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Turbulence measurements and implications for gravity wave dissipation during the MaCWAVE/MIDAS rocket program

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[1] Three altitude profiles of turbulent energy dissipation rates measured during the MaCWAVE/MIDAS summer rocket program are presented. All measurements show near continuous turbulent layers from ~72–90 km altitude. Above 82 km altitude measured dissipation rates are comparable to former results. Below 82 km the MaCWAVE/MIDAS measurements provide the first evidence for turbulence in summer at these altitudes ever obtained. This unusual turbulence activity is accompanied by a reduced altitude of the zonal wind maximum, colder temperatures below 85 km, and enhanced gravity wave amplitudes above ~75 km. The larger gravity wave amplitudes can be explained by the different local thermal structure through the wave amplitude dependence on the buoyancy frequency. These larger wave amplitudes lead to wave breaking, turbulence production, and forcing of the zonal wind at lower altitudes. Our measurements hence imply that the altitude of the zonal wind maximum is a sensitive indicator for the altitude distribution of turbulence in the upper mesosphere. *INDEX TERMS:* 0342 Atmospheric Composition and Structure: Middle atmosphere—energy deposition; 3319 Meteorology and Atmospheric Dynamics: General circulation; 3332 Meteorology and Atmospheric Dynamics: Mesospheric dynamics; 3379 Meteorology and Atmospheric Dynamics: Turbulence; 3384 Meteorology and Atmospheric Dynamics: Waves and tides. **Citation:** Rapp, M., B. Strelnikov, A. Müllemann, F.-J. Lübken, and D. C. Fritts (2004), Turbulence measurements and implications for gravity wave dissipation during the MaCWAVE/MIDAS rocket program, *Geophys. Res. Lett.*, *31*, L24S07, doi:10.1029/2003GL019325.

1. Introduction

[2] It is now well established that the upper mesosphere is subject to a gravity wave driven residual pole-to-pole circulation [e.g., *Holton and Alexander*, 2000] leading to two outstanding features of the polar summer environment: first, the mesopause temperature reaches very low values of 130 K being ~100 K below the radiative equilibrium temperature [e.g., *Lübken*, 1999]. Second, the momentum deposition by breaking gravity waves leads to a closure of the mesospheric jet and reversal of the zonal wind close to the mesopause [e.g., *Manson et al.*, 2004].

[3] While several single aspects of the mutual interplay between gravity wave propagation, dissipation and turbulence generation, and the dynamical and thermal structure of the mesosphere have been studied before (see *Fritts and Alexander* [2003], for a recent review of experiments and theory), there have so far been no experimental campaigns that have addressed all these issues in one comprehensive project. In July 2002, the international MaCWAVE/MIDAS-campaign was conducted from the Andya Rocket Range (69°N, 16°E) in Northern Norway involving launches of sounding rockets, meteorological rockets, and balloons together with ground based measurements with VHF- and MF radars as well as Rayleigh- and resonance lidars. An overview of the objectives of the program together with scientific results regarding the atmospheric background state during the campaign is presented by *Goldberg et al.* [2004].

[4] In the overview, *Goldberg et al.* [2004] present evidence for several differences in observed quantities as compared to observations during previous years (see also Figures 1d and 1e): falling sphere temperature measurements indicate lower temperatures at altitudes between ~70 and 83 km (by up to 8 K) and a less negative (and more stable) gradient between 83 km and the mesopause at 89 km where temperatures around 130 K were reached. In addition, the zonal wind measurements from the same falling sphere flights show stronger westward directed winds compared to 'normal' conditions below ~75 km, and they imply that the zonal wind maximum appeared at lower altitudes than normal, i.e., at ~75 km instead of ~80 km in more typical years. This lowering of the zonal wind maximum is confirmed by independent measurements obtained with the ALOMAR MF radar [Singer et al., Tides and planetary waves during the MaCWAVE/MIDAS summer rocket program, submitted to *Geophys. Res. Lett.*, 2004]. Finally, the MF radar measurements show clear evidence of a reduced meridional wind at altitudes around ~85 km together with a slightly enhanced meridional wind below ~75 km altitude.

