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Enhanced Arctic stratospheric gravity wave activity above a tropospheric jet

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Abstract. Meteorological balloon measurements were applied to investigate gravity waves in the stratosphere above three weather stations in the Canadian Arctic. It was found that a distinct enhancement in the amount of wave activity occurred at each of the three stations simultaneously while a tropospheric jet stream crossed the Arctic during mid-November of 1996. An interpretation is proposed in which the enhanced wave activity occurs as the tropospheric jet provides conditions that are favourable for the upward propagation of mountain waves. Further propagation into the stratosphere is then facilitated during winter when the tropospheric and stratospheric jets coincide.

Introduction

It is well known that atmospheric gravity waves play a major role in determining the climate at heights above the tropopause [*Lindzen,* 1981; *Holton,* 1983]. These waves are believed to cause large scale circulations that have extreme effects in the polar regions. For example, the coldest part of the atmosphere is at the summer mesopause [*Theon and Smith,* 1970], and the winter stratopause is warmest inside the polar vortex [*Duck et al.,* 1998; *Kanzawa,* 1989]. Further, the turbulence induced by breaking gravity waves affects vertical mixing. There are measurements that clearly show the generation of turbulence by wave breaking [*Worthington,* 1998] and there are also measurements that indicate the associated vertical mixing of heat [*Whiteway et al.,* 1995] and constituents [*Schilling et al.,* 1999]. Recently, much attention has been drawn to the role that gravity waves play in inducing formation of the polar stratospheric clouds that initiate chemical depletion of ozone [*Carslaw et al.,* 1998; *Cariolle et al.,* 1989].

If the influence of gravity waves is to be fully appreciated (and properly incorporated into models that predict weather and climate), then advancements must be made in our knowledge of the spatial distribution and variability of wave characteristics relative to specific meteorological patterns. Observations have associated gravity wave activity in the tropopause region with mountains, convection, fronts and the jet stream (e.g., *Fritts and Nastrom* [1992], *Eckermann and Vincent* [1993]). However, the influence of meteorological conditions on gravity waves in the stratosphere and above has not yet been clearly identified. Fortunately, there is an excellent observational base from which to approach the problem of stratospheric gravity wave variability: the global network of daily meteorological balloon soundings.

This letter presents findings from the analysis of radiosonde balloon measurements in the Canadian Arctic. The high Arctic is a unique region that is normally quiescent and separated from the frequent weather patterns associated with the jet stream at mid-latitudes. When the jet stream does penetrate into the high Arctic, it is possible to observe a distinct response in gravity wave activity to such an isolated event. It will be shown here how an enhancement in stratospheric gravity wave activity occurred over a wide area as the tropospheric jet stream passed over the high Arctic.

Observations

The radiosondes used in this study provide vertical profiles of temperature, wind and pressure at intervals of approximately 50 m. Gravity waves are observed by the fluctuations they induce in temperature and the analysis technique used here is the same as that applied by *Whiteway* [1999]. The amount of gravity wave activity is gauged by the perturbation potential energy per unit mass, E_p: the fractional temperature variance (along the vertical) multiplied by $0.5(g/N)^2$, where g is acceleration due to gravity and N is the mean buoyancy frequency (rad/s). The vertical wavenumber spectrum of perturbation potential energy was computed by scaling the power spectral density of temperature fluctuations by $(g/N)^2$. The analysis in this study focuses only on gravity waves in the lower stratosphere, between heights of 15 and 22 km.

Figure 1 shows the time series of E_p during the latter half of 1996 from radiosonde balloon measurements (twice daily) at three weather stations in the Canadian High Arctic: Eureka, Mould Bay, and Resolute. The main feature at each station is a pronounced increase in gravity wave activity during mid-November. That the peak in wave activity occurred around the same time at each station suggests the enhancement was associated with a change in meteorological conditions across the entire region of the Canadian high Arctic.

