Estimation of Gravity Wave Momentum Flux and Phase Speeds from Quasi-Lagrangian Stratospheric Balloon Flights. Part II: Results from the Vorcore Campaign in Antarctica

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ABSTRACT

The stratospheric gravity wave field in the Southern Hemisphere is investigated by analyzing observations collected by 27 long-duration balloons that flew between September 2005 and February 2006 over Antarctica and the Southern Ocean. The analysis is based on the methods introduced by Boccara et al. in a companion paper. Special attention is given to deriving information useful to gravity wave drag parameterizations employed in atmospheric general circulation models. The balloon dataset is used to map the geographic variability of gravity wave momentum fluxes in the lower stratosphere. This flux distribution is found to be very heterogeneous with the largest time-averaged value (28 mPa) observed above the Antarctic Peninsula. This value exceeds by a factor of ~10 the overall mean momentum flux measured during the balloon campaign. Zonal momentum fluxes were predominantly westward, whereas meridional momentum fluxes were equally northward and southward. A local enhancement of southward flux is nevertheless observed above Adélie Land and is attributed to waves generated by katabatic winds, for which the signature is otherwise rather small in the balloon observations. When zonal averages are performed, oceanic momentum fluxes are found to be of similar magnitude to continental values (2.5–3 mPa), stressing the importance of nonorographic gravity waves over oceans. Last, gravity wave intermittency is investigated. Mountain waves appear to be significantly more sporadic than waves observed above the ocean.

1. Introduction

The role of gravity waves (GWs) in forcing the global-scale circulation and the thermal structure of the middle atmosphere has long been recognized (e.g., Holton 1983; Shepherd 2002). Owing to horizontal and vertical scales, respectively ~10–1000 km, and ~100 m–10 km, that are in general too short to be explicitly re-
stratosphere as the chemical processes responsible for ozone depletion are very dependent on temperature (Eyring et al. 2006).

The paucity of GW momentum-flux observations in the atmosphere is known to be a limiting factor in the improvement of GWD parameterizations (e.g., McLandress and Scinocca 2005). Most observations have been obtained by radar technique at widely spaced locations around the globe (e.g., Vincent and Reid 1983; Nakamura et al. 1993). Recently, the analysis of infrared radiances measured from space during the two week-long Cryogenic Infrared Spectrometers and Telescopes for the Atmosphere (CRISTA) missions provided useful insights into the distribution of GW momentum fluxes at global scale (Ern et al. 2004, 2006). Alexander et al. (2008) similarly derived absolute momentum fluxes from the High Resolution Dynamics Limb Sounder (HIRDLS) observations in May 2006. Nevertheless, because of the short duration of these space-borne datasets and their limited horizontal resolution, new observations of GW momentum fluxes are needed to further constrain GWD parameterizations.

The effect of gravity waves on the large-scale structure of the atmosphere is particularly important at Southern Hemisphere (SH) polar latitudes in winter: wave breaking at mesospheric heights induces significant changes in temperature down to the lower stratosphere (Garcia and Boville 1994). Indeed, models that do not represent the correct flux of momentum associated with gravity wave propagation in the SH polar latitudes suffer from strong cold temperature biases that can reach several tens of degrees in the stratospheric vortex (e.g., Hamilton et al. 1995). In spite of the difficulties of performing observations in Antarctica, useful information on GW activity in the SH polar latitudes has been obtained from radiosounding profiles (Allen and Vincent 1995; Pfenninger et al. 1999; Yoshiki and Sato 2000; Yoshiki et al. 2004), MLS and AMSU radiances (Wu and Waters 1996; Wu and Jiang 2002; Wu 2004), and GPS radio occultations (Tsuda et al. 2000; Ratnam et al. 2004a,b; Baumgaertner and McDonald 2007). These studies described the annual cycle of GW potential and/or kinetic energy and reported on enhancements of GW activity associated with disturbances of the stratospheric polar vortex induced by planetary waves.

Here we complement these previous studies by providing information on the distributions of GW momentum fluxes and GW propagation directions at SH polar latitudes. Our results are based on meteorological observations gathered during quasi-Lagrangian, long-duration balloon flights performed during the Vorcore campaign (September 2005–February 2006) (Vial et al. 1995; Hertzog et al. 2007). Such observations have already been used to estimate the momentum fluxes carried by gravity waves (Hertzog and Vial 2001; Vincent et al. 2007). This study, however, will make use of new theoretical developments described in a companion paper (Bocca et al. 2008, hereafter B08).

The article is organized as follows: The next section briefly describes the main characteristics of the Vorcore observations and reports on the limits of the dataset relevant to GW studies. The characteristics of the observed momentum fluxes are described in detail in section 3. The wide geographical coverage of balloonborne observations enables us to study the relative importance of orographic and nonorographic waves (section 4), as well as the intermittency of wave activity in the lower stratosphere (section 5). Section 6 briefly discusses some aspects of our results, and the final section summarizes our findings.

