Turbulent kinetic energy dissipation rates in the polar mesosphere measured by a 3-MHz-Doppler radar

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Introduction

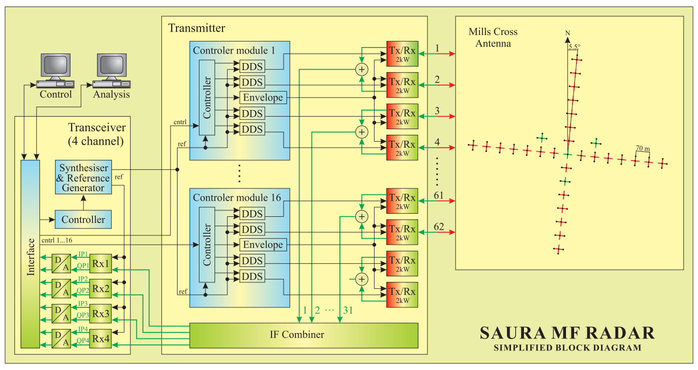
Turbulence is a heat source in the mesosphere and lower thermosphere and also important for diffusive processes. It transfers potential and kinetic energy from medium scales (e.g. generated by the breaking of gravity waves) to very small spatial scales, where the energy is converted to heat by viscous dissipation. Typical turbulent energy dissipation rates for mesospheric altitudes are 10 to 200 mW/kg which correspond to heating rates of about 1 to 20 K/d. The turbulent heating is comparable to other heating mechanisms, such as absorption of solar UV and EUV radiation. In addition, turbulence also indirectly affects the thermal and dynamical structure of the atmosphere by frictional forces on the momentum budget. The breaking of gravity waves induces drag via turbulent friction which changes the global circulation system and finally results in strong cooling or heating (depending on season) due to vertical motion.

A new narrow beam Doppler radar operating at 3.17MHz was installed close to the Andøya Rocket Range in Andenes, Norway in summer 2002 in order to improve the ground based capabilities for measurements of turbulence in the mesosphere. The main feature of the radar is it's transmitting/receiving antenna consisting of 29 crossed half-wave dipoles arranged as a Mills Cross what results in a minimum beam width of 6.6° (Half-Power-Full-Width, one way).

Turbulent kinetic energy dissipation rates based on radar observations are presented and compared with climatological data from rocket measurements in summer and winter as well as with results from a general circulation model.

The Saura MF radar

Radar frequency	3.17 MHz
Peak power	116 kW
Mean power	230 W (0.2% dc)
Pulse shape	Gaussian
Pulse width	>7µs
Range resolution	1000m
Antenna	29 crossed dipoles
Beam width	6.4°
Beam directions	Vertical, 8 off -zenith



The method

Turbulence produces changes in the spectral width of a backscattered radar signal what can be used to deduce turbulent energy dissipation rates at the region of the scatter. The observed spectral width f_{obs} of a received radar signal is defined as the half power half width of its power density spectrum. The radar signal spectrum is also influenced by the background wind field causing broadening of the spectrum.

$$f_{obs}^2 = f_{turb}^2 + f_{nonturb}^2$$

A system with a relative small beam width as well as a corresponding method to correct the non-turbulent broadening of the spectrum $f_{nonturb}$ are necessary to estimate energy dissipation rates. Once the turbulent contribution f_{turb} to the spectral width has been separated it can be converted into mean square fluctuating velocity

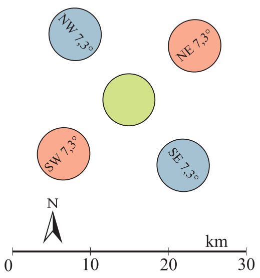
$$v_{RMS}^2 = \left(\frac{\lambda}{2}\right)^2 \cdot \frac{f_{turb}^2}{2 \cdot \ln(2)}$$

where λ is the radar wave length. With the assumption that v^2_{RMS} is caused by small scale 3D turbulence and short period gravity waves, the turbulent kinetic energy dissipation rate ε can be derived as

$$\varepsilon_{turb} \approx c \cdot \left(\frac{\lambda}{2}\right)^2 \cdot \frac{f_{turb}^2}{2 \cdot \ln(2)} \cdot \omega_B \cdot \left(\frac{1}{c_f}\right)^{\frac{2}{3}}$$

