Measurements of gravity wave activity within and around the Arctic stratospheric vortex

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Abstract. Lidar measurements of gravity wave activity have been conducted at Eureka in the High Arctic since 1993. The waves are detected by the fluctuations they induce in temperature. It has been found that the amount of wave energy in the upper stratosphere is related to the position of the stratospheric polar vortex. In each of the four winters reported here, the wave activity was a maximum within the westerly jet at the edge of the vortex, a minimum inside the vortex near its centre and intermediate outside the vortex. The spectra of wave induced fluctuations show that it is at the longest resolved vertical wavelengths (8 to 15 km) that wave energy is being influenced by the background meteorological conditions. These findings are interpreted in terms of the Doppler shifting and critical level filtering that is imposed by the background wind profile.

Introduction

The transport of momentum by internal gravity waves is a fundamental process in atmospheric dynamics. The influence of this is most apparent within the middle atmosphere where there are large departures from radiative equilibrium above the polar regions. An approximation to the effects of gravity wave breaking has been the key factor in simulations of the climatological mean thermal structure of the polar stratosphere and mesosphere [Lindzen 1981; Holton 1982; Hitchman et al. 1989]. However, the state of the polar stratosphere at any particular time and place is quite different from the climatological mean, and it remains to be determined how gravity waves propagate through and interact with realistic dynamical conditions. This study concerns the propagation of gravity waves through the most significant meteorological feature of the stratosphere: the polar vortex.

Since 1993, lidar measurements of gravity wave activity have been carried out during winter at the Arctic Stratospheric Observatory in the Canadian High Arctic. It is located on a mountain ridge near Eureka Weather Station (80°N,86°W) on Ellesmere Island. This location is ideal for studies of stratospheric dynamics since the variability in the thermal and dynamic state of the stratosphere is a maximum above the Canadian High Arctic [Harvey and Hitchman 1996]. The reason for the large variability is the changing position of the stratospheric polar vortex. As demonstrated in Fig. 1, the vortex position may change such that Eureka is situated beneath: (a) the westerly jet (or vortex edge), (b) the vortex centre and (c) outside the vortex. At the vortex centre and outside, wind speed is low at all altitudes while wind direction changes substantially between ground level and the stratosphere. Within the westerly jet the wind speed increases with height and its direction does not change substantially. We have been able to observe how the gravity wave activity changed in response to these distinct changes in the background dynamical conditions.

Observations

The lidar at Eureka is able to measure profiles of temperature within the upper stratosphere and lower mesosphere. (Details of the measurement and analysis technique are described elsewhere [Whiteway and Carswell 1994, 1995].) The vertical resolution in the measurement is 300 m and for gravity wave studies we use half hour average profiles. Figure 2a shows a half hour average temperature profile that has been smoothed in the vertical with a

