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The MaCWAVE program to study gravity wave influences on the polar mesosphere

R. A. Goldberg[1], D. C. Fritts[2], F. J. Schmidlin[3], B. P. Williams[2], C. L. Croskey[4], J. D. Mitchell[4], M. Friedrich[5], J. M. Russell III[6], U. Blum[7], and K. H. Fricke[8]

[1]NASA/Goddard Space Flight Center, Code 612.3, Greenbelt, MD 20771, USA
[2]NorthWest Research Assoc., Colorado Research Associates Div., Boulder, CO 80301, USA
[3]NASA/Goddard Space Flight Center, Wallops Flight Facility, Code 972, Wallops Island, VA 23337, USA
[4]Pennsylvania State University, Department of Electrical Engineering, University Park, PA 16802, USA
[5]Graz University of Technology, A-8010 Graz, Austria
[6]Hampton University, Center for Atmospheric Research, Hampton, VA 23681, USA
[7]Forsvarets forskningsinstitutt, Postboks 25, NO-2027 Kjeller, Norway
[8]Physikalisches Institut der Universität Bonn, D-53115 Bonn, Germany

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Abstract. MaCWAVE (**M**ountain **a**nd **C**onvective **W**aves **A**scending **VE**rtically) was a highly coordinated rocket, ground-based, and satellite program designed to address gravity wave forcing of the mesosphere and lower thermosphere (MLT). The MaCWAVE program was conducted at the Norwegian Andøya Rocket Range (ARR, 69.3° N) in July 2002, and continued at the Swedish Rocket Range (Esrange, 67.9° N) during January 2003. Correlative instrumentation included the ALOMAR MF and MST radars and RMR and Na lidars, Esrange MST and meteor radars and RMR lidar, radiosondes, and TIMED (**T**hermosphere **I**onosphere **M**esosphere **E**nergetics and **D**ynamics) satellite measurements of thermal structures. The data have been used to define both the mean fields and the wave field structures and turbulence generation leading to forcing of the large-scale flow. In summer, launch sequences coupled with ground-based measurements at ARR addressed the forcing of the summer mesopause environment by anticipated convective and shear generated gravity waves. These motions were measured with two 12-h rocket sequences, each involving one Terrier-Orion payload accompanied by a mix of MET rockets, all at ARR in Norway. The MET rockets were used to define the temperature and wind structure of the stratosphere and mesosphere. The Terrier–Orions were designed to measure small-scale plasma fluctuations and turbulence that might be induced by wave breaking in the mesosphere. For the summer series, three European MIDAS (**Mi**ddle Atmosphere **D**ynamics **a**nd **S**tructure) rockets were also launched from ARR in coordination with the MaCWAVE payloads. These were designed to measure plasma and neutral turbulence within the MLT. The summer program exhibited a number of indications of significant departures of the mean wind and temperature structures from "normal" polar summer conditions, including an unusually warm mesopause and a slowing of the formation of polar mesospheric summer echoes (PMSE) and noctilucent clouds (NLC). This was suggested to be due to enhanced planetary wave activity in the Southern Hemisphere and a surprising degree of interhemispheric coupling. The winter program was designed to study the upward propagation and penetration of mountain waves from northern Scandinavia into the MLT at a site favored for such penetration. As the major response was expected to be downstream (east) of Norway, these motions were measured with similar rocket sequences to those used in the summer campaign, but this time at Esrange. However, a major polar stratospheric warming just prior to the rocket launch window induced small or reversed stratospheric zonal winds, which prevented mountain wave penetration into the mesosphere. Instead, mountain waves encountered critical levels at lower altitudes and the observed wave structure in the mesosphere originated from other sources. For example, a large-amplitude semidiurnal tide was observed in the mesosphere on 28 and 29 January, and appears to have contributed to significant instability and small-scale structures at higher altitudes. The resulting energy deposition was found to be competitive with summertime values. Hence, our MaCWAVE measurements as a whole are the first to characterize influences in the MLT region of planetary wave activity and related stratospheric warmings during *both* winter and summer.

Correspondence to: R. A. Goldberg
(richard.a.goldberg@nasa.gov)

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1 Introduction

Observational and theoretical studies during the last few decades have revealed a rich spectrum of dynamical, radiative, chemical, and photochemical processes that act (and interact) to control the circulation, thermal structure, and composition of the mesosphere and lower thermosphere (MLT). These efforts have defined qualitatively the mean state, the broad character of the motion spectrum, and some of the causes and effects of variability in these regions (Holton, 1982; Garcia and Solomon, 1985). Yet the energy inputs, their source distributions and temporal character, the processes coupling various regions, and the detailed responses to periodic and secular forcings are poorly understood at this time. Seasonal differences are especially dramatic at polar latitudes, where gravity waves are believed to provide the majority of the mean forcing and variability and to account for the seasonal differences in mean structure (see Fritts and Alexander, 2003, for a recent review of these various processes and effects).

