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Gravity Wave Forcing of the Mesosphere and Lower Thermosphere: Mountain and Convective Waves Ascending Vertically (MaCWAVE)

Final Report
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Covering the period 31 May 2001 to 30 May 2004

By

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Gravity Wave Forcing of the Mesosphere and Lower Thermosphere: Mountain and Convective Waves Ascending Vertically (MaCWAVE)

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Project Principal Investigator: Richard A. Goldberg (NASA/GSFC)

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Research Objectives:

The specific objectives of this research effort included the following:

1. Quantification of gravity wave propagation throughout the lower and middle atmosphere in order to define the roles of topographic and convective sources and filtering by mean and low-frequency winds in defining the wave field and wave fluxes at greater altitudes;

2. The influences of wave instability processes in constraining wave amplitudes and fluxes and generating turbulence and transport;

3. Gravity wave forcing of the mean circulation and thermal structure in the presence of variable motion fields and wave-wave interactions, since the mean forcing may be a small residual when wave interactions, anisotropy, and momentum and heat fluxes are large;

4. The statistical forcing and variability imposed on the thermosphere at greater altitudes by the strong wave forcing and interactions occurring in the MLTI.

Research Methodology:

Our goals for the summer MaCWAVE rocket and ground-based measurement program were addressed through a comprehensive measurement program at ARR and ALOMAR to define and quantify the gravity wave forcing, interactions, and instability processes accounting for the summer mesopause thermal, wind, and constituent structure in a manner not possible at any other location. This program included two ~12-hr rocket salvoes launched on 1/2 and 4/5 July 2002 during intervals of clear weather and active PMSE, allowing us to take advantage fully of correlative instrumentation at ALOMAR. Additional correlative measurements of MLT temperatures and turbulence fluctuations were provided by German/Norwegian MIDAS sounding rocket launches as a part of each rocket sequence.

We then attempted to quantify mountain wave excitation, upward propagation, and MLTI effects, including momentum flux divergence, mean flow forcing, and wave instability, interactions, and turbulence generation under winter conditions. This was done using rocket, ground-based, and balloon measurements from ESRANGE, ARR, and ALOMAR (northern Scandinavia is a preferred site for such MLTI penetration of mountain waves, see below). These measurements were further enhanced by correlative TIMED SABER temperature measurements.

In both cases, key correlative data were collected using the comprehensive ground-based lidar and radar measurement capabilities of ALOMAR along with radiosonde measurements of wave structures at tropospheric and stratospheric altitudes. Additional ground-based measurements at ESRANGE and aircraft measurements of winds, temperatures, and wave structures contributed correlative data of value to the winter campaign.

Summary of Research Results:

Initial efforts focused on coordination of our summer and winter rocket campaigns with our European colleagues. This worked to great benefit with the successful completion of the summer MaCWAVE campaign in July 2002. A total of 31 rockets were launched in two sequences, including 26 MET rockets and 5 sounding rockets (2 MaCWAVE and 3 MIDAS payloads). Additionally, three of the MET rockets were coordinated with TIMED satellite overpasses so as to maximize the potential for correlative studies and participation in TIMED validation and science. Dr. Fritts was at the Andoya Rocket Range throughout the experiment to assist the project PI, Dr. R. A. Goldberg, with launch decisions and coordination. The summer MaCWAVE campaign was further supported with a variety of ground-based instrumentation. This included two MF radars (the new Saura MF radar), a meteor radar, an ST radar, the Weber sodium lidar, the ALOMAR Rayleigh/Mie/Raman lidar, the ALOMAR ozone lidar, and routine balloon launches.

Analyses of our summer data are now complete and we have prepared five papers on dynamics among eight papers for a special section of Geophysical Research Letters now being assembled, with R. A. Goldberg and D. C. Fritts as organizers. The major highlights of the GRL papers that will cite this research support include:

1) the identification of unusually strong gravity wave forcing of the mesopause environment, with corresponding departures of the mean wind and temperature fields from normal mesopause conditions,
2) the presence of extreme gradients of winds and temperatures due to these large amplitude gravity waves,
3) the occurrence of enhanced levels of turbulence below and above the mesopause due to strong gravity wave forcing,
4) the presence of an altered temperature structure in the lower thermosphere because of enhanced wave breaking and mixing, and
5) evidence of the filtering of the gravity wave spectrum with altitude in the MaCWAVE balloon and MET rocket falling sphere data.

