The MaCWAVE/MIDAS Rocket and Ground-based Measurements of Polar Summer Dynamics: Overview and Mean State Structure

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Abstract.

The MaCWAVE/MIDAS collaborative rocket and ground-based measurement programs were performed at the Andøya Rocket Range (69.3°N) and the nearby ALOMAR observatory in northern Norway during July 2002. The summer component of the MaCWAVE (Mountain and Convective Wves Ascending Vertically) program was focused on gravity wave propagation, instability, and wave-wave and wave-mean flow interaction dynamics contributing to summer mesopause structure and variability. The MIDAS (Middle Atmosphere Dynamics and Structure) program concentrated on small-scale dynamical and microphysical processes near the summer mesopause. Our merged program yielded a comprehensive data set comprising two ∼12-hour rocket salvoes, including 26 MET rockets and 5 sounding rockets, ground-based lidar, radar, and balloon data, and coordinated overpasses of the TIMED satellite. This paper describes the measurement program and rationale, the mean state observed during the rocket salvoes, and evidence that the mean state structure during 2002 differed in important respects from previous years.

1. Introduction

Observational and theoretical studies during the last few decades have revealed a rich spectrum of dynamical, radiative, chemical, and microphysical 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, the impacts of wave-mean flow interactions, 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 variable 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).

Gravity waves arise in the lower atmosphere primarily due to convection, orography, and wind shear (*Nastrom and Fritts*, 1992; *Fritts and Nastrom*, 1992), while other sources likely become more important at greater altitudes. Gravity waves may achieve large amplitudes as they propagate upward, due to density decreases with altitude, and they are strongly filtered by mean and large-scale wave motions. This results in preferred propagation with phase speeds opposed to the zonal mean mesospheric jets. Wave instability and turbulence lead to dissipation, momentum flux divergence, mean wind decelerations, induced mean meridional winds, and upward (downward) motions in the upper mesosphere leading to mean temperatures far below (above) radiative equilibrium values in the summer (winter) hemisphere (*Garcia*, 1989; *McIntyre*, 1989). Under summer conditions, these dynamics lead to a mean thermal structure that approaches an adiabatic lapse rate in the upper mesosphere. Such an environment results in expanded vertical scales and reduced tendencies for instability in the upper mesosphere, with the opposite tendencies in the highly-stratified lower thermosphere (*VanZandt and Fritts*, 1989).

The MaCWAVE/MIDAS campaign was conducted in July 2002 to explore the dynamics and microphysics of the polar summer atmosphere, with a focus near the mesopause. The campaign instrumentation and measurement program were described by *Goldberg et al.* (2003). Interesting aspects addressed here include evidence for a lower and weaker residual (vertical and meridional) circulation, a corresponding colder middle mesosphere and warmer mesopause, and a smaller occurrence frequency of polar mesosphere summer echoes (PMSE) and noctilucent clouds (NLC) than under more typical summer conditions. Companion papers address a number of aspects of the large- and small-scale dynamics and microphysics under summer conditions. In several cases, we identify aspects of the dynamics that appear to be unique to the summer 2002 environment. Interesting aspects of the dynamics include planetary and tidal wave structure (*Singer et al.*, 2004), influences of southern hemisphere planetary wave dynamics in the northern hemisphere polar summer (*Becker et al.*, 2004), enhanced gravity wave amplitudes and gradients (*Schöch et al.*, 2004; *Williams et al.*, 2004; *Fritts et al.*, 2004), and significantly increased turbulence intensities and occurrence near the summer mesopause (*Rapp et al.*, 2004). The corresponding microphysics observed during the campaign is addressed by *Mitchell et al.* (2004).

2. Programmatics

The MaCWAVE/MIDAS campaign was conducted from Andøya Rocket Range (ARR, 69.3°N, 16.0°E), Norway during the first week of July 2002. This site was selected to permit the study of the dynamics of the polar summer mesosphere and the associated

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Paper number .
0094-8276/04/$5.00

microphysics relating to PMSE and NLC. ARR is an ideal site because of its proximity to the ALOMAR Observatory, housing a variety of radar, lidar, and other instrumentation. The plan in summer was to quantify gravity wave propagation and effects, including wave breaking, turbulence generation and mixing, mean-flow interactions, and associated microphysics. To accomplish this, two sequences of rocket and balloon payloads were launched from ARR in early July 2002. The meteorological falling spheres (FS) were used to obtain the large-scale meteorology of the MLT region and define gravity wave perturbations throughout the middle atmosphere. The FS were also coordinated with TIMED satellite overpasses to permit comparison with temperatures determined by the SABER instrument (*Mertens et al.*, 2004). Meteorological radiosondes were launched approximately once every two hours during each sequence, to provide continuity of the MLT meteorological information into the lower stratosphere and troposphere.

