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Gravity waves in the middle atmosphere during the MaCWAVE winter campaign: evidence of mountain wave critical level encounters

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Abstract. Falling sphere and balloon wind and temperature data from the MaCWAVE winter campaign, which was conducted in northern Scandinavia during January 2003, are analyzed to investigate gravity wave characteristics in the stratosphere and mesosphere. There were two stratospheric warming events occurring during the campaign, one having a maximum temperature perturbation at ∼45 km during 17–19 January, and the other having a maximum perturbation at ∼30 km during 24–27 January. The former was a major event, whereas the latter was a minor one. Both warmings were accompanied by upper mesospheric coolings, and during the second warming, the upper mesospheric cooling propagated downward. Falling sphere data from the two salvos on 24–25 January and 28 January were analyzed for gravity wave characteristics. Gravity wave perturbations maximized at ∼45–50 km, with a secondary maximum at ∼60 km during Salvo 1; for Salvo 2, wave activity was most pronounced at ∼60 km and above.

Gravity wave horizontal propagation directions are estimated using the conventional hodographic analysis combined with the S-transform (a Gaussian wavelet analysis method). The results are compared with those from a Stokes analysis. They agree in general, though the former appears to provide better estimates for some cases, likely due to the capability of the S-transform to obtain robust estimates of wave amplitudes and phase differences between different fields.

For Salvo 1 at ∼60 km and above, gravity waves propagated towards the southeast, whereas for Salvo 2 at similar altitudes, waves propagated predominantly towards the northwest or west. These waves were found not to be topographic waves. Gravity wave motions at ∼45–50 km in Salvo 1 were more complicated, but they generally had large amplitudes, short vertical scales, and their hodographs revealed a northwest-southeast orientation. In addition, the ratios between wave amplitudes and intrinsic phase speeds generally displayed a marked peak at ∼45–50 km and decreased sharply at ∼50 km, where the background winds were very weak. These results suggest that these wave motions were most likely topographic waves approaching their critical levels. Waves were more nearly isotropic in the lower stratosphere.

Keywords. Meteorology and atmospheric dynamics (Middle atmosphere dynamics; Waves and tides; Turbulence)

1 Introduction

Atmospheric gravity waves (GWs) and their dissipation associated with wave saturation have long been recognized to play an important role in the large-scale circulation and the temperature and constituent structures of the middle atmosphere. For example, the zonal-mean forces associated with GW dissipation are believed to cause the closure of the mesospheric jets and a mean meridional circulation that leads to a warm winter mesopause, a cold summer mesopause, and a reversal of the latitudinal temperature gradient than would have been expected from an atmosphere in radiative equilibrium (e.g., Houghton, 1978; Lindzen, 1981; Holton, 1982); GWs contribute to driving the tropical quasi-biennial oscillation (QBO) (e.g., Dunkerton, 1997) and semiannual oscillation (SAO) in both the stratosphere and mesosphere (e.g., Hitchman et al., 1992); topographic wave drag is believed to slow the westerly winds above the midlatitude tropospheric jet maximum and significantly affect the northern winter climate (e.g., Palmer et al., 1986; McFarlane, 1987); they also play a role in driving the summer hemisphere meridional transport circulation (e.g., Alexander and Rosenlof, 1996) expressed through the downward control principle, and contribute to the formation of the winter stratospheric polar vortex (e.g., Hitchman et al., 1989). The interested readers are referred to Fritts (1984) and Fritts and Alexander (2003) for extensive reviews of the history and our current understanding of GW dynamics and their effects in the atmosphere. As noted in Fritts and Alexander (2003), observational and

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theoretical studies have also revealed considerable temporal and geographic variability of the GW source spectrum and its effects in the middle atmosphere. To date, however, our knowledge about the spatial and temporal variations of GW sources is still very limited, and more detailed observations are needed to characterize and quantify GW sources and their effects on the atmosphere at greater altitudes.

With the aim to study GW forcing of the polar mesosphere and lower thermosphere (MLT) region, two MaCWAVE (Mountain and Convective Waves Ascending Vertically) collaborative rocket and ground-based measurement campaigns were performed in northern Scandinavia (Goldberg et al., 2003, 2004, 2006). The summer component, which was coordinated closely with the MIDAS (Middle Atmosphere Dynamics and Structure) rocket program, was performed at the Andoya Rocket Range, Norway (69.3° N, 16.1° E) and the nearby ALOMAR observatory during July 2002 and has been described in detail in Goldberg et al. (2004) and Becker and Fritts (2006). Briefly, the mean state structure and GW activity from the troposphere to the mesosphere were characterized (Goldberg et al., 2004; Schöch et al., 2004; Rapp et al., 2004; Williams et al., 2004). It was found that there was a warmer mesopause, a colder middle mesosphere, and thus a more stable temperature gradient in the upper mesosphere during July 2002 than observed during previous summers. Meanwhile, the mean meridional circulation was markedly weaker near the mesopause than previous years. The unusual mean circulation and thermal structure were found to be consistent with the GW characteristics measured (Becker et al., 2004; Becker and Fritts, 2006).