The mean temperature structure observed by falling spheres in 2002 and its departures from more typical means are displayed in Figure 1. The important aspects here include the colder than normal middle mesosphere and a more stable than normal temperature gradient in the upper mesosphere. This structure arises in response to a lower than normal mean vertical and meridional motion, the meridional component of which is shown in Figure 2. The extreme summer mesopause temperature gradients observed with the Weber lidar and the MICAS CONE instrument are shown in Figure 3. Rocket measurements of turbulence and large gradients at lower altitudes with MaCWAVE instrumentation are consistent with these data. The filtering of gravity waves by mean winds is indicated in the vector propagation plots shown in Figure 4. Papers reporting these and other results that cite this research support are listed below.

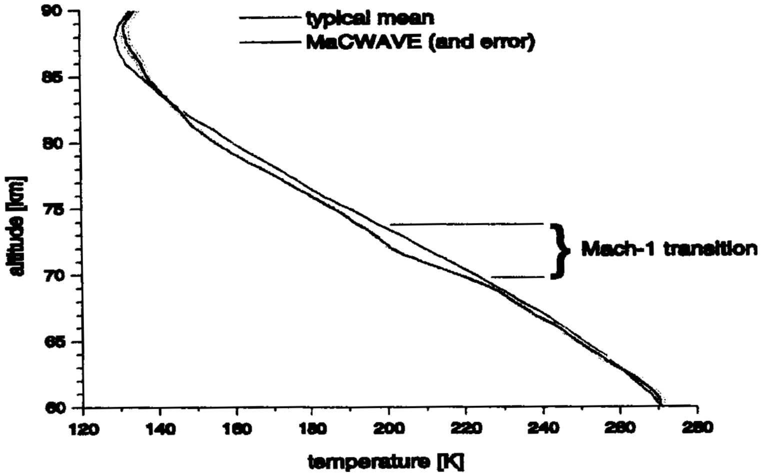

Figure 1. Mean temperature profiles obtained by falling spheres comparing summer 2002 with previous years.

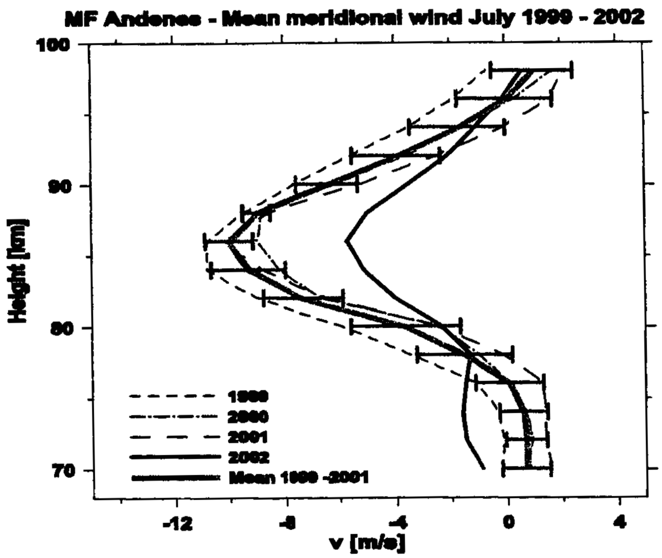

Figure 2. Mean meridional winds obtained with the ALOMAR MF radar comparing July 2002 with previous years.