The large MaCWAVE payloads were designed to observe small-scale structure in the local plasma, with the assumption that any observed instabilities or turbulence outside ice-loaded altitude regions would also relate to the neutral atmosphere. The MaCWAVE payloads (*Goldberg et al.*, 2003) were coordinated with three MIDAS payloads (*Blix et al.*, 2003) which could also observe neutral turbulence, and temperature structure to higher altitudes than capable with the FS. Figure 1 depicts the PMSE conditions as measured by the Alwin VHF radar for each sequence, along with the launch time for each rocket. Active PMSE conditions were selected as possible regions for local turbulence, and as a tracer of gravity wave activity near the mesopause. ALOMAR lidar (Na and RMR) and radar (VHF, MF, and meteor) data provided continuous ground-based measurements throughout the campaign. The Na lidar is capable of providing temperature information within the Na layer (∼87-96 km) even under daytime conditions. The RMR lidar provided temperatures to ∼60 km and information on NLC occurrence near the mesopause. The MST radar monitored the existence and structure of PMSE's, while MF and meteor radars were used to define the wind structure in the MLT region.

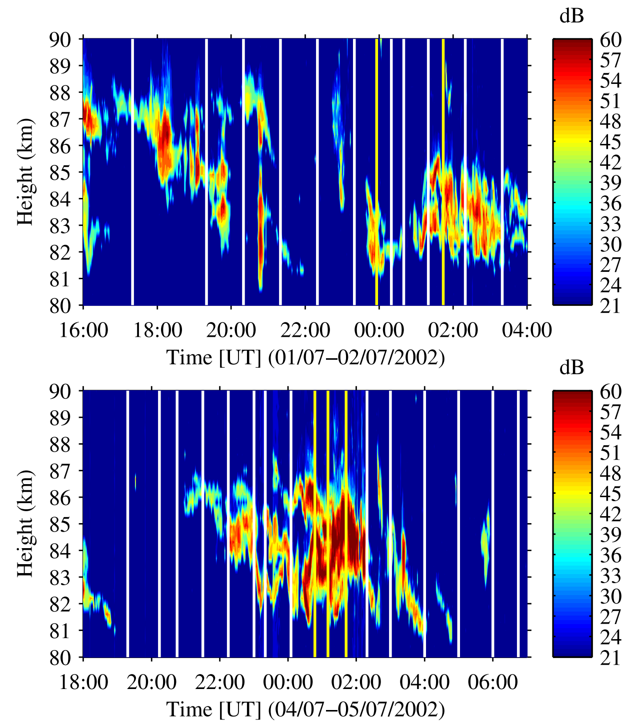

Figure 1. Time-height displays of PMSE intensity showing the variability in PMSE, modulations due to gravity wave activity, and the various FS and sounding rocket measurement times during the two summer MaCWAVE/MIDAS (MM) salvos (white-FS, yellow-MM).

