Quasi-Lagrangian measurements in the lower stratosphere reveal an energy peak associated with near-inertial waves

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[1] In March 2001, three superpressure balloons were launched from Kiruna, Sweden (67.9°N, 21.1°E). The balloons drifted for several weeks in the stratospheric polar vortex at about 19 km. The corresponding trajectories exhibit cycloid-like patterns due to the presence of near-inertial waves. Consistently, it is found that the intrinsic-frequency spectra of the horizontal velocity components are enhanced around the inertial frequency in reference to the generally assumed power-law distribution. A large spectral gap is also found between gravity waves and Rossby waves in the polar stratosphere, in contrast to the continuum found in the equatorial lower stratosphere. *INDEX TERMS:* 3334 Meteorology and Atmospheric Dynamics: Middle atmosphere dynamics (0341, 0342); 3384 Meteorology and Atmospheric Dynamics: Waves and tides; 3394 Meteorology and Atmospheric Dynamics: Instruments and techniques

1. Introduction

[2] Inspired by the work of *Garrett and Munk* [1975] in the oceanic context, several studies [e.g., *VanZandt*, 1982; *Sidi et al.*, 1988] have proposed that atmospheric gravity-wave energy spectra follow simple, "universal" laws. A large body of work followed on the verification of the proposed laws using observational data. Radiosondes, radars and lidars have provided information on the vertical-wavenumber spectra, and estimates of the horizontal-wavenumber spectra have been derived from aircraft data. In contrast, even though they are used to constrain several gravity-wave models [e.g., *Gardner*, 1994; *Dewan*, 1997], intrinsic-frequency spectra were only recently obtained for the atmosphere [*Hertzog and Vial*, 2001].

[3] The present study reports on data gathered during a campaign based on ultra-long-duration balloons that were released from Kiruna, Sweden (67.9°N, 21.1°E) and flew in the polar stratosphere during March–April 2001. In particular, we present estimates of the power spectrum density of the horizontal wind field, which contains unprecedented information on near-inertial waves in the lower stratosphere.

[4] We start in section 2 by describing the balloons, gondolas, and data collected during the Kiruna 2001 campaign. Section 3 describes the flight trajectories. In section 4 we perform a spectral analysis of the inferred horizontal wind data and analyze the results. Finally in section 5, we briefly discuss the possible implications of our findings and compare our results with those obtained during earlier balloon flights in the equatorial lower stratosphere.

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2. Balloons and Gondolas

[5] The Kiruna 2001 campaign used 10-m-diameter, superpressure balloons (SPBs) developed by the French Space Agency (CNES) for the Stratole/Vorcore experiment [*Vial et al.*, 1995]. The SPBs are designed to drift in the lower stratosphere for several weeks carrying a scientific payload of about 15 kg. By design, SPBs move on isopycnic surfaces (i.e., surface of constant density), and therefore behave as quasi-Lagrangian atmospheric tracers (relative variations of potential temperature along the trajectories are of the order of a few percents). When exposed to solar radiation the balloon envelope slightly expands, which induces residual vertical displacements of the SPB. The amplitude of this diurnal cycle, however, seldom exceeds 50 m, which implies relative density variations of ~1%. Further details on the SPBs and their behavior in the atmosphere can be found in *Vial et al.* [2001], *Hertzog and Vial* [2001] and *Cocquerez et al.* [2001].

[6] Two different gondolas (the CNES "Samba" and the Laboratoire de Mtorologie Dynamique "Rumba") were flown during the Kiruna 2001 campaign [see, e.g., *Vial et al.*, 2001; *Pommereau et al.*, 2001, for their description]. Both gondolas carry instruments to measure ambient air temperature and pressure, and use the Global Positioning System (GPS) satellites for localization. The zonal and meridional velocities are deduced by finite differences from successive GPS points. The sampling interval is 10 min for Samba and 15 min for Rumba. Data are sent to ground monitoring stations via ARGOS satellites.

3. Balloon Trajectories

[7] Three SPBs were flown during the Kiruna 2001 campaign. The first two (SPB1 and SPB2) were launched on March 17 and March 21 (days 76 and 80 in 2001, respectively), and carried Samba gondolas. The third device (SPB3) was released on March 27 (day 86) and carried a Rumba gondola. The SPB1 and SPB3 flights lasted 24 and 19 days, respectively. The SPB2 flight lasted more than 90 days, but the GPS system in the gondola failed 6 days after launch, which prevented a precise positioning after March 27. All SPBs drifted at ~60 hPa (~18.5 km). The trajectories are shown in Figure 1.

[8] The balloons were advected eastward by the weak vortex present in the lower stratosphere at the time of the campaign. SPB1 remained at an approximately constant latitude (except at the end of the flight), while the SPB3 trajectory was disturbed by a planetary-scale Rossby wave with apparent zonal wavenumber 3. The SPB2 trajectory was intermediate between those of SPB1 and SPB3. Low-precision ARGOS positions (not shown in Figure 1) show that this remains true after the GPS failure.