The winter MaCWAVE rocket campaign in January 2003 was moved to Esrange, Sweden (67.9° N, 21.1° E), which is located on the east side (or lee) of the Scandinavian mountains. The rocket measurements were also supplemented by coordinated satellite and ground-based measurements at both Esrange and Andoya. Northern Scandinavia has been found to be a preferred site for penetration of mountain waves into the middle atmosphere in winter, and several independent campaigns have already examined the influences of the Scandinavian mountain ridge on GWs and polar stratospheric cloud formation (e.g., Dörnbrack et al., 2002; Blum et al., 2005; Eckermann et al., 2006). GWs excited by topography, or mountain waves, have phase speeds near zero, so critical levels occur where the background wind is zero in the direction of wave propagation. A significant stratospheric warming immediately prior to our winter measurement program led to a reversal of the zonal wind, which prevented the penetration of mountain waves into the mesosphere. Nevertheless, there existed clear GW perturbations, some of which appear to be clear indications of mountain wave critical level encounters, with GW motions at higher altitudes due to sources other than topography.

Our goal in this study is to investigate in detail GW characteristics in the stratosphere and mesosphere employing data collected during the winter MaCWAVE rocket program. Because this campaign occurred during a major stratospheric warming, a major focus is on the behavior of apparent mountain waves approaching their critical levels. We employ both conventional and wavelet methods to assess GW structure in the stratosphere and mesosphere.

6 Conclusions

Falling sphere and balloon wind and temperature measurements from the MaCWAVE winter campaign in January 2003 were analyzed to investigate GW characteristics in the stratosphere and mesosphere over northern Scandinavia.

The background was dominated by a minor stratospheric warming at ∼30 km on 24–27 January, which was accompanied by a downward-propagating upper mesospheric cooling during the same period. There was an earlier major stratospheric warming at ∼45 km during 17–19 January which was also accompanied by an upper mesospheric cooling.

Among the nearly three dozen FS soundings conducted during the winter campaign were two salvos which were launched on 24–25 and 28 January, respectively. Within each salvo, the temporal resolution was ∼1 h, thus allowing for credible estimates of the mean fields and the extraction of GW perturbations for each sounding. GW perturbations for each sounding within each salvo were derived by removing the salvo mean field from the raw soundings which were then subjected to a high-pass filter to minimize the possible contamination of planetary waves and tides. The dominant GW perturbations for each sounding were identified using the S-transform, a Gaussian wavelet analysis. For soundings in Salvo 1, the strongest wave perturbations occurred at ∼45–50 km with vertical wavelengths of ∼4 km. There was also a secondary maximum in GW amplitudes at ∼60 km with vertical wavelengths of ∼9–10 km. For soundings in Salvo 2, the dominant wave amplitudes occurred at ∼60 km with vertical wavelengths of ∼7 km for winds and ∼9–10 km for temperature.

A new approach, which is a variation of the conventional hodographic analysis, was introduced to estimate GW horizontal propagation directions for the dominant wave motions. Estimates from the new approach are generally consistent with the Stokes analysis, though the new approach seems to provide better estimates for some cases. For soundings in Salvo 1 at ∼60 km and above, GWs generally propagated towards the southeast, whereas for soundings in Salvo 2 in the same altitude range, GWs generally propagated towards the northwest or west. None of these waves could have been topographic waves due to the existence of mountain wave critical levels below 60 km. The source of the waves at these altitudes in Salvo 1 were mostly likely shear instability, likely at much lower altitudes.

The wind perturbation hodographs for soundings in Salvo 1 at ∼45–50 km did not depict well-defined ellipses, indicating a possibility of moutain waves at higher intrinsic frequencies. Nevertheless, the hodographs suggested wave motions having short vertical wavelengths and large amplitudes, and they were aligned in a northwest-southeast orientation, which was within the selective transmission window for topographic waves to propagate upward until they encountered critical levels at ∼50 km. The ratios of perturbation amplitudes and intrinsic phase speeds for nearly all the soundings in Salvo 1 exhibited sharp peaks at 45–50 km and a remarkable reduction of these ratios just above 50 km. These results suggest that these GWs were most likely mountain waves approaching their critical levels.