The changing meteorological conditions during November 1996 are illustrated in Fig. 2 with maps of wind speed at the 300 hPa pressure level (height of about 9 km). These are shown for dates before (Nov. 6), during (Nov. 16), and after (Nov. 27) the gravity wave enhancement. It is clear that the gravity wave activity was related to the position of the tro-

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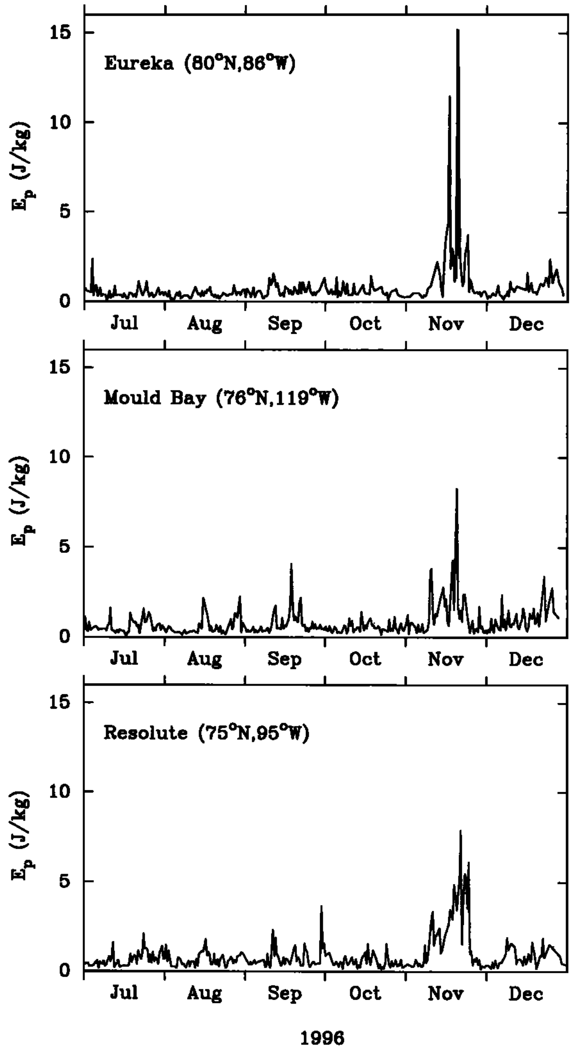

Figure 1. Time series of gravity wave perturbation potential energy per unit mass, E_p, measured above three weather stations in the Canadian high Arctic during the second half of 1996. The period between observations is 12 hours. Occasionally a balloon will burst below the region of interest but this is infrequent and there are no data gaps longer than two days.

pospheric jet stream. The wave activity was enhanced when a high pressure ridge deflected the jet stream across the Canadian Arctic. Before and after the enhancement, the meteorological conditions in the Arctic were quiescent as usual, with the jet stream at mid-latitudes.

Figure 3 shows both the gravity wave potential energy and the wind profiles measured with the radiosondes at Eureka during November 1996. Again, the enhancement in wave activity clearly corresponds to the increase in wind speed during the passage of the jet stream in mid-November. It is also noted that the greatest wave activity occurred when large wind speeds were observed well into the stratosphere above 20 km. These upper level winds are associated with the jet of the stratospheric polar vortex. The episode of enhanced wave activity occurred when the tropospheric and stratospheric jets coincided.

Figure 4 shows average potential energy vertical wavenumber spectra. For each station, the average spectrum during the mid-November enhancement is compared with the average spectrum during the month of October. It is seen that the enhancement in wave energy occurred at all resolved vertical wavelengths. The mid-November enhanced spectral magnitude was slightly less than the broadband convective instability saturation limit of Smith et al. [1987]: $N^2/10m^3$, where N is the buoyancy frequency and m is the vertical wavenumber. This is consistent with the findings of *Whiteway* [1999], where it was shown that the increase in spectral magnitude occurred just above the tropopause when the conditions were favourable for the upward propagation of mountain waves.

