back to the sea (June and July, Fig-
 532 ure 9-middle panels), suggesting that hypotheses (1) and (3) may also influence other
 533 regions downstream of orography.

534 Another striking feature of the waves traced back to sea is the hotspot of activity
 535 over the ocean stretching from the south of Africa ($\approx 30^\circ\text{W}$) clockwise around the con-

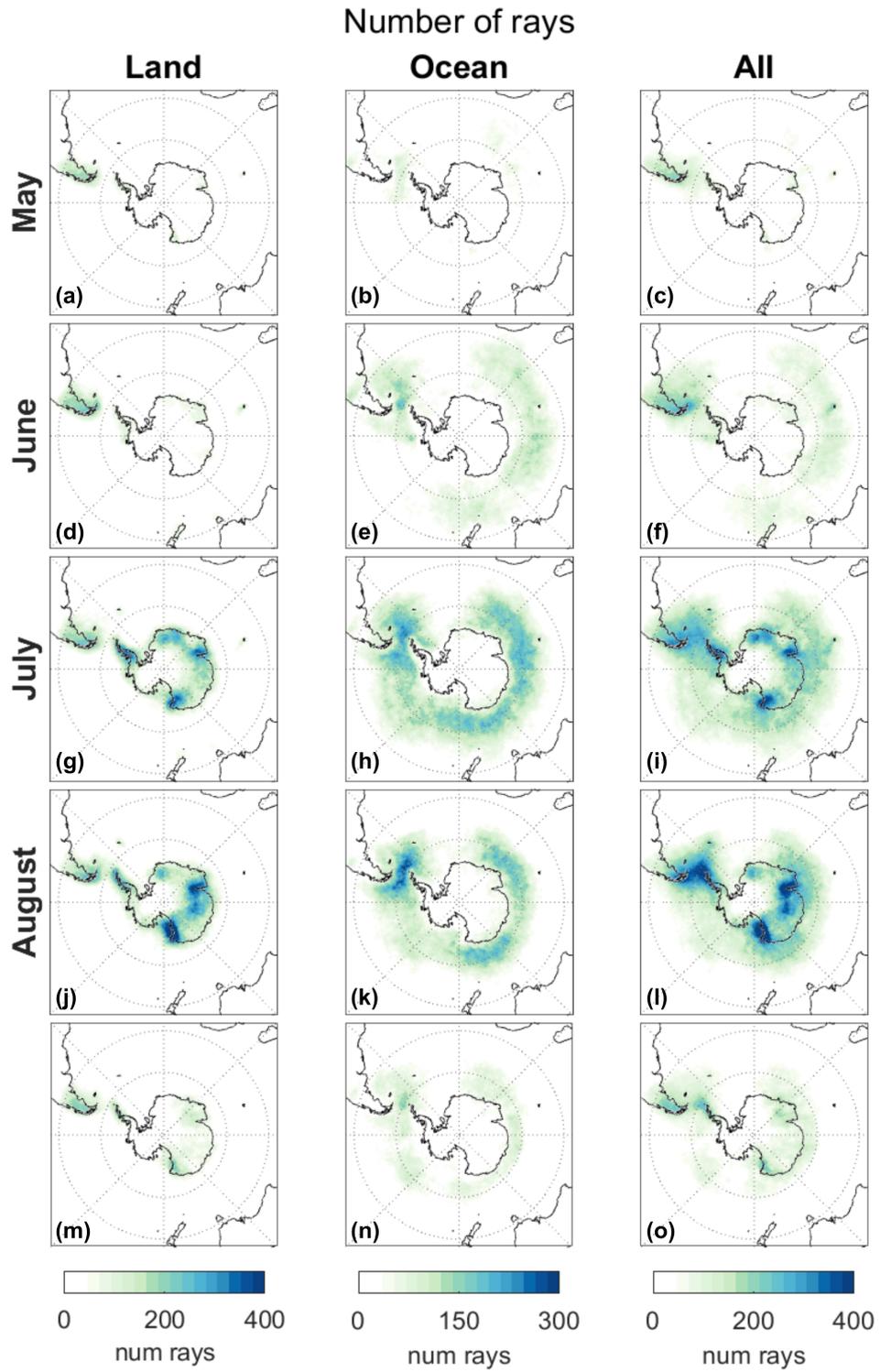


Figure 8. Number of rays traced back to land (left column), ocean (middle column) and both (right column), positioned by the observation location of the ray.

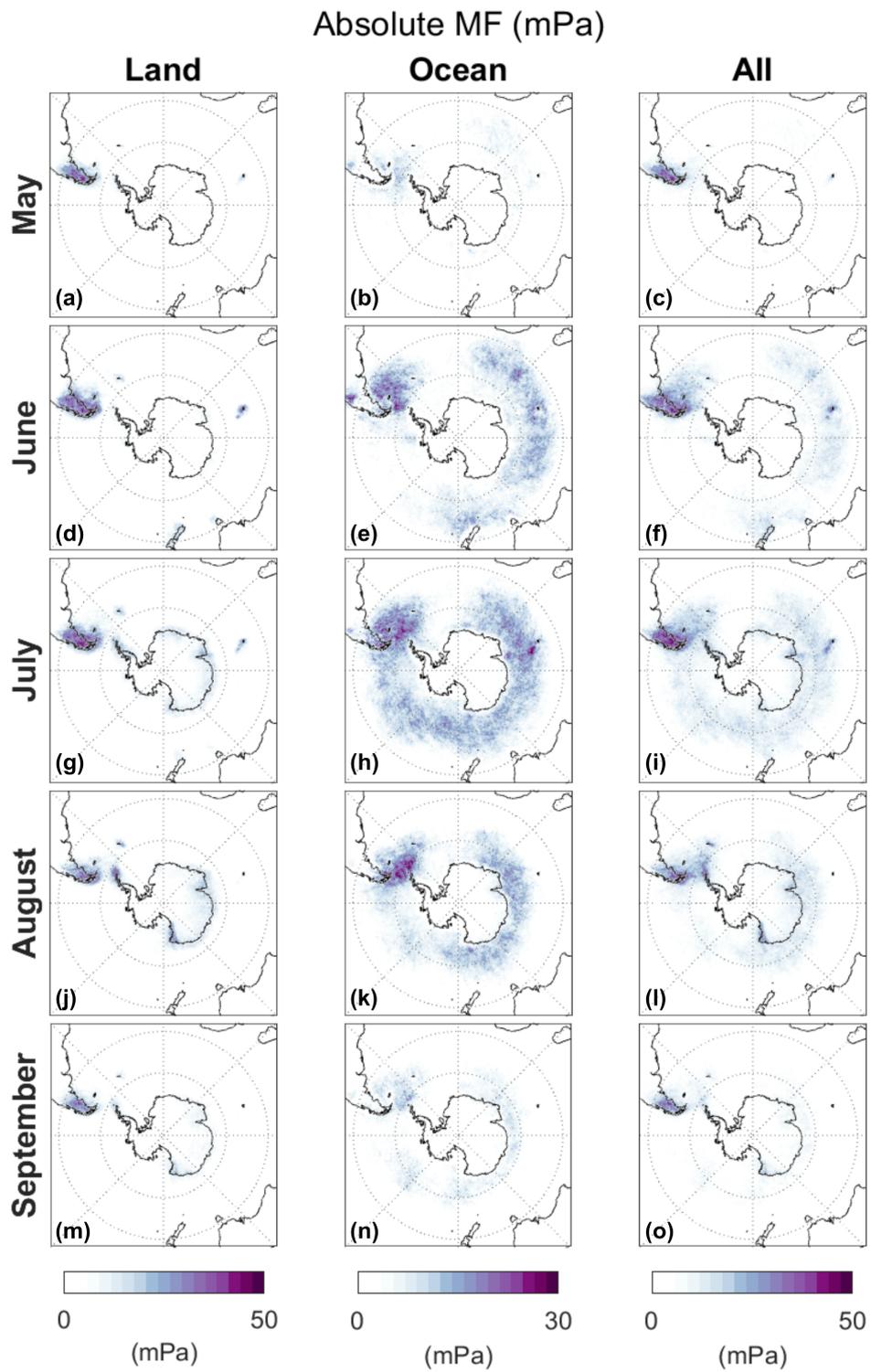


Figure 9. Absolute Momentum Flux (mPa) of rays traced back to land (left column), ocean (middle column) and both (right column), positioned by the observation location of the ray.

