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Evidence for critical level filtering of atmospheric gravity waves

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Abstract. Radiosonde measurements were used to investigate gravity wave activity within the lower stratosphere above the Canadian High Arctic. The sondes were launched from the weather station at Eureka (80°N,86°W) on Ellesmere Island. Gravity waves were detected by the fluctuations they induced in temperature and the associated perturbation potential energy density was used to gauge the amount of wave activity. It was found that, over a 15 month period, there were isolated episodes of enhanced wave activity rather than any distinct seasonal cycle. Profiles of wind velocity were also measured and used here to show that periods of high wave activity occurred only when there would be no (or very little) critical level filtering of the stationary waves generated by flow over the rough terrain in the vicinity of Eureka. It was also found that the potential energy spectral density was enhanced at all resolvable scales during the periods of high wave activity.

Introduction

While the effects of atmospheric gravity waves transporting momentum upward into the stratosphere and mesosphere are very well appreciated [Lindzen, 1981; Holton, 1983; McFarlane, 1987], there remain many important questions. The incomplete knowledge of temporal and spatial variability in gravity wave activity is a problem which can be readily addressed using the existing worldwide network of radiosonde (weather balloon) observations [Allen and Vincent, 1995]. The recently introduced radiosonde system (Vaisala RS80), with a vertical resolution of about 50 m, is capable of resolving the fluctuations in temperature that are induced by atmospheric gravity waves. Also, by simultaneously measuring profiles of wind velocity, the radiosonde provides a means to study the factors which influence the amount of wave activity entering the stratosphere.

It is well known that flow over mountains is a relatively major source of atmospheric gravity waves [Nastrom et al., 1987; Bacmeister et al., 1990]. Upward propagating waves will be generated if the ground level wind speed is sufficiently large and the overlying meteorological conditions are not such that the waves are trapped [Durran, 1986]. However, an enhancement of stratospheric wave activity over rough terrain is also dependent on the directional filtering applied by the underlying wind profile. A gravity wave will not propagate upward through a "critical level" where the component of background wind in the direction of wave propagation is equal to the wave's horizontal phase speed [Booker and Bretherton, 1967]. As a wave approaches a critical level its vertical group velocity and wavelength will approach zero and it may be dissipated or reflected.

Since waves generated directly by topography have zero phase speed (relative to ground), a critical level will occur where the background wind direction is perpendicular to the wave's propagation direction. Figure 1 illustrates the wave orientations that would be filtered out by a change in wind direction between two height levels (following Dunkerton and Butchart [1984]). If the wind direction were to change by a full 180 degrees within the troposphere, then stationary gravity waves of all possible orientation would encounter critical levels and would be blocked from entering the stratosphere.

Radiosonde measurements have been used here to study the variability of gravity wave activity within the lower stratosphere above Eureka NT (80°N,86°W) in the Canadian High Arctic. The topography in the vicinity of Eureka is quite variable and on any given flight the radiosonde would be advected over numerous ridges with elevations up to several hundred meters. Flow over this rough terrain is likely the main gravity wave generation mechanism in this region; rather than convective, jet stream or frontal activity. It would then be expected that the critical level filtering process described above is a major factor influencing the amount of gravity wave activity entering the lower stratosphere. The analysis presented here will demonstrate that this was indeed the case. Consideration will also be given to the character of the vertical wavenumber spectrum.

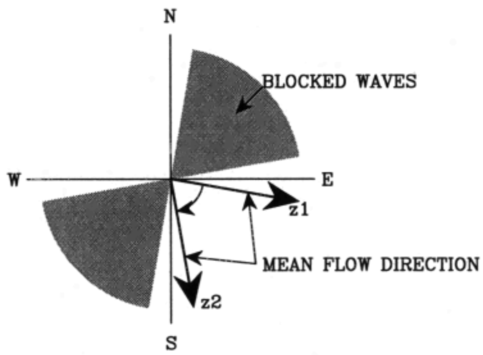

Figure 1. A depiction of the propagation directions (shaded regions) of stationary gravity waves that would be blocked by critical levels as the wind changes direction between heights z1 and z2.

