FIRST RESULTS OF HIGH RESOLUTION BALLOON-BORNE TURBULENCE MEASUREMENTS IN THE STRATOSPHERE

Anne Theuerkauf, Michael Gerding, and Franz-Josef Lübken

Leibniz-Institut für Atmosphärenphysik, Schlossstr. 6, 18225 Kühlungsborn, Germany

ABSTRACT

We have developed a compact balloon payload for wind turbulence soundings up to 35 km altitude. The wind measurements are performed with a hot wire anemometer (or constant temperature anemometer, CTA) and have a vertical resolution of 2.5 mm, which enables us to measure the turbulent spectrum down to the viscous subrange. The balloon payload has been launched successfully several times since autumn 2007 from our site at Kühlungsborn (54°N, 12°E), Germany. In October 2008 the sensor has been flown as part of the BEXUS 6 balloon payload from Kiruna (67°N, 21°E), Sweden. In the stratosphere our measurements show thin turbulent layers with a vertical extent of at most 200 m and sharp dividing boundaries. Due to the high measurement resolution it is possible to measure the turbulent spectrum in the stratosphere down to the viscous subrange. The power spectra within the turbulent layers correspond to the turbulent spectra expected from theory. By fitting a spectral model to our measured spectra we determine the inner scale and therewith the energy dissipation rate.

1. INTRODUCTION

Gravity waves and turbulence in the atmosphere play a crucial role in understanding the energy and momentum transfer as well as the trace gas distribution. Breaking gravity waves produce structures in the temperature and wind fields down to the size of turbulence cells. At the same time new gravity waves can be induced. Because turbulence is the random fluctuation of air mass at very small scales it is difficult to forecast and difficult to measure in the atmosphere. Hence turbulence soundings are still technically challenging and the number of soundings is small. Turbulence in the stratosphere is strongly related to shear instabilities and the breaking of gravity waves. It occurs in thin layers with sharp dividing boundaries extending some ten or hundred meters along the vertical and some hundred kilometers along the horizontal. The occurrence of these isolated and sporadic patches in strongly stable regions is well known for a long time and goes back to early atmospheric observations in the 1960s [1]. Later in the 1980s pioneering work concerning stratospheric turbulence has been done by J. Barat and coworkers with balloon-borne sensors (e.g. [2, 3]). Their in-situ wind measurements resolved scales down to some ten centimeters which is well within the inertial subrange. But full knowledge e.g. on turbulent energy dissipation rates can only be deduced by even higher resolved measurements covering the turbulent inner scale and parts of the viscous subrange. These measurements have not been available in the 1980s. Only few soundings have been made in the last decades, so there is still only little knowledge about turbulence in the stratosphere. Although stratospheric turbulence is weak on average compared e.g. to mesospheric turbulence (e.g. [4]), breaking gravity waves in the stratosphere can modify the energy transfer from the troposphere into the mesosphere. Even in the statically stable stratosphere the vertical growth rate of gravity waves is smaller than expected for undisturbed propagation (e.g. [5]). Obviously the wave energy already deposited in the stratosphere can not contribute to the mesospheric energy budget. Moreover stratospheric turbulence is a potentially important process in the vertical mixing of trace species [6].

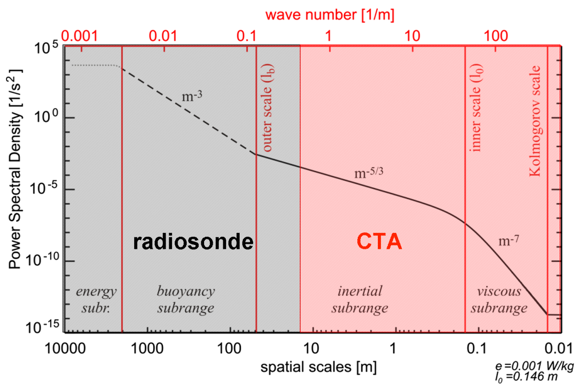

Figure 1. Theoretical calculated turbulent spectrum with typical values of the inner scale and the energy dissipation rate for 20 km altitude. In contrast to a normal radiosonde the constant temperature anemometer (CTA) enables the measurement of the spectrum down to the viscous subrange.