536 tinent. There is a clear gap between activity upstream of here. Non-orographic sources
 537 have not been explored in detail in previous studies; however, Hendricks et al. (2014) sug-
 538 gests that some of these hotspots may be attributable to storms. Holt et al. (2017) in-
 539 vestigated absolute MF from a high-resolution GEOS5 Nature Run in relation to both
 540 precipitation and frontogenesis. They found that fronts and precipitation were weakly
 541 correlated with absolute MF between 30°S-80°S at most longitudes, although correla-
 542 tions were higher at the lower latitudes. Plougonven et al. (2017) explored the relation-
 543 ship between wind speeds and GWs in the lower stratosphere in a mesoscale model (which
 544 would not suffer from the observational filter problem that observations do) and found
 545 that large values of non-orographic MF was more likely in regions of strong winds. They
 546 suggest several possible reasons for this, including spatial variations in tropospheric sources,
 547 lateral propagation, local generation of GWs in the stratospheric winds or vertical wind
 548 shear. More recently, Green et al. (2024) calculated momentum fluxes from Project Loon
 549 superpressure balloon data. They analysed the relationship between zonal momentum
 550 fluxes in the lower stratosphere (16-21 km altitude) and zonal background winds over the
 551 Southern Ocean (excluding orographic regions), and found increasing MF with increas-
 552 ing background winds which they argued are due to a combination of wave sources and
 553 filtering.

554 Strube et al. (2021) used backwards ray-tracing to carry out a case study on prop-
 555 agation paths and sources of gravity waves over New Zealand in the ECMWF-IFS model
 556 from 25 km altitude. A strength of this study is in the self-consistency of tracing ECMWF
 557 waves through the ECMWF background atmosphere reducing the likelihood of waves
 558 being mis-traced. They found that firstly, stratospheric gravity waves are subject to far
 559 lateral displacement, in strong agreement with the results of our study (Section 4.2 and
 560 4.3). Secondly, their source attribution revealed that both non-orographic and orographic
 561 sources are important in the region around New Zealand and corroborates the findings
 562 in our work that non-orographic waves can originate over the open ocean.

563 In future work using this ray-traced dataset we aim to better quantify the source
 564 mechanisms of non-orographic GWs, particularly the puzzling enhancement in the Drake
 565 Passage region.

566 4.5 Momentum flux from different source regions

567 We next quantify the fraction of observed stratospheric MF which traces back to
 568 specific geographic regions, illustrated in Figure 10a. These regions are defined as fol-
 569 lows:

- 570 • We first split Antarctica into three regions, specifically a Transantarctic region from
 571 0°-135°E, an Antarctic Peninsula region from 135°W-0° and an East Antarctic
 572 region from 135°E-135°W
- 573 • We next define additional land regions equatorward of Antarctica, specifically (i)
 574 the Southern Andes, including the Falkland Islands, (ii) South Georgia, (iii) Ker-
 575 guelen, including Heard Island, (iv) Australia including Tasmania, and (v) New
 576 Zealand.
- 577 • Finally, we divide the remaining area into a Drake Passage region (55°-80°W) and
 578 a general ocean region covering all remaining areas within 6000 km of the pole.

579 All defined land regions include a 200 km coastline padding on interfaces with the ocean,
 580 as discussed above. Figure 10b shows the proportion of area that each region makes up.
 581 The general ocean region covers the vast majority of this region, making up 78% of the
 582 area; second largest is the East Antarctic region at 7%, then the Antarctic Peninsula at
 583 5%. At the other end of the scale, small islands such as Kerguelen and South Georgia
 584 cover $\sim 0.4\%$ and $\sim 0.2\%$ of the total area.

