INSITU MEASUREMENTS OF MESOSPHERIC TURBULENCE DURING SPRING TRANSITION

A. Müllemann, M. Rapp, F.-J. Lübken, and P. Hoffmann
Leibniz-Institute of Atmospheric Physics, 18225 Kühlungsborn, Germany

ABSTRACT

The first insitu measurements of turbulence in the upper polar mesosphere in spring were performed during the MIDAS/SPRING campaign in May 2000. The high resolution ionization gauge CONE onboard two sounding rockets identified height ranges with turbulent neutral density fluctuations. The measurement of internal parameters of the sensor with a new electronics allowed us to exclude disturbances from instrumental effects. The measurements of both rocket flights are discussed in the light of accompanying insitu temperature measurements with falling spheres and background wind measurements with the ALOMAR MF radar. We find that the rapid transition of the thermal and large scale dynamical structure of the atmosphere between the winter and summer state is accompanied by an equal rapid change in the turbulent structure of the atmosphere.

1. INTRODUCTION

In the past decades many experimental and theoretical efforts have lead to a better understanding of the dynamics and the thermal structure of the middle atmosphere. For example the extremely low temperatures of the polar summer mesopause and the rapid change of the mesospheric thermal structure from the winter to the summer state and vice versa are well known characteristics [*Stroud et al.*, 1959; *Lübken and von Zahn*, 1991]. These features of the thermal structure are a direct consequence of the global circulation pattern, i.e., the upwelling and downwelling of the atmosphere above the summer and winter pole, respectively [*Murgatroyd and Goody*, 1958]. It is generally assumed that the circulation is driven by a drag force created by the breaking of gravity waves. A direct consequence of the gravity wave breaking is the generation of turbulence. During the turbulent processes energy is transferred from large to small scales by cascading processes which efficiently converts energy from the wave field to heat. The strength of turbulence, however, and thus its contribution to the energy budget of the mesosphere is only poorly known at the present stage.

Label	Type	Date	Time (UT)
MSFS01	FS	May 6	16:21 (failure)
MSFS02	FS	May 6	16:41
MSMI03	MIDAS	May 6	17:08
MSFS04	FS	May 15	00:32
MSMI05	MIDAS	May 15	00:46
MSMM06	Mini-MIDAS	May 15	01:12

Table 1. Rocket launches during the MIDAS/SPRING campaign 2000. All flights were performed from Andøya (69° N). ('FS' stands for falling sphere).

One aim of the MIDAS/SPRING (Middle atmosphere Investigation of Dynamics And Structure in Spring) campaign in 2000 was to investigate the thermal and dynamical structure of the arctic mesosphere by means of rocket and ground based instruments in the transition period from the winter to the summer state of the upper atmosphere. In the first half of May two MIDAS sounding rockets were launched from the Andøya Rocket Range (69°N) to study turbulence, temperatures, and the plasma of the D-region. They were accompanied by falling spheres to provide insitu background measurements of temperatures and winds. All launches are listed in Table 1. In this study data from both MIDAS launches and from the two successful falling sphere launches are presented. The plasma probes of the MIDAS payload and the Mini-MIDAS payload were operated by the Norwegian Defence Research Establishment. In addition, the ALOMAR (Arctic Lidar Observatory for Middle Atmospheric Research next to the Andøya Rocket Range) MF radar [*Singer et al.*, 1997] was operating continuously to provide ground based measurements of horizontal winds in the upper mesosphere.

Proceedings of the 15th ESA Symposium on European Rocket and Balloon Programmes and Related Research, Biarritz, France, 28 — 31 May 2001 (ESA SP-471, August 2001)

In the following sections we describe the turbulence measurements with the CONE sensor [Combined measurement of Neutrals and Electrons, *Giebeler et al.*, 1993] which was part of the MIDAS payload. We then present wind measurements from the ALOMAR MF radar and temperatures obtained from the falling sphere flights. Finally, we discuss the turbulent structure of the upper mesosphere observed during the MIDAS/SPRING campaign in the light of the wind and temperature data.