High resolution measurements of turbulence in the middle stratosphere are still technical challenging. In-situ measurements are performed either below 15 km with

Proc. '19th ESA Symposium on European Rocket and Balloon Programmes and Related Research, Bad Reichenhall, Germany, 7–11 June 2009 (ESA SP-671, September 2009)

aircrafts or above 60 km with sounding rockets. Radar and lidar systems are used for turbulence investigation within the stratosphere, but these systems can not provide a sufficient resolution for small scale turbulence. So for detailed observations in-situ high resolution soundings are required. New developments in instrumentation since the 1980s made it possible to measure turbulence down to scales of millimeter and thus to study the whole turbulence spectrum down to the viscous subrange. With the help of hot wire anemometers (also called constant temperature anemometers, CTA) we are able to measure velocity fluctuations with a vertical resolution of 2.5 mm (Fig. 1).
The experimental method is presented in the next section. Observations and first results of the analysis are described in section 3.

2. THE EXPERIMENTAL METHOD

High resolution wind measurements are performed with a constant temperature anemometer (CTA). The CTA is located 50-100 m below a balloon. Due to its large diameter the balloon is following the ambient wind field during the ascent and is assumed as ideal Langrangian tracer (see Fig. 2).

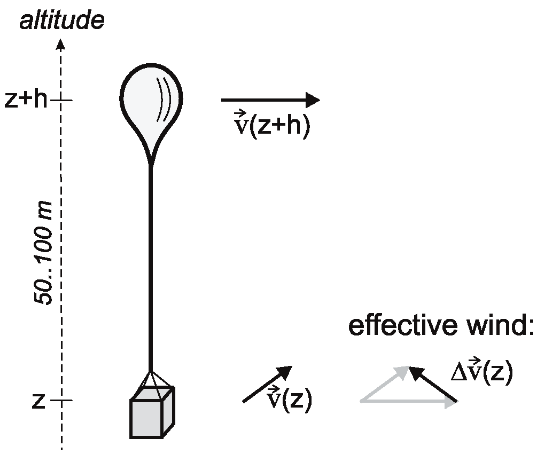

Figure 2. Schematic drawing of the principle of balloon borne wind turbulence soundings.

The distance between the gondola and the balloon is large in order to assure that we measure atmospheric turbulence and not turbulence caused by the balloon wake. If we neglect pendulum motions the payload is following the wind field in the height of the balloon. Therefore, for a wind constant with altitude the observed wind in the reference frame of the payload would be zero. Any altitude variation of the wind is observed by the CTA as the difference between the wind vectors in balloon height and in payload height. As a result we get an altitude profile of wind differences with very high vertical resolution.
The measurement principle of the CTA is based on the cooling effect caused by the atmospheric air flow passing the wire. The cooling effect is balanced by the electrical

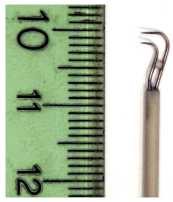

Figure 3. Sensor probe with the platinum-plated wire (Type 55P03, Dantec Dynamics) which has a diameter of 5 μm and a length of 1.25 mm. The wire is welded to the prongs.

current to the wire using a Wheatstone bridge. Thus the wire is held at a constant temperature (e.g. 245 °C in our case). The change in the current shows up as a voltage variation at the anemometer output and directly depends on the wind fluctuations. These data are sampled at a rate of 2000 Hz which refers to a vertical resolution of 2.5 mm assuming a balloon ascent rate of 5 m/s. The platinum-plated wire (Type 55P03, Dantec Dynamics) is 5 μm in diameter and 1.25 mm long (Fig. 3). The measurement axis of the anemometer is horizontal, to measure horizontal wind fluctuations. The data are saved on board and also transmitted to a ground antenna.