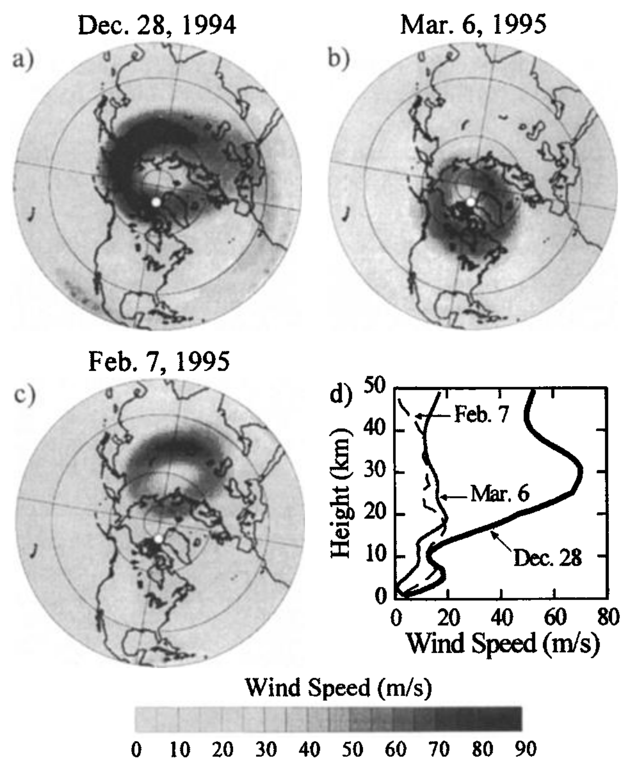

Figure 1. Maps of geostrophic wind speed computed from the NCEP analysis at the 10 hPa pressure level (height approximately 30 km) above the northern hemisphere for a) 28 Dec. 1994, b) 6 Mar. 1995, and c) 7 Feb. 1995. The position of Eureka is indicated by the white dot. The dark ring is the westerly (eastward) jet of the polar vortex (counter-clockwise motion). The corresponding height profiles of wind speed above Eureka are shown in d).

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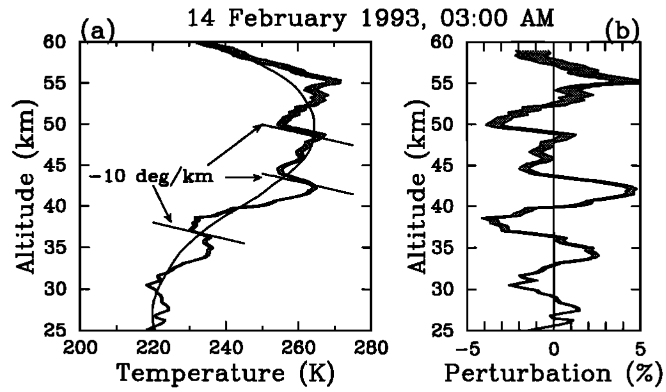

Figure 2. (a) A measured half hour average temperature profile. The smooth solid line is the estimated unperturbed background state. (b) The corresponding profile of fractional temperature perturbation from the background state. Shading indicates the limits of uncertainty in the measurement.

three point running mean (900 m). The fluctuations that are induced by atmospheric gravity waves are extracted from an estimate of the unperturbed background state (a combination of cubic polynomial fits to the night's mean temperature profile). The corresponding profile of fractional perturbation from the estimated background is shown in Fig. 2b. In this case there is a dominant wave with amplitude growing exponentially. This exponential growth appears to cease above 43 km where the dominant wave is inducing a marginally unstable lapse rate (-10 deg/km). Also, waves with smaller vertical scales appear to be combining with the dominant one to induce marginal convective instability (eg. at 37 km).

Several half hour average profiles are typically measured over a single night of observations. The variance in the fractional temperature fluctuations is computed at each altitude and the contribution from measurement noise is subtracted. The gravity wave potential energy density is determined by multiplying the fractional temperature variance by $(\frac{1}{2})(g/N(z))^2$, where g is acceleration due to gravity and $N(z)$ is the buoyancy frequency (which is derived from the night's mean temperature profile). Each energy profile shown here has been smoothed vertically by a 5 km running mean (ie. after computing the variance). Figure 3 shows the profiles of gravity wave potential energy density measured on the same three days that are used in Fig. 1. There was clearly an enhancement in the gravity wave activity on Dec. 28 in comparison with the other two days. It is seen in Fig. 1 that this relatively

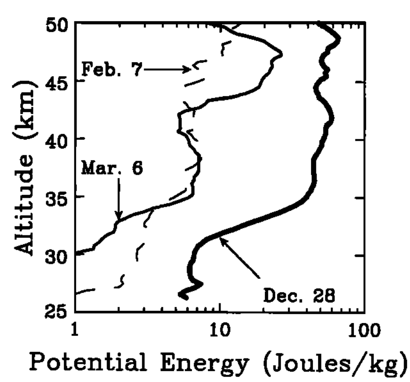

Figure 3. Profiles of gravity wave potential energy density measured on the three nights used in Fig. 1.