2. The Vorcore campaign

a. Observations

The aim of the Stratéole/Vorcore campaign was to study the dynamics of the lower stratosphere in winter and spring to document the various regimes of the polar-night vortex. The originality of the project comes from the use of quasi-Lagrangian devices to sample the atmosphere. These devices are superpressure, helium-filled balloons that have the ability to remain aloft for several months while being advected by the wind. During Vorcore, 27 such balloons were released from McMurdo, Antarctica (77.8°S, 166.7°E), between 5 September and 28 October 2005. The mean flight duration during the campaign was 59 days, and the longest flight lasted almost four months (109 days). The last flight terminated on 1 February 2006 (i.e., during the SH summer).

As discussed in B08, each balloon carried a scientific payload that essentially performed 15-min observations of air temperature and 3D position from which the horizontal velocities of the wind were deduced. The air pressure was also measured, but at a higher rate (every minute) in order to explicitly resolve the balloon’s neutral oscillations. Owing to better precision with respect to absolute GPS, the pressure observations are also used to document the vertical motions of the balloons induced by geophysical phenomena (waves, seasonal cycle, etc.)

Figure 1 shows the total number of observations in 10° × 5° longitude–latitude boxes. All balloons were released in the stratospheric vortex; therefore, the observations were mostly gathered south of 60°S. While relatively well centered around the pole in September...
and October 2005, the lower-stratospheric vortex moved to the Atlantic sector of Antarctica in November, which explains the higher number of observations in that region. The final warming took place in early December, and after that time the remaining balloons were free to sample the midlatitudes. For safety reasons, however, flights were automatically terminated when the balloons crossed the 40°S parallel, so no observations were gathered equatorward of that latitude. Further details on the campaign, the scientific payload, and the evolution of the stratospheric vortex during the 2005 winter can be found in Hertzog et al. (2007).

b. Observational filter

As for other observation techniques, observations performed during Vorcore tend to filter out parts of the overall GW spectrum. In the case of observations gathered onboard long-duration balloons that drift with the horizontal wind, the observational filter is best expressed in terms of the GW intrinsic frequency $\omega$. The low frequency part of the intrinsic-frequency gravity wave spectrum ($\omega \to f$, where $f$ is the inertial frequency) is fully resolved by the observations owing to flight lengths that far exceed the longest inertial period in the flight domain (i.e., $\sim$19 h at 40°S). On the other hand, the high frequency part of the GW spectrum, $\omega \to N$, where $N$ is the Brunt–Väisälä frequency, cannot be resolved because of the limited sampling rate of the observations. Although the Nyquist period during Vorcore is 30 min, we only computed momentum fluxes for waves with intrinsic periods longer than 1 h. This limit was set to ensure a sufficient resolution of the highest frequency waves studied as our momentum flux estimates critically rely on subtle phase differences between velocity and pressure time series (see B08). This theoretical observational filter is displayed with the thick curve in Fig. 2. For comparison, the typical Brunt–Väisälä period ($2\pi/N$) during Vorcore was $\sim$4 min 40 s.

Additional filtering is implicitly produced by the algorithms used to analyze the dataset and to isolate GW packets. As shown in B08, the algorithms result in an underestimation of the wave momentum flux depending on the amount of wave packet overlapping in the time–frequency space. B08 reported a $\sim$25% underestimation on average when 10 GW packets were present in 10-day-long flights. However, the magnitude of this effect also depends on the wave intrinsic period. This additional effect is shown with the thin curve in Fig. 2. It is up to 50% larger at the highest resolved frequencies and less than 15% for quasi-inertial waves.

The GW dispersion relation (e.g., Fritts and Alexander 2003) can be used to convert the long-duration balloon observational filter in terms of horizontal and vertical wavelengths, $\lambda_h$ and $\lambda_z$. Wavelength space is more convenient for most other observational techniques: radiosondes, spaceborne limb sounders, or GPS radio occultations. Since the high frequency part of the GW spectrum cannot be observed with Vorcore observations, the resolved horizontal and vertical wavelengths are not totally independent. The wavelength domain that can be observed by the long-duration balloons with the Vorcore sampling is displayed in Fig. 2. A good approximation to the Vorcore observational limit is

$$\lambda_z \leq \frac{\lambda_h}{12}. $$

For comparison purposes, the CRISTA-1 observational domain is also represented in this figure (Preusse et al.
2002; Ern et al. 2004). The balloon and limb-sounder observational domains are very similar. The main difference lies in the ability of the balloons to observe waves with vertical wavelengths shorter than the CRISTA vertical resolution. [The vertical resolution of recent limb-sounding instruments (e.g., HIRDLS) have, however, been improved, and waves with vertical wavelengths of \( \frac{2}{2} \) km can be observed by these new instruments (Alexander et al. 2008).] On the other hand, under favorable observing conditions, CRISTA can detect waves with shorter horizontal wavelengths than the balloons. It can also be noticed that both domains are typically wider than the observational domain of radiosoundings, which typically is \( \frac{8}{8} \) km (Alexander 1998).

