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# Seasonal transition in gravity wave activity during the springtime stratospheric vortex breakdown

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**Abstract.** Profiles of temperature and wind measured by meteorological balloons are used to examine the changes in gravity wave activity at high latitudes during a final springtime breakdown of the Arctic stratospheric vortex. The measurements show that gravity wave potential energy densities in the lower stratosphere decreased dramatically as the cyclonic wintertime vortex gave way to the weak anticyclonic summertime circulation. The reduction in gravity wave activity after the vortex breakdown is attributed primarily to increased critical level filtering of orographic waves and lowered stratospheric wind speeds.

## Introduction

The mean state and variability of the polar stratosphere is broadly influenced by atmospheric gravity waves of tropospheric origin [*Hitchman et al.*, 1989; *Duck et al.*, 1998]. A more detailed understanding requires advancement in our knowledge of how gravity waves interact with the large-scale dynamical structure. During winter, the stratospheric flow is dominated by a nearly circumpolar vortex. Owing its existence to the lack of insolation at high latitudes, the vortex ultimately breaks down after the polar sunrise in a sudden and spectacular yearly circulation change. This annual event provides an excellent opportunity to observe the response of gravity wave activity to a distinct change in the stratospheric flow pattern.

Detailed observations of lower stratospheric dynamics are now obtained with high-resolution radiosondes (meteorological balloons) at weather stations worldwide [*Hamilton and Vincent*, 1995]. Studies that have used high-resolution radiosondes for gravity wave research include those by *Allen and Vincent* [1995], who produced a gravity wave climatology for the continent of Australia, and *Whiteway and Duck* [1996], who found evidence of critical level filtering. In another study, *Whiteway and Duck* [1999] showed a dramatic enhancement of gravity wave activity in the Arctic stratosphere during a poleward incursion of the tropospheric jet stream.

We employ measurements from the following four high-latitude weather stations (shown in Figure 1) to examine the evolution of gravity wave activity during the final breakdown of the Arctic stratospheric vortex in 1996: Alert (82.3°N, 62.2°W), Eureka (80.0°N, 86.0°W), Cambridge Bay (69.1°N, 105.1°W) and Baker Lake (63.4°N, 96.1°W). Gravity wave potential energy densities in the lower stratosphere above each station decreased dramatically during the transition from wintertime to summertime flow. The reduction in gravity wave activity is related to increased critical level filtering and decreased stratospheric wind speeds.

## Observations

Gravity wave potential energy densities measured in the lower stratosphere from 15 February to 25 May 1996 are shown in Figure 2. This measure of gravity wave activity is calculated from the small-scale irregularities apparent in individual temperature profiles between 15 and 22 km in altitude. In this study, we use the same gravity wave extraction technique employed by *Whiteway and Duck* [1996, 1999] and *Whiteway* [1999] to determine the gravity wave potential energy densities. As is shown in Figure 2, the gravity wave energies in the lower stratosphere during late February and March were spread from small values to about