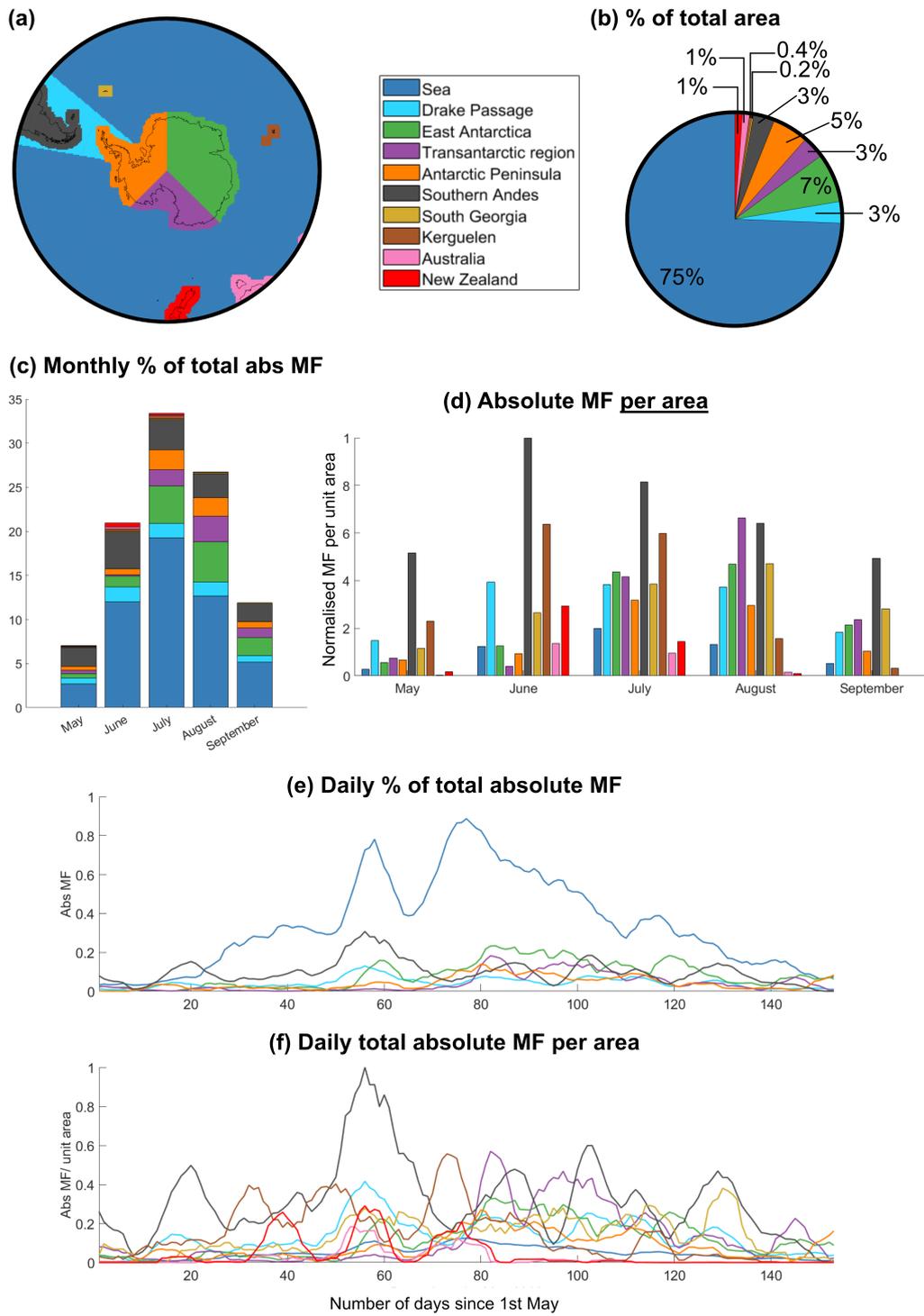


Figure 10. The proportion of observed absolute stratospheric momentum flux traced back to different regions. Panel (a), the different regions. Panel (b) the fraction of the total area that each region makes up, (c) the percentage of total flux split per month and per region, (d) the same absolute momentum flux scaled by the area of each region. Panel (e) shows the daily momentum flux attributed to each region and (f) the daily MF per unit area.

	May	June	July	August	September	Average
Sea	38.6 %	57.3 %	57.8 %	47.3 %	43.1 %	48.8 %
Drake Passage	9.0 %	8.0 %	4.9 %	5.9 %	6.6 %	6.9 %
Total non-orographic	47.6 %	65.4 %	62.6 %	53.3 %	49.6 %	55.7 %
Southern Andes	30.8 %	20.1 %	10.3 %	10.1 %	17.4 %	17.7 %
East Antarctica	7.7 %	5.8 %	12.7 %	17.1 %	17.4 %	12.1 %
Transantarctic region	4.7 %	0.9 %	5.5 %	10.9 %	8.7 %	6.1 %
Antarctic Peninsula	6.7 %	3.2 %	6.7 %	7.8 %	6.1 %	6.1 %
Kerguelen	1.6 %	1.4 %	0.9 %	0.3 %	0.1 %	0.9 %
New Zealand	0.3 %	2.0 %	0.6 %	0.1 %	0.0 %	0.6 %
South Georgia	0.5 %	0.4 %	0.3 %	0.5 %	0.7 %	0.5 %
Australia	0.1 %	0.9 %	0.4 %	0.1 %	0.0 %	0.3 %
Total orographic	52.4 %	34.6 %	37.4 %	46.7 %	50.4 %	44.3 %

Table 1. Percentage of monthly observed stratospheric absolute momentum flux, separated by region traced back to. Columns sum to 100% (when excluding orographic and non-orographic subtotals)

585 In Figure 10c, we show the percentage of absolute MF attributed to each region.
586 This is computed by considering the location each ray is backwards traced to and weight-
587 ing this by the observed absolute MF of this ray at its stratospheric start point. For sim-
588 plicity we scale by the total observed stratospheric MF over May-September (not time-
589 varying values). MF peaks in mid-winter in July, when almost 35% of the overall observed
590 MF across the May-September period is measured.

591 We clearly see that waves traced to sources over the ocean make up the largest pro-
592 portion of MF in the stratosphere. The split between orographic and non-orographic sources
593 vary significantly between months: in May, the split between orographic and non-orographic
594 is even, whereas in July momentum flux from non-orographic regions contributes almost
595 two thirds of the total momentum flux observed.

596 This mix is also illustrated by Figure 10e, where we show the same absolute MF
597 traced to regions (similar to Figure 10c, but as a daily time series smoothed with a 7-
598 day moving mean). We again see that the MF traced to the ocean dominates, and peaks
599 in mid-winter. The second largest-contributing region is the Southern Andes (grey) which
600 shows some temporal variability but is overall more consistent over the time period. In
601 the later winter, i.e. from day 80 onwards, East Antarctica becomes an important source
602 of MF, overtaking the Southern Andes on occasion.

603 In Figure 10d and 10f, we scale the MF traced back to each region by the area of
604 the region, normalising each time series to a maximum of 1. This thus quantifies the MF
605 originating in each region per unit area. We find that waves traced to the ocean contribute
606 only a very small amount of MF per unit area to the total whilst, consistent with our
607 expectations from previous studies, the Southern Andes (grey) contribute the highest
608 MF per unit area across all months. Small islands such as Kerguelen (brown) and South
609 Georgia (yellow) contribute a disproportionately high percentage of observed MF per unit
610 area. This is in agreement with Alexander and Grimsdell (2013) who carried out a com-
611 prehensive analysis of GW activity observed by AIRS over 14 islands in the Southern
612 Ocean and concluded that including these island waves in climate models could contribute
613 a significant fraction of the missing drag on Southern Hemisphere winds. Eckermann et
614 al. (2016) studied the dynamics of orographic GWs observed in the mesosphere over the
615 Auckland Islands (50.7°S 166.1°E) using the aircraft based Advanced Mesospheric Tem-

616 perature Mapper (AMTM) concluding that orographic gravity wave drag due to sub-
 617 antarctic islands contributes significantly to the overall momentum budget and control-
 618 ling the middle atmospheric dynamics. Our results here confirm the importance of MF
 619 generated due to these small islands and precisely quantify the MF values from each re-
 620 gion.

621 Figure 10d shows that the Drake Passage region (light blue) contributes a much
 622 higher MF per unit area than the rest of the sea (blue). As discussed in Section 4.4, this
 623 is likely a combination of high-MF orographic events that have been mis-traced to the
 624 Drake Passage instead of the large sources of the Southern Andes and Antarctic Penin-
 625 sula, non-orographic activity from storms in the Drake Passage region or orographic-jet
 626 induced gravity waves.

627 In Figure 10f we show momentum flux per unit area smoothed with a 7-day mov-
 628 ing mean. Despite this smoothing, the strong intermittency of different sources can still
 629 be seen, in agreement with previous observational studies on intermittency (J. H. Jiang
 630 et al., 2002; Wright et al., 2013, 2017; Minamihara et al., 2020, and others). In partic-
 631 ular, Kerguelen (brown), South Georgia (yellow) and New Zealand (red) exhibit seemingly-
 632 periodic activity, which may be related to lower-stratospheric planetary waves modulat-
 633 ing gravity wave excitation and also influencing the visibility of these waves to AIRS.
 634 Vertical gravity wave propagation from tropospheric sources into the middle atmosphere
 635 over New Zealand was studied extensively during the DEEPWAVE campaign (for ex-
 636 ample, Fritts et al., 2016; Kaifler et al., 2015; Bramberger et al., 2017, and many oth-
 637 ers). Kaifler et al. (2015) carried out a detailed study of gravity wave activity over New
 638 Zealand using observations from the ground-based TELMA lidar (Temperature Lidar
 639 for Middle Atmosphere Research) during winter and spring 2014 (covering the DEEP-
 640 WAVE campaign period). They found that GW activity over New Zealand was dom-
 641 inated by individual events of 1-3 days duration alternating with quieter periods, whilst
 642 in our results, momentum flux peaks in roughly 20 day periods, this is possibly due to
 643 observational filter effects with different instruments seeing different parts of the GW
 644 spectrum.

645 Finally, we quantify the contribution of momentum flux from the different regions
 646 in Table 1. This shows the percentage of total observed monthly MF attributed to each
 647 region. On average, 55.7% of absolute MF traces back to land, while 44.3% is traced
 648 back to the ocean. This means that whilst orographic sources contribute much more MF
 649 per unit area and as a result appear as hotspots of activity, non-orographic GW activ-
 650 ity contributes more to the overall observed MF. This proportion varies temporally, with
 651 orographic sources contributing as much as 52.4% in May and as little as 34.6% in June
 652 to the total.

