# In situ measurements of mesospheric turbulence during spring transition of the Arctic mesosphere

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[1] The first in situ measurements of turbulence in the upper Arctic mesosphere during the transition period from winter to summer were performed during the MIDAS/SPRING campaign in May 2000 from the Andóya Rocket Range in northern Norway (69°N). The ionization gauge CONE on board two sounding rockets identified height ranges with turbulent neutral density fluctuations which were used to determine turbulent energy dissipation rates. Accompanying in situ temperature measurements with falling spheres and remote wind measurements with a MF radar revealed the rapid seasonal change of the mesosphere's thermal structure and large scale dynamics just during the campaign. Our in situ measurements give evidence of an equally rapid change of the turbulent structure of the mesosphere within only ~10 days. Models that take into account upward propagating gravity waves which break in the mesosphere show reasonable agreement with our findings. *INDEX TERMS:* 0342 Atmospheric Composition and Structure: Middle atmosphere—energy deposition; 3332 Meteorology and Atmospheric Dynamics: Mesospheric dynamics; 3379 Meteorology and Atmospheric Dynamics: Turbulence

## 1. Introduction

[2] In the past decades our knowledge about the thermal structure and the dynamics of the upper Arctic mesosphere has significantly increased due to numerous experiments and theoretical efforts. Rocket-borne in situ measurements and ground based observations revealed the thermal structure of the polar mesopause region with two different states: A summer state with very low temperatures and a 'warm' winter state. There is a rapid change of the mesospheric thermal structure from the winter to the summer state and vice versa [*Stroud et al.*, 1959; *Lübken and von Zahn*, 1991; *Lübken*, 1999]. The mesospheric wind field is closely associated with the thermal structure. Below 88 km altitude it shows prevailing westward winds in the northern hemispheric summer, prevailing eastward winds in winter, and a change of the wind field during the transition times [see e.g., *Manson et al.*, 2002, and references therein].

[3] Neutral air turbulence also shows a distinct seasonal variation [*Lübken*, 1997]. In winter, turbulence occurs throughout the altitude range from 60 km up to 100 km with relatively low turbulent heating rates of 1–2 K/d (corresponding to turbulent energy dissipation rates $\epsilon \approx 10–25$ mW/kg). In contrast, turbulence in summer is confined to a relatively small altitude range of ~80–95 km but exhibits much higher intensity leading to heating rates of up to 200 K/d ($\epsilon \approx 2300$ mW/kg) in single events [*Lübken et al.*, 2002].

[4] It is now well accepted that the thermal structure of the Arctic mesosphere and its seasonal change is a result of the global meridional circulation from the summer to the winter pole with corresponding downwelling and upwelling air masses above the winter and summer pole, respectively [*Murgatroyd and Goody*, 1958]. It is generally assumed that this circulation is driven by a drag force created by the breaking of gravity waves in the upper mesosphere [*Lindzen*, 1981] which leads to the production of turbulence. On the other hand the spectrum of gravity waves reaching the upper mesosphere is determined by the filtering characteristics of the zonal wind field in the stratosphere and mesosphere which itself varies with season. This implies that the dynamics on the smallest scales, i.e., turbulence, is related to the dynamics on the global scale, i.e., the meridional and zonal circulation pattern. Measurements of the mesospheric thermal structure, wind field, and turbulence in summer and winter thus most likely represent the seasonal differences on the largest and smallest scale of this relation. However, the details of the connection between both scales are not yet completely known. The interaction between the large scale circulation patterns and the corresponding turbulent activity during the transition period and the timescale of this interaction are still not understood.

[5] In order to study the turbulent state of the Arctic mesosphere during the transition period from winter to summer the MIDAS/SPRING campaign (MIddle atmosphere Dynamics And Structure in Spring) was conducted in May 2000.

[6] In the following sections we present experimental results from the rocket-borne and radar measurements used to investigate the seasonal change of the mesospheric thermal structure, dynamics and turbulent structure. Finally we discuss our results in the light of current theoretical studies.

## 2. Measurements and Results

[7] The MIDAS/SPRING campaign was conducted at the Andóya Rocket Range (69°N) in May 2000. Rocket-borne as well as remote sensing instruments were used to determine the dynamical and thermal state of the upper mesosphere. Table 1 summarizes the experiments which were used for this study.