The experiment

Beams	SE-NW	SW-NE	vertical
PRF [Hz]	80	80	80
Polarisation	O	O	O/X
Pulse width [µs]	10	10	10
Coherent integrations	2	2	2
Range [km]	40 – 103	40 – 103	40 – 103
Sampling res. [m]	1000	1000	1000
Data points / beam + pol.	3500	3500	3500
Time series / beam [s]	175	175	175
Δt [ms]	50	50	50
Δf [Hz]	0.057	0.057	0.057
Nyquist frequency	10	10	10
Δv_{rad} [m/s]	0.27	0.27	0.27



Illuminated area at 85 km

A sequence of tilted and vertical beams allows to determine both the spectral width of the signal as well as the background wind and wind gradient used for the determination of the non-turbulent spectral component. The pulse repetition frequency of 80 Hz corresponds to a maximum unambiguous range of 1875 km and prevents range aliasing of multiple reflections from E or F layer. The small number of coherent integrations results in a wide available spectral range (±10Hz) and avoids frequency aliasing of interfering signals into the frequency band (± 0.5 Hz) of the atmospheric signal. The large number of data points or long time series of 180s (at least 120s) respectively are necessary to obtain reliable spectra at altitudes below 70 km where long fading times often appear.

References

Becker, E., Direct heating rates associated with gravity wave saturation, *J. Atmos. Solar-Terr. Phys.* 66, 683--696, 2004.

Hocking, W. K., On the extraction of atmospheric turbulence parameters from radar backscatter Doppler spectra - I. Theory, *J. Atmos. Terr. Phys.* 45(2/3), 89-102, 1983.

Hocking, W. K., Fast and accurate calculation of spectral beam-broadening for turbulence studies, *Proceedings of the Tenth International Workshop on Technical and Scientific Aspects of MST Radar (MST10)*, pp. 214-217, 2003.

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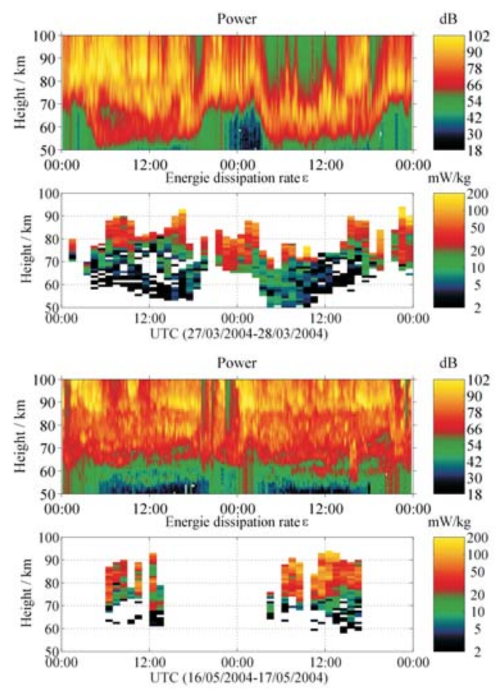
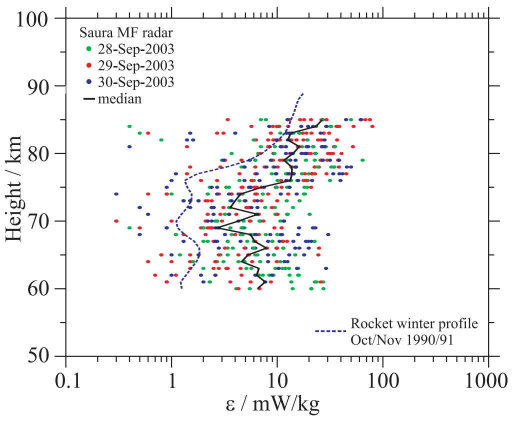
Results

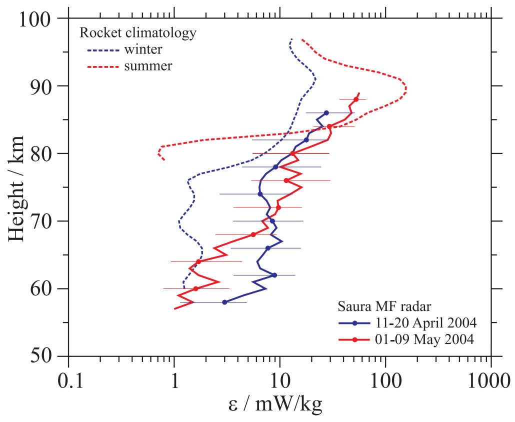
Continuous radar observations of turbulent energy dissipation rates for conditions of enhanced (upper figure below) and normal (lower figure below) ionization are shown in the figures beside. The depicted time period in March 2004 was characterized by enhanced ionization due to a geomagnetic disturbance with particle precipitation resulting in an increased radar backscatter below 70 km.