653 This is the first time that the relative contributions of these sources to the total
 654 observed momentum flux have been definitively quantified. For context, using stratosphere-
 655 level data only, Hindley et al. (2019) attributed 20-37% of the zonal momentum flux ob-
 656 served by AIRS between 68-35°S to the Southern Andes throughout June, July and Au-
 657 gust by comparing the observed zonal total to the fraction observed in the 80-55°W lon-
 658 gitude range. Our work significantly expands upon this both by employing ray-tracing
 659 methods to push the calculation back from the stratosphere to the source level and by
 660 quantifying all plausible source regions contributing to this belt. The Southern Andes,
 661 as expected, is the largest land source and contributes 10.1%-30.8%, then next strongest
 662 are the East Antarctic region (5.8%-17.4%) and the Transantarctic region (0.9%-10.9%).
 663 The large range on each of these values represents the significant seasonal variability at
 664 play: the Antarctic Peninsula contributes the same to the total observed MF on aver-
 665 age as the Transantarctic region (6.1%) but with a much more consistent range (3.2%-
 666 7.8%). Kerguelen's contributes 0.1%-1.6% to the monthly average, with New Zealand
 667 just behind at 0%-0.7%. This zero lower bound is because in September there was al-
 668 most no contribution to the total observed momentum flux, most likely due to the po-

669 sitioning of the jet away from New Zealand in that month. Finally, South Georgia and
670 Australia contribute 0.3%–0.7% and 0.1%–0.9% across the winter months.

671 5 Conclusions

672 In this work, we have backwards ray-traced all AIRS polar winter observations of
673 GWs over Antarctica and the surrounding area for the period May - September 2012.
674 AIRS is sensitive to gravity waves long vertical wavelength waves which carry the ma-
675 jority of momentum flux. We use these 14.2 million traced waves to systematically ex-
676 plore the meridional propagation and downstream propagation of waves from key oro-
677 graphic regions. Examine the spatial split between orographically and non-orographically
678 generated waves, and, for the first time, explicitly quantify the contributions of differ-
679 ent source regions to the overall observed momentum flux. Our key conclusions are:

- 680 • Waves converge to 60°S at all longitudes, and not just over the Andes and Antarc-
681 tic Peninsula. We measure an average meridional propagation distance ~ 500 km
682 from tropospheric sources to ~ 40 km of altitude.
- 683 • Waves observed thousands of kilometres downstream of the Southern Andes, Antarc-
684 tic Peninsula, Transantarctic Mountains, Prince Charles Mountains, Kerguelen,
685 South Georgia and New Zealand can be traced back to distant sources. Such down-
686 stream propagation of these orographic waves is highly dependent on the back-
687 ground stratospheric wind, partly due to the strong winds of the jet refracting the
688 waves to longer vertical wavelengths and increasing their observability to AIRS.
- 689 • Of those waves which trace back to sources over the ocean, we see a pattern dom-
690 inated by strong non-orographic GW activity at all longitudes around 60°S ex-
691 cept for the region between $\approx 20^\circ$ W and $\approx 10^\circ$ E. In future work with this dataset
692 we will specifically investigate the role non-orographic sources in the southern pol-
693 ar region.
- 694 • We quantify the proportion of observed MF that is traced back to different regions
695 (see Table 1). On average, orographic sources contribute 44% and non-orographic
696 sources 56%. Land covers less than a quarter of this region, and thus it is likely
697 that orographic-source waves contribute almost three times as much MF per unit
698 area, but this is counterbalanced by the much larger area available for non-orographic
699 sources to act. The measured values vary significantly by month.
- 700 • The small islands of Kerguelen and South Georgia contribute strongly to total over-
701 all MF observed despite only making up $< 1\%$ of the land area. In May, Kergue-
702 len was responsible for 1.6% of the overall observed MF in the stratosphere, and
703 this contribution is likely to be even higher at shorter timescales due to the in-
704 termittency of these island sources.

705 Our work provides strong observational evidence of GW behaviour across the win-
706 ter Southern Hemisphere and quantifies the propagation and momentum fluxes from dif-
707 ferent sources to aid future GW parametrisations.

708 Open Research Section

709 The 3-D AIRS temperature retrieval used in this work is described in (Hoffmann
710 & Alexander, 2009) and is publicly available at (Hoffmann, 2021). ERA5 reanalysis used
711 is also publicly available (Copernicus Climate Change Service, 2017).

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722 References

- 723 Alexander, M. J. (1998, APR). Interpretations of observed climatological patterns
 724 in stratospheric gravity wave variance. *Journal of Geophysical Research: Atmo-*
 725 *spheres*, *103*(D8), 8627–8640. doi: 10.1029/97jd03325
- 726 Alexander, M. J., & Barnet, C. (2007). Using satellite observations to constrain
 727 parameterizations of gravity wave effects for global models. *J. Atmos. Sci.*, *64*,
 728 1652–1665. doi: 10.1175/JAS3897.1
- 729 Alexander, M. J., Eckermann, S. D., Broutman, D., & Ma, J. (2009). Mo-
 730 mentum flux estimates for South Georgia Island mountain waves in the
 731 stratosphere observed via satellite. *Geophys. Res. Lett.*, *36*, L12816. doi:
 732 10.1029/2009GL038587
- 733 Alexander, M. J., Geller, M., McLandress, C., Polavarapu, S., Preusse, P., Sassi, F.,
 734 ... Watanabe, S. (2010, JUL). Recent developments in gravity-wave effects
 735 in climate models and the global distribution of gravity-wave momentum flux
 736 from observations and models. *Quart. J. Roy. Meteor. Soc.*, *136*(650, A),
 737 1103–1124. doi: {10.1002/qj.637}
- 738 Alexander, M. J., Gille, J., Cavanaugh, C., Coffey, M., Craig, C., Eden, T., ...
 739 Dean, V. (2008, May). Global estimates of gravity wave momentum flux from
 740 high resolution dynamics limb sounder observations. *Journal of Geophysical*
 741 *Research*, *113*(D15), 0148–0227. Retrieved from [https://doi.org/10.1029/](https://doi.org/10.1029/2007jd008807)
 742 [2007jd008807](https://doi.org/10.1029/2007jd008807) doi: 10.1029/2007jd008807
- 743 Alexander, M. J., & Grimsdell, A. W. (2013). Seasonal cycle of orographic gravity
 744 wave occurrence above small islands in the Southern Hemisphere: Implications
 745 for effects on the general circulation. *J. Geophys. Res.*, *118*, 11589–11599. doi:
 746 10.1002/2013JD020526
- 747 Aumann, H., Chahine, M., Gautier, C., Goldberg, M., Kalnay, E., McMillin, L.,
 748 ... Susskind, J. (2003, Feb). Airs/amsu/hsb on the aqua mission: de-
 749 sign, science objectives, data products, and processing systems. *IEEE*
 750 *Transactions on Geoscience and Remote Sensing*, *41*(2), 253–264. doi:
 751 10.1109/TGRS.2002.808356
- 752 Bacmeister, J. T., & Schoeberl, M. R. (1989). Breakdown of Vertically Propagat-
 753 ing Two-Dimensional Gravity Waves Forced by Orography. *J. Atmos. Sci.*, *46*,
 754 2109–2134.
- 755 Banyard, T. P., Wright, C. J., Hindley, N. P., Halloran, G., Krisch, I., Kaifler, B., &
 756 Hoffmann, L. (2021). Atmospheric gravity waves in aeolus wind lidar observa-
 757 tions. *Geophysical Research Letters*, *48*(10), e2021GL092756. (e2021GL092756
 758 2021GL092756) doi: <https://doi.org/10.1029/2021GL092756>
- 759 Bramberger, M., Dörnbrack, A., Bossert, K., Ehard, B., Fritts, D. C., Kaifler, B., ...
 760 Witschas, B. (2017). Does strong tropospheric forcing cause large-amplitude
 761 mesospheric gravity waves? a deepwave case study. *J. Geophys. Res.*, *122*(21),
 762 11,422–11,443. doi: 10.1002/2017JD027371
- 763 Chahine, M. T., Pagano, T. S., Aumann, H. H., Atlas, R., Barnet, C., Bblaisdell, J.,
 764 ... Zhou, L. (2006, 07). AIRS: Improving Weather Forecasting and Provid-
 765 ing New Data on Greenhouse Gases. *Bulletin of the American Meteorological*
 766 *Society*, *87*(7), 911–926. doi: 10.1175/BAMS-87-7-911
- 767 Copernicus Climate Change Service. (2017). *ERA5: Fifth generation of ECMWF*
 768 *atmospheric reanalyses of the global climate*. European Centre For Medium-