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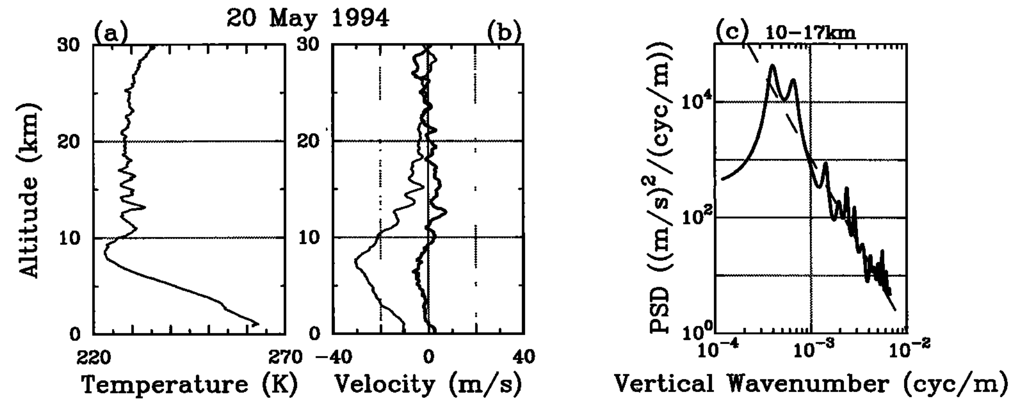

Figure 2. Profiles of (a) temperature and (b) the zonal (thick) and meridional (thin) wind measured during a radiosonde flight. (c) The potential energy spectral density computed from the temperature fluctuations extracted from the 10 to 17 km height range. The dashed line represents $N^2/10m^3$, where N is the buoyancy frequency and m the vertical wavenumber.

Observations

Radiosondes are launched twice daily from the weather station at Eureka. A new high vertical resolution (Vaisala RS80) system was installed during January 1994. The wind and temperature profiles measured during one flight are shown in Figs. 2a and 2b. The wave-like disturbances, clearly resolved in the lower stratosphere, will be interpreted here as being induced by atmospheric gravity waves.

The wave induced temperature perturbations were extracted by approximating the unperturbed background state with a cubic polynomial fit. The potential energy spectrum was determined by computing the power spectrum of the fractional temperature perturbations scaled by g/N, where g is acceleration due to gravity and N is the buoyancy frequency. Since these data were not equally spaced, an interpolation to 50 m intervals was applied prior to computing the spectrum. The vertical wavenumber spectrum, in the height range 10-17 km from the profile in Fig. 2a is shown in Fig. 2c. The maximum entropy technique was applied here [Anderson, 1974; Berryman, 1978] but essentially identical results were also obtained using a Fourier Transform. A correction for the finite time response in the temperature measurement was applied as described by Allen and Vincent [1995]. This was negligible at all but the largest wavenumbers for the height range used here. The potential energy density within the gravity wave field was computed by integrating the potential energy spectrum then dividing by a factor of two. This analysis, in principle, is quite similar to that applied to lidar observations of gravity wave activity by Whiteway and Carswell [1995].

Only the 10 to 17 km height range was used for this study. This was selected as being below the altitude where balloons often burst during winter and above the tropopause. The few profiles containing a sharp tropopause above 10 km were not used since the wave induced fluctuations could not be realistically separated from the background.

Figure 3 shows a fifteen month time series of gravity wave potential energy density in the 10 to 17 km height range. It is interesting that there is no distinct annual cycle as is typically observed at greater altitudes and lower latitudes [Hirota, 1984; Wilson, 1991; Mitchell, 1991; Whiteway and Carswell, 1995]. Instead, there are episodes of greatly enhanced wave activity; such as September and early November of 1994. The following analysis will determine if the difference between periods of high and low wave activity was a result of critical level filtering of stationary orographically generated gravity waves.

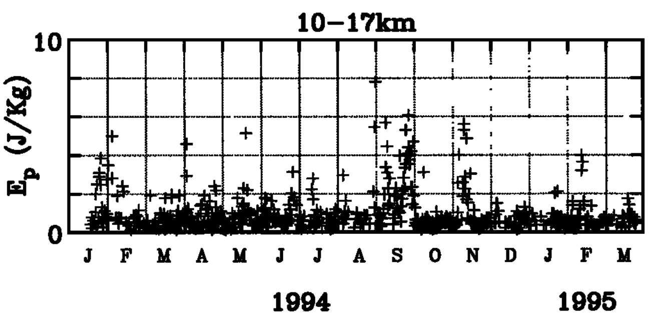

Figure 3. The time series of potential energy density (E_p) in the 10 to 17 km height range.