3. Mean State of the Atmosphere

Mean temperature and wind profiles for each of the MaCWAVE/MIDAS rocket salvoes in July 2002 were assembled from a variety of rocket, radar, lidar, and balloon instrumentation and are displayed in Figure 2. Balloon data below 35 km indicate a troposphere with a lapse rate of ∼6.5 Kkm^{-1} below ∼6 km, with a more nearly adiabatic gradient above, a positive gradient extending from ∼9 to 11 km in the lower stratosphere, a nearly isothermal profile from ∼11 to 25 km, and an increasing positive gradient above (see Figure 2a). This panel also shows the RMR lidar mean profiles, which overlap the rocket/balloon results. Rocket and RMR lidar data exhibit agreement with the balloon data at 35 km, increasing temperatures to a maximum of ∼280 K near 50 km, a gradual decrease to ∼270 K at 60 km, and a lapse rate of ∼6.5 Kkm^{-1} extending to above 80 km. Note that the mean temperature and wind profiles discussed here and below represent salvo, daily, or shorter-term averages. Thus they exhibit variability about monthly or seasonal means where low-frequency motions (primarily gravity waves and tides) make large contributions. This is seen in the winds above ∼ 40 km and in the temperatures above ∼ 80 km. Error bars show the uncertainties in the mean temperature and zonal wind obtained with the Na lidar above 87 km (see Figure 2d) and likewise reveal a mesopause at ∼89 km and a mean mesopause temperature of ∼140 K, with a slightly colder and higher mesopause during Salvo 1 on July 1/2 and a warmer and lower mesopause during Salvo 2 on July 4/5. The lidar mesopause temperature estimate is warmer than inferred by FS, but represents more limited data (8 and 5 hours, respectively, for Salvoes 1 and 2) and thus is likely influences by lower-frequency motions. Lidar data also exhibit a positive gradient of ∼10 Kkm^{-1} from ∼90 to 96 km and an isothermal or slightly negative gradient above.

Turning to the mean wind profiles for the two salvoes (Figures 2b, c, e, and f), we see, apart from variations that likely result from inadequate sampling and removal of gravity wave effects below ∼25 km, zonal and meridional mean winds that decrease from weak positive values near the tropopause to significant negative values near 80 km and above. FS data suggest a mean westward jet peaking at 45 to 50 ms^{-1} from 70 to 80 km altitude, a zonal wind shear of ∼5 $ms^{-1}km^{-1}$ above 80 km, and a zero zonal wind crossing near 90 km. Mean meridional (southward) winds increase to magnitudes above ∼10 ms^{-1} between 75 and 80 km. Meteor radar data above 80 km (not shown) suggest more positive zonal winds than inferred with FS, perhaps because of diurnal tide influences not removed with rocket sequences spanning only 12 hours. Mean southward winds peak near 85 km between 10 and 15 ms^{-1} in MF radar data and agree well with FS inferences at lower altitudes. In both cases, however, mean wind magnitudes or offsets are comparable to diurnal tidal amplitudes, leading to some uncertainties in estimates of mean winds at higher altitudes.

4. Discussion and Comparison with Previous Years

There are a number of aspects of the summer 2002 MaCWAVE/MIDAS mean temperature and wind fields that differ in important respects from previous years. FS data during July 2002 suggest a somewhat warmer mesopause (∼133 K near 89