- 769 Range Weather Forecasts (ECMWF), <https://cds.climate.copernicus>
770 [.eu/](https://cds.climate.copernicus.eu/). ([Accessed March 2023])
- 771 Dunkerton, T. J. (1984, 12). Inertia–Gravity Waves in the Stratosphere. *Journal*
772 *of the Atmospheric Sciences*, *41*(23), 3396–3404. doi: 10.1175/1520-0469(1984)
773 041<3396:IWITS>2.0.CO;2
- 774 Eckermann, S. D., Broutman, D., Ma, J., Doyle, J. D., Pautet, P.-D., Taylor, M. J.,
775 ... Smith, R. B. (2016, OCT). Dynamics of orographic gravity waves observed
776 in the mesosphere over the Auckland Islands during the deep propagating
777 gravity wave experiment (DEEPWAVE). *J. Atmos. Sci.*, *73*(10), 3855–3876.
778 doi: 10.1175/JAS-D-16-0059.1
- 779 Eckermann, S. D., & Marks, C. J. (1997). Grograt: A new model of the global prop-
780 agation and dissipation of atmospheric gravity waves. *Advances in Space Re-*
781 *search*, *20*(6), 1253–1256. Retrieved from [https://www.sciencedirect.com/](https://www.sciencedirect.com/science/article/pii/S0273117797007801)
782 [science/article/pii/S0273117797007801](https://www.sciencedirect.com/science/article/pii/S0273117797007801) (Coupling and Energetics in the
783 Stratosphere-Mesosphere-Thermosphere- Ionosphere System) doi: [https://doi](https://doi.org/10.1016/S0273-1177(97)00780-1)
784 [.org/10.1016/S0273-1177\(97\)00780-1](https://doi.org/10.1016/S0273-1177(97)00780-1)
- 785 Eckermann, S. D., & Preusse, P. (1999). Global Measurements of Stratospheric
786 Mountain Waves from Space. *Science*, *286*, 1534–1537. doi: 10.1126/science
787 .286.5444.1534
- 788 Eichinger, R., Rhode, S., Garny, H., Preusse, P., Pisoft, P., Kuchař, A., ...
789 Kern, B. (2023). Emulating lateral gravity wave propagation in a global
790 chemistry–climate model (emac v2.55.2) through horizontal flux redistri-
791 bution. *Geoscientific Model Development*, *16*(19), 5561–5583. Retrieved
792 from <https://gmd.copernicus.org/articles/16/5561/2023/> doi:
793 10.5194/gmd-16-5561-2023
- 794 Ern, M., Preusse, P., Alexander, M. J., & Warner, C. D. (2004). Absolute values
795 of gravity wave momentum flux derived from satellite data. *J. Geophys. Res.*,
796 *109*, D20103. doi: 10.1029/2004JD004752
- 797 Ern, M., Trinh, Q. T., Preusse, P., Gille, J. C., Mlynczak, M. G., III, J. M. R., &
798 Riese, M. (2018, April). GRACILE: a comprehensive climatology of atmo-
799 spheric gravity wave parameters based on satellite limb soundings. *Earth*
800 *System Science Data*, *10*(2), 857–892. doi: 10.5194/essd-10-857-2018
- 801 Fritts, D. C., & Alexander, M. J. (2003). Gravity wave dynamics and ef-
802 fects in the middle atmosphere. *Reviews of Geophysics*, *41*, 1003. doi:
803 10.1029/2001RG000106
- 804 Fritts, D. C., Riggan, D. M., Balsley, B. B., & Stockwell, R. G. (1998). Recent re-
805 sults with an mf radar at mcmurdo, antarctica: Characteristics and variability
806 of motions near 12-hour period in the mesosphere. *Geophys. Res. Lett.*, *25*(3),
807 297–300. doi: 10.1029/97GL03702
- 808 Fritts, D. C., Smith, R. B., Taylor, M. J., Doyle, J. D., Eckermann, S. D.,
809 Dörnbrack, A., ... Ma, J. (2016). The deep propagating gravity wave ex-
810 periment (deepwave): An airborne and ground-based exploration of gravity
811 wave propagation and effects from their sources throughout the lower and mid-
812 dle atmosphere. *Bulletin of the American Meteorological Society*, *97*(3), 425 -
813 453. Retrieved from [https://journals.ametsoc.org/view/journals/bams/](https://journals.ametsoc.org/view/journals/bams/97/3/bams-d-14-00269.1.xml)
814 [97/3/bams-d-14-00269.1.xml](https://journals.ametsoc.org/view/journals/bams/97/3/bams-d-14-00269.1.xml) doi: 10.1175/BAMS-D-14-00269.1
- 815 Garcia, R. R., Smith, A. K., Kinnison, D. E., de la Camara, A., & Murphy, D. J.
816 (2017). Modification of the gravity wave parameterization in the whole at-
817 mosphere community climate model: Motivation and results. *Journal of the*
818 *Atmospheric Sciences*, *74*(1), 275–291. doi: 10.1175/JAS-D-16-0104.1
- 819 Garfinkel, C. I., & Oman, L. D. (2018). Effect of gravity waves from small islands in
820 the southern ocean on the southern hemisphere atmospheric circulation. *Jour-*
821 *nal of Geophysical Research: Atmospheres*, *123*(3), 1552–1561. doi: 10.1002/
822 2017JD027576
- 823 Geldenhuys, M., Preusse, P., Krisch, I., Züllicke, C., Ungermann, J., Ern, M., ...