[5] In the current paper we investigate the morphology of neutral air turbulence under these unusual mesospheric background conditions. After a short description of the experimental and data analysis technique we present three profiles of turbulent energy dissipation rates derived from small scale neutral density measurements with rocket borne ionization gauges. We compare these energy dissipation rates to previous mean profiles of this quantity and discuss our findings in terms of gravity wave activity derived from falling sphere measurements. Finally, we interpret our results in terms of the current

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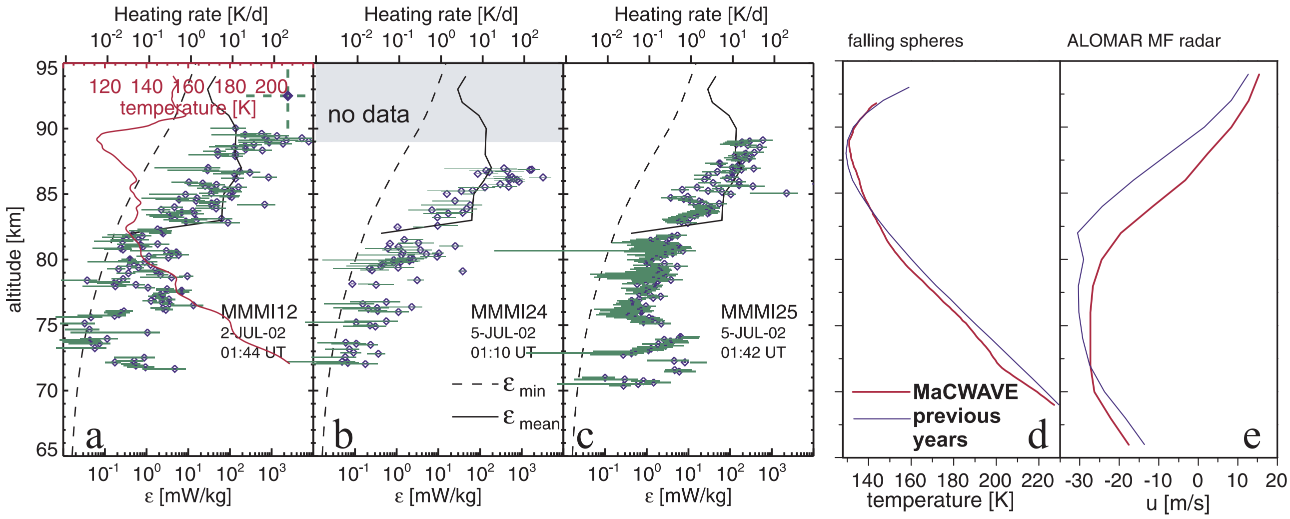

Figure 1. Panels a–c: Turbulent energy dissipation rates ϵ (blue symbols, lower abscissa) and errors (green horizontal bars) as a function of altitude for the sounding rocket flights MMMI12, MMMI24, and MMMI25. The uppermost abscissa converts ϵ to heating rates. The dashed line indicates a gross-estimate of the 'minimum' turbulent energy dissipation rate $\epsilon_{\min}$ (see text). The solid black line indicates the mean ϵ-profile (ϵ_{mean}) derived from ten former sounding rocket flights in summer [*Lübken et al.*, 2002]. The red line (panel a, red upper abscissa) shows the temperature profile measured during flight MMMI12, and the grey shaded area in the panel b indicates the low apogee of only 89.2 km during flight MMMI24 (see text). Panels d and e show mean temperatures and zonal winds from MaCWAVE/MIDAS (red) and previous years (blue), reproduced from [*Goldberg et al.*, 2004] and [*Singer et al.*, 2004].

theoretical understanding of gravity wave-mean flow interactions.