[8] As part of the MIDAS payload the CONE sensor (COmbined measurement of Neutrals and Electrons, *Giebeler et al.*, 1993) measured turbulence in the upper mesosphere during two rocket flights on May 6 and May 15 labeled MSMI03 and MSMI05, respectively. Both flights were accompanied by launches of meteorological rockets (falling spheres) which measured densities and temperatures between approximately 95 and 40 km altitude. In addition, the MF radar located at the Andóya Rocket Range was continuously in operation to determine winds in the upper mesosphere [*Singer et al.*, 1997].

### 2.1. The Seasonal Change of the Background Atmosphere

**2.1.1. Wind measurements with the MF radar.** [9] To describe the seasonal change of the Arctic mesosphere from winter to summer during spring transition we make use of the zonal winds measured by the MF radar at altitudes from 70 km up to 98 km. The radar was continuously in operation throughout the year 2000. The tidal and short period components of the wind field have been removed to yield mean background winds as described in *Singer et al.* [1992]. Results from beginning of April until end of


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**Table 1.** Experiments Utilized During the MIDAS/SPRING Campaign in 2000

| Experiment | Rocket Flight/Operation | |
|---|---|---|
| Falling sphere | MSFS02 May 6, 16:41 UT | MSFS04 May 15, 00:32 UT |
| CONE | MSMI03 May 6, 17:08 UT | MSMI05 May 15, 00:46 UT |
| MF radar | continuously | |

June are shown in Figure 1. The lower right part of Figure 1 displays the summer state of the mesospheric zonal wind field with prevailing westward winds below ~90 km altitude. The beginning of the summer period is indicated by the change from prevailing eastward winds (zonal wind >0 m/s) to westward winds (zonal wind <0 m/s) with season. The zero-crossing of the zonal wind appears at ~80 km altitude in the beginning of May and at ~90 km altitude in mid May which indicates that the spring transition in this altitude range took place in the first half of May. At this point we note that in 2000 the spring transition of the wind field occurred at least one month later than in the climatological mean [see e.g., *Manson et al.*, 2002].

[10] Coming back to Figure 1, it demonstrates that the first rocket, MSMI03, was launched before spring transition in the mesopause region, and the second, MSMI05, thereafter.

**2.1.2. Temperature measurements.** [11] The thermal state of the mesosphere at the time of the MIDAS launches was measured with falling spheres which were launched prior to the instrumented rockets. A description of the falling sphere technique can be found in *Schmidlin* [1991]. (We also note in passing that the results of the falling sphere wind measurements agree reasonably well with the MF radar wind measurements.) In addition to the falling sphere temperatures we have derived temperatures from the high resolution CONE density measurements during flight MSMI03 [*Rapp et al.*, 2001]. Unfortunately it was not possible to derive high resolution temperatures for flight MSMI05 due to the large coning angle of the payload during the flight which prevents a correction of densities for aerodynamical effects.

[12] The results of the temperature measurements for altitudes above 65 km are shown in Figure 2. The temperatures of the falling sphere measurements at the upper boundaries have to be taken from independent measurements or from a model. For MSFS02 we choose this 'start temperature' $T_0$ from the measurements with the CONE sensor on flight MSMI03. The measurements with the falling sphere and CONE agree nicely. The CONE sensor resolves the fine scale temperature structure, whereas the falling sphere measurements represent the average state of the upper mesosphere (typical height resolution = 7 km at altitudes above 75 km, see, e.g., *Lübken* [1999]). We estimate the natural variability for May 6 from the differences between the CONE and falling sphere temperatures below 85 km altitude to be less than ±5 K. For MSFS04 we took the start temperature $T_0$ from the mean temperatures of mid-May from *Lübken* [1999]. To demonstrate the effect of the uncertainty in $T_0$ we have determined temperature profiles for MSFS04 with $T_0$ modified by ±40 K. It can be easily seen that the uncertainty introduced by $T_0$ on the derived temperature profiles disappears quickly at lower altitudes (for a further discussion of the influence of $T_0$ see *Schmidlin* [1991] and references therein). Even if temperatures as high as the temperatures from MSFS02 and MSMI03 are chosen for $T_0$, or even if unrealistic low temperatures of ~110 K are chosen for $T_0$, the temperature uncertainty due to the start temperatures is reduced to ±5 K at an altitude of 82 km approximately 10 km below the initial altitude.