The MLT is influenced from above and below in a variety of ways. Extreme ultraviolet solar radiation and particle fluxes account primarily for the mean thermal forcing and structure in the lower thermosphere. Ion drag and Joule heating also contribute to the large-scale structure at thermospheric altitudes. However, the major dynamical forcing and the sources of spatial and temporal variability on multiple scales in the MLT likely accompany the upward propagation and dissipation of wave motions arising from sources within the troposphere and stratosphere. This occurs because wave amplitudes grow approximately exponentially with height due to the decrease in the mean density, and thus attain very large values (and large influences) in the MLT. Tidal and planetary wave motions are excited primarily through the absorption of solar radiation by water vapor and ozone, through latent heat release due to deep tropical convection, topography, and from differential land/sea solar heating. In contrast, gravity waves are excited preferentially by orography, frontal processes, convection, and jet streams.

At lower altitudes, gravity wave and tidal influences are generally less than those of the planetary-wave motions. In the MLT, in contrast, gravity wave and tidal influences are much more dramatic. Their influences include, among others, interactions, filtering, and dissipation that result in strong local body forces (Reid et al., 1988; Fritts and Yuan, 1989), modulation of wave motions at lower and higher frequencies (Fritts and Vincent, 1987; Wang and Fritts, 1990; Forbes et al., 1991; Lu and Fritts, 1993; McLandress and Ward, 1994; Broutman et al., 1997; Eckermann, 1997; Norton and Thuburn, 1996; Mayr et al., 1998; Meyer, 1999a, 1999b), closure of the mesospheric jets in the summer and winter hemispheres (Dunkerton, 1982; Holton, 1982, 1983; Garcia and Solomon, 1985), and a strong vertical and meridional circulation from the summer to the winter hemisphere near the mesopause that accounts for the cold summer mesopause and warm winter mesopause (Nastrom et al., 1982; Fritts and Yuan, 1989; Garcia, 1989; Fritts and Luo, 1995; Fritts and Alexander, 2003). For these reasons, the mesopause is a site of intense current scientific interest.

The major influence of these motions in the MLT is exerted through the vertical transport of horizontal momentum by gravity waves with high intrinsic frequencies (Fritts and Vincent, 1987). This momentum flux and its vertical convergence control the mean vertical and meridional circulation, and thus the thermal field at these heights, via a process known as “downward control” (McIntyre, 1989; Haynes et al., 1991; Garcia and Boville, 1994). These processes are poorly understood at present, but are important drivers of the middle atmospheric circulation, structure, and large-scale variability that can be addressed with appropriate and comprehensive high-latitude in situ and ground-based measurements. Indeed, our understanding (and parameterizations) of mountain wave penetration into the MLT in winter is severely lacking, while virtually nothing is known of the sources and propagation of waves that influence the summer mesopause.

These factors were the drivers for our comprehensive MaCWAVE (Mountain and Convective Waves Ascending VErtically) summer and winter rocket and ground-based measurement programs that are the subject of this special issue. The summer MaCWAVE/MIDAS (Middle Atmosphere Dynamics and Structure) launch sequences were performed at Andøya Rocket Range (ARR, 69.3° N, 16.0° E) and coordinated with ground-based measurements at the ALOMAR Observatory. These addressed the forcing of the summer mesopause environment by anticipated convective and shear generated gravity waves. A sequence of papers in Geophysical Research Letters (e.g. Goldberg and Fritts, 2004; Goldberg et al., 2004) described the initial results from this program.

The winter MaCWAVE rocket program was performed at Esrange (67.9° N, 21.0° E) to measure the structure and propagation of mountain waves that often arise in the lee of the Scandinavian mountains and which are expected to penetrate, under suitable conditions, to very high altitudes. The winter program employed radars, lidars, and balloons at both Esrange and ARR to characterize both upstream and downstream conditions. However, a stratospheric warming just prior to the rocket launch window induced small or reversed stratospheric zonal winds, which prevented mountain wave penetration to higher altitudes. This caused a refocusing of our measurement goals and analyses, but resulted in a very interesting data set and a number of useful scientific results. These results represent some of the major contributions to this MaCWAVE special issue. This paper provides an overview of the overall MaCWAVE program, including both summer and winter measurements, in order to introduce the reader to those papers that follow.