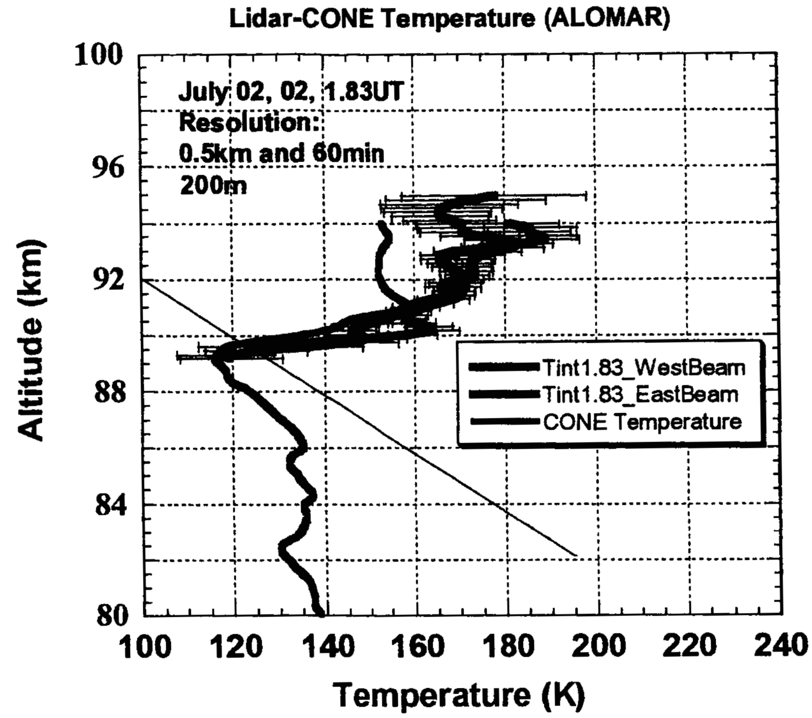

Figure 3. Temperature profiles obtained with the Weber lidar in the east (blue) and west (red) beams and with CONE aboard the MIDAS rocket during the first MaCWAVE summer salvo. Differences between the profiles are due to different locations in a very dynamically active mesopause gravity wave field. Spacing between the lidar beams (at 20° zenith angles) was ~60 km and the CONE measurement was ~30 km north of the west lidar beam. Gradients are ~50 K/km for CONE to ~100 K/km for the Weber lidar.

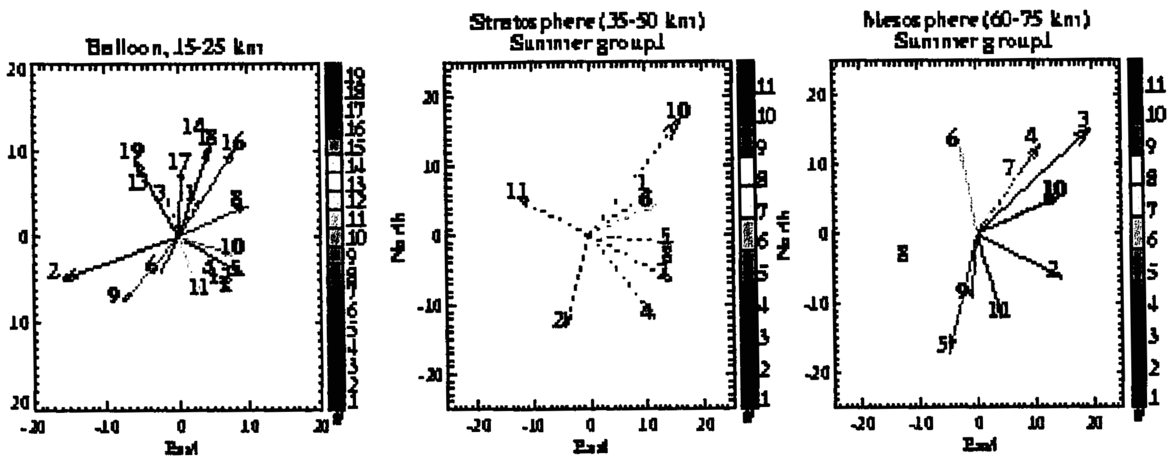

Figure 4. Distributions of propagation direction and horizontal phase speed for gravity waves inferred from a hodograph analysis of balloon and falling sphere data during the summer MaCWAVE salvoes. The trend is toward an increasing eastward propagation bias with increasing altitude, consistent with expectations of filtering theory.

The MaCWAVE winter rocket sequences were also very successful. As noted above, we had hoped to capture mountain wave penetration to both lower and very high altitudes with the two rocket sequences. Because of a stratospheric warming, however, we were able to achieve sensitivity to only the lower altitude penetration of mountain waves, their penetration to higher altitudes being blocked by critical levels in the mean winds. We were, nevertheless, successful in capturing a very large wave event during the second salvo at a time when correlative data were obtained at both ALOMAR and ESRANGE employing radar and lidar instrumentation at both sites because of fortuitous clear skies. This has proven to be primarily a manifestation of an especially large semidiurnal tide, with coherent wind and thermal fields at ESRANGE and ALOMAR with superposed higher-frequency gravity wave activity. An example of the correlative data obtained with the sodium lidar at ALOMAR accompanying the second winter rocket sequence at ESRANGRE is shown in Figure 5.