2. MEASUREMENT OF TURBULENCE WITH THE CONE SENSOR

We use relative density fluctuations measured with the CONE sensor as a conservative and passive tracer for turbulent motions in the upper mesosphere [*Lübken*, 1992]. In this section we describe the sensor and the main features of the sensor electronics. Then turbulent parameters are derived from the flight data.

2.1. The CONE sensor and its new electronics

The CONE sensor consists of an ionization gauge to measure neutral density and a DC probe to measure electron density which is operated by the Norwegian Defence Research Establishment.

The electrodes of the sensor are made up of spherical grids which are mounted concentrically on a conical structure. The ionization gauge consists of the three inner grids: Cathode (the innermost grid), ion collector and anode which are at potentials of 10 V, 0 V and 85 V, respectively, relative to the payload structure. The cathode is electrically heated to emit electrons and this emission current is kept constant at 14 μA. A fraction of these electrons ionize air molecules on their path from the cathode to the anode. The ions are collected at the ion collector and detected by an electrometer. The electron probe and a shielding grid (at potentials of +6 V and -15 V, respectively) protect the ionization gauge against the surrounding plasma in the upper mesosphere and lower thermosphere. For a pressure range from 1 to 10^{-4} mbar (which corresponds to a height range from 60 to 115 km) the ion current I_{ion} at the ion collector is proportional to the neutral density ϱ of the atmosphere and to the emission current I_{emi} at the cathode

$$I_{ion} \propto \varrho \cdot I_{emi}. \qquad (1)$$

As mentioned above I_{emi}=14 μA is kept constant. Due to the open geometry of the sensor the time constant of the density measurement is ~1 ms which corresponds to a height resolution of less than 1 m.

The ion current I_{ion} is measured by a logarithmic electrometer which measures currents from 1 nA to 16 μA in 5 ranges. The data is sampled at a rate of 3,3 kHz with a resolution of 16 bits in the mantissa. The noise level of the electrometer is equal to or better than 0,1 % of the actual value of I_{ion}. A new feature of the recently newly developed electronics is the measurement of the emission current with the same sampling rate as high as as the ion current and with a resolution of 12 bits in the range of 0 to 33 μA. Our measurement of turbulence relies on the measurement of small differences in density. As the measured signal is both proportional to the ambient density as well as to the emission current (see equation 1), the latter has to be extremely stable as a prerequisite of an accurate density measurement. Taking advantage of the full resolution measurement of the emission current we are now able to proof that our density measurements are not disturbed by instrumental effects.

2.2. Measurement of neutral density fluctuations

To derive relative density fluctuations we determine smoothed densities $n(z)$ by a third order polynomial fit over height ranges of about 1km. From the differences Δn between the actual measured values and the smoothed values n at altitude z we determine relative fluctuations $\Delta n/n$, also called residuals. In Figure 1 a) an example of such residuals at an altitude range of 84,1±0,3 km during flight MSMI03 are shown as a function of time. Fluctuations occur

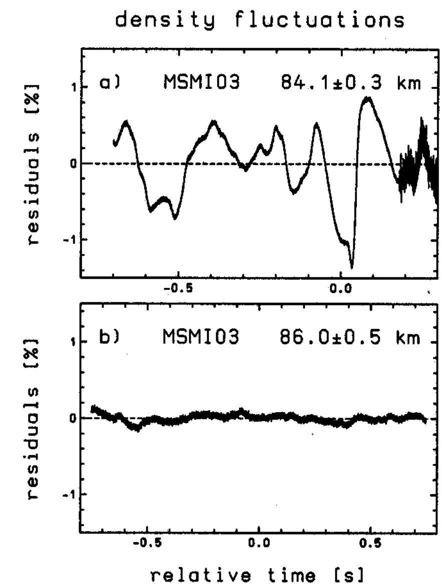

Figure 1. Relative density fluctuations at altitudes of a) 84,1±0,3 km and b) 86±0,5 km versus time (time relative to t_0=0 s at 84 km and 86 km altitude, respectively) measured by the CONE Sensor on flight MSMI03. (In panel a) the noise level increases suddenly at ~0,18 s due to a range switch of the ion current electrometer.)