For the analysis of turbulence it is not necessary to derive absolute wind speeds from the CTA signal. Instead we make spectral analyses of the voltage signal to retrieve the spectral slope of the observed variation. Typically we analyse 4-10 s of data for a single voltage fluctuations spectrum. Within this period the density and temperature are sufficiently constant. Any remaining effects of temperature and density influences are eliminated during the detrending necessary for the spectral analysis. In the future we will derive absolute wind values by converting the measured voltage fluctuations to velocity fluctuations. Hence each CTA sensor has to be calibrated separately to obtain an individual calibration function. It is obvious that the CTA sensor has to be calibrated under conditions similar to the ambient conditions during the measurements. In our case an exact calibration for any possible combination of temperature, density, humidity and flow velocities occurring from ground to the middle stratosphere means an comprehensive task (for more details the reader is referred to [7]). However their small size and light weight make CTA sensors particularly suitable for balloon-borne measurements.
Additionally a radiosonde measures the atmospheric temperature, humidity and wind velocity with lower resolution.

3. OBSERVATION/RESULTS

Since December 2007 we successfully launched several balloons in Kühlungsborn (54°N, 12°E). In October 2008 the sensor has been flown as part of the BEXUS 6 balloon payload from Kiruna (67°N, 21°E). The BEXUS 6 balloon with a volume of 10000 m^3 was launched on 8

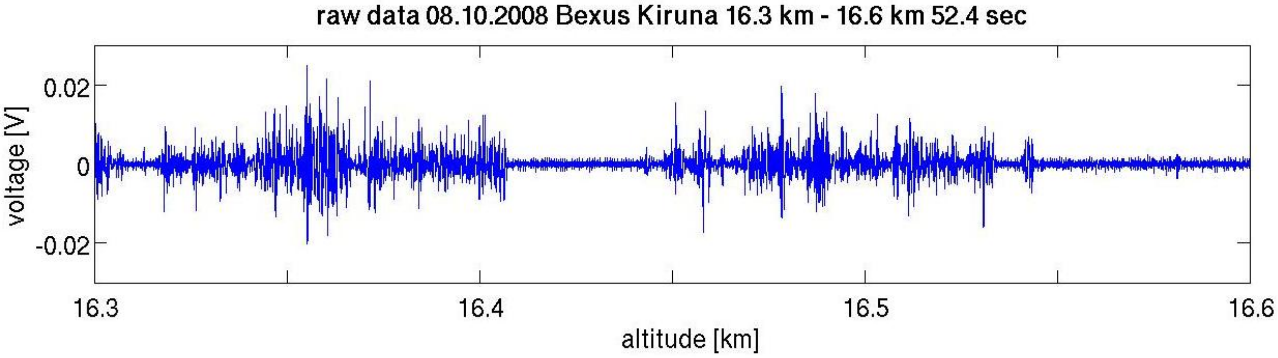

Figure 4. Time record of the measured voltage fluctuations during the BEXUS 6 flight on 8 October 2008. Thin turbulent layers with sharp dividing boundaries have been measured.

October 2008. Figure 4 shows an example of the voltage fluctuations obtained during the BEXUS 6 flight for the altitude region between 16.3 km and 16.6 km measured by the hot wire anemometer. We removed the spline trend from the signal to eliminate low frequency disturbing effects caused e.g. by the movement of the gondola. One can clearly distinguish layers of turbulence from regions were no disturbances are observed. This implies that the observed fluctuations are due to atmospheric velocity fluctuations and are not an instrumental artifact. The small remaining fluctuations in the non-turbulent region are due to instrumental noise. Barat ([2]) mentioned that the thin turbulent layers have often sharp dividing boundaries, which is confirmed by our measurements. This sharp boundaries can easily be seen in figure 4.

3.1. Spectral analysis of the BEXUS 6 timeseries

It is possible to obtain information about turbulence from the measured relative voltage fluctuation. In Figure 5 the Fourier spectrum of the turbulent region from 16345 m to 16365 m (see Fig. 4) is shown.