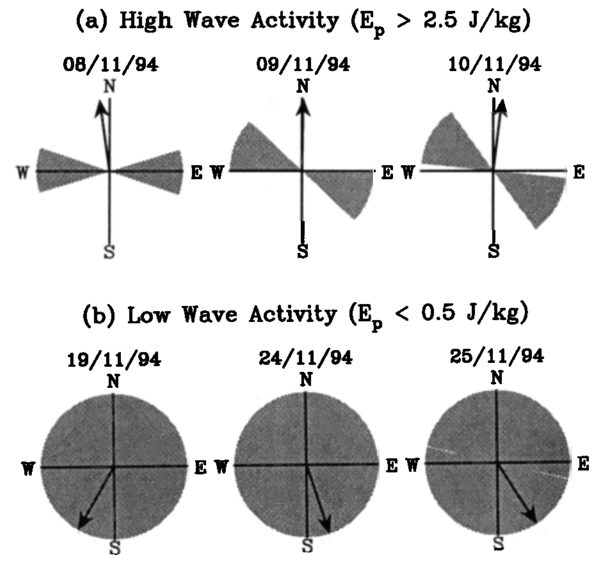

Figure 4. Examples of blocking diagrams during periods of (a) high and (b) low wave activity. The arrow indicates the wind direction at 1 km above ground.

A blocking diagram similar to Fig. 1 was produced from the wind profile between 1 and 12 km for each sonde flight. Figure 4 shows a selection of blocking diagrams during the episode of high wave activity in early November 1994 in comparison with a selection from the following weeks of low wave activity. It will be assumed here that topographically generated waves would be aligned with their wave vectors within about 45° of the surface wind (depending on the orientation and shape of topographical features). The cases shown in Fig. 4 then clearly suggest that critical level filtering is influencing the level of wave activity in the lower stratosphere.

All of the cases with no critical levels (as in Fig. 4a) were separated from the cases with total blocking (as in Fig. 4b). The criterion for no critical level was that the blocked (shaded) region did not come within 45° of the wind speed near ground (1 km). Figure 5 shows the two separate time series of potential energy density. It is clear that all episodes with enhanced wave activity occurred when there was no critical level filtering of stationary gravity waves. There were no cases with greater than average wave activity when there was total blocking.

The absence of a critical level is obviously not the only criterion for enhanced stationary wave activity. Other factors include trapping of waves near ground and wind speed over the terrain. A definitive test of whether or not waves are trapped is not possible with the data available but it can easily be determined if wind speed at ground level is a factor. Figure 6 shows potential energy density (10-17 km) plotted against the wind speed at a height of 1 km. There is clearly a tendency for greater wave activity with larger ground level wind speed.

The average potential energy spectrum was computed from all cases of Fig. 5a (with critical level) and 5b (no critical level) separately. It was found that the average no critical level spectrum was greater at all resolved wavenumbers (not shown here). However, it was also found that the spectrum averaged from all the no critical level cases with integrated potential energy density less than 1 J/kg had essentially the same magnitude as the average critical level spectrum at all resolved wavenumbers. Figure 7 shows this average low energy spectrum (no critical level) in comparison with the average spectrum for all the cases when potential energy density was greater that 2 J/kg. Both spectra are seen to have the often observed -3 slope (dashed line) at high wavenumbers but the magnitude is enhanced at all

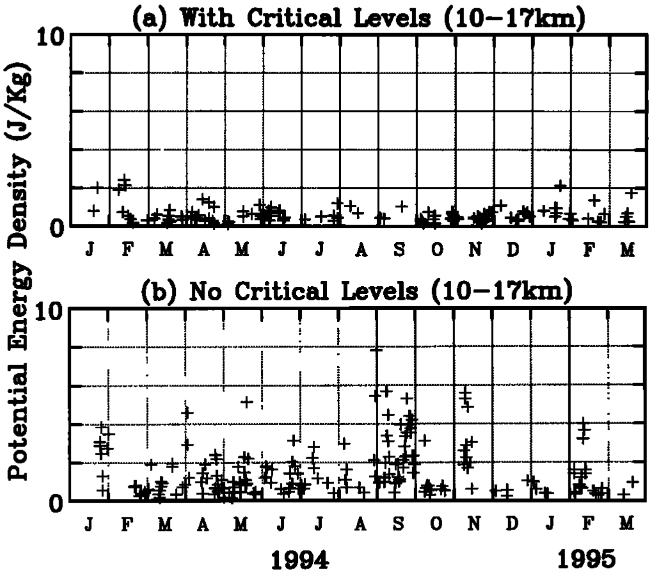

Figure 5. Time series of potential energy density (10-17 km) for cases (a) with and (b) without critical level filtering of stationary gravity waves below 12 km.