stochastically and reach amplitudes of up to 1,4%. And the fluctuations are significantly larger than the noise level. This is evident from Figure 1 b) when we show residuals from an altitude range of 86±0,5 km where no atmospheric fluctuations are observed.

In order to proof that the density measurements are not affected by disturbances in the emission current (according to equation 1) we also present the corresponding relative fluctuations of the emission current in Figure 2. Obviously the density fluctuations in Figure 1 a) are not produced by fluctuations in the emission current and thus represent unaffected atmospheric data. The remaining small sinusoidal oscillation of less than 0,3% in the emission current is due to the eigenfrequency of the heating circuit of the cathode. Such an oscillation only occurred at few

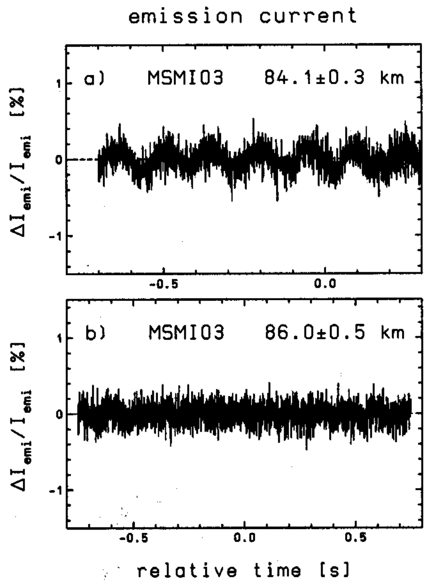

Figure 2. Relative fluctuations of the emission current $\Delta I_{emi}/I_{emi}$ at altitudes of a) 84,1±0,3 km and b) 86±0,5 km versus time (time relative to t_0=0 s at 84 km and 86 km altitude, respectively) measured by the CONE sensor on flight MSMI03.

altitudes and not in the altitude range of 86±0,5 km e.g. which is shown in Figure 2 b). Here is visible that due to the choice of a sampling with 12 bits the noise level of ~0,2 % of the emission current measurement (already limited by the bit resolution) is larger than the noise level of the ion current electrometer at this altitude which is less than 0,1 % (see Figure 1) b)).

2.3. Derivation of turbulent parameters

To quantitatively determine the strength of turbulence we calculate power spectral densities of the relative density fluctuations. The basic idea to derive turbulent parameters is to fit a theoretical turbulent spectrum to the data. Details of this method can be found in *Lübken* [1992]. The power spectral densities of the density fluctuations in Figures 1 a) and b) are shown in Figures 3 and 4 respectively. We have fit-

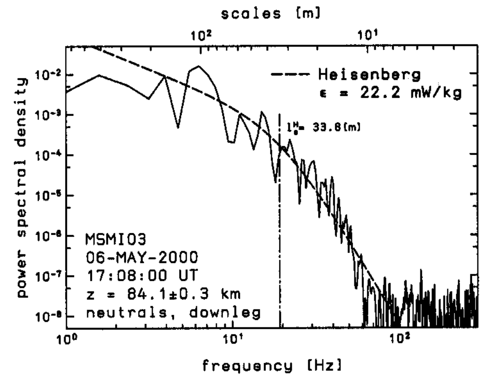

Figure 3. Power spectral densities of the relative density fluctuations of Figure 1 a) versus frequency (lower axis) and scale (upper axis) from flight MSMI03 at an altitude of 84,1±0,3 km. A Heisenberg spectrum of turbulence for ϵ=22,2 mW/kg as best fit to the data is shown by the dashed line: l_0^H denotes the inner scale of the Heisenberg model.