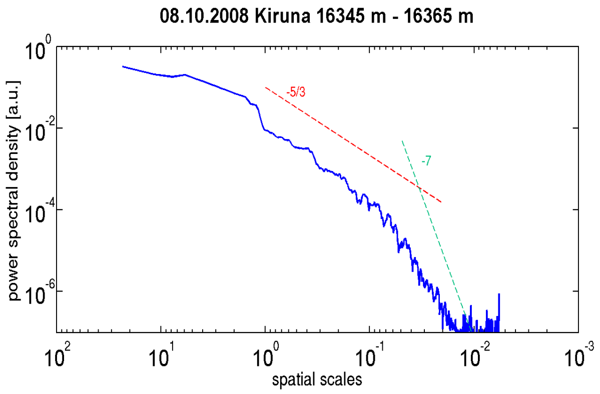

Figure 5. Calculated spectrum for a turbulent region during the BEXUS 6 launch. The theoretical expected behavior for a turbulent spectrum in the inertial and viscous subrange is observed.

The power spectral densities are plotted as a function of spatial scales. The spatial scales are derived from $L = \lambda = 2\pi/k = \nu/f$ (f=frequency, ν=balloon velocity). We observe a -5/3 slope and the transition to a -7 slope of our turbulence spectrum. It is known from theory that the spectrum of turbulence shows exactly this behavior in the inertial and the viscous subrange (see Fig. 1). As far as we know this is the first in-situ measurement of the turbulent spectrum down to the viscous subrange in the stratosphere. Within this spectrum it is also possible to see the transition to the noise level of our instrument at very small spatial scales. This demonstrates that our instrument has the required resolution to cover the viscous subrange of the turbulent spectrum. For comparison we plotted also the Fourier spectrum of the less turbulent region from 16582 m to 16600 m in Fig. 6.

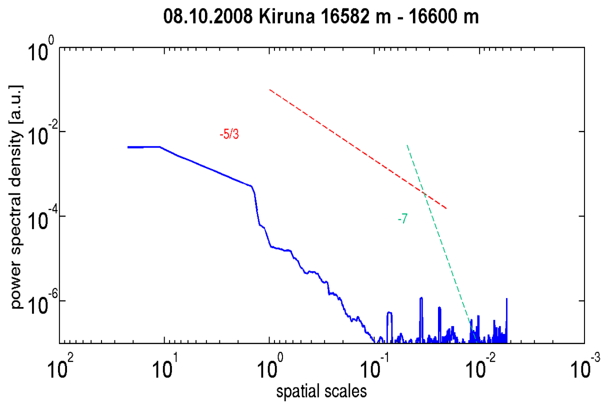

Figure 6. Calculated spectrum for a less turbulent region during the BEXUS 6 launch.

In contrast to the turbulent spectrum in Fig. 5 the slope in this spectrum does not follow the characteristical -5/3 and -7 behavior. Also the values of the power spectral densities are much lower than in the turbulent case. There are still some apparent irregularities within the noise level, which require further analysis to identify the sources. So far we found that these disturbances are quite monochromatic and could probably result from our electronics.

3.2. Altitude analysis of power spectral densities

Since we observe that stratospheric turbulence occurs within thin layers we investigated our measurements to get an overview on the altitudinal behavior of the power spectral densities. We divided the measured profile in 5 s sections over the whole altitude range and calculated the Fourier spectra. After that we averaged the power spectral density values for 30 to 50 Hz for each section. If there is turbulence the mean power spectral densities for this frequency region should be higher than without turbulence (see Fig. 5 and Fig. 6). Therefore it is possible to differentiate between turbulent and less turbulent regions and to identify thin turbulent layers. In Figure 7 the result of this analysis between 17.5 km and 21.5 km is shown.