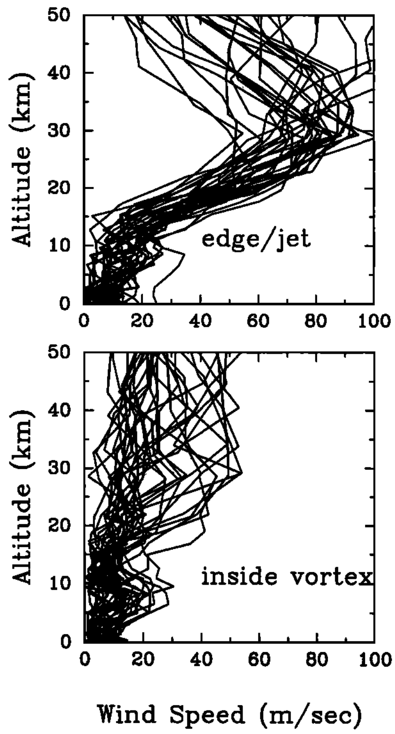

Figure 4. Profiles of computed geostrophic wind speed for the days when Eureka was beneath the westerly jet at the edge of the polar vortex (top) and inside (bottom).

large amount of wave activity occurred within the westerly jet of the stratospheric polar vortex.

For each of the past four winters of observations we have identified and separated measurements that were inside, on the edge (within the westerly jet) and outside of the stratospheric polar vortex. This analysis included only the occasions in which the vortex position did not change substantially with height relative to the vertical line viewed by the lidar. (The computed geostrophic wind profiles corresponding to the cases selected as being inside and within the jet of the vortex are shown in Fig. 4.) The profiles of gravity wave potential energy density were then averaged separately for each of the three different vortex positions. Figure 5 shows the average profiles for each of the four winters. During each year the wave activity was greatest within the westerly jet at the edge of the polar vortex at all observed heights. The minimum in wave activity occurred inside the vortex during each of the four winters. When measurements were obtained outside the vortex the wave activity was intermediate to the two other extremes.

To determine at which vertical wavelengths the wave activity is being most influenced by the background dynamics, we used the potential energy spectral density. This was obtained by computing the power spectrum of the vertical profile of fractional temperature perturbations scaled by g/N. For each night of observation, the spectra computed from each half hour profile were averaged and the measurement noise component was removed. An average spectrum corresponding to each of the three separate vortex positions was computed from the daily average spectra. Figure 6 shows average spectra that were determined from all measurements inside the vortex and within the jet. The difference in wave energy between the two extremes occurs at the longest vertical wavelengths - greater than 8 km. At shorter wavelengths, the decrease in energy with wavenumber is consistent with the commonly observed "universal" spectrum. The controversy

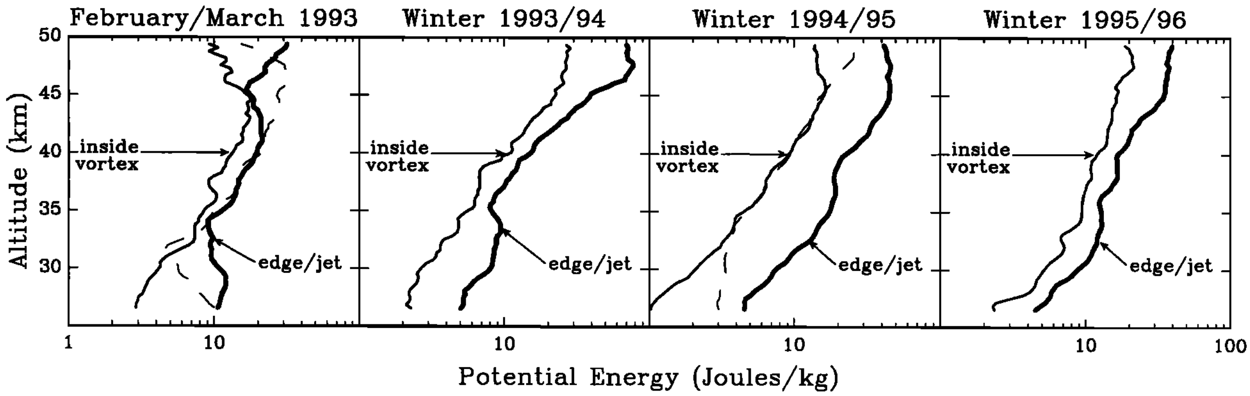

Figure 5. Profiles of mean gravity wave potential energy density averaged separately according to vortex position: inside (thin), edge/jet (thick) and outside (dashed).

regarding spectral shape and magnitude [Hines 1996] is beyond the context of this letter.