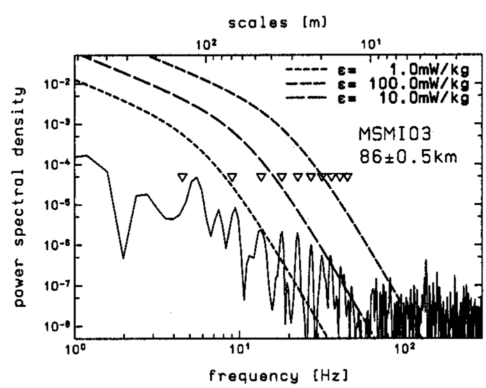

Figure 4. Power spectral densities of the relative density fluctuations of Figure 1 b) versus frequency (lower axis) and scale (upper axis) from flight MSMI03 at an altitude of 86±0,5 km. Heisenberg spectra of turbulence for weak, medium and strong turbulence (ϵ=1, 10, and 100 mW/kg, respectively) are shown by the dashed lines. Triangles mark the spin frequency of the payload and its harmonics.

ted a theoretical spectrum due to *Heisenberg* [1948] to the data at 84,1±0,3km altitude. The inner scale l_0^H of the spectrum which is visible as 'the spectral knee' in Figure 3 is unambiguously related to the Kolmogoroff microscale of homogeneous turbulence η by the relation

$$l_0^H = 9,90\eta = 9,90\left(\frac{\nu^3}{\epsilon}\right)^{1/4}.$$

Here ϵ is the turbulent energy dissipation rate and ν is the kinematic viscosity [*Lübken et al.*, 1993]. With l_0^H from the fit and ν from the background temperature and density measurement of the accompanying falling sphere we get ϵ=22,2 mW/kg corresponding to a heating rate of 1,8 K/d.

Comparing the measured spectrum in Figure 4 with theoretical spectra of very low, medium, and strong turbulence, i.e. ϵ=1, 10, and 100 mW/kg, it is clear that no turbulence existed in this altitude. The remaining maxima in the spectrum are due to not completely removed influences of the spin of the payload on the data. As can be seen in Figure 4 the maxima only occur at frequencies of the spin frequency and its harmonics.

To demonstrate that the spectra of turbulent neutral density fluctuations are not disturbed by instrumental effects the spectrum of the relative emission current fluctuations of Figure 2 a) is shown in Figure 5. It is almost a white noise spectrum and only

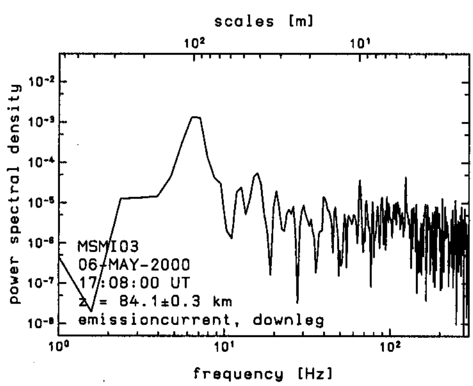

Figure 5. Power spectral densities of the relative fluctuations of the emission current of Figure 2 a) versus frequency (lower axis) and scale (upper axis) from flight MSMI03 at an altitude of 84,1±0,3 km.

one maximum occurs at ~7Hz as expected (this is due to the small sinusoidal variation of the emission current apparent in Figure 1 a). At altitudes where this oscillation did not occur as e.g. shown in Figure 2 b) the spectra are completely flat.).

After the analysis of all data from both MIDAS flights we find that only in two height ranges in each flight turbulent activity occurred; no turbulence was found at all other altitudes from 95 km down to 70 km. In Table 2 the results of the turbulence measurements are summarized.