2. Experimental and Data Analysis Techniques

[6] In order to derive turbulent energy dissipation rates, the rocket borne ionization gauge CONE (=COmbined sensor for Neutrals and Electrons) onboard a MIDAS sounding rocket [*Blix et al.*, 2003] was applied to measure relative neutral air density fluctuations as a conservative and passive tracer for turbulent eddy motions [*Lübken*, 1992; *Giebeler et al.*, 1993]. As recently described by *Strelnikov et al.* [2003], the spectral content of the measured time series of density fluctuations is retrieved applying wavelets which allow us to robustly derive so called global wavelet power spectra with a vertical resolution of ~100 m. Each of these spectra is subsequently fitted with a theoretical turbulence spectrum [*Heisenberg*, 1948] with the turbulent energy dissipation rate ϵ as the free parameter. In addition, the CONE measurements also allow us to derive absolute densities and temperatures (subject to the hydrostatic approximation) at a vertical resolution of ~200 m and a relative accuracy of 2% [*Rapp et al.*, 2001]. In order to complement the measurements with CONE, we further make use of falling sphere temperature measurements. The falling sphere technique is described in detail elsewhere [*Schmidlin*, 1991].

3. Results

[7] In Figures 1a, 1b, and 1c we present altitude profiles of the turbulent energy dissipation rate ϵ derived from measurements with CONE during three sounding rocket flights labeled MMMI12 (July, 2, 01:44 UT), MMMI24 (July, 4, 01:10 UT), and MMMI25 (July, 4, 01:42 UT).

[8] For flight MMMI12 we also show the temperature profile derived from the CONE absolute density measurements assuming hydrostatic equilibrium. For the flights MMMI24 and MMMI25, temperatures could not be derived due to a large coning of the payloads which led to density modulations that can not be corrected (note that this does not influence the turbulence analysis since the coning produces a modulation with a wavelength of ~5 km whereas the turbulent density fluctuations occur on spatial scales between ~10 m and 1 km). Note further that flight MMMI24 had a rather low apogee of 89.2 km (104.8 km and 102.5 km for MMMI12 and MMMI25, respectively) such that no data is available for higher altitudes during this flight.

[9] Figure 1 shows several interesting features: all three altitude profiles show near-continuous turbulent layers between ~72 km and 90 km altitude. Among ten former sounding rocket flights in the polar summer a comparably broad turbulent layer has only been observed once [*Müllemann et al.*, 2003] whereas all the other flights showed rather patchy layers of turbulent activity often confined to just a few kilometers in extent [*Lübken et al.*, 2002]. Concerning the observed turbulence strength, we note that above 82 km altitude all measured values resemble closely the average profile from *Lübken et al.* [2002]. Only for flight MMMI12, we have found very large ϵ-values of ~2.5 W/kg between 90 and 95 km altitude. Unfortunately, however, a large spin modulation forbids a vertical resolution of better than ~5 km at these altitudes and also leads to a rather large error bar for ϵ.

[10] The outstanding characteristics of all three profiles, however, is the fact that all three measurements show clear evidence of turbulent activity below 82 km. This has not

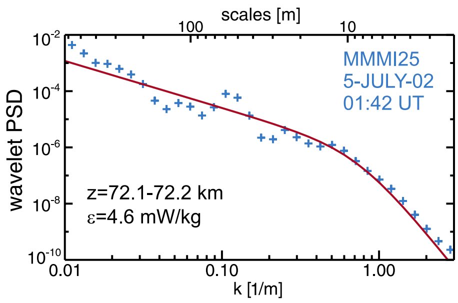

Figure 2. Power spectrum as a function of wavenumber (lower abscissa) observed at ~72 km altitude during the flight MMMI25 (blue symbols). The red solid line shows the corresponding best fit by a Heisenberg-spectrum, yielding an ϵ-value of 4.6 mW/kg. The upper abscissa converts wavenumbers to spatial scales.

been observed in any of the ten former sounding rocket measurements (though the instrumental sensitivity has not changed). In order to demonstrate the data quality of the spectra at low altitudes we show one typical spectrum from a low altitude around ~72 km (see Figure 2).