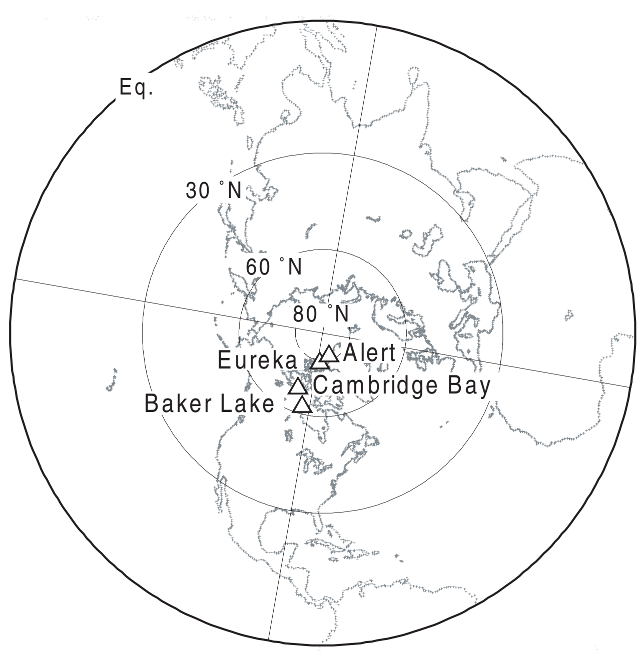


**Figure 1.** A map showing the locations of the four high-latitude stations considered in this study.

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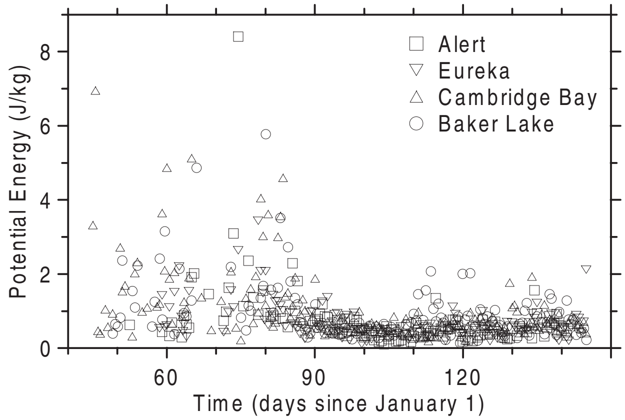


**Figure 2.** The daily gravity wave potential energy densities measured in the 15 - 22 km height range by radiosondes at the four stations during winter/spring 1996.

5 J/kg. At the end of March, the amount of gravity wave activity decreased sharply, and remained low through May (and throughout the summer, not shown).

The sudden reduction of gravity wave activity shown in Figure 2 is associated with the springtime breakdown of the Arctic stratospheric vortex, as may be seen by viewing National Centers for Environmental Prediction (NCEP) constant pressure height analyses. A few representative maps of geopotential height on the 30 hPa (∼23 km) and 70 hPa (∼18 km) pressure levels are given in Figure 3 and Figure 4, respectively. Note that the 70 hPa pressure level is within the gravity wave observation height interval, whereas the 30 hPa pressure level overlies it. As is shown in Figure 3a, the height field at 30 hPa before the breakdown event was dominated by a deep low (the wintertime stratospheric vortex), and the circulation around it is cyclonic (counterclockwise rotation). Before the breakdown onset, the vortex was positioned so that the northernmost pair of stations (Alert and Eureka) were located primarily below the vortex core or beneath a westward directed stratospheric jet, and the two southernmost stations (Cambridge Bay and Baker Lake) were most often beneath an eastward directed stratospheric jet. The breakdown onset began with a movement of the vortex from northern Canada to over northern Europe, where it quickly dissipated and was replaced by the weak high (anticyclone) shown in Figure 3b.

As is shown in Figure 4a, the height field at 70 hPa before the vortex breakdown closely resembled that at the higher level. Figure 4b shows that the flow at 70 hPa after the vortex breakdown remained weakly cyclonic, and so was reversed in direction from the higher level circulation at 30 hPa. The direction of the flow at 70 hPa was the same as that for the tropospheric jet stream (which is always cyclonic), and so the vortex breakdown corresponded to a period of transition at 70 hPa from the direction of the middle stratospheric flow to that of the tropospheric circulation.

A view of the winds above each station during the vortex breakdown may be constructed from the radiosonde measurements. As is shown in Figure 5, the wind speeds at the 18.5 km height level were spread through generally high values during late February and March, and then dropped suddenly to the lower values apparent through late April and May. The decrease in wind speed was observed first at the two southernmost stations as the vortex moved from over northern Canada. Because the vortex breakdown event apparently evolved between days 90 and 100, in what follows the measurements obtained before this interval will be referred to as pre-breakdown and those after as post-breakdown observations.