- 824 Riese, M. (2021). Orographically induced spontaneous imbalance within
 825 the jet causing a large-scale gravity wave event. *Atmos. Chem. Phys.* doi:
 826 10.5194/acp-21-10393-2021
- 827 Geller, M., Alexander, M. J., Love, P., Bacmeister, J., Ern, M., Hertzog, A., ...
 828 Zhou, T. (2013). A Comparison between Gravity Wave Momentum Fluxes in
 829 Observations and Climate Models. *Journal of Climate*, *26*, 6383–6405. doi:
 830 10.1175/JCLI-D-12-00545.1
- 831 Green, B., Sheshadri, A., Alexander, M. J., Bramberger, M., & Lott, F. (2024).
 832 Gravity wave momentum fluxes estimated from project loon balloon data.
 833 *Journal of Geophysical Research: Atmospheres*, *129*(5), e2023JD039927.
 834 Retrieved from [https://agupubs.onlinelibrary.wiley.com/doi/abs/](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2023JD039927)
 835 [10.1029/2023JD039927](https://doi.org/10.1029/2023JD039927) (e2023JD039927 2023JD039927) doi: [https://](https://doi.org/10.1029/2023JD039927)
 836 doi.org/10.1029/2023JD039927
- 837 Hasha, A., Bühler, O., & Scinocca, J. (2008). Gravity wave refraction by
 838 three-dimensionally varying winds and the global transport of angular mo-
 839 mentum. *Journal of the Atmospheric Sciences*, *65*(9), 2892 - 2906. Re-
 840 trieved from [https://journals.ametsoc.org/view/journals/atsc/65/9/](https://journals.ametsoc.org/view/journals/atsc/65/9/2007jas2561.1.xml)
 841 [2007jas2561.1.xml](https://journals.ametsoc.org/view/journals/atsc/65/9/2007jas2561.1.xml) doi: 10.1175/2007JAS2561.1
- 842 Hendricks, E., Doyle, J., Eckermann, S. D., Jiang, Q., & Reinecke, P. (2014). What
 843 Is the Source of the Stratospheric Gravity Wave Belt in Austral Winter? *J.*
 844 *Atmos. Sci.*, *71*, 1583–1592. doi: 10.1175/JAS-D-13-0332.1
- 845 Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J.,
 846 ... others (2020). The era5 global reanalysis. *Quarterly Journal of the Royal*
 847 *Meteorological Society*, *146*(730), 1999–2049.
- 848 Hertzog, A., Alexander, M. J., & Plougonven, R. (2012). On the Intermittency of
 849 Gravity Wave Momentum Flux in the Stratosphere. *J. Atmos. Sci.*, *69*, 3433–
 850 3448. doi: 10.1175/JAS-D-12-09.1
- 851 Hertzog, A., Boccara, G., Vincent, R. A., Vial, F., & Cocquerez, P. (2008). Estima-
 852 tion of gravity wave momentum flux and phase speeds from quasi-Lagrangian
 853 stratospheric balloon flights. Part II: Results from the Vorcore campaign in
 854 Antarctica. *J. Atmos. Sci.*, *65*, 3056–3070. doi: 10.1175/2008JAS2710.1
- 855 Hindley, N. P., Smith, N. D., Wright, C. J., Rees, D. A. S., & Mitchell, N. J. (2016,
 856 June). A two-dimensional stockwell transform for gravity wave analysis of
 857 AIRS measurements. *Atmospheric Measurement Techniques*, *9*(6), 2545–2565.
 858 doi: 10.5194/amt-9-2545-2016
- 859 Hindley, N. P., Wright, C. J., Gadian, A. M., Hoffmann, L., Hughes, J. K., Jackson,
 860 D. R., ... Ross, A. N. (2021). Stratospheric gravity waves over the mountain-
 861 ous island of south georgia: testing a high-resolution dynamical model with 3-d
 862 satellite observations and radiosondes. *Atmospheric Chemistry and Physics*,
 863 *21*(10), 7695–7722. Retrieved from [https://acp.copernicus.org/articles/](https://acp.copernicus.org/articles/21/7695/2021/)
 864 [21/7695/2021/](https://acp.copernicus.org/articles/21/7695/2021/) doi: 10.5194/acp-21-7695-2021
- 865 Hindley, N. P., Wright, C. J., Hoffmann, L., Moffat-Griffin, T., & Mitchell, N. J.
 866 (2020, November). An 18-year climatology of directional stratospheric gravity
 867 wave momentum flux from 3-d satellite observations. *Geophysical Research*
 868 *Letters*, *47*(22), e2020GL089557. doi: 10.1029/2020gl089557
- 869 Hindley, N. P., Wright, C. J., Smith, N. D., Hoffmann, L., Holt, L. A., Alexander,
 870 M. J., ... Mitchell, N. J. (2019). Gravity waves in the winter stratosphere
 871 over the southern ocean: high-resolution satellite observations and 3-d spectral
 872 analysis. *Atmospheric Chemistry and Physics*, *19*(24), 15377–15414. doi:
 873 10.5194/acp-19-15377-2019
- 874 Hindley, N. P., Wright, C. J., Smith, N. D., & Mitchell, N. J. (2015). The southern
 875 stratospheric gravity wave hot spot: individual waves and their momentum
 876 fluxes measured by cosmic gps-ro. *Atmos. Chem. Phys.*, *15*(14), 7797–7818.
 877 doi: 10.5194/acp-15-7797-2015
- 878 Hoffmann, L. (2021). *Airs/aqua observations of gravity waves [dataset]*. doi: 10