[13] Comparing the temperature profiles at altitudes above 70 km and taking into account the uncertainties due to $T_0$ for May 15 and due to the natural variability for May 6 we find that the thermal structure of the upper mesosphere has changed significantly within nine days only (= time between the rocket launches). We measure a cooling of ~20 K at an altitude of 82 km. This is expected from earlier observations during May in the transition period from winter to summer in the Arctic mesosphere [*Lübken*, 1999]. During flight MSFS04 (May 15) we observe a temperature of ~159 K at 82 km altitude. This value is already close to the temperature of the 'equithermal submesopause' [*Lübken et al.*, 1996; *Lübken*, 2001], i.e., 150 K at 82 km altitude, typical for summer conditions in the past 40 years at polar latitudes.

[14] In summary, our wind and temperature measurements show that the MIDAS launches took place prior and after the change of the thermal and dynamical structure of the upper mesosphere in the transition from the winter to the summer state.

## 2.2. Turbulence Measurements with the CONE Sensor

[15] Relative density fluctuations measured with the CONE sensor have been used as a conservative and passive tracer for turbulent motions in the upper mesosphere [*Lübken*, 1992]. To

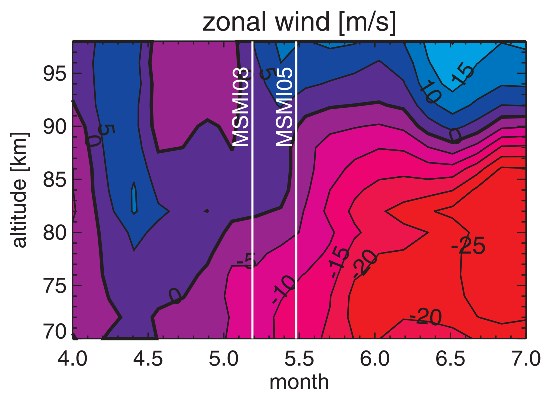


**Figure 1.** Background zonal winds from the MF radar at altitudes from 70 km to 98 km in April, May, and June 2000. The contour colors range from blue = eastward (positive values) to red = westward (negative values) winds. The contour level of 0 m/s is emphasized by a thick black line. The times of the MIDAS launches are marked by white vertical lines.

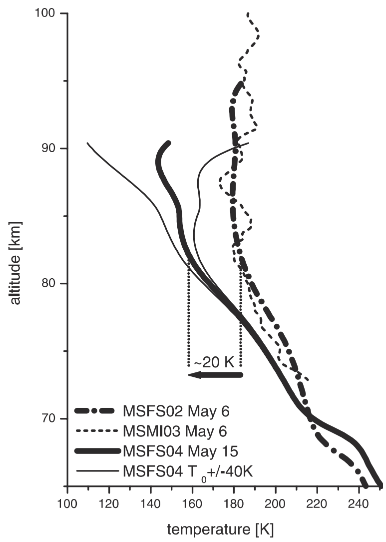


**Figure 2.** Temperature measurements by the falling spheres MSFS02 and MSFS04 (thick lines) and by the CONE sensor on MSMI03 (thin dashed line). The influence of the start temperature on the measurements with MSFS04 is shown by thin lines (see text for details). The change in temperature between MSFS02 and MSFS04 at 82 km altitude is marked by an arrow.

quantitatively determine the strength of turbulence, power spectral densities are calculated from the relative fluctuations (for details of the data reduction procedure see *Lübken et al.* [1993] and *Hillert et al.* [1994]). The basic idea to derive turbulent parameters is to fit a theoretical turbulent spectrum to the data (see *Lübken* [1992] for more details). As an example we show in Figure 3 the power spectral densities of relative density fluctuations measured on MSMI03 at an altitude of 84.1 ± 0.3 km. We have fitted a theoretical spectrum due to *Heisenberg* [1948] to the data. The inner scale $l_0^H$ of the spectrum which marks the intersection between the inertial-convective subrange and the viscous-diffusive subrange in the Heisenberg spectrum is unambiguously related to the Kolmogoroff microscale of homogeneous and isotropic turbulence, $\eta$, by the relation [*Lübken et al.*, 1993]:

$$l_0^H = 9.90\ \eta = 9.90 \left(\frac{\nu^3}{\epsilon}\right)^{1/4}$$

where $\epsilon$ is the turbulent energy dissipation rate and $\nu$ is the kinematic viscosity. With $l_0^H = 33.8 \pm 1.7$ m from the fit and $\nu$ from the background temperature and density measurement of the accompanying falling sphere we get $\epsilon = 22.2 \pm 4.5$ mW/kg (error estimates are determined from the uncertainty of the fit) corresponding to a heating rate of ~1.9 K/d.