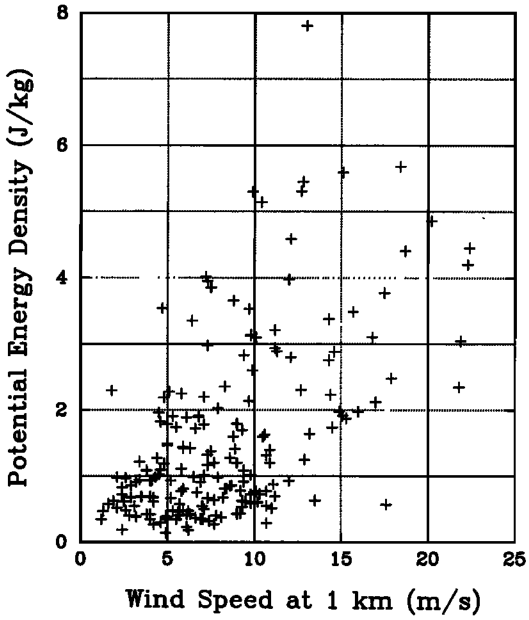

Figure 6. The potential energy density (10-17 km) vs. wind speed near ground for all the cases with no critical level filtering of stationary waves.

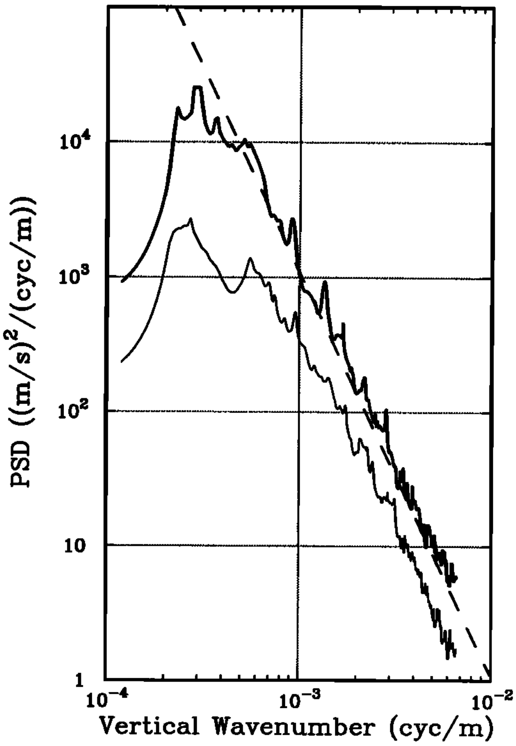

Figure 7. Potential energy spectra (10-17 km) averaged separately for the cases with $E_p > 2$ J/kg (thick) and $E_p < 1$ J/kg (thin) when there was no critical level filtering.

resolvable scales (on average) when the total wave energy is greater. This intriguing result may have important implications for the controversy regarding gravity wave spectra [Dewan and Good, 1986; Weinstock, 1990; Hines, 1991] but further discussion is beyond the main theme of this letter.

Discussion

The radiosonde is now an effective and readily available tool for the investigation of atmospheric gravity waves. The regular radiosonde measurements at Eureka NT were used here to study the variability of gravity wave activity in the High Arctic lower stratosphere. It was found that episodes of enhanced gravity wave activity occurred only when there would not be significant critical level filtering of stationary waves by the underlying wind profile.

That the wave energy appeared to be directly related to wind speed at ground gives support to the assumption that the major source of gravity waves in the lower stratosphere above Eureka is flow over the rough terrain. However, there were certainly other mechanisms generating the lower background level of wave activity, having the characteristic spectral form, when stationary waves would have been blocked by critical levels.

Evidence for critical level filtering of mountain waves has also been found by Bacmeister et at. [1990] using an aircraft based microwave temperature profiler. They assumed mountain waves to have their wave vectors oriented parallel to the ground wind direction so the criterion for a critical level was that the wind direction had rotated by at least 90 degrees. In our analysis we have only assumed the waves to be stationary. Since there are numerous ridges with widely varying orientation in the vicinity of Eureka, the more extreme criterion of a 180 degree wind rotation was applied here.

McLandress and McFarlane [1993] simulated the distribution of mountain wave vertical momentum flux entering the Northern Hemisphere stratosphere during winter. It was demonstrated (in their Fig. 1) that, within the model, critical level filtering was blocking the wave activity generated by the rough terrain in the Canadian High Arctic. The results reported here also give support to theoretical studies which consider a reduction in gravity wave activity due to critical level filtering of stationary waves during stratospheric warming events [Lindzen, 1981; Holton, 1983; Dunkerton and Butchart, 1984].

Whiteway and Carswell [1994], applying a lidar, observed a reduction in upper stratospheric gravity wave activity above Eureka during a stratospheric warming event. Unfortunately, measured winds were not available to sufficient altitudes and the new high vertical resolution radiosonde system had not yet been installed at the time of that study. Future studies of gravity wave activity at Eureka will involve simultaneous radiosonde and lidar observations as well as winds derived from NMC geopotential height fields within the upper stratosphere.

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