- 879 .26165/JUELICH-DATA/LQAAJA
- 880 Hoffmann, L., & Alexander, M. J. (2009). Retrieval of stratospheric temperatures
881 from Atmospheric Infrared Sounder radiance measurements for gravity wave
882 studies. *J. Geophys. Res.*, *114*, D07105. doi: 10.1029/2008JD011241
- 883 Hoffmann, L., Alexander, M. J., Clerbaux, C., Grimsdell, A. W., Meyer, C. I.,
884 Roessler, T., & Tournier, B. (2014). Intercomparison of stratospheric gravity
885 wave observations with AIRS and IASI. *Atmos. Meas. Tech.*, *7*(12), 4517-4537.
886 doi: {10.5194/amt-7-4517-2014}
- 887 Hoffmann, L., Grimsdell, A. W., & Alexander, M. J. (2016). Stratospheric
888 gravity waves at southern hemisphere orographic hotspots: 2003–2014
889 airs/aqua observations. *Atmos. Chem. Phys.*, *16*(14), 9381–9397. doi:
890 10.5194/acp-16-9381-2016
- 891 Hoffmann, L., Xue, X., & Alexander, M. J. (2013). A global view of stratospheric
892 gravity wave hotspots located with Atmospheric Infrared Sounder observa-
893 tions. *J. Geophys. Res.*, *118*, 416–434. doi: 10.1029/2012JD018658
- 894 Holt, L. A., Alexander, M. J., Coy, L., Liu, C., Molod, A., Putman, W., & Pawson,
895 S. (2017). An evaluation of gravity waves and gravity wave sources in the
896 southern hemisphere in a 7km global climate simulation. *Quarterly Journal of*
897 *the Royal Meteorological Society*, *143*(707), 2481-2495. doi: 10.1002/qj.3101
- 898 Holt, L. A., Brabec, C. M., & Alexander, M. J. (2023). Exploiting high-
899 density zonal-sampling of hirdls profiles near 60°s to investigate miss-
900 ing drag in chemistry-climate models. *Journal of Geophysical Re-*
901 *search: Atmospheres*, *128*(8), e2022JD037398. Retrieved from [https://](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2022JD037398)
902 agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2022JD037398
903 (e2022JD037398 2022JD037398) doi: <https://doi.org/10.1029/2022JD037398>
- 904 Jewtoukoff, V., Hertzog, A., Plougonven, R., de la Camara, A., & Lott, F. (2015).
905 Comparison of gravity waves in the southern hemisphere derived from balloon
906 observations and the ecmwf analyses. *Journal of the Atmospheric Sciences*,
907 *72*(9), 3449-3468. doi: 10.1175/JAS-D-14-0324.1
- 908 Jiang, J. H., Wu, D. L., & Eckermann, S. D. (2002). Upper atmosphere research
909 satellite (uars) mls observation of mountain waves over the andes. *Journal of*
910 *Geophysical Research: Atmospheres*, *107*(D20), SOL 15-1-SOL 15-10. doi: 10
911 .1029/2002JD002091
- 912 Jiang, Q., Doyle, J. D., Eckermann, S. D., & Williams, B. P. (2019). Stratospheric
913 trailing gravity waves from new zealand. *Journal of the Atmospheric Sciences*,
914 *76*(6), 1565 - 1586. Retrieved from [https://journals.ametsoc.org/view/](https://journals.ametsoc.org/view/journals/atsc/76/6/jas-d-18-0290.1.xml)
915 [journals/atsc/76/6/jas-d-18-0290.1.xml](https://journals/ametsoc.org/view/journals/atsc/76/6/jas-d-18-0290.1.xml) doi: 10.1175/JAS-D-18-0290.1
- 916 Kaifler, B., Kaifler, N., Ehard, B., Dörnbrack, A., Rapp, M., & Fritts, D. C. (2015,
917 November). Influences of source conditions on mountain wave penetration into
918 the stratosphere and mesosphere. *Geophysical Research Letters*, *42*(21), 9488–
919 9494. doi: 10.1002/2015gl066465
- 920 Krasauskas, L., Kaifler, B., Rhode, S., Ungermann, J., Woiwode, W., & Preusse,
921 P. (2023). Oblique propagation and refraction of gravity waves over the an-
922 des observed by gloria and alima during the southtrac campaign. *Journal*
923 *of Geophysical Research: Atmospheres*, *128*(10), e2022JD037798. Retrieved
924 from [https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2022JD037798)
925 [2022JD037798](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2022JD037798) (e2022JD037798 2022JD037798) doi: [https://doi.org/10.1029/](https://doi.org/10.1029/2022JD037798)
926 [2022JD037798](https://doi.org/10.1029/2022JD037798)
- 927 Krisch, I., Preusse, P., Ungermann, J., Dörnbrack, A., Eckermann, S. D., Ern, M.,
928 ... Riese, M. (2017). First tomographic observations of gravity waves by
929 the infrared limb imager gloria. *Atmospheric Chemistry and Physics*, *17*(24),
930 14937–14953. doi: 10.5194/acp-17-14937-2017
- 931 Lighthill, M. J. (1967). Waves in fluids. *Communications on Pure and Applied*
932 *Mathematics*, *20*(2), 267-293. Retrieved from [https://onlinelibrary.wiley](https://onlinelibrary.wiley.com/doi/abs/10.1002/cpa.3160200204)
933 [.com/doi/abs/10.1002/cpa.3160200204](https://onlinelibrary.wiley.com/doi/abs/10.1002/cpa.3160200204) doi: <https://doi.org/10.1002/cpa>

- 934 .3160200204
- 935 Marks, C. J., & Eckermann, S. D. (1995). A three-dimensional nonhydrostatic ray-
 936 tracing model for gravity waves: Formulation and preliminary results for the
 937 middle atmosphere. *Journal of the Atmospheric Sciences*, *52*(11), 1959-1984.
 938 doi: 10.1175/1520-0469(1995)052<1959:ATDNRT>2.0.CO;2
- 939 McDonald, A. J. (2012). Gravity wave occurrence statistics derived from paired
 940 COSMIC/FORMOSAT3 observations. *J. Geophys. Res.*, *117*, D15106. doi: 10
 941 .1029/2011JD016715
- 942 McLandress, C., Shepherd, T. G., Polavarapu, S., & Beagley, S. R. (2012). Is Miss-
 943 ing Orographic Gravity Wave Drag near 60°S the Cause of the Stratospheric
 944 Zonal Wind Biases in Chemistry–Climate Models? *J. Atmos. Sci.*, *69*, 802–
 945 818. doi: 10.1175/JAS-D-11-0159.1
- 946 McLandress, C., Shepherd, T. G., Scinocca, J. F., Plummer, D. A., Sigmund, M.,
 947 Jonsson, A. I., & Reader, M. C. (2011). Separating the dynamical effects of
 948 climate change and ozone depletion. part ii: Southern hemisphere troposphere.
 949 *Journal of Climate*, *24*(6), 1850-1868. doi: 10.1175/2010JCLI3958.1
- 950 Minamihara, Y., Sato, K., & Tsutsumi, M. (2020). Intermittency of gravity waves
 951 in the antarctic troposphere and lower stratosphere revealed by the pansy
 952 radar observation. *Journal of Geophysical Research: Atmospheres*, *125*(15),
 953 e2020JD032543. Retrieved from [https://agupubs.onlinelibrary.wiley](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2020JD032543)
 954 [.com/doi/abs/10.1029/2020JD032543](https://doi.org/10.1029/2020JD032543) (e2020JD032543 2020JD032543) doi:
 955 <https://doi.org/10.1029/2020JD032543>
- 956 Moffat-Griffin, T., Colwell, S. R., Wright, C. J., Hindley, N. P., & Mitchell, N. J.
 957 (2020). Radiosonde observations of a wintertime meridional convergence of
 958 gravity waves around 60°s in the lower stratosphere. *Geophysical Research*
 959 *Letters*, *47*(20), e2020GL089740. doi: <https://doi.org/10.1029/2020GL089740>
- 960 Perrett, J., Wright, C. J., Hindley, N. P., Hoffmann, L., Mitchell, N. J., Preusse, P.,
 961 ... S., E. (2020). Determining gravity wave sources and propagation in the
 962 southern hemisphere by ray-tracing airs measurements. *Geophysical Research*
 963 *Letters*. doi: 10.1029/2020GL088621
- 964 Plougonven, R., de la Cámara, A., Hertzog, A., & Lott, F. (2020). How does
 965 knowledge of atmospheric gravity waves guide their parameterizations? *Quar-*
 966 *terly Journal of the Royal Meteorological Society*, *146*(728), 1529-1543. doi:
 967 10.1002/qj.3732
- 968 Plougonven, R., Hertzog, A., & Guez, L. (2013). Gravity waves over Antarctica and
 969 the Southern Ocean: consistent momentum fluxes in mesoscale simulations and
 970 stratospheric balloon observations. *Quart. J. Roy. Meteor. Soc.*, *139*, 101–118.
 971 doi: 10.1002/qj.1965
- 972 Plougonven, R., Jewtoukoff, V., de la Cámara, A., Lott, F., & Hertzog, A. (2017).
 973 On the relation between gravity waves and wind speed in the lower strato-
 974 sphere over the southern ocean. *Journal of the Atmospheric Sciences*, *74*(4),
 975 1075-1093. doi: 10.1175/JAS-D-16-0096.1
- 976 Pramitha, M., Kumar, K. K., Ratnam, M. V., Praveen, M., & Rao, S. V. B. (2020).
 977 Gravity wave source spectra appropriation for mesosphere lower thermosphere
 978 using meteor radar observations and grograt model simulations. *Geophys-*
 979 *ical Research Letters*, *47*(19), e2020GL089390. Retrieved from [https://](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2020GL089390)
 980 [agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2020GL089390](https://doi.org/10.1029/2020GL089390)
 981 (e2020GL089390 2020GL089390) doi: <https://doi.org/10.1029/2020GL089390>
- 982 Preusse, P., Dörnbrack, A., & Eckermann, S. (2002). Space-based measurements of
 983 stratospheric mountain waves by CRISTA 1. Sensitivity, analysis method, and
 984 a case study. *J. Geophys. Res.*, *107*, 8178. doi: 10.1029/2001JD000699
- 985 Preusse, P., Eckermann, S. D., Ern, M., Oberheide, J., Picard, R. H., Roble, R. G.,
 986 ... Mlynarczyk, M. G. (2009). Global ray tracing simulations of the saber
 987 gravity wave climatology. *Journal of Geophysical Research: Atmospheres*,
 988 *114*(D8). Retrieved from <https://agupubs.onlinelibrary.wiley.com/doi/>