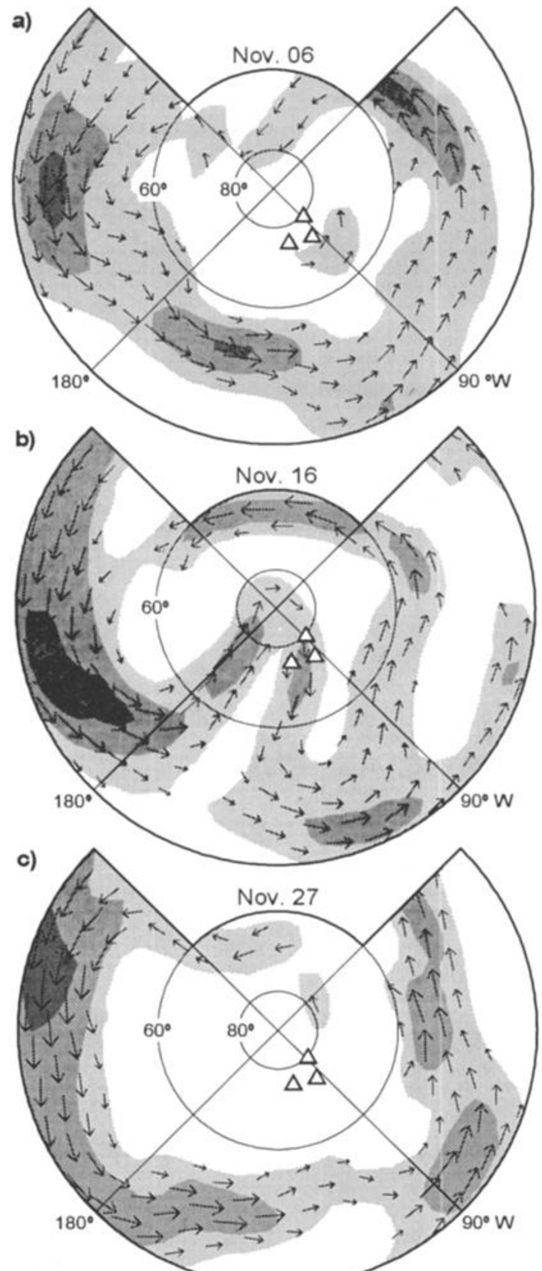

Figure 2. Maps of geostrophic wind velocity computed from the NCEP analyses at the 300 hPa pressure level (height approximately 9 km). The dates correspond to periods before (Nov. 6), during (Nov. 16), and after (Nov. 27) the enhancement in gravity wave activity. Light, medium, and dark shading indicates wind speeds greater than 20 m/s, 40 m/s, and 60 m/s respectively. The positions of the three weather stations used in this study are indicated by the triangles.