Under such conditions it is possible to determine reliable winds down to 50 km, whereby the calculation of non-turbulent spectra and finally the determination of turbulent energy dissipation rates from these heights is possible, too. The values of ε show a behaviour with small values less than 10 mW/kg below 70 km, and larger values up to 200 mW/kg increasing with height.

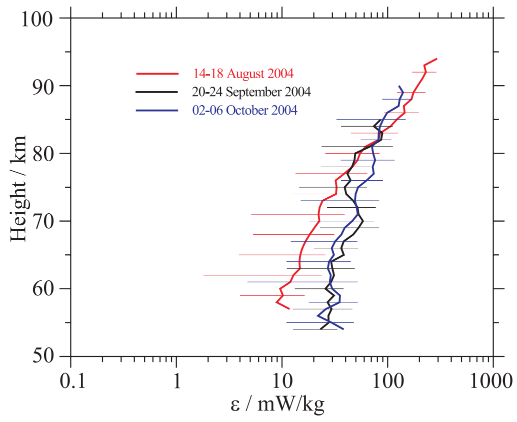




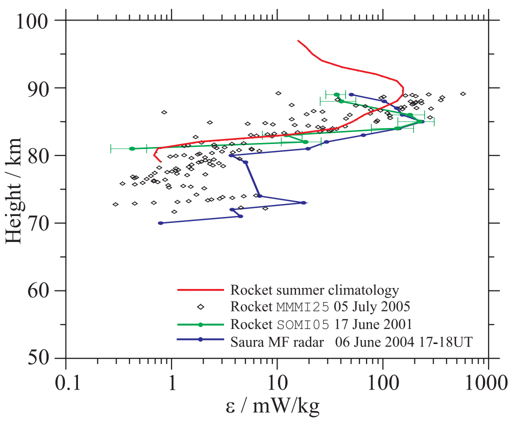
Short time variability of ε: Hourly mean values (dots) of energy dissipation rates from three days radar observations in September2003. The median (black line) derived from the spectral width measurements and the ε profile (dashed blue line) from previous rocket soundings during winter are in qualitative agreement.



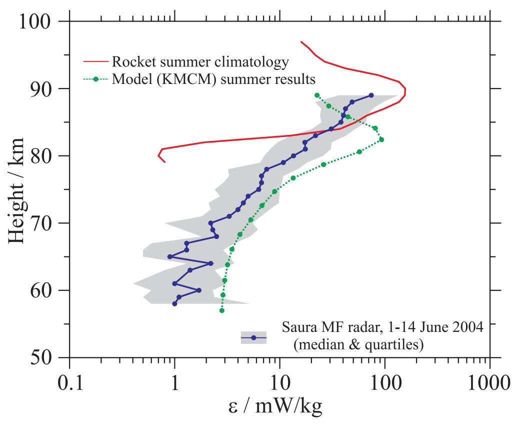
ε variations related to the spring transition of the mesospheric circulation: ε profiles from radar (solid lines) and rocket measurements (dashed lines) before (blue lines) and after (red lines) spring transition of the mesospheric circulation in 2004. The horizontal bars indicate the range between lower and upper quartile.



Summer to winter transition of turbulence: The ε profiles based on radar measurements (mean values with standard deviation) show smaller values below 85 km in August (red) than in September/October (blue and black) but the inverse relation above 80 km. This relation corresponds qualitatively to previous rocket observations.



Individual profiles of turbulent energy dissipation rates: Individual ε profiles derived from radar observations and rocket soundings are compared with a summer climatology based on sounding rocket data. The radar ε profile shows also a steep increase of energy dissipation above 80 km comparable to the in-situ data.



Climatological turbulence data from radar and rocket observations, and the Kühlungsborn Mechanistic general Circulation Model [Becker, 2004]: The model profile for a run simulating heating rates associated with gravity wave saturation for summer conditions at mid-latitudes fits very well in shape to the radar profile but peaks at a lower altitude and lower latitude.

Summary and outlook

The new Saura MF radar provides continuous real-time estimations of turbulent energy dissipation rates among undisturbed measurement conditions in the altitude range from 50km to about 85km with a time resolution of 1 hour and a range resolution of 1 km since September 2003.

The energy dissipation rates vary in the order of 2 to 10 mW/kg around 70km and between about 10 and 200mW/kg around 85km. The radar observations are in qualitative good agreement with model results and results from previous rocket soundings.

The current time and height coverage of the data is quite good during daytime but limited during night time due to external interferences. To reduce the influence of these disturbances on the radar echo signal, future upgrades will include weighting of the transmit and receive antenna polar diagram.