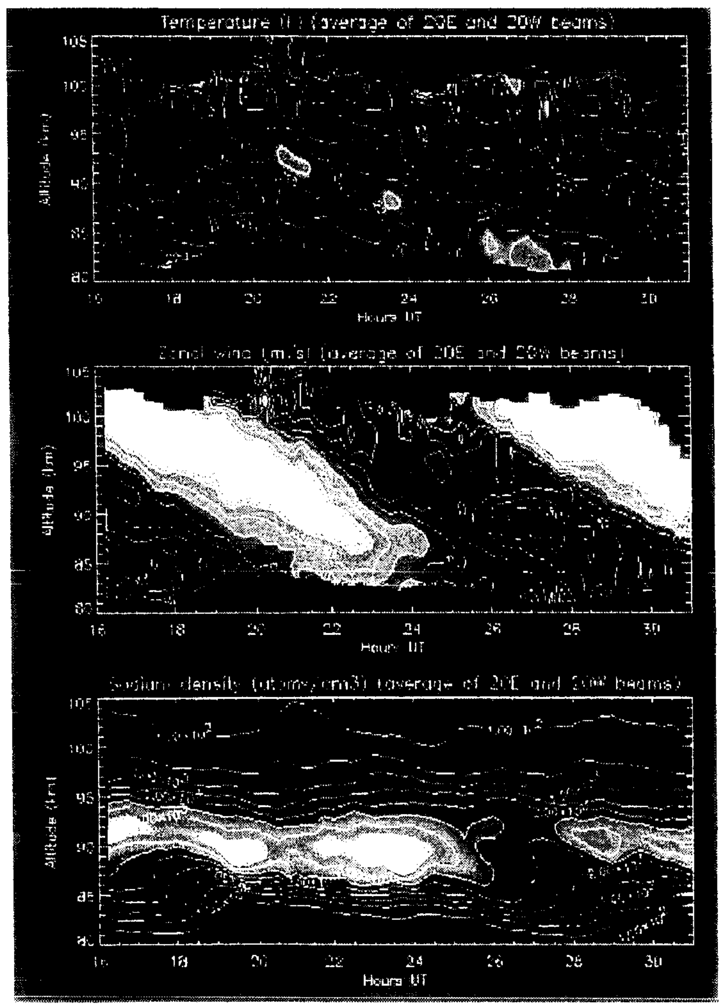

Figure 5. Sodium lidar measurements of temperature, zonal wind, and sodium density (top to bottom) at ALOMAR accompanying the large semidiurnal tide captured with the second winter rocket sequence at ESRANGE. These and other data suggest a highly dynamically active environment during this interval.

Analyses of winter data now underway are examining both an apparent mountain wave that was blocked from further upward propagation in the middle stratosphere by zonal wind reversals accompanying a stratospheric warming and the large-amplitude semi-diurnal tide that was observed with rocket, lidar, and radar instrumentation at ESRANGE and Andoya (see Figure 5), and which is a very unique, multiple-site data set employing a comprehensive suite of instrumentation. Publications employing the winter MaCWAVE data have not yet been written, but will benefit considerably from the comprehensive measurements obtained at ESRANGE and ALOMAR when they appear.

Papers in Press, Submitted, or in Preparation to Date:

Fritts, D. C., B. Williams, J. Vance, C.-Y. She, F. J. Schmidlin, R. A. Goldberg, F.-J. Luebken, and M. Rapp, 2004: Measurements and implications of extreme gradients of wind and temperature near the summer mesopause during the summer MaCWAVE/MIDAS rocket campaign, *Geophys. Res. Lett.,* in press.

Goldberg, R. A., D. C. Fritts, B. P. Williams, F.-J. Luebken, M. Rapp, W. Singer, R. Latteck, P. Hoffmann, A. Muellemann, G. Baumgarten, F. J. Schmidlin, C.-Y. She, and D. A. Krueger, 2004: The MaCWAVE/MIDAS rocket and ground-based measurements of polar summer dynamics: Overview and mean state structure, *Geophys. Res. Lett.,* in press.

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Singer, W., Schmidt, G., R. Latteck, B. Williams, D. C. Fritts, and Murayama, 2004: Mesopause tidal structure during the MaCWAVE/MIDAS rocket campaign, *Geophys. Res. Lett.,* in preparation.

Williams, B., J. Vance, C.-Y. She, D. C. Fritts, F. J. Schmidlin, R. A. Goldberg, U.-P. Hoppe, R. Latteck, W. Singer, M. Rapp, and F.-J. Luebken, 2004: Evidence of unusually high gravity wave variability near the summer mesopause during the summer MaCWAVE/MIDAS rocket campaign, *Geophys. Res. Lett.,* submitted.