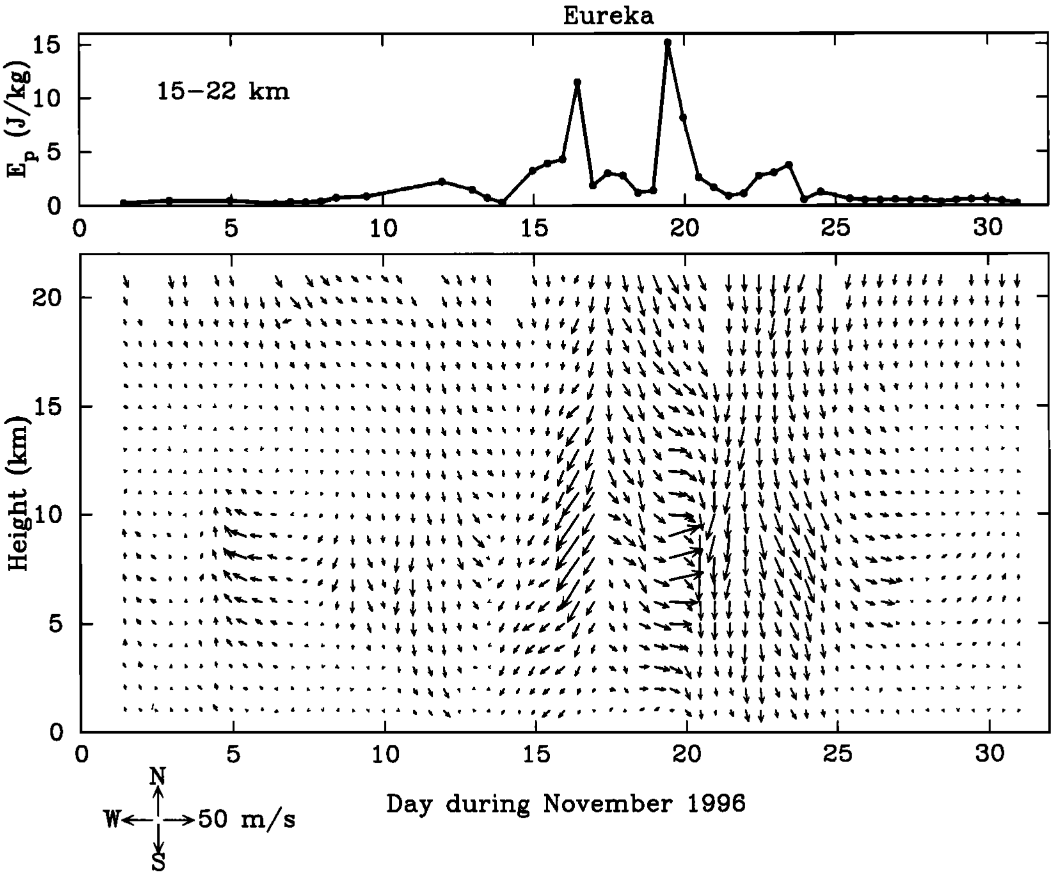

Figure 3. The time series of gravity wave perturbation potential energy (top) and wind vector profiles (bottom) measured with radiosondes above Eureka during November 1996.

Discussion

Our interpretation of the mid-November enhancement in wave activity is that the tropospheric and stratospheric jets provide favourable conditions for upward propagation of gravity waves that were generated by flow over hills and mountains. This follows from previous studies with radiosondes at Eureka: it was found that the gravity wave activity was enhanced in the lower stratosphere only when the background meteorological conditions were favourable for the upward propagation of mountain waves [*Whiteway and Duck,* 1996; *Whiteway,* 1999]. The most important factor is critical level filtering. A gravity wave will not propagate through a critical level where the background wind is equal to the ground based horizontal phase speed of the wave [*Booker and Bretherton,* 1967]. For stationary mountain waves, this occurs where the