Discussion

From the observations carried out during four winters, we have found that gravity wave activity is generally a maximum within the westerly jet at the edge of the stratospheric polar vortex. The lowest level of wave activity occurs near the centre of the vortex and the wave activity outside the vortex is intermediate. This finding is in agreement with recent satellite observations reported by Wu and Waters [1996]. They found that the variance in temperature within the stratosphere (at the smallest scales resolvable by the MLS instrument on the Upper Atmosphere Research Satellite) was a maximum within the westerly jet of the polar vortex.

The difference in wave activity between the edge (jet) and inside the vortex can be explained by the effect of the background wind. In the simplest form of the gravity wave dispersion relation, the vertical wavelength is $\lambda_z = (c - U\cos\theta)\tau_b$ where c is the wave's horizontal phase speed, U is the background wind speed, θ is the angle between the wind and wave propagation direction and τ_b is the buoyancy period. The vertical wavelength is proportional to the difference between phase velocity and background wind speed - ie. *Doppler shifting*. We can expect that much of the wave spectrum will have small phase speeds since flow over the rough terrain in the vicinity of Eureka would be a major source of gravity waves. Then a substantial portion of the wave spectrum will have vertical wavelengths that are proportional to the background wind speed.

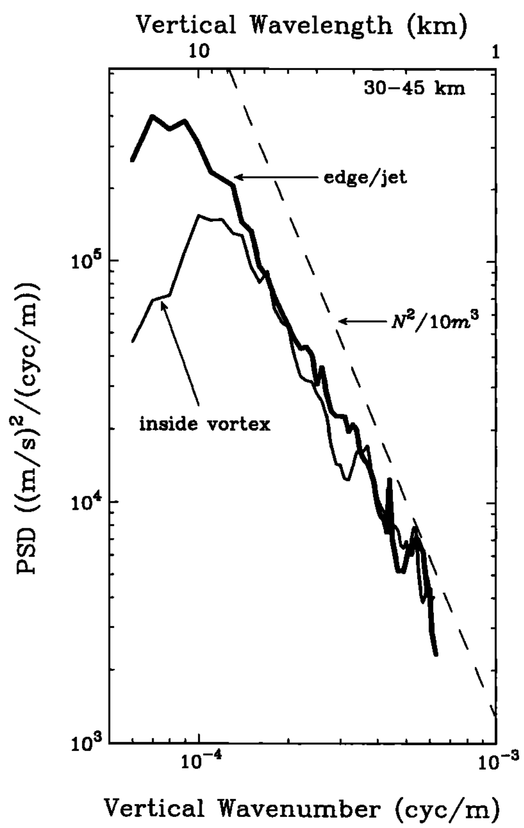

Figure 6. Mean potential energy spectra averaged separately according to vortex position: inside (thin) and at the edge/jet (thick). This result includes all the measurements used in Fig. 5. The dashed line represents the broadband convective instability limit $N^2/10m^3$, where m is the vertical wavenumber [Smith et al. 1987].