[11] Fitting this spectrum by a theoretical spectrum due to *Heisenberg* [1948] yields an ϵ-estimate of 4.6 mW/kg, which is significantly larger than the theoretically lower limit of ϵ (given by $\epsilon_{\min} = \nu \cdot N^2$ where ν is the kinematic viscosity of air and N is the buoyancy-frequency) which is ~0.01 mW/kg at this altitude.

[12] The most striking feature of the temperature profile from flight MMMI12 is the very strong positive gradient above ~89 km altitude (dT/dz ~ +40 K/km). This strong positive gradient coincides with very large values of ϵ of ~1 W/kg corresponding to a heating rate of ~100 K/day. Similar strong gradients have also been observed in independent data sets from other instruments and are discussed in detail by *Fritts et al.* [2004].

4. Discussion

[13] In order to identify the reason for the observed unusual turbulence activity we now investigate gravity wave signatures derived from the accompanying falling sphere measurements (see *Goldberg et al.* [2004] for a general discussion of this data set). In Figure 3 we compare two profiles of the quantity $(T'/T_0)^2$, one from 12 falling sphere measurements during the MaCWAVE/MIDAS campaign (red), and the other from 12 falling sphere measurements accompanying the turbulence measurements during previous summers (black) [*Lübken et al.*, 2002]. Here, $T' = \sqrt{\sum_{i=1}^{12}(T_i - T_0)^2/12}$ is the rms-variability of the 12 measurements at a fixed altitude, and T_0 is the corresponding mean temperature. Uncertainties of $(T'/T_0)^2$ are shown with the shaded values.

[14] Note that we have carefully checked that the rms-variability at a certain altitude is not due to systematic changes of the background temperature profile in either of the data sets but real small scale variability presumably due to waves. In addition, the rocket soundings of the two data sets are similarly distributed over local time so that the data should not be biased due to tidal variations. Our analysis shows that differences are insignificant below ~75 km, but at greater altitudes there is a systematic difference in magnitudes of a factor of ~2–4.

[15] In order to identify the geophysical origin of this difference, it is instructive to compare the mean buoyancy-frequencies of both data sets since gravity wave theory predicts that $(T'/T_0)^2 \propto N^3$ for unsaturated ($\propto N^2$ for saturated) waves [*Eckermann*, 1995, equations (21) and (22)]. From the mean temperature profiles underlying Figure 3 we derive mean buoyancy-frequencies at 81 km of 0.019 ± 0.001 Hz for MaCWAVE/MIDAS and 0.015 ± 0.001 Hz for the 'normal summer state'. The ratio of these frequencies cubed (squared) is ~2 (1.6) which largely explains the observed difference in $(T'/T_0)^2$. These considerations imply that the larger gravity wave amplitudes during MaCWAVE/MIDAS are a direct consequence of

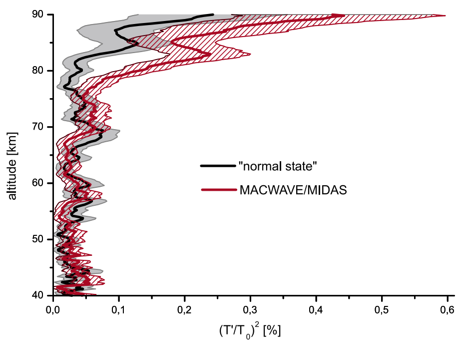

Figure 3. Profiles of $(T'/T_0)^2$ and corresponding uncertainties derived for 12 falling sphere measurements during the MaCWAVE/MIDAS project (red) and 12 falling sphere measurements accompanying the former turbulence measurements under polar summer conditions (black).