3. WIND AND TEMPERATURE MEASUREMENTS

In order to interpret our results of turbulence measurements we now describe the state of the background atmosphere during both MIDAS launches. For that purpose we use data from the ALOMAR MF radar yielding the large scale structure of the horizontal wind as well as temperature measurements by the falling spheres.

flight	altitude [km]	ϵ [mW/kg]
MSMI03	84,1 ± 0,3	22,2
	76,2 ± 0,7	0,8
	all other altitudes	0
MSMI05	86,2 ± 0,3	148,9
	84,2 ± 0,3	1,7
	all other altitudes	0

Table 2. Results of the turbulence measurements with the CONE sensor during flights MSMI03 and MSMI05.

3.1. Background wind measurements

The ALOMAR MF radar continuously measured horizontal winds in the upper mesosphere and lower thermosphere from altitudes of 70 km up to 98 km [see *Singer et al.*, 1997, for a description of the radar]. To derive the mean background winds the tidal and short period components are removed. The background zonal winds for April, May, and June 2000 are presented in Figure 6. The MIDAS launches

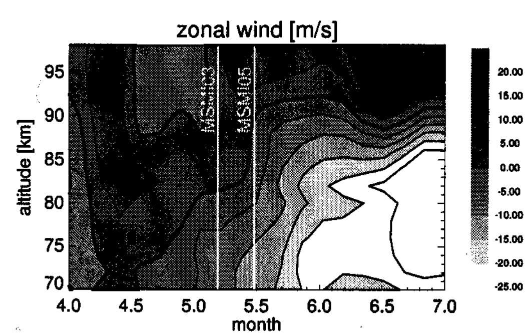

Figure 6. Background zonal winds from the ALOMAR MF radar at altitudes from 70 km to 98 km in April, May, and June 2000. The grey scale of the shading ranges from dark grey=eastward (positive values) to white=westward (negative values) winds. The transition at 0 m/s in the contours is emphasized by a thick black line. The times of the MIDAS launches are marked by white vertical lines.

took place on May 5 and on May 15. During this time the zonal winds change from eastward to westward winds at altitudes below 90 km indicating the mesosphere's transition from the winter to the summer state. Fortunately, both MIDAS launches took place during the changes of the dynamical structure in the transition period.

3.2. Results of temperature measurements

Prior to the MIDAS launches falling spheres were launched to get background temperatures and densities. A description of the falling sphere technique can be found in *Schmidlin* [1991]. In addition to the falling sphere temperatures we have also derived temperatures from the CONE density measurements during flight MSMI03. Unfortunately it was not possible to derive high resolution temperatures from MIDAS flight MSMI05 due to the poor attitude of the payload during the flight.

The results of the temperature measurements during flights MSFS02, MSFS04, and MSMI03 are shown in Figure 7. The temperatures of the falling sphere

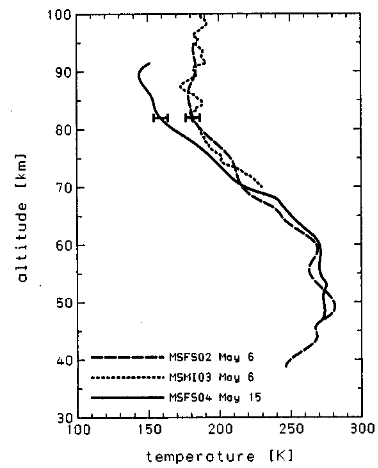

Figure 7. Temperature measurements by of the falling spheres MSFS02 and MSFS04 and from the CONE sensor on MSMI03. The bars at the falling sphere profiles at 82km altitude indicate the maximum uncertainty taking all error sources into account (see text).

measurements at the upper boundaries have to be taken from independent measurements or from a model and were chosen from the CONE temperatures and from the mean temperatures in mid-May of *Lübken* [1999] for MSFS02 and MSFS04, respectively. The influence of this 'start temperature' disappears quickly at lower altitudes and was included into the estimates of the errors at 82 km altitude in Figure 7. The measurements of the falling sphere and CONE on May 6 agree nicely. The CONE sensor resolves the fine scale structure of the temperature, whereas the falling sphere measurements (typical height resolution of 7 km at altitudes down to 75 km) represent the average state of the upper mesosphere.