[16] Analyzing all data from both MIDAS launches it turns out that only in two height ranges in each flight turbulent activity was found; at all other altitudes from 95 km down to 70 km no turbulence was found. Note that the coning of MSMI05 which prevented us from deriving temperatures does not affect the relative density fluctuations which we use for the turbulence analysis. The coning interferes with the data only on very low frequencies (~0.1 Hz corresponding to scales >5 km) and not with the higher frequency components (1–3 Hz to 100–300 Hz corresponding to scales ≤1 km) which determine the turbulent spectra. We present the results of the turbulence measurements for MSMI03 on May 5 and for MSMI05 on May 16 in Figure 4a and Figure 4b, respectively.

[17] To compare our results with former in situ measurements, average energy dissipation rates for winter and for summer are also shown in Figures 4a and 4b , respectively [*Lübken*, 1997; *Lübken et al.*, 2002]. Evidently, the measurements of MSMI03 match the mean winter values well and the measurements of MSMI05 are consistent with the mean summer values. In order to corroborate our results we stress two points:

1. We detected weak but clearly identifiable turbulence of ~1 mW/kg at 76.2 ± 0.7 km altitude during flight MSMI03 which is typical for winter conditions [*Lübken*, 1997]. In contrast, turbulence has never been observed before at altitudes below 80 km in summer [*Lübken et al.*, 2002]. Thus MSMI03 represents typical winter and not typical summer conditions.
2. We observed an $\epsilon$ of ~150 mW/kg during flight MSMI05 at an altitude of 86.2 ± 0.3 km. Similar and even higher values of $\epsilon$ have been observed before in summer at this altitude [*Lübken et al.*, 2002], whereas an $\epsilon$ value as high as this value has never been observed before in winter [*Lübken*, 1997]. Thus MSMI05 represents typical summer and not typical winter conditions.

[18] We conclude that despite the rather poor statistics of only two measurements we have obtained evidence of a rapid change from winterly to summerly conditions of the turbulent state of the upper mesosphere within only a few days.

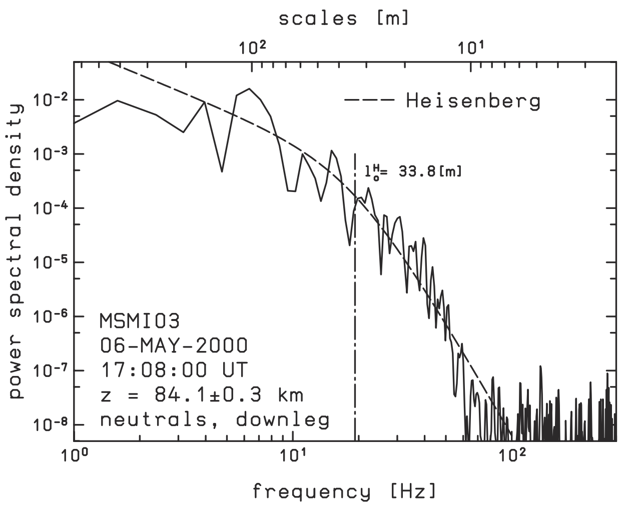


**Figure 3.** Power spectral densities of the relative density fluctuations versus frequency (lower axis) and scale (upper axis) from flight MSMI03 at an altitude of 84.1 ± 0.3 km. A Heisenberg spectrum of turbulence calculated from the best fit results (see text) is shown by the dashed line. $l_0^H$ denotes the inner scale of the Heisenberg model.