3. Gravity wave momentum flux

Exploiting the methodology described in B08, Vorcore flight data are used to estimate gravity wave absolute momentum flux, that is, the vertical flux of momentum along the wave direction of propagation \((u'w')\). Based on the results obtained by Allen and Vincent (1995) and Yoshiki and Sato (2000) in the lower stratosphere, we made the assumption that the observed waves were propagating upward so that this flux is always a positive quantity. The wave propagation direction, relative to east (\( \theta \)), was identified for each wave packet, and the zonal \((u'w')\) and meridional \((u'w')\) momentum flux were obtained as \(u'_w \cos \theta\) and \(u'_w \sin \theta\). In contrast with the absolute momentum fluxes, those latter fluxes are signed quantities: waves propagating either toward the west or the south carry negative zonal or meridional momentum fluxes, respectively.

The results presented here were obtained with the 24 longest out of the 27 balloon flights performed during Vorcore. The three discarded flights lasted less than 2 days and were therefore not long enough to allow wavelet analysis. The vertical gradient of background temperature, which is needed to estimate gravity wave momentum fluxes from the balloon dataset [see Eqs. (14) and (15) in B08], was computed from the operational analyses released by the European Centre for Medium-Range Weather Forecasts (ECMWF). According to B08, the 1\( \sigma \) uncertainty in the momentum flux values reported below is 11\%–13\%.

The following results are presented in terms of density-weighted momentum flux, that is, \(\rho_0 u'_w w'\), or \(\rho_0 u' w'\), where \(\rho_0\) is the mean density along each balloon flight. It is computed from the balloonborne pressure and temperature observations. Density-weighted momentum fluxes have the advantage of being independent of altitude, if the waves propagate without breaking, so that the lower-stratospheric estimates presented here can, in principle, be directly compared with

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FIG. 2. (left) Theoretical observational filter in terms of wave intrinsic frequency in Vorcore observations (thick line) and an observational filter deduced from Monte Carlo simulations presented in B08 (thin line). Note that the observational filter is defined in terms of momentum flux in the Monte Carlo simulations. (right) Vorcore observational filter in horizontal–vertical wavelength space. The gray-colored zone (delimited by the thick line) corresponds to spectral areas that cannot be observed with the Vorcore dataset. Typical values for \(f\) and \(N\) corresponding to the Vorcore dataset were assumed. For comparison purposes, the CRISTA-1 observational domain is also displayed and corresponds to the half space on the upper right hand side of the thin lines. The dashed area corresponds to horizontal wavelengths that can be resolved by CRISTA-1 if gravity waves propagate at favorable angles with respect to the instrument line of sight (Preusse et al. 2002; Ern et al. 2004).
results obtained at different altitudes. The use of flight-mean densities is justified by the fact that the super-pressure balloons used during Vorcore drift on constant density surfaces to first order. Typical residual variations of density are generally less than 2%. Balloons with two different sizes were used during Vorcore, resulting in two density flight levels separated by about 1.5 km. Both balloon types have nevertheless been combined in the following results as it is expected that the density-weighted momentum fluxes would not significantly vary over this short vertical range.

a. Geographical distribution

1) Absolute momentum flux

To obtain the geographical distribution of the density-weighted absolute momentum flux, we averaged these fluxes in $10^\circ \times 5^\circ$ longitude–latitude boxes. Note that the area covered by each box varies with latitude, so the individual boxes do not contribute equally to the global GW flux. Furthermore, the polarmost boxes, south of $85^\circ$S, were merged to increase the statistical confidence in that region. The resulting total number of observations south of $85^\circ$S is 4223.

Figure 3 displays the box-averaged distribution of the density-weighted absolute momentum flux $\rho_0 u'_w$. Although the Vorcore observations extend up to $40^\circ$S, there are only a few observations per box northward of $50^\circ$S. The map therefore extends only up to $50^\circ$S. Furthermore, no statistics were computed in boxes with less than 200 balloon observations.

Figure 3 reveals a strong heterogeneity of GW momentum fluxes in the southern high latitudes, with the largest fluxes observed above the Antarctic Peninsula and its lee and to a lesser extent above the southern tip of South America. The overall campaign-averaged momentum flux amounts to 2.5 mPa, whereas the campaign-averaged momentum flux above the peninsula locally reaches 28 mPa, exceeding by a factor of $\sim 10$ the overall mean flux. This confirms the preliminary results of Vincent et al. (2007), which were obtained from only one Vorcore flight. They are also in agreement with previous satellite observations of gravity wave activity above Antarctica that already stressed the importance of the peninsula in the generation of gravity waves (e.g., Tsuda et al. 2000; Wu and Jiang 2002; Ern et al. 2004; Wu 2004; Ern et al. 2006; Baumgaertner and McDonald 2007; Alexander and Barnet 2007). Away from the Antarctic Peninsula and the southern Andes, the momentum fluxes are more homogeneously distributed. Slightly larger fluxes are nevertheless observed above mountainous western Antarctica and to some extent along the Antarctica coastline. On the other hand, most of the eastern Antarctica plateau is a region of very weak GW activity.

This geographical distribution of absolute momentum flux emphasizes the importance of orographic gravity waves at SH polar and subpolar latitudes. In particular, the Antarctic Peninsula and the southern Andes are characterized by meridionally aligned mountain ridges, which are almost perpendicular to the low-level eastward flow and are therefore favored regions for the generation of mountain waves.