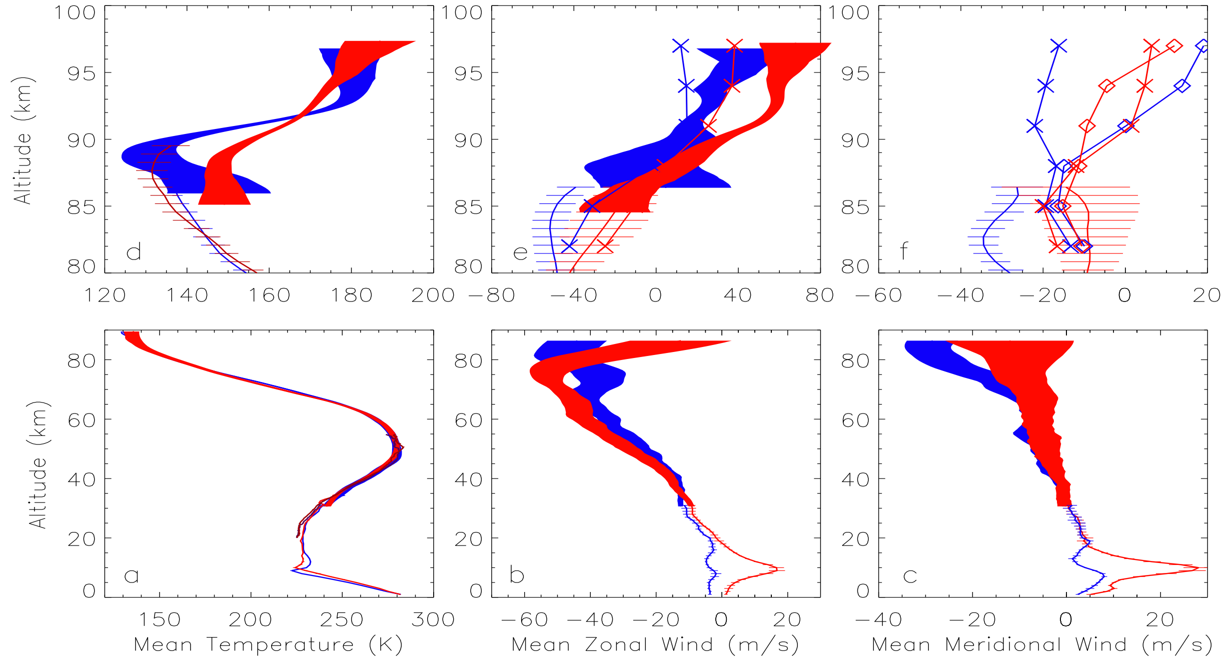

Figure 2. Mean temperature (a) and zonal (b) and meridional winds (c) obtained with balloons, FS, and RMR lidar during Salvoes 1 (blue) and 2 (red) of the MaCWAVE/MIDAS summer rocket and ground-based measurement program. Mean temperature (d) and zonal (e) and meridional winds (f) between 80 and 100 km obtained with FS, the Na lidar (d and e), and the ALOMAR meteor radar (f). Salvo 1 (2) data are blue (red) and meteor radar means for July 1and 4 (2 and 5) are shown with x's (diamonds). Widths show measurement uncertainties in all cases.

km), a colder middle mesosphere, and thus a significantly more stable temperature gradient in the upper mesosphere than observed during previous summers (see Figure 3a and *Lübken*, 1999). The degree of departure is exhibited more clearly in Figure 3b, which shows the 2002 mean with measurement uncertainty compared to a typical mean profile and suggests that the observed departures are

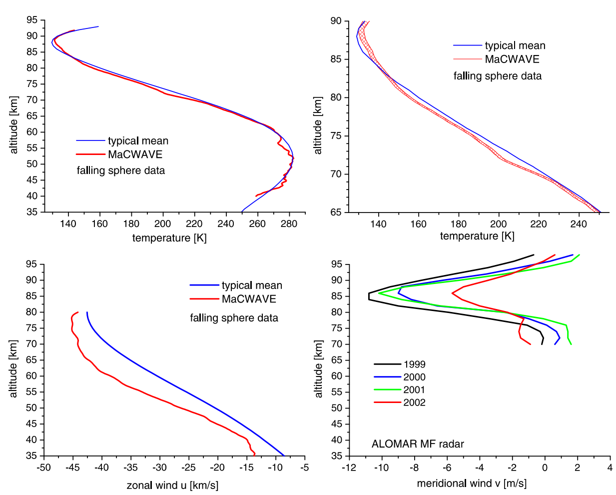

Figure 3. Mean temperature (top) and zonal wind (lower left) obtained with FS, and mean meridional winds obtained with the ALOMAR MF radar (lower right) comparing summer 2002 with previous years. Summer 2002 means are shown in red, previous mean temperatures and zonal winds are averaged over previous summers, and previous meridional winds are from 1999 to 2001. The blow-up of the temperature comparison at upper right shows the MaCWAVE/MIDAS mean with uncertainties and exhibits significant departures from previous years.

significant. This temperature profile, if representative of mean summer conditions, suggests an altered residual circulation and gravity wave forcing of the summer mesosphere relative to previous years (see below). Additional evidence for mean temperature influences on gravity wave activity (enhanced due to greater stability near the mesopause) is provided by *Fritts et al.* (2004) and *Rapp et al.* (2004) in this issue.

Figure 3d displays the mean meridional wind profile for July 2002 (red line) compared with the mean profiles for 1999 to 2001. Compared to previous years, the mean profile during 2002 is markedly weaker (by a factor of ∼2) near the mesopause, but is also significantly more southward below ∼75 km. These features imply a stronger upwelling at lower altitudes and a weaker upwelling just below the mesopause than in previous years. They also appear to be consistent with the observed colder middle mesosphere and warmer mesopause compared to earlier years noted above.