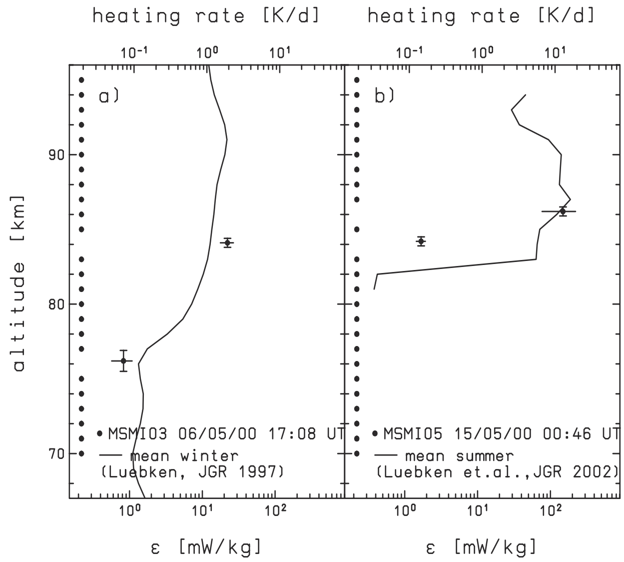


**Figure 4.** Panel (a): Turbulence measurements during flight MSMI03 and the mean winter profile of $\epsilon$ from *Lübken* [1997]. The turbulent energy dissipation rates are plotted versus altitude. The upper axis converts dissipation rates into heating rates. Values for MSMI03 near the left ordinate were arbitrarily chosen to indicate that no turbulence was found at these altitudes. The vertical bars at the non zero results show the altitude range of the measured turbulent layer. Horizontal bars indicate error estimates of $\epsilon$. Panel (b): Same as in panel (a) but for the flight MSMI05 and the mean summer profile from *Lübken et al.* [2002].

## 3. Discussion

[19] In the preceding section we have presented three independent observational indications of the mesosphere's rapid transition from its winter to its summer state: In the time frame of only nine days the mean zonal wind changed from eastward to westward winds, the mesopause region cooled by 20 K, and the turbulent energy dissipation rate changed from winterly to summerly values. This is the first simultaneous identification of the spring transition in all three relevant parameters representing the large scale and small scale dynamics as well as the thermal structure. In the past, temperatures and zonal winds have been observed during spring transition [see, e.g., *Lübken and von Zahn*, 1991; *Lübken*, 1999;

*Manson et al.*, 2002], however, our turbulence measurements during MIDAS/SPRING constitute the first measurements of this type during spring ever. In the following we now discuss the geophysical implications of our results.

[20] Breaking of gravity waves is supposed to be the direct link between the dynamics on very different spatial scales, namely from global circulation to turbulence. Since the gravity wave activity during the transition time and the filtering characteristics in the stratosphere during this time change, 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 the processes on the different scales governing the seasonal change appears to be rather small, i.e., not more than $\sim$10 days.

[21] How do our observational results compare with model descriptions of these processes? In a recent work, *Akmaev* [2001] modeled the thermal structure of the Arctic mesosphere for summer, winter, spring equinox, and autumn equinox conditions. His model predictions show an excellent agreement with the in situ results from *Lübken and von Zahn* [1991] and *Lübken* [1999]. In addition, *Akmaev* [2001] presents estimates of the energy deposition due to breaking gravity waves. His results show dissipation rates of less than 20 mW/kg below 90 km altitude at spring equinox. Under summer conditions, his model yields dissipation rates of up to 200 mW/kg between 80 to 90 km altitude. Thus both his spring and summer results resemble our measurements well. Unfortunately, *Akmaev* [2001] (like to our knowledge most of the presently available model studies) presents results for the equinox and solstice conditions only but not for the seasonal change itself during April to June. One exception is the study by *Garcia and Solomon* [1985] which shows zonal winds and eddy diffusion constants (which directly depend on $\epsilon$) for a one year cycle at 61°N (their Figure 8 and 10c). Obviously, the increase of eddy diffusion above 80 km altitude from the end of April to the end of May together with the gradually changing zonal winds in the mesosphere resemble our measurements well. During the transition time the model shows a jump in the breaking levels of gravity waves in first half of May together with the change in the winds and in eddy diffusion. Thus, it clearly demonstrates that the coupling of the large scale and small scale dynamics is able to drive the seasonal change at least on a timescale of less than a month. The model by *Luo et al.* [1995] is especially dedicated to the thermal structure and dynamics of the Arctic mesopause region in the summer with the transition times during spring and autumn. Profiles of the energy dissipation rate from spring equinox to the second half of July with a temporal separation of approximately one month are shown in their Figure 7. The model results do not match our observations as the model shows no change in the energy dissipation rate below an altitude of 80 km. More to that, it does not show a change in the energy dissipation rates up to approximately 86 km altitude from April to June. Only between equinox and April the model shows a significant increase in the energy dissipation rates between 80 and 86 km altitude. In contrast, the model predictions for the thermal structure in this altitude range (their Figure 5) show a cooling from April to May which matches our temperature measurements very well.

[22] In summary, we find support for our measurements in theoretical studies. However, more work, in particular with emphasis on temporal developments, needs to be done to obtain a better understanding of all factors controlling the seasonal change in the upper mesosphere.

[23] **Acknowledgments.** We would like to thank T. A. Blix for organizing and successfully performing the MIDAS/SPRING campaign. The excellent work by the crews of the Mobile Raketenbasis (Germany) and the Andóya 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.

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