Comparing these profiles to the measurements obtained on May 15 it can be seen that the thermal structure in the upper mesosphere at an altitude of 82 km changed significantly, revealing a decrease of 20 K, within only nine days between the launches. A cooling of this order is expected during May in the transition from the winter to the summer state [*Lübken*, 1999]. We note that this rapid change of the thermal structure is another strong indication that the MIDAS payloads were launched exactly during the transition from the winter to the summer state of the polar mesosphere.

4. DISCUSSION

As is shown in the previous section both ground based wind and insitu temperature measurements clearly reveal the seasonal change from winter to summer conditions in the upper polar mesosphere during the MIDAS/SPRING campaign within only a few days. Obviously, the question arises if we can find evidence for a seasonal change of the turbulent structure of the mesosphere.

To investigate this point we compare in Figures 8 and 9 the turbulence measurements obtained during the flights MSMI03 and MSMI05 with the average winter and summer profiles of the turbulent energy dissipation rate from *Lübken* [1997] and *Lübken et al.* [2001], respectively. Evidently, the measurements

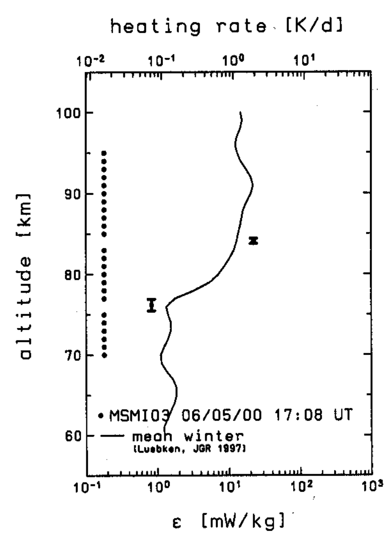

Figure 8. Turbulence measurements during flight MSMI03 and the mean winter profile of ϵ of former insitu measurements from Lübken [1997]. The turbulent energy dissipation rates are plotted versus altitude. The upper axis converts dissipation rates into heating rates. Values for MSMI03 at ϵ=0.18 mW/kg indicate that no turbulence was found at that altitudes.

of MSMI03 match the mean winter values well and the measurements of MSMI05 are consistent with the mean summer values. We have to bear in mind that two flights present a rather poor statistics. Nevertheless, we want to stress two points:

- An ϵ value as high as 148,9 mW/kg has never

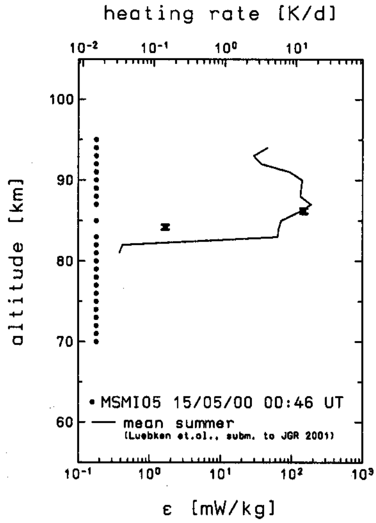

Figure 9. Same as in Figure 8 but for the flight MSMI05 and the mean summer profile of former in-situ measurements from Lübken et al. [2001].

been seen before in winter, whereas it occurred at an altitude of 84,1±0,3 km on flight MSMI05. And similar and even higher values of ϵ has been observed before in summer at this altitude [*Lübken et al.*, 2001].

- In summer turbulence was never seen before at altitudes below 80 km whereas turbulence was detected at 76,2±0,7 km altitude during flight MSMI03.