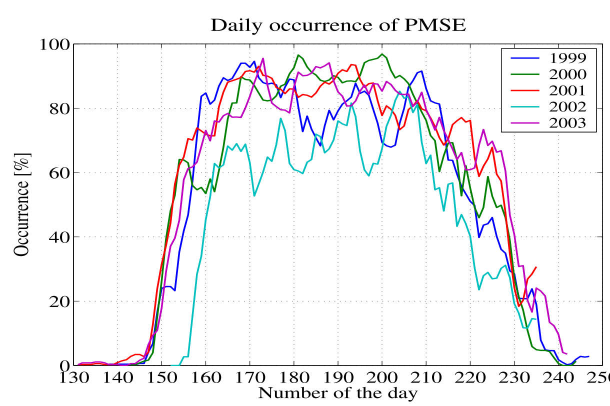

Figure 4. Occurrence frequency of PMSE from 1999 to 2003. Data for 2002 are shown in light blue.

Mean zonal winds during the MaCWAVE/MIDAS program are compared with those observed during previous years in Figure 3c. While the offset between the two profiles below ∼70 km appears significant, it is the behavior at ∼70 km and above that is of interest here. The mean meridional wind for 2002 shown in Figure 3d implies enhanced gravity wave drag and mean zonal wind decelerations below ∼77 km via downward control (*McIntyre*, 1989), exactly where we observe both colder mesospheric temperatures (due to stronger upwelling) and weaker decelerations above ∼80 km, where temperature gradients are significantly more positive than in previous years. While mean winds are not displayed above 80 km because their uncertainties are large, this scenario is consistent with the model study by *Becker et al.* (2004). That study found that the unusually strong planetary wave activity in the 2002 southern hemisphere winter suggests increased (more positive) gradients of zonal wind and temperature and a lower residual circulation near the summer mesopause than normal. Thus inferences from the mean temperature profile and the zonal and meridional wind profiles are internally consistent and all point to significant departures of the mean structure near the mesopause from previous years, in reasonable agreement with the study by *Becker et al.* (2004).

Two final pieces of evidence supporting a different mean state in 2002 than in previous years are provided by the occurrence statistics of PMSE and NLC, which are surrogates for mesopause temperatures and the strength of the wave-driven residual (meridional and vertical) circulation. PMSE data are shown in Figure 4 and demonstrate a clear tendency for less frequent PMSE, and implied warmer mesopause temperatures and a weaker residual circulation, than in other years. An even more dramatic reduction of NLC during summer 2002 is reported by *Bailey et al.* (2004) and provides stronger and more direct evidence of warmer mean temperatures during this unique summer.

The picture that emerges is one of an unusual mean circulation and thermal structure having origins in the unusually strong planetary wave activity in the southern hemisphere and wave-mean flow interactions extending to high northern latitudes (*Becker et al.*, 2004). A stronger than normal zonal jet at high latitudes likely filters the gravity wave spectrum more strongly at lower altitudes, leading to stronger and lower eastward forcing, a lower closure of the summer westward jet, and stronger induced mean meridional and vertical motions at lower altitudes (below ∼77 km). Above ∼77 km, weaker zonal forcing results in weaker mean meridional and vertical motions and warmer temperatures. The altered mean temperatures result in significantly higher mean stability in the upper mesosphere and enable the unusually high gravity wave and turbulence activity extending to lower than normal altitudes near the 2002 summer mesopause. Note that observations of larger than normal gravity wave amplitudes, gradients, and turbulence intensities (*Williams et al.*, 2004; *Rapp et al.*, 2004) are a consequence of the increased stratification (*VanZandt and Fritts*, 1989) and need not imply stronger gravity wave forcing where we have argued above that it appears to be weaker.

Acknowledgments. We thank the Wallops Flight Facility Team under the leadership of Rick Weaver for their excellent support during payload design, testing, and launch activities. Tim Wheeler provided critical payload support during the design and launch of the payloads. Kudos also go to the Andøya Rocket Range, under the direction of Kjell Bøen, for their strong support during launch activities. Patti Twigg and Alfred Beebe contributed valuable programming support for the data analysis. Support for this research was provided by NASA including contracts NAG5-01075 and NAS5-02036, by AFOSR under contracts F49620-00-C-0008 and F49620-03-C-0045, by NSF under grants ATM-0137354 and ATM-0137555, and by the German BMBF under DLR grants 50 OE 9802, 50 OE 9901, and AFO-2000 grant 07ATF41.

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