2) Zonal and meridional momentum flux

The geographical distributions of zonal and meridional density-weighted momentum fluxes are displayed in Fig. 4. Recall that these signed fluxes are representative of the mean wave field and are not easily linked to the absolute momentum flux. For instance, a perfectly symmetric field of waves propagating equally in each direction would produce a net zero zonal or meridional flux, the momentum flux carried by one wave packet being cancelled by that of another wave packet propagating in the opposite direction. On the other hand, the absolute momentum flux of this field, and thus its ability to interact with the mean flow, would be nonzero (see, e.g., Sato and Dunkerton 1997; Hertzog and Vial 2001).

In agreement with the results of Yoshiki and Sato (2000) at the Japanese Antarctic station Syowa, the zonal momentum fluxes are found to be predominantly negative (i.e., westward) in the winter lower strato-
sphere, which means that gravity waves are essentially propagating against the mean eastward stratospheric flow. This feature is particularly emphasized over the Antarctic Peninsula, the southern Andes, and the Ellsworth Mountains, which again suggests that the gravity waves generated there have an orographic origin. Although of smaller amplitudes than over mountainous areas, the oceanic zonal momentum fluxes are also mostly negative. The largest westward oceanic zonal fluxes are observed above the Atlantic and the western Indian Oceans and typically amount to \( \sim -1 \) mPa.

In contrast with the zonal fluxes, the meridional fluxes exhibit both positive and negative values. The largest northward fluxes are found above the Antarctic Peninsula and are likely to be associated with the main southwest–northeast orientation of the mountain ridges there. On the other hand, southward propagating waves are observed above the tip of South America, which is also consistent with the main orientation of the southern Andes. However, the largest negative meridional flux is found on the edge of Antarctica between 140° and 150°E, a region that includes Adélie Land. This region is associated with strong meridional gradients of elevation between the ocean and the Antarctic Plateau and is known as one of the windiest places on earth (Wendler et al. 1997; Parish and Walker 2006). If the waves observed there are also produced by the orography, the southward momentum flux would imply a northward near-surface flow, that is, from the plateau to the sea. This suggests, therefore, that the waves at the edge of the continent can be linked to katabatic winds that are particularly important in this region (Watanabe et al. 2006; Parish and Bromwich 2007). Possible reasons why similar enhancements of meridionally propagating waves are not observed all along the Antarctic coast are discussed further below.

**b. Temporal variations**

The results above were obtained using all data acquired during the campaign, from early September 2005 to late January 2006. However, several studies have shown that there is a seasonal cycle of GW activity at SH high latitudes (e.g., Pfenninger et al. 1999; Tsuda et al. 2000; Yoshiki and Sato 2000; Ratnam et al. 2004a; Ern et al. 2006; Baumgaertner and McDonald 2007). Based on those studies, GW potential energy appears to maximize in the polar lower stratosphere between September and November (spring), whereas Ern et al. (2006) report smaller momentum flux in November than in August. While this may be due to the interannual variability of wave activity, which is significant in the polar lower stratosphere (Baumgaertner and McDonald 2007), another explanation could be that the GW potential energy is not directly linked to the wave momentum flux, as suggested in Ern et al. (2004) and Alexander et al. (2008).

The temporal variation of GW momentum flux during the campaign is shown in Fig. 5. This figure was obtained by computing the mean value of the absolute momentum flux in 10-day intervals starting from the beginning of September 2005. Each value therefore combines all observations performed in the corre-
sponding interval, whatever the latitudes or longitudes of the balloons. Apart from the first interval, which has few observations, Fig. 5 shows a general tendency of momentum flux to decrease from winter to summer. Typically, momentum fluxes are found to be about twice as large in September–October than in December–January. However, it should be noted that the precise ratio is difficult to estimate with our observations; it is probably biased by the evolution of the balloon flotilla during the campaign. For instance, the balloons sampled midlatitude regions only after the stratospheric vortex had broken down in early December 2005 (Hertzog et al. 2007). A modest enhancement of GW momentum fluxes is observed, nevertheless, in the first two weeks of December when the 2005 stratospheric vortex broke down, as suggested in Yoshiki et al. (2004).

Another interesting feature of the momentum-flux temporal evolution is the peak of activity observed in early October. At that time 14 balloons were already flying and sampling the interior of the stratospheric vortex. In fact, this sudden enhancement of wave activity is due to the encounter of a very strong gravity wave by two balloons above the Antarctic Peninsula (Hertzog et al. 2007). A modest enhancement of GW momentum fluxes is observed, nevertheless, in the first two weeks of December when the 2005 stratospheric vortex broke down, as suggested in Yoshiki et al. (2004).

\[ F(\epsilon_v) = F_m \text{sgn}(\epsilon_v) \exp\left(-\frac{|\epsilon_v|}{\epsilon_p}\right), \]  

This section presents results on the distribution of the observed momentum fluxes versus wave phase speeds. B08 showed that wave phase speeds are retrieved with less accuracy than either momentum fluxes or directions of propagation. Thus, although we believe that those results give further insights into the GW field above Antarctica, they certainly require further confirmation. Note also that the phase speed retrieval uses time series of the balloon density. For two of the 24 balloons used in this study (balloons 8 and 16), both thermistors were broken during launching operations. The results presented here are therefore obtained from the remaining 22 balloons.