[9] A closer look at the trajectories reveals cycloid-like patterns (see the zoom on Figure 1). This feature is especially apparent in periods when the horizontal wind is weak (such as the beginning of all flights, or over western North-America in the SPB3 flight). The balloon loops are also visible on the raw wind velocity shown in Figure 2 for SPB1.

[10] The zonal and meridional components exhibit "high-frequency" oscillations throughout the flight, with a mean amplitude

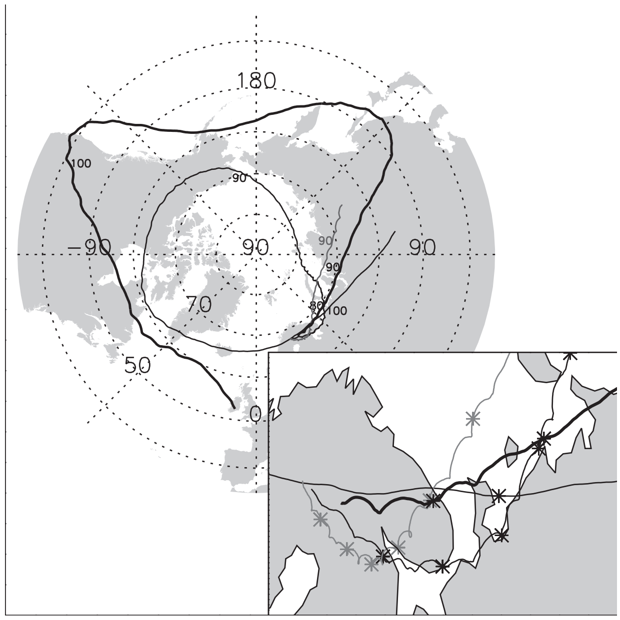

Figure 1. Trajectories of the three SPBs (SPB1: black; SPB2: grey; SPB3: thick black). Days in 2001 are indicated along the trajectories. Lower right: SPB trajectories over northern Scandinavia with stars plotted every 24 h.

of ~3–4 m s^{-1}. Wind data from SPB2 and SPB3 present very similar features.

4. Spectral Analysis

[11] A major feature of the SPBs is that they allow for estimations of the intrinsic-frequency spectra (i.e., spectra versus the frequency measured by an observer moving with the wind). In this paper, we apply a classical multi-taper algorithm to obtain the spectra of the horizontal components of the wind velocities [*Percival and Walden*, 1993]. The results are shown in Figure 3.

[12] The spectra for SPB1 and SPB2 are very similar. In particular, they both exhibit an energy peak close to the inertial frequency (f). (The averaged inertial period in this case is about 13 hours.) Gravity waves have intrinsic frequencies (ω_0) higher than f and fill the high-frequency part of these spectra. It has often been assumed that the total-energy spectrum of gravity waves follows a power-law

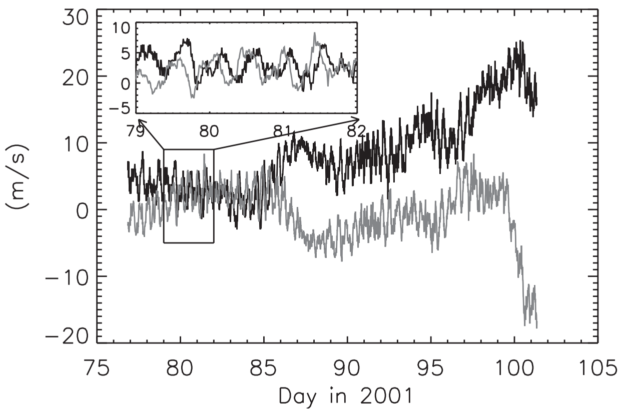

Figure 2. Zonal (black) and meridional (grey) velocities during the SPB1 flight. A zoom between days 79 and 82 (upper left) shows the phase quadrature between the meridional and zonal velocities.