Measurements of a variety of parameters that are important for gravity wave propagation are given in Table 1, averaged separately for the pre-breakdown and post-breakdown intervals. In previous studies (named below), it has been found suitable to treat the gravity wave field above the Arc-

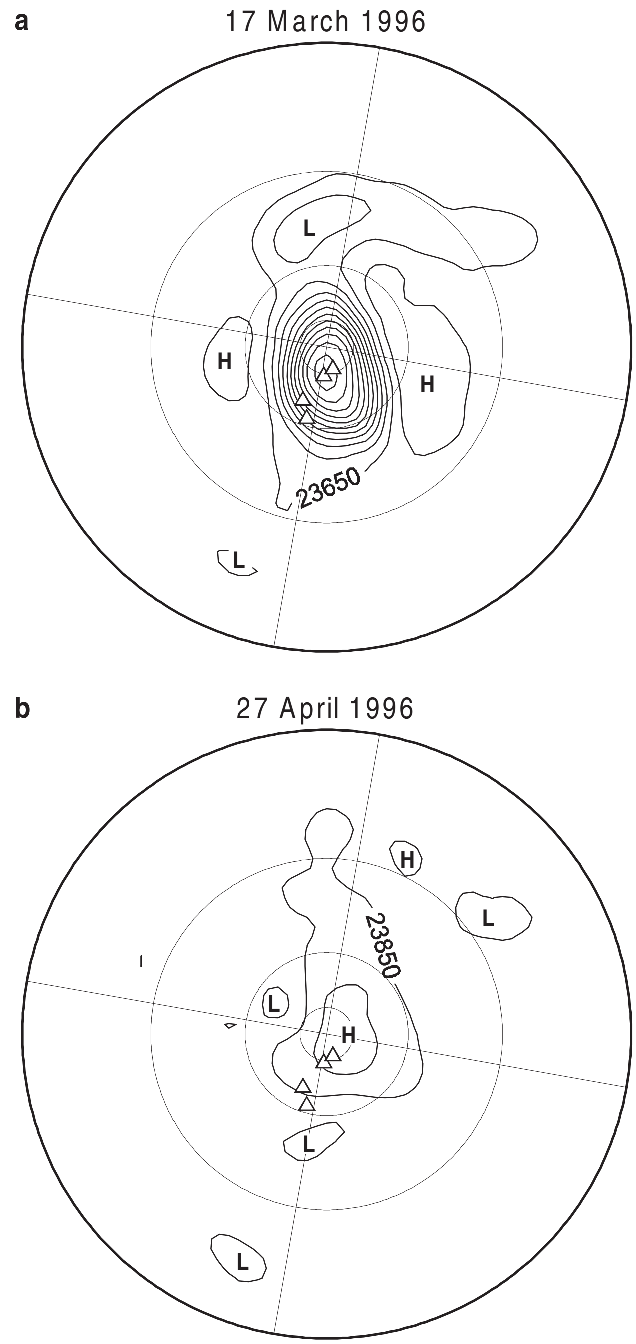


**Figure 3.** Maps of height on the 30 hPa pressure surface for **a**, 17 March 1996 (pre-breakdown), and **b**, 27 April 1996 (post-breakdown). The contour interval is 150 m.