Observational distributions of momentum flux versus phase speed are most directly relevant to the gravity wave drag parameterization developed by Alexander and Dunkerton (1999, hereafter AD99), which uses such a wave spectrum at the source level. Nevertheless, as shown in McLandress and Scinocca (2005), AD99 does not essentially differ from other spectral parameterizations (e.g., Hines 1997a,b; Warner and McIntyre 2001).

The distribution of zonal and meridional momentum flux versus intrinsic phase speed are displayed in black and gray, respectively, in the left panel of Fig. 6. Whereas the meridional momentum distribution is almost symmetric with respect to zero phase speed, the zonal distribution clearly exhibits larger fluxes at negative intrinsic phase speeds. This difference between the distributions is consistent with the geographical distribution of zonal and meridional momentum (Fig. 4), which shows a negative net value for the former and no significant tendency for the latter. The largest differences between westward and eastward momentum fluxes occur at relatively low phase speeds. Such behavior is likely to be a signature of mountain waves, which propagate against the mean eastward wind in the vicinity of the Antarctic Peninsula. In part, it may also result from the filtering of eastward propagating waves by upper tropospheric winds (Alexander 1998).

In an attempt to provide quantitative numbers from the observed momentum flux distribution versus phase speed, we made an analytic fit to the meridional distribution since it is less subject to wind filtering and thus may be more representative of the source spectrum. AD99 used Gaussian and exponential-like functions to represent their source spectra. A Gaussian function does not fit very well to our observed distribution, so we used the following exponential model:
where $\hat{c}_y$ is the meridional intrinsic phase speed of the wave.

The result of this fit is shown with the dashed curve in Fig. 6. The best estimates for $F_m$ and $\hat{c}_p$ are $5.5 \times 10^{-2}$ mPa and $92$ m s$^{-1}$: $F_m$ depends on the phase speed resolution (here 10 m s$^{-1}$) chosen to compute the momentum distribution as well as on the sampling by the balloon flotilla of various wave sources and their inherent intermittency. The characteristic intrinsic phase speed $\hat{c}_p$ is found to be significantly larger than the values used in AD99, even for the value used in their “broad” spectrum. As shown in B08, our algorithm tends to overestimate phase speeds, so the real $u'w'(\hat{c}_x)$ and $v'w'(\hat{c}_y)$ distributions almost certainly contain more momentum flux at low phase speeds than is represented in the left panel of Fig. 6. Consequently, the value of $\hat{c}_p$ derived here should be considered an upper bound to the real atmospheric value.

The right panel of Fig. 6 shows the zonal and meridional momentum fluxes versus their respective zonal and meridional ground-based phase speeds. In contrast to the distribution versus intrinsic phase speed, the momentum flux in each bin is a sum of both positive and negative values. This is obvious in the meridional spectrum; waves with small meridional ground-based phase speed ($c_\gamma \sim 0$) carry either positive or negative momentum flux depending on the mean meridional velocity of the wind. As the campaign-averaged meridional velocity is nearly zero, both cases occur equally, and the net meridional flux in the vicinity of $c_\gamma = 0$ is small. On the other hand, waves with small zonal ground-based phase speed carry preferentially negative momentum, as the mean zonal wind is directed eastward. Actually, the sign of the net zonal momentum flux changes at $c_x \sim 20$ m s$^{-1}$, which corresponds to typical values of zonal velocities observed during the campaign. Finally, the largest zonal momentum fluxes are found near $c_x \sim 0$, which once again emphasizes the role of mountain waves.

### 4. Wave sources

GW drag parameterizations used in GCMs generally consist of two distinct contributions associated with waves that are either generated by orographic processes or other processes. In particular, little is yet known about the momentum flux carried by nonorographic waves on a global scale. Numerical simulations tend to show that these waves play an important role in the mean thermodynamic state of the middle atmosphere (e.g., Eyring et al. 2006). Nonorographic waves can be generated by a wide variety of processes: deep convection, midlatitude jets and fronts, geostrophic adjustment, etc. During Vorcore, however, because most observations were gathered at polar and subpolar latitudes, it is reasonable to expect a stronger contribution...
of wave sources other than deep convection, which is predominantly expected in the tropics.

It is thus of some importance to try to distinguish in the Vorcore dataset the respective role of orographic and nonorographic waves in carrying the momentum fluxes reported in the previous sections. As described in Vincent et al. (2007), the approach that we took was to use a very simple geographical criterion based on the topography gradient computed from the NOAA 5’ × 5’ gridded elevation dataset. Each of the geographical boxes that we used previously was thus flagged as orographic or nonorographic depending on the mean of the 10% largest elevation gradient within the box. Typically, most of western West Antarctica, the Antarctic coast and peninsula, as well as the tip of South America were flagged as orographic. This classification is obviously an oversimplification as nonorographic waves may be produced over areas with steep topography, while orographic waves may propagate over flat terrain and be observed by the balloons there. To limit this last effect, we also flagged boxes located in the direct lee of the Antarctic Peninsula as orographic. We believe that our classification tends to give an upper-bound estimation to the actual momentum flux of orographic waves, whereas the converse is true for nonorographic waves.