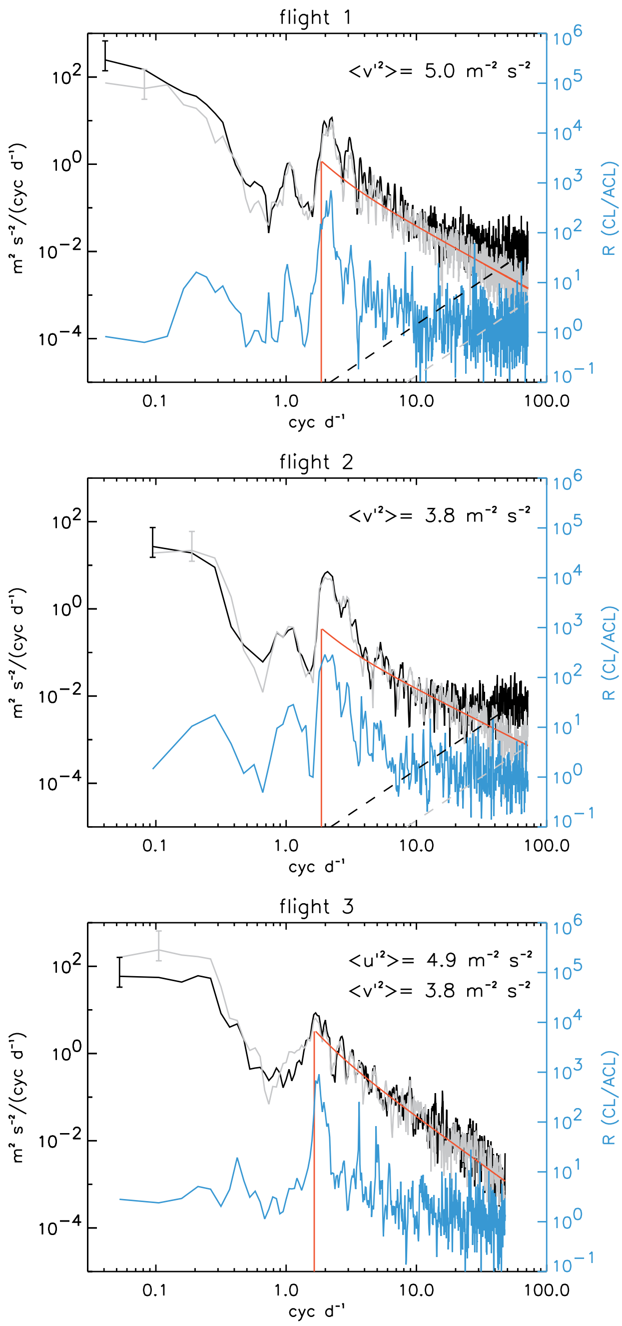

Figure 3. Zonal (black) and meridional (grey) velocity spectra and associated noise levels (dashed) for SPB1 (up), SPB2 (middle), and SPB3 (bottom). Note that the SPB3 noise levels are too low to appear on the bottom plot. The 90% confidence interval for the spectra, which looks constant on a log-log plot, is plotted at the smallest frequency. Red spectra are built assuming a power-law form for the total energy spectrum (see text). The ratio of clockwise to anticlockwise motions is plotted in blue (right scale). Variances induced by gravity waves ($\omega_0 > f$) are indicated on each plot.

of the intrinsic frequency [*VanZandt*, 1982; *Gardner*, 1994; *Dewan*, 1997]. Under these conditions, the kinetic energy spectrum scales as:

$$\omega_0^{-p}\left(1+f^2\omega_0^2\right), \qquad (1)$$

where p gives the slope in a log-log plot [*Fritts and VanZandt*, 1993]. To estimate p we used the high-frequency part of the meridional velocity spectra (i.e., $\omega_0 > 3f$). The Samba gondola in

SPB1 and SPB2 transmits longitudes less accurately than latitudes. This increases the noise level in the zonal velocity spectrum and prevents using it to calculate p. We found that p = 1.7 ± 0.1 and 1.5 ± 0.1 for SPB1 and SPB2, respectively. The kinetic energy spectra, reconstructed with equation (1) and with the slope estimates, are shown in Figure 3. It is apparent that the observed enhancement of wave energy at near-inertial frequencies departs from the simple power-law form.

[13] The polarization of the horizontal-wind vector is studied with a rotary-spectrum analysis, i.e., the spectral decomposition of the complex variable $u' + iv'$, where $u'$and v' stands respectively for the zonal and meridional components of the horizontal wind [*Gonella*, 1972]. The ratio (R) between the clockwise- and the counterclockwise-rotating component (i.e., the ratio between the powers associated with, respectively, negative and positive frequencies) is shown in blue in Figure 3. $R \gg 1$ corresponds to a nearly circular, clockwise-rotating hodograph, whereas $R \sim 1$ corresponds to zonal and meridional velocities that are linearly polarized. The inertial energy peak is associated with clockwise-rotating motions, as it must be for inertia-gravity waves in the Northern Hemisphere. This ratio tends to 1 as the intrinsic frequency increases, since the hodograph ellipse becomes more eccentric.