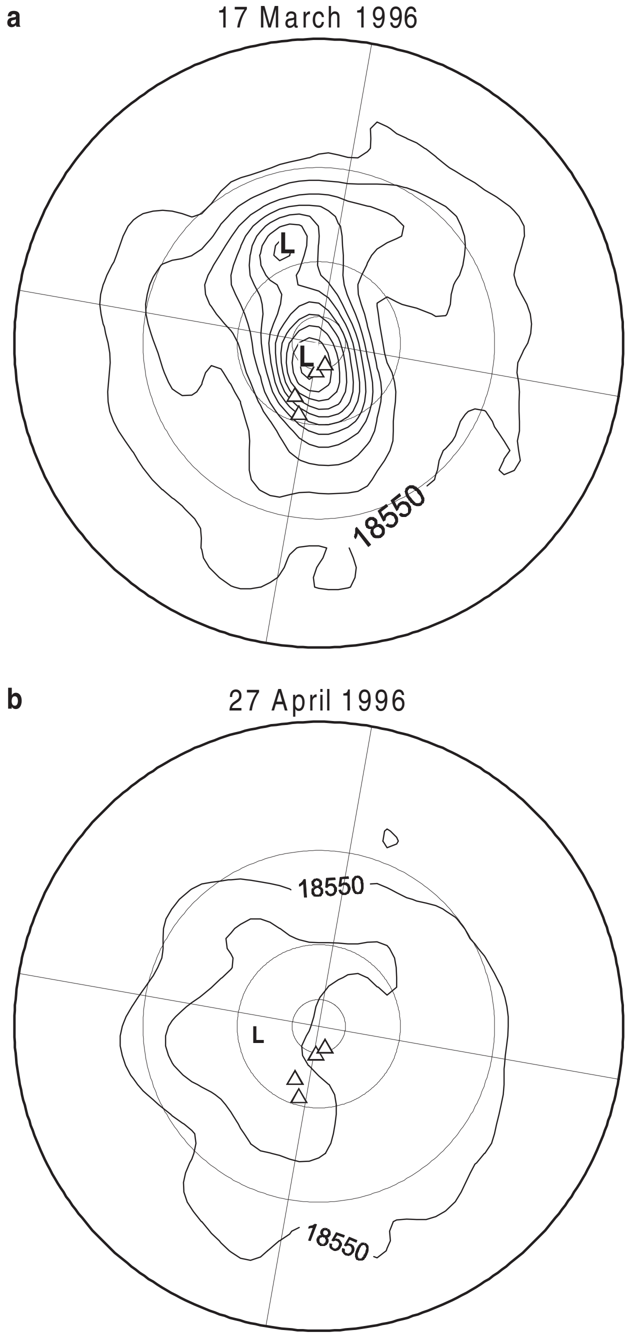


**Figure 4.** Maps of height on the 70 hPa pressure surface for **a**, 17 March 1996 (pre-breakdown), and **b**, 27 April 1996 (post-breakdown). The contour interval is 150 m.

tic as if it were forced by orography; we follow the same approach here. Using this approximation, *Whiteway and Duck* [1996] showed that the wind speed at 1 km corresponds to the gravity wave forcing strength. Furthermore, the lidar measurements of *Whiteway et al.* [1997] indicated that the Doppler shifting of gravity waves to long vertical wavelengths by stratospheric winds significantly increases the gravity wave activity; here we consider the wind speed at 18.5 km in height, i.e., the wind speed in the middle of the gravity wave measurement interval. In general, strong winds at any altitude provide conditions amenable to gravity wave activity. *Whiteway and Duck* [1996] also showed that the critical level filtering imposed when the background wind turns with altitude is important; when the wind turns by 0° (180°), no (all) waves are filtered out of an originally isotropic orographic gravity wave spectrum. Here, we use a gravity wave transmission index that ranges linearly with increasing background wind rotation between 1 (when no waves are removed) and 0 (when all waves are filtered). The transmission index is calculated considering the maximum range of wind directions between 1 and 18.5 km in height.

As is shown in Table 1, the average gravity wave potential energy densities decreased dramatically at each station after the vortex breakdown, as did the wind speeds at 18.5 km in height. The transmission decreased at all stations, although to a much greater extent at the two southernmost stations. It should be noted that the transmission calculations for measurements obtained after the vortex breakdown are somewhat affected by the top altitude chosen, as the post-breakdown circulation was weak and reversed between the 70 and 30 hPa pressure surfaces (as discussed above and shown in Figures 3b and 4b).

Closer examination reveals that prior to the vortex breakdown the gravity wave activity above the northernmost pair of stations was significantly lower than at the two southernmost stations, even though the stratospheric winds were high in each case. The lower gravity wave activity at the northernmost stations correlates with the lower source level winds and transmissions found there. The transmissions above the northernmost stations were low due to frequent measurements in either the vortex core or a westward directed vortex jet, which would yield significant wind rotation with height for cyclonic tropospheric flow. Thus, the source level winds and critical level filtering can affect the gravity wave activity independently of the upper level winds.

Finally, it is interesting to note that the post-breakdown gravity wave activity decreases with increasing latitude; the winds at both the source and stratospheric levels and the transmission generally decrease as well. The reduction in gravity wave energies with latitude during summer is therefore determined by the same diagnostics that lower the gravity wave activity when the wintertime vortex breaks down.