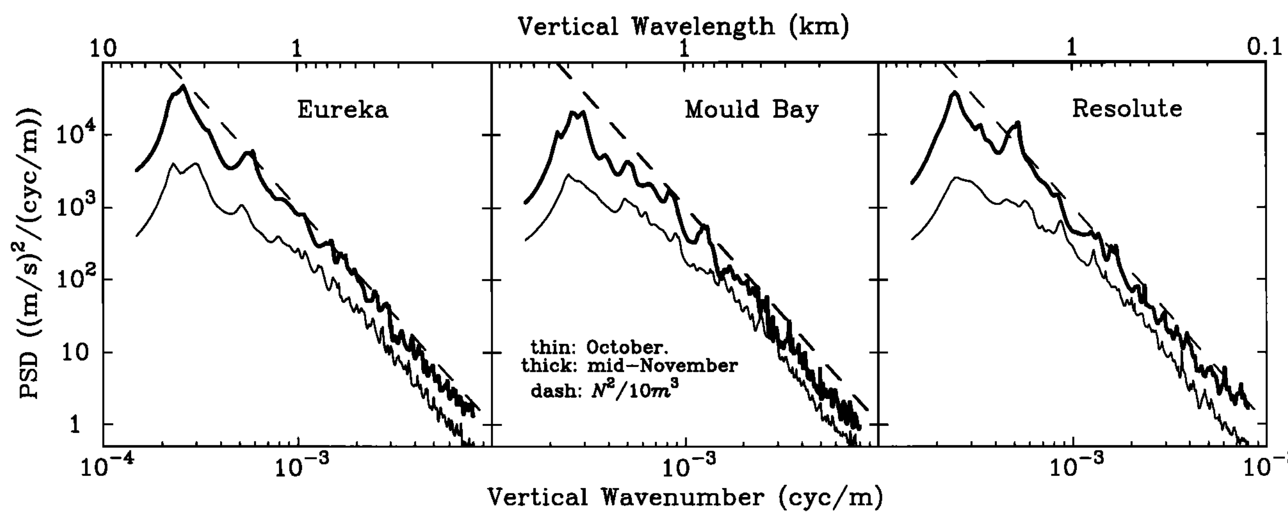

Figure 4. Vertical wavenumber spectra of perturbation potential energy in the 15-22 km height range. These are averages during October (thin line) and during the mid-November enhancement (thick line). The dashed line is the broadband convective instability saturation limit: $(2\pi)^{-2} N^2/10m^3$.

wind direction is perpendicular to the wave propagation vector or where the wind speed is zero. As a result, no mountain waves will propagate into the stratosphere when the wind direction changes by more than 180° in the troposphere or when the speed goes to zero. The conditions that favour propagation of mountain waves into the stratosphere are small directional shear and large wind speed at the ground and above. The changes in wave activity and background conditions during November 1996 above the Arctic are consistent with this mountain wave interpretation.

Figure 5 shows average profiles of wind speed and the range of wind directions between each height and 1 km above sea level. These correspond to periods before, during and after the mid-November enhancement in wave activity at Eureka. The wind profiles before and after the wave enhancement (early and late November) would have inhibited the upward propagation of mountain waves: the wind speed was weak at the ground (weak generation), close to zero just above 10 km (critical level filtering), and the direction changed by more than 180° below 15 km (critical level filtering). During the wave enhancement the wind profiles were favourable for upward propagation of mountain waves: the wind speed was large at the ground (strong generation) and above while there was little change in wind direction (no critical level filtering). These favourable conditions corresponded to a coincidence of the tropospheric and stratospheric jets. This is consistent with previous lidar measurements at Eureka which have shown that the maximum wave activity in the upper stratosphere is in the jet of the polar vortex [*Whiteway et al.*, 1997].

It is of interest that the adiabatic cooling associated with vertical motions induced directly by gravity waves has been identified as a significant mechanism for the formation of polar stratospheric clouds [*Cariolle et al.*, 1989; *Carslaw et al.*, 1998]. Not only is there more gravity wave activity above the tropospheric jet stream, but the background meteorological conditions are also favourable for PSC formation. The anticyclonic weather systems that deflect the tropospheric flow poleward are known to induce cooling in the lower stratosphere and this has been linked with PSC formation [*McKenna et al.*, 1989]. We would then expect to find increased occurrence of gravity wave induced PSCs near the edge of the polar vortex, when there is a coincidence of the tropospheric and stratospheric jets.

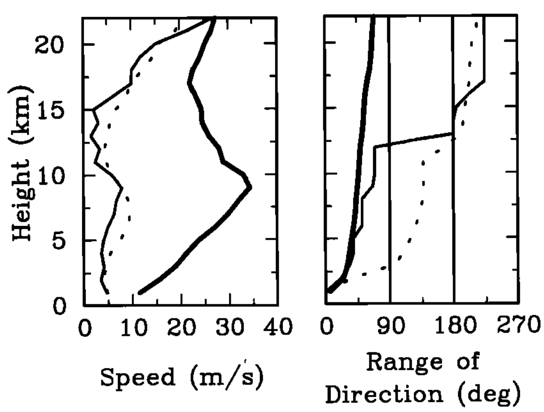

Figure 5. Left: profiles of average wind speed. Right: profiles of the full range of wind directions (between the extremes) from 1 km above ground up to each height level. These are averages of the measurements at Eureka that correspond to periods prior to (thin solid), during (thick) and after (dotted) the enhancement in gravity wave activity.

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