[14] Another interesting feature of the SPB1 and SPB2 spectra shown in Figure 3 is the peak at periods close to 1 day, associated with the predominance of clockwise-rotating motions. This feature cannot result from the diurnal vertical excursion of the SPBs in the presence of mean horizontal-wind vertical shear since in this case R should stay close to 1. We rather attribute this feature to the vertical sampling of the structure of the inertia-gravity waves caused by the SPB diurnal cycle. Consider the dispersion relation for inertia-gravity waves [*Andrews et al.*, 1987]:

$$m^2 = N^2 - \omega_0^2\omega_0^2 - f^2\left(k^2 + l^2\right), \qquad (2)$$

where m, k, l are the vertical, zonal, and meridional wave-numbers, respectively, and N is the Brunt-Visl frequency. As ω_0 tends to f, m tends to ∞ provided the horizontal wavelength stays finite, so that near-inertial waves tend to have small vertical wavelengths [e.g., *Eckermann*, 1995]. Therefore, even a small vertical displacement (like the diurnal cycle in the SPB height) can induce a significant signature on the spectra. Furthermore, numerical simulations (not included here) show that in this case R can significantly depart from 1, and that the vertical wavelength of the inertia-gravity waves is ~1 km.

[15] There is a significant spectral gap at frequencies lower than the inertial frequency between Rossby waves and gravity waves. In agreement with the gravity-wave theory, such a scale separation in the intrinsic-frequency space does not have a counterpart in the data gathered by SPBs in the equatorial lower stratosphere [*Hertzog and Vial*, 2001].

[16] Let us now focus on the SPB3 spectra. The Rumba gondola used in this case transmits longitudes and latitudes with the same resolution, so the zonal velocity spectrum does not have a flat tail at high frequencies. As previously, the spectra show a continuum of high-frequency gravity waves (here p = 2.1 ± 0.1, and 2.2 ± 0.1 for the zonal and meridional components, respectively) and R presents the same features as in the SPB1 and SPB2 spectra. The spectral gap between gravity and Rossby waves is also observed on the SPB3 spectra. The main difference between the spectra for SPB3 and those for SPB1 and SPB2 is the absence of the peak at the inertial frequency (and consequently at the diurnal frequency). Since the SPB3 trajectory also exhibits loops and the raw horizontal-wind measurements are very similar to those presented in Figure 2, the most likely reason for this absence is that, in contrast to the first two flights, SPB3 experienced much larger meridional excursions. The inertial period, therefore, varies significantly along the trajectory of SPB3, i.e., from ~13 h at the beginning of the flight to more than 19 h at the southernmost part of it. This variation tends to blur the near-inertial signal, which consequently does not significantly depart from the power-law spectrum.

5. Discussion

[17] The horizontal-wind spectra of the SPBs that stayed at an approximately constant latitude exhibit a peak at near-inertial frequencies. It has been checked that this energy enhancement cannot be due to the semi-diurnal tide: for instance, the wind fluctuations are not sun synchronous. SPB flights therefore reveal the presence of near-inertial waves in the lower stratosphere. This inertial peak has already been observed in the oceans [e.g., *Thomson et al.*, 1990] but seldom in the atmosphere, particularly if one considers the Doppler shift associated with ground-based frequency estimates. Note, however, that *Thompson* [1978] noticed a quite similar feature in the spectra that he obtained when the mean wind was weak. This inertial peak may explain previous results that were not fully understood. For instance, *Barat and Cot* [1992] and *Nastrom et al.* [1997] reported values greater than 5 for the ratio between kinetic and potential energy of gravity waves. This ratio should, however, be equal to p (i.e., between 1 and 2) if one assumes that the gravity-wave total-energy spectrum scales as ω_0^{-p}. Our results suggest that such high values are due to the enhancement of wave activity at near-inertial frequencies, as hypothesized by *Nastrom et al.* [1997].

[18] The gravity-wave spectra from SPB1 and SPB2 are found to be significantly shallower than that from SPB3. The wind data collected during the first two flights were noisier than during the third one. This noise may bias our spectral slope estimates for SPB1 and SPB2. *Hertzog and Vial* [2001] used data gathered during three equatorial SPB flights to obtain intrinsic-frequency kinetic-energy spectra with slopes ~ -2, which is close to what we found here in the spectra for SPB3. Further balloon campaigns are necessary to confirm the possible variability of the intrinsic-frequency spectral slope.

[19] Comparison of the spectra obtained in the polar and equatorial regions also reveals interesting differencies. For example, the equatorial spectra do not show any significant enhancement of activity at low frequencies [*Hertzog and Vial*, 2001]. In fact, in the equatorial lower stratosphere, the gravity-wave continuum extends down to very low frequencies ($f = 0$ at the equator) and no spectral gap is found between gravity waves and longer Rossby, Rossby-gravity and Kelvin waves. The spectral magnitudes for periods shorter than 12 h are yet compatible in the equatorial and polar lower stratosphere. Lastly, these results are very close to those that *Sato et al.* [1999] obtained with a high-resolution GCM able to explicitly resolve gravity waves.

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