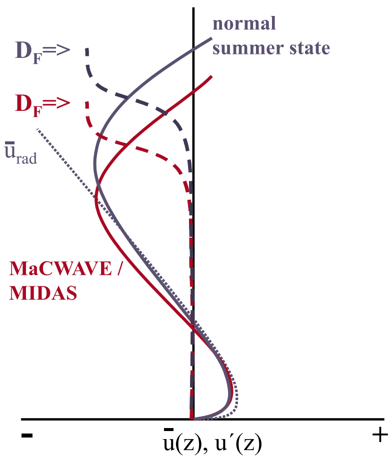

Figure 4. Dotted line: Radiative equilibrium zonal wind in the absence of wave forcing. Dashed line: Idealized gravity wave amplitude growing up to the saturation level above which dissipation by turbulence damps the wave effectively (in blue for the 'normal' summer state and in red for MaCWAVE/MIDAS). Solid lines: Zonal wind profiles due to radiative equilibrium including wave forcing. (Reprinted from *Fritts* [2003] with permission from Elsevier.)

differences in the local stratification as compared to previous years without the need for any difference in the gravity wave source.

[16] With this last piece of evidence, we are now ready to interpret all observed signatures as follows: Guided by [*Fritts*, 2003] we have sketched the principal understanding of the interplay between gravity wave saturation, momentum deposition, and its feedback on the zonal wind profile (Figure 4).

[17] Figure 4 illustrates that in the absence of gravity wave dissipation in the mesopause region the westward directed zonal wind would be expected to grow monotonically with increasing altitude (blue dotted line). However, the amplitudes of upward propagating gravity waves increase due to the density decrease of the atmosphere until they finally reach the altitude level where the waves become unstable (either statically or dynamically) and break, thereby producing turbulence. This wave dissipation leads to a non-zero momentum flux divergence - or wave-drag D_F - due to the gravity wave ($\propto -\frac{1}{\rho}\frac{d}{dz}(\rho\, \overline{u'w'})$) - where ρ is the mass density and u' and w' are the gravity wave amplitudes of the zonal and vertical wind component) and hence to a deceleration of the zonal wind. This deceleration ultimately leads to a wind reversal at an altitude near the mesopause.

[18] With this picture in mind we may now understand our observations during MaCWAVE/MIDAS: as described above, the differences in the mean stratification (described by the buoyancy-frequency) lead to larger gravity wave amplitudes. Due to their larger amplitudes, the waves reach their breaking level at lower altitudes and produce turbulence at lower altitudes than normal. This wave dissipation then creates a wave-drag at lower altitudes and hence leads to the observed lower altitude of the mesospheric zonal wind maximum.

[19] For an explanation of the different mean stratification see the accompanying paper by *Becker et al.* [2004]. These authors have studied the global effects of the unusual high Rossby wave activity in austral winter 2002 [*Baldwin et al.*, 2003] using an idealized general circulation model and focusing on the modulation of gravity wave saturation via the altered mean winds in the mesosphere and lower thermosphere.

5. Summary

[20] We have presented experimental results on the turbulent structure of the upper mesosphere during the MaCWAVE/MIDAS summer program from three sounding rocket flights. All three measurements indicate near continuous turbulent layers between 72 and 90 km altitude. While energy dissipation rates between 82 and 90 km are comparable to previous experimental results, the MaCWAVE/MIDAS-flights have provided the first evidence for neutral air turbulence below 82 km in polar summer. This unusual turbulence activity between 72 and 82 km altitude is accompanied by larger gravity wave amplitudes above $\sim$75 km as observed in falling sphere temperature soundings, lower temperatures than normal between 70–83 km, a more stable temperature gradient between 83 km and the mesopause, and a reduced altitude of the mesospheric zonal wind maximum. All these measurements can be consistently explained in the scope of our current understanding of gravity wave dissipation, turbulence generation, and the corresponding momentum deposition due to the wave and its impact on the zonal wind field. Our measurements further imply that the altitude of the zonal wind maximum is a suitable indicator for the altitude distribution of gravity wave breaking and related turbulence production in the upper mesosphere. We suggest that this relation be investigated in depth on a larger data base that will soon be available from the new narrow-beam MF radar at Saura/Northern Norway [*Latteck et al.*, 2003].

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