We conclude that the turbulence measurements of the two MIDAS flights reflect the change from more winterly to more summerly conditions of the turbulent state of the upper mesosphere.

In summary we have found three independent measurements indicating the mesosphere's rapid transition from its winter to its summer state: 1. the mean zonal wind changed from eastward to westward winds, 2. the mesopause region cooled by approximately 20 K in nine days, and 3. the turbulent energy dissipation rates changed from winterly to summerly values. It is interesting to note that the small scale dynamics seem to follow the seasonal variation of the large scale dynamics in the mean winds and in the thermal structure instantaneously. The link between the different spatial scales of the dynamics is most probably the breaking of gravity waves. With a change in gravity wave activity and with a change in the filtering characteristics in the stratosphere the spectrum of waves reaching the upper mesosphere changes [*Lindzen*, 1981]. Therefore the breaking level, the generation of turbulence and the impact on the background atmosphere changes, too. We conclude from our measurements that the timescale of the mutual dependence of these processes appears to be very small. More work needs to be done to obtain a better understanding of all factors controlling the seasonal change in the upper mesosphere.

ACKNOWLEDGEMENTS

The excellent work by the crews of the Mobile Raketenbasis (Germany) and the Andøya Rocket Range (Norway) is gratefully acknowledged. The project was supported by the Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie under grant No. 50 OE 9802.

REFERENCES

Giebeler, J., F.-J. Lübken, and M. Nägele, CONE - a new sensor for in-situ observations of neutral and plasma density fluctuations, in *ESA-SP-355*, pp. 311 – 318, 1993.

Heisenberg, W., Zur statistischen Theorie der Turbulenz, *Z. Physik*, *124*, 628–657, 1948.

Lindzen, R. S., Turbulence and stress owing to gravity wave and tidal breakdown, *J. Geophys. Res.*, *86*, 9707–9714, 1981.

Lübken, F.-J., On the extraction of turbulent parameters from atmospheric density fluctuations, *J. Geophys. Res.*, *97*, 20,385–20,395, 1992.

Lübken, F.-J., Seasonal variation of turbulent energy dissipation rates at high latitudes as determined by insitu measurements of neutral density fluctuations, *J. Geophys. Res.*, *102*, 13,441–13,456, 1997.

Lübken, F.-J., Thermal structure of the Arctic summer mesosphere, *J. Geophys. Res.*, *104*, 9135–9149, 1999.

Lübken, F.-J., and U. von Zahn, Thermal structure of the mesopause region at polar latitudes, *J. Geophys. Res.*, *96*, 20,841–20,857, 1991.

Lübken, F.-J., W. Hillert, G. Lehmacher, and U. von Zahn, Experiments revealing small impact of turbulence on the energy budget of the mesosphere and lower thermosphere, *J. Geophys. Res.*, *98*, 20,369–20,384, 1993.

Lübken, F.-J., M. Rapp, and P. Hoffmann, Neutral air turbulence and temperatures in the vicinity of polar mesosphere summer echoes, *J. Geophys. Res., (submitted)*, 2001.

Murgatroyd, R. J., and R. M. Goody, Sources and sinks of radiative energy from 30 to 90 km, *Quart. J. R. Met. Soc.*, *83*, 225–234, 1958.

Schmidlin, F. J., The inflatable sphere: A technique for the accurate measurement of middle atmosphere temperatures, *J. Geophys. Res.*, *96*, 22,673–22,682, 1991.

Singer, W., D. Keuer, and W. Eriksen, The ALOMAR MF radar: Technical design and first results, in *ESA-SP-397*, pp. 101–103, 1997.

Stroud, W. G., W. Nordberg, W. Bandeen, F. L. Bartman, and P. Titus, Rocket-grenade observation of atmospheric heating in the arctic, *J. Geophys. Res.*, *64*, 1342–1343, 1959.