Figure 7 shows the results of this classification, that is, the latitudinal distribution of zonal-mean density-weighted absolute momentum flux carried by orographic waves (thin solid), nonorographic waves (thin dashed), and by both types of waves (thick solid). The wave classification is based on a simple geographical criterion (see text). The latitudes used to plot the distribution correspond to the centers of the geographical boxes (e.g., the polarmost point is plotted at 87.5°S).

The importance of nonorographic waves above the southern oceans contrasts somewhat with the geographical distribution of total momentum flux displayed in Fig. 3. The discrepancies are explained by the fact that the values displayed in Fig. 3 correspond to local averages of total momentum flux, whereas Fig. 7 shows zonal means. Hence, even though momentum fluxes about 10 times larger than the zonal means are observed above the Antarctic Peninsula, the zonal average significantly reduces the importance of this location. On the other hand, momentum fluxes associated with nonorographic waves are much more zonally symmetric, so the values reported in Fig. 7 are of the same order as the fluxes observed above the oceans, as shown in Fig. 3.

Figure 7 also shows that the nonorographic momentum fluxes exhibit significant variations from the South Pole to the southern midlatitudes. Values north of 60°S are 4 to 5 times larger than those south of 70°S. This maximum at the latitudes of the Southern Hemisphere storm tracks (Trenberth 1991) further supports the hypothesis that the nonorographic waves observed during Vorcore were associated with synoptic-scale tropospheric disturbances. Similar enhancements of GW activity were reported by Yoshiki et al. (2004) at Syowa when such disturbances were observed in the vicinity to the station.

5. Gravity wave intermittency

An as yet poorly constrained parameter of several GW parameterizations is the so-called GW intermit-
Intermittency factor $\epsilon$, that is, the measure of the probability with which the parameterized wave source effectively generates GW packets. Source intermittency has profound consequences on GW forcing of the mean flow. For instance, for a given long-term mean momentum flux, waves produced by an intermittent source will break lower in the atmosphere than those produced by a steady source (see, e.g., Bühler 2003; Piani et al. 2004).

Long-duration balloons, which can stay in the atmosphere for months and sample wide geographic areas, are particularly well suited to characterize the intermittency of the GW field irrespective of the underlying surface or weather conditions. Here, two methods are applied to the balloon dataset to characterize GW intermittency. The first method is very similar to that used by Bühler (2003). It consists of considering wave sources that sporadically emit packets that always have the same amplitude so that the source has “on” and “off” phases. Such behavior is mathematically modeled by a random Bernoulli process, and the probability with which the source emits GW, the intermittency, can be computed from the expectation $\mu$ and the variance $\sigma^2$ of the Bernoulli process; that is,

$$\epsilon_1 = \frac{1}{1 + \sigma^2/\mu^2}. \quad (2)$$

This equation is equivalent to (27) in Bühler (2003). In this approach, GW intermittency is thus estimated simply from the expectation and mean of the absolute momentum-flux probability distribution function (pdf) in each of the geographical boxes. It is displayed in the left panel of Fig. 8.

Although this is generally the approach used in GW parameterization schemes, it is obviously oversimplified since, more realistically, wave sources generate waves with varying amplitudes. A better proxy of GW intermittency should rely therefore on the whole pdf of the momentum flux distribution rather than on its two first moments (Piani et al. 2004). A first step in that direction is the second approach that we applied to the Vorcore dataset. In this approach, we define the intermittency as

$$\epsilon_2 = \frac{p_{0.5}}{p_{0.9}}, \quad (3)$$

where $p_{0.5}$ and $p_{0.9}$ are, respectively, the 50% (i.e., the median) and 90% percentiles of the momentum-flux pdf in each geographical box. The resulting intermit-
tencies are shown in the right panel of Fig. 8.

Although the GW intermittencies obtained with both methods differ in magnitude, the relative variations within each map are well correlated. Actually, the absolute magnitude of the GW intermittency computed with the second method is not very significant as it depends strongly on the quantiles in (3); one could, for instance, use the 80% percentile rather than $p_{0.9}$, which would increase $\epsilon_2$.

What stands out from the two maps in Fig. 8 is that the most intermittent sources, associated with the low-
est probability of observation, are found above mountainous areas, such as the Antarctic Peninsula, the Ellsworth Range, and the Antarctic coast in several places, including Adélie Land. In contrast, the probability of observing gravity waves is largest, and the intermittency smallest, above the oceans and to a lesser extent above the Antarctic Plateau. With the orographic classification used in the previous section, one obtains averaged values of $e_i$ that amount to 0.09 over mountainous areas, 0.43 over flat areas, and 0.56 over the oceans north of 60°S. There is thus a clear distinction in the Vorcore observations between orographic waves that possess a very sporadic character and non-orographic waves in the midlatitudes that tend to be much steadier. This result is consistent with the variability of GW activity already noticed above the Antarctic Peninsula and also with previous findings from satellite observations and mountain wave modeling, which display large day-to-day variability (Eckermann and Preusse 1999; Jiang et al. 2002). If confirmed, such results would thus argue for intermittency parameters that vary with different sources in GWD parameterizations.