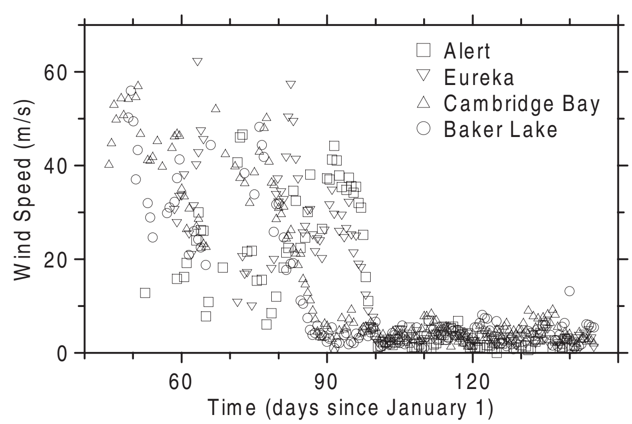


**Figure 5.** The daily wind speeds at 18.5 km in altitude measured by radiosondes the four stations.

**Table 1.** Gravity wave propagation diagnostics

| Parameter | | Alert (82.3°N) | Eureka (80.0°N) | Cam. Bay (69.1°N) | Baker Lake (63.4°N) |
|---|---|---|---|---|---|
| $E_p$ (J/kg) | - pre: | $1.13 \pm 0.12$ | $1.06 \pm 0.11$ | $1.70 \pm 0.17$ | $1.48 \pm 0.18$ |
| | - post: | $0.461 \pm 0.029$ | $0.528 \pm 0.035$ | $0.618 \pm 0.031$ | $0.714 \pm 0.044$ |
| U(z=1 km) (m/s) | - pre: | $7.34 \pm 0.79$ | $5.55 \pm 0.44$ | $10.1 \pm 0.6$ | $10.0 \pm 0.6$ |
| | - post: | $6.48 \pm 0.39$ | $5.57 \pm 0.41$ | $7.57 \pm 0.35$ | $8.17 \pm 0.55$ |
| U(z=18.5 km) (m/s) | - pre: | $23.5 \pm 2.0$ | $31.5 \pm 1.9$ | $32.8 \pm 1.9$ | $25.9 \pm 2.4$ |
| | - post: | $2.51 \pm 0.18$ | $3.16 \pm 0.13$ | $4.51 \pm 0.22$ | $3.92 \pm 0.23$ |
| $\tau$ | - pre: | $0.227 \pm 0.042$ | $0.253 \pm 0.040$ | $0.654 \pm 0.027$ | $0.470 \pm 0.043$ |
| | - post: | $0.154 \pm 0.023$ | $0.206 \pm 0.027$ | $0.275 \pm 0.028$ | $0.229 \pm 0.026$ |

Diagnostics found important for gravity wave propagation, averaged during the pre- and post- vortex breakdown periods: $E_p$, the gravity wave potential energy density measured in the 15-22 km height range; wind speeds, U, measured at altitudes, z, of 1 km and 18.5 km; $\tau$, the transmission index for orographic waves calculated using the maximum range of wind directions between 1 and 18.5 km. The uncertainties are given by the standard deviation of the mean. The pre-breakdown $E_p$ outlier for Alert in Figure 2 (with $E_p$=8.41 J/kg, U(z=1 km)=10.6 m/s, U(z=18.5 km)=21.8 m/s and $\tau$=0.717) was excluded from the calculation.

## Discussion

Radiosonde measurements show that gravity wave potential energy densities in the high-latitude lower stratosphere dropped suddenly as the wintertime stratospheric vortex gave way to the anticyclonic summertime circulation. The general reduction in gravity wave activity was caused by increased critical level filtering and decreased stratospheric wind speeds. Differences between stations before the breakdown event were mostly due to variations in critical level filtering alone. After the vortex breakdown, the gravity wave activity decreased with increasing latitude as did the upper and lower level winds and transmission.

Because orographic gravity waves transport momentum vertically and deposit it into the flow below critical levels, the gravity waves may have played some role in the vortex breakdown; however, assessing this scenario is beyond the scope of this observational study. Measurements of gravity waves at higher altitudes would also be useful, since it would be interesting to know whether gravity waves in the upper stratosphere carry momentum away as the vortex dissipates. Upper stratospheric observations by lidars and satellite instrumentation may be used to investigate this possibility.

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