- 989 [abs/10.1029/2008JD011214](https://doi.org/10.1029/2008JD011214) doi: <https://doi.org/10.1029/2008JD011214>
- 990 Preusse, P., Ern, M., Bechtold, P., Eckermann, S. D., Kalisch, S., Trinh, Q. T., &
- 991 Riese, M. (2014). Characteristics of gravity waves resolved by ECMWF.
- 992 *Atmos. Chem. Phys.*, *14*. doi: 10.5194/acp-14-10483-2014
- 993 Pulido, M., Rodas, C., Dechat, D., & Lucini, M. M. (2013). High gravity-
- 994 wave activity observed in patagonia, southern america: generation by a
- 995 cyclone passage over the andes mountain range. *Quarterly Journal of*
- 996 *the Royal Meteorological Society*, *139*(671), 451-466. Retrieved from
- 997 <https://rmets.onlinelibrary.wiley.com/doi/abs/10.1002/qj.1983>
- 998 doi: <https://doi.org/10.1002/qj.1983>
- 999 Rapp, M., Kaifler, B., Dörnbrack, A., Gisinger, S., Mixa, T., Reichert, R., ... Engel,
- 1000 A. (2021). Southtrac-gw: An airborne field campaign to explore gravity
- 1001 wave dynamics at the world's strongest hotspot. *Bulletin of the Ameri-*
- 1002 *can Meteorological Society*, *102*(4), E871 - E893. Retrieved from [https://](https://journals.ametsoc.org/view/journals/bams/102/4/BAMS-D-20-0034.1.xml)
- 1003 journals.ametsoc.org/view/journals/bams/102/4/BAMS-D-20-0034.1.xml
- 1004 doi: 10.1175/BAMS-D-20-0034.1
- 1005 Rhode, S., Preusse, P., Ern, M., Ungermann, J., Krasauskas, L., Bacmeister, J., &
- 1006 Riese, M. (2023). A mountain ridge model for quantifying oblique moun-
- 1007 tain wave propagation and distribution. *Atmospheric Chemistry and Physics*,
- 1008 *23*(14), 7901–7934. Retrieved from [https://acp.copernicus.org/articles/](https://acp.copernicus.org/articles/23/7901/2023/)
- 1009 [23/7901/2023/](https://acp.copernicus.org/articles/23/7901/2023/) doi: 10.5194/acp-23-7901-2023
- 1010 Sato, K., Tateno, S., Watanabe, S., & Kawatani, Y. (2011). Gravity Wave Charac-
- 1011 teristics in the Southern Hemisphere Revealed by a High-Resolution Middle-
- 1012 Atmosphere General Circulation Model. *J. Atmos. Sci.*, *69*, 1378–1396. doi:
- 1013 10.1175/JAS-D-11-0101.1
- 1014 Strube, C., Preusse, P., Ern, M., & Riese, M. (2021). Propagation paths and source
- 1015 distributions of resolved gravity waves in ecmwf-ifs analysis fields around the
- 1016 southern polar night jet. *Atmospheric Chemistry and Physics Discussions*,
- 1017 *2021*, 1–39. doi: 10.5194/acp-2021-160
- 1018 Vosper, S. B. (2015). Mountain waves and wakes generated by south georgia: impli-
- 1019 cations for drag parametrization. *QJRMMS*, *141*(692), 2813-2827. doi: 10.1002/
- 1020 qj.2566
- 1021 Watanabe, S., Kawatani, Y., Tomikawa, Y., Miyazaki, K., Takahashi, M., & Sato, K.
- 1022 (2008). General aspects of a T213L256 middle atmosphere general circulation
- 1023 model. *J. Geophys. Res.*, *113*, D12110. doi: 10.1029/2008JD010026
- 1024 Watanabe, S., Sato, K., & Takahashi, M. (2006). A general circulation model
- 1025 study of the orographic gravity waves over antarctica excited by katabatic
- 1026 winds. *Journal of Geophysical Research: Atmospheres*, *111*(D18). Retrieved
- 1027 from [https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2005JD006851)
- 1028 [2005JD006851](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2005JD006851) doi: <https://doi.org/10.1029/2005JD006851>
- 1029 Wrasse, C. M., Nakamura, T., Takahashi, H., Medeiros, A. F., Taylor, M. J., Gobbi,
- 1030 D., ... Admiranto, A. G. (2006). Mesospheric gravity waves observed near
- 1031 equatorial and low-middle latitude stations: wave characteristics and reverse
- 1032 ray tracing results. *Annales Geophysicae*, *24*(12), 3229–3240. Retrieved
- 1033 from <https://angeo.copernicus.org/articles/24/3229/2006/> doi:
- 1034 10.5194/angeo-24-3229-2006
- 1035 Wright, C. J., & Gille, J. C. (2013). Detecting overlapping gravity waves using the
- 1036 S-Transform. *Geophys. Res. Lett.*, *40*, 1850–1855. doi: 10.1002/grl.50378
- 1037 Wright, C. J., Hindley, N. P., Alexander, M. J., Holt, L. A., & Hoffmann, L.
- 1038 (2021). Using vertical phase differences to better resolve 3d gravity wave
- 1039 structure. *Atmospheric Measurement Techniques*, *14*(9), 5873–5886. Re-
- 1040 trieved from <https://amt.copernicus.org/articles/14/5873/2021/> doi:
- 1041 10.5194/amt-14-5873-2021
- 1042 Wright, C. J., Hindley, N. P., Hoffmann, L., Alexander, M. J., & Mitchell, N. J.
- 1043 (2017). Exploring gravity wave characteristics in 3-d using a novel s-transform

- 1044 technique: Airs/aqua measurements over the southern andes and drake
1045 passage. *Atmospheric Chemistry and Physics*, 17(13), 8553–8575. doi:
1046 10.5194/acp-17-8553-2017
- 1047 Wright, C. J., Hindley, N. P., Moss, A. C., & Mitchell, N. J. (2016). Multi-
1048 instrument gravity-wave measurements over tierra del fuego and the drake
1049 passage - part 1: Potential energies and vertical wavelengths from airs, cosmic,
1050 hirdls, mls-aura, saamer, saber and radiosondes. *Atmospheric Measurement*
1051 *Techniques*, 9(3), 877–908. doi: 10.5194/amt-9-877-2016
- 1052 Wright, C. J., Osprey, S. M., & Gille, J. C. (2013). Global observations of gravity
1053 wave intermittency and its impact on the observed momentum flux morphol-
1054 ogy. *J. Geophys. Res.*, 118, 10,980–10,993. doi: 10.1002/jgrd.50869
- 1055 Wu, D. L. (2004). Mesoscale gravity wave variances from amsu-a radiances. *Geophys.*
1056 *Res. Lett.*, 31(12), 1944-8007. (L12114) doi: 10.1029/2004GL019562
- 1057 Wu, D. L., & Eckermann, S. D. (2008). Global gravity wave variances from aura
1058 mls: Characteristics and interpretation. *Journal of the Atmospheric Sciences*,
1059 65(12), 3695-3718. doi: 10.1175/2008JAS2489.1