It should be recognized, however, that intermittency derived from the balloon observations differs in several aspects from the intermittency used in GWD parameterizations. First, the intermittency obtained with the Vorcore observations is representative of the whole GW spectrum (within the observational limits specified above) and only depends on the geographical location. In contrast, the intermittency in AD99 depends on the phase-speed resolution used to represent the GW sources. More importantly, in GWD parameterizations the intermittency is an intrinsic property of a wave source. In our observations, on the other hand, the computed intermittency results from both the source intrinsic intermittency and the filtering of the wave packets by the mean flow. For instance, the propagation of small phase-speed orographic waves up to the balloon altitude depends strongly on the wind profile between the mountains and the balloons. This filtering can a priori have a nontrivial effect on the observed $e_i$ acting to either increase or decrease it with respect to the wave source intermittency. At this stage it is unclear if wind filtering has a systematic effect and biases the observed intermittency. This possible systematic effect can be assessed in the future with ray-tracing simulations.

6. Discussion

a. Momentum flux underestimation

An important goal is to provide observational estimates of GW momentum fluxes at the Southern Hemisphere high latitudes in order to help improve GW drag parameterizations. However, as stated earlier, our values are likely to underestimate the actual GW flux. The first factor is caused by the algorithm used to compute the momentum fluxes from the balloon observations. Nevertheless, B08 demonstrated that this factor can be estimated from the corresponding attenuation produced in the retrieved GW kinetic energy. Using this proxy, we found that the analysis algorithm underestimates the momentum fluxes by 25% in the Vorcore dataset. As previously mentioned, the raw value of the campaign-averaged absolute momentum flux is 2.5 mPa. Applying the correction factor yields a value of 3.2 mPa for the absolute momentum flux carried by the gravity waves discussed here.

Another factor leading to underestimation is caused by the observational filter associated with the sampling rate used during Vorcore. Only the low intrinsic frequency part of the spectrum is addressed in this study. Momentum fluxes carried by waves with intrinsic periods ranging from the Brunt–Väisälä period up to 1 h are missed. To estimate the contribution of the high-frequency waves to the total GW momentum flux, we show in Fig. 9 the campaign-averaged wavelet spectrum of absolute momentum flux. This spectrum roughly scales as the inverse of the intrinsic frequency at frequencies higher than twice the (campaign averaged) inertial frequency. If we assume that such scaling is valid up to the Brunt–Väisälä frequency, the resolved and unresolved momentum flux should be comparable (to within about 10%).
given typical values for the buoyancy \((2\pi/N \sim 5 \text{ min})\) and inertial \((2\pi/f \leq 12 \text{ h})\) periods. Notice, however, that there is likely to be more momentum flux in the resolved periods owing to the small enhancement in the spectrum close to the inertial frequency, which is associated with the ubiquitous presence of quasi-inertial waves in the balloon observations (Hertzog et al. 2002). Hence, the upper bound to the total absolute GW momentum flux during the campaign is likely to be about 6.4 mPa. We also note that the spectrum displayed in Fig. 9 exemplifies an important aspect of quasi-Lagrangian observations. At these high latitudes there is a clear separation in the balloon dataset between GW (\(\omega \approx f\)) and the longer period motions due to planetary-scale Rossby waves for which the energy maximizes at much longer periods than the inertial period. The absence of such scale separation is often an issue in more classical observations such as radiosonde soundings, where a high-pass spatial filter has to be applied to isolate gravity waves.

b. Gravity waves generated by katabatic winds

Somewhat of a surprise in our results is the near lack of momentum flux enhancement at the border of Antarctica, with the exception of a small region between 140° and 150°E, Adélie Land. The eastern Antarctic coast is actually the location of strong katabatic winds that descend from the Antarctic Plateau to the ocean (Parish and Bromwich 2007), which can favor the generation of orographic gravity waves (Watanabe et al. 2006). Two factors may explain this behavior. First, the Vorcore dataset is mostly representative of late winter and spring conditions. Katabatic winds result from the radiative cooling of near-surface air over the Antarctic Plateau and therefore maximize around the winter solstice. It is possible, therefore, that the balloon flights did not occur at the optimum time to observe orographic waves generated by katabatic winds.