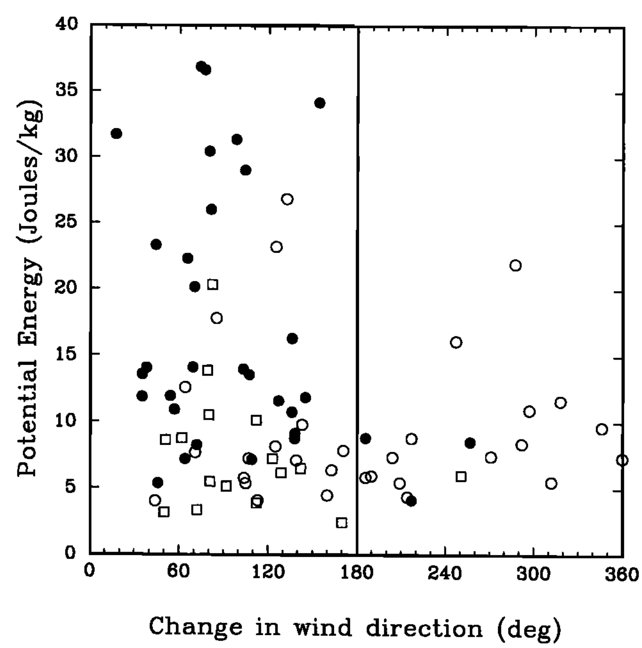

Figure 7. Gravity wave potential energy density in the 30-45 km region vs. the change in geostrophic wind direction between heights of about 2 km and 30 km. The energy density was determined by integrating the spectra between wavelengths of 15 and 1 km. Different symbols are used for measurements at the edge/jet (filled circle), inside (open circle) and outside (open square) of the vortex.

As wind speed is largest within the westerly jet at the edge of the vortex (Fig. 4), we can expect to observe longer vertical wavelengths which can grow to larger amplitudes before inducing instability (as in Fig. 2) and saturating. This is consistent with Fig. 6 which shows greater energy at longer wavelengths within the westerly jet.

Another means by which the background flow affects the amount of wave activity is by *critical level filtering*. A gravity wave will not propagate through a level where the component of the background wind in the direction of wave propagation is equal to the wave's horizontal phase speed. As a wave approaches the critical level its vertical wavelength will approach zero, the wave induced gradients in wind and temperature will increase until becoming unstable and the wave will be dissipated. The waves generated directly by flow over topography, which have zero phase speed, will encounter a critical level where the background wind direction is perpendicular to the wave's propagation direction [Dunkerton and Butchart 1984]. The amount of critical level filtering, and thus the amount of wave activity, depends strongly on the change in wind direction between the ground and stratosphere. If the wind direction changes by 180 degrees then all of the waves generated by flow over topography (of all possible orientations) would encounter critical levels. Figure 7 shows the potential energy density (integrated spectra) as a function of the change in wind direction with different symbols for each vortex position. It is seen that, in general, the change in wind direction was smallest within the westerly jet (edge) of the polar vortex, where the wave activity was greatest. The largest changes in wind direction occurred inside the vortex, where the wave activity was smallest. Similar evidence for critical level filtering has been observed above Eureka using radiosonde measurements [Whiteway and Duck 1996]. Bacmeister et al. [1990] also found that the variance in temperature above significant topographical features was a minimum when the wind direction changed such that a critical level would be encountered.

These results have interesting implications for the role that gravity waves play in the southern hemisphere. The stratospheric polar vortex there is much less disturbed and has a stronger jet than in the northern hemisphere. On the basis of the above discussion we would expect the edge (jet) of the southern polar vortex to transmit even more wave energy than in the northern hemisphere. Bacmeister [1993] demonstrated this by using a simple mountain-wave parameterization scheme. Wu and Waters [1996] have in fact reported that the temperature variance in the upper stratosphere at high latitudes (over the jet) during June in the southern hemisphere is larger than it is during January in the northern hemisphere. This is consistent with the numerical modelling study of Garcia and Boville [1994]. They found that gravity wave drag should play a larger role in determining the thermal structure within the southern polar vortex since planetary wave driving is much less prominent than in the northern hemisphere. Kanzawa [1989] has pointed out that the winter stratopause above the Antarctic is warmer than above the Arctic. This could be explained by the greater transmission of gravity waves through the stratospheric jet in the southern hemisphere. Dissipation of the waves in the upper stratosphere and mesosphere will cause a stronger circulation poleward and downward with the associated adiabatic warming being greater above the Antarctic. In order to close the jet, the upper stratosphere must be warmer inside the vortex than outside. The strength of the vortex may then be regulated by the transmission of gravity waves.

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