Another possible reason for the absence of GW enhancement along the Antarctic coast is the presence of critical levels in the troposphere for orographic waves generated by katabatic winds, preventing them from propagating to balloon flight levels in the stratosphere. Watanabe et al. (2006) reported such critical levels in their GCM simulation of flow over Antarctica. Actually, near-surface winds mainly blow from the south or south-southeast during katabatic wind episodes, whereas the stratospheric flow is mainly eastward. During such periods, the wind therefore veers by at least 90° and likely prevents the propagation of orographic gravity waves into the stratosphere. Such filtering of the waves by the mean wind can also explain the low observational probability of wave events over Adélie Land (see Fig. 8): a continuous northward component of the wind from the surface to the stratosphere (implying a disturbed vortex) is needed for the waves generated by katabatic winds to reach the stratosphere.

c. Comparison with CRISTA and HIRDLS

Apart from long-duration superpressure balloon measurements, there have been only two estimations of GW momentum flux on a global scale. Both of them have been obtained with limb-sounding instruments, either with CRISTA in November 1994 (CRISTA-1) and August 1997 (CRISTA-2) (Ern et al. 2004, 2006) or with HIRDLS onboard Aura in May 2006 (Alexander et al. 2008). The temperature profiles recorded during these satellite missions were used to detect the amplitudes of GW-induced disturbances, as well as the wave vertical and horizontal wavelengths, from which absolute values of GW momentum fluxes were derived. Unfortunately, in both cases, the satellite orbits were such that the spaceborne observations only marginally overlap with those of the Vorcore balloons. In this section, we will nevertheless compare our momentum flux estimates with those obtained during the first CRISTA mission since this dataset was recorded in roughly the same period of the year as the Vorcore campaign.

During CRISTA-1, no observations were performed south of 57°S. Therefore, to compare both datasets, only the balloon observations performed in the 50°–60°S latitude band were used. Balloonborne absolute momentum fluxes \((\hat{\rho}_u \hat{w}^2)\) were furthermore multiplied by \((1 - f^2/\hat{\omega}^2)\) to compute the wave pseudomomentum flux, which is the quantity used in Ern et al. (2004, 2006). This operation is easily done with the Vorcore dataset as the wave intrinsic frequencies are directly inferred from the balloon observations. On the other hand, the CRISTA-1 observations were restricted to 50°–57°S and were corrected for aliasing, as described in Ern et al. (2006).

Vorcore and CRISTA-1 results are compared in Fig. 10. The campaign-averaged Vorcore pseudomomentum fluxes, as well as those representative of November 2005 to better match the CRISTA period, are shown in this figure. Both momentum flux estimates agree very well. In particular, the signature of the southern Andes (at \(\sim 70°W\)) is observed in both datasets. The larger magnitude of the CRISTA pseudomomentum flux in this region possibly results from the relatively poor sampling of that region by the Vorcore balloons (see, e.g., Fig. 3), from the interannual variability of GW.

\[
\int_{2\pi/1h}^{2\pi/1h} \dot{\omega}^{-1} d\dot{\omega} \leq \int_{2\pi/1h}^{N} \dot{\omega}^{-1} d\dot{\omega},
\]

\(f\)
activity in the stratosphere, or from an overcorrection for aliasing effects in the CRISTA momentum fluxes. More strikingly, excellent agreement is observed above the Atlantic and Indian Oceans, where Vorcore observations are more numerous than above the Pacific. Such agreement between two very different techniques gives further confidence in the GW momentum flux values reported in this study and in the previous work on CRISTA datasets.

Finally, there is also good qualitative agreement between Vorcore and HIRDLS observations, despite the fact that the HIRDLS measurements only extend as far as 60°S (Alexander et al. 2008). Once again, the largest fluxes observed with HIRDLS occur near the southern tip of South America. Over the oceanic regions, the largest fluxes occur over the South Atlantic and Indian Oceans with smallest fluxes over the South Pacific, in good agreement with the balloon findings.

7. Conclusions

Characteristics of gravity waves over Antarctica observed during long-duration superpressure balloon flights performed from September 2005 to February 2006 are reported. The observations enable us to derive momentum fluxes carried by the waves in the lower stratosphere. The largest fluxes were found above the mountainous western Antarctica and especially over the Antarctic Peninsula. Over the latter region the time-averaged momentum flux locally reached values 10 times larger than the overall mean momentum flux computed with the balloon observations. Because of its steep orography and of its roughly north–south orientation, the Antarctic Peninsula is confirmed as a very active area for the generation of gravity waves and, therefore, is likely to have a profound impact not only on the dynamics of the SH polar stratosphere but also on its chemistry and microphysics (Höpfner et al. 2006; Noel et al. 2008). The signature of waves generated by katabatic winds was found to be rather small except over Adélie Land where a significant enhancement of southward momentum flux was found. Westward zonal momentum fluxes were larger than eastward fluxes, indicating that waves that reached the stratosphere were propagating predominately against the mean flow. On the other hand, meridional momentum fluxes did not display any net contribution. Finally, the momentum fluxes were generally larger at the beginning of the campaign (September–October) than at the end (December–January).

Mechanisms responsible for wave generation were explored. A simple geographic proxy was used to determine whether waves were generated by orographic processes. Mountain waves were found to account for about two thirds of the total momentum flux over Antarctica. Interestingly, we found zonally averaged fluxes over the ocean similar in magnitude to those above the continent, which underlines the importance of nonorographic gravity waves in the SH polar and subpolar latitudes.

The intermittency of GW events in the balloon dataset was assessed. Mountain waves were found to be significantly more sporadic than the waves observed above the ocean.

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REFERENCES