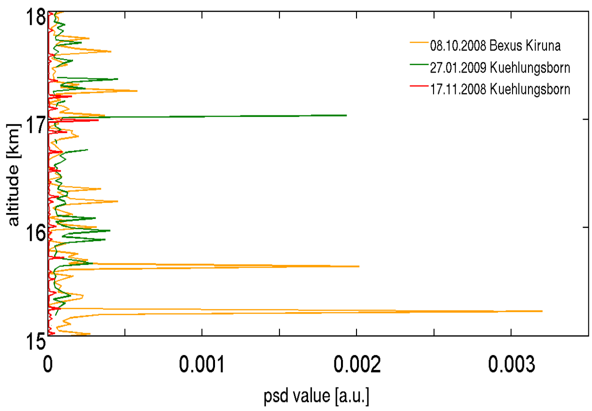

Figure 7. Mean power spectral density values of the frequency range between 30 and 50 Hz for the altitude region 17.5 to 21.5 km. Profiles for three flights in Kühlungsborn and Kiruna are shown. During two flights several thin turbulent layers have been detected.

In addition to the results of the BEXUS 6 flight we plotted here also the profiles obtained for flights from Kühlungsborn (17 November 2008, 27 January 2009). We observe many layers of turbulence during the BEXUS 6 flight and on 27 January 2009 over Kühlungsborn. The vertical extent of these layers range from few meters to some hundred meter, but normally do not exceed 500 m. The flight profile from the 17 November 2008 shows smaller power spectral densities for the selected frequency range than the other two profiles. This indicates the sporadic characteristic of stratospheric turbulence layers. Another aspect one should bear in mind is the difference between the topographic landscape in Kühlungsborn and Kiruna. Hence for both sites certainly exist different wave spectra. However, these measurements make it possible to study the different characteristics of turbulent layers and allow to deepen the knowledge of stratospheric turbulence.

3.3. Calculation of energy dissipation rate

From the measured spectra it is now possible to derive relevant geophysically parameters like the turbulent energy dissipation rate. A first approach to determine the energy dissipation rate is adapted from Lübken, 1992 and 1993 ([4],[8]). They have used the "spectral model method" to deduce turbulent parameters from rocket measurements of density fluctuations. Their routine includes the fitting of a theoretical spectral model to the measured turbulent spectrum by adjusting two free parameters. The theoretical model goes back to Heisenberg, 1948 ([9]) and exhibits the classical -5/3 power law in the inertial subrange and the -7 behavior in the viscous subrange. In this way it is possible to calculate the inner scale which characterizes the transition between the inertial and the viscous subrange and basically determines the turbulent energy dissipation rate. Further details of this procedure can be found in [4] and [8].
Figure 8 shows an example of the fitted theoretical spectrum to our measured spectrum. We calculated an inner scale of 3,6 cm and an energy dissipation rate of 4.4 mW.

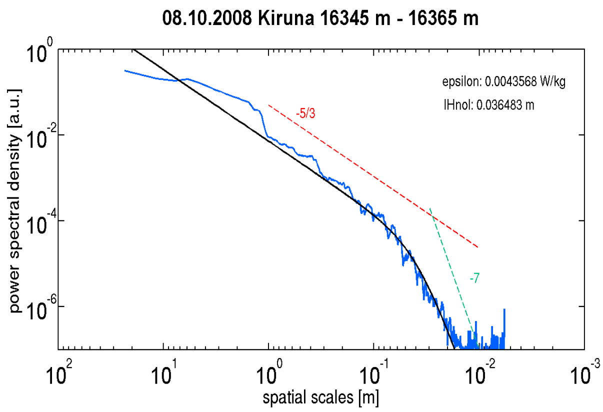

Figure 8. Power spectrum of the voltage fluctuations together with the model fit. Values for the inner scale and the energy dissipation rate are derived from the fit routine.

4. DISCUSSION, SUMMARY AND OUTLOOK

We have presented first results of measurements obtained by a new balloon-born instrument which measures the velocity fluctuations in the stratosphere with very high vertical resolution. The balloon payload has been launched successfully several times from Kühlungsborn, Germany, and Kiruna, Sweden. The instrument contains a constant temperature anemometer (CTA) and we can achieve a vertical resolution of 2.5 mm at an ascent rate of 5 m/s. We deduce information about the stratospheric turbulence from the unscaled voltage signal since our aim is to calculate e.g. the energy dissipation rate and these numbers depend on relative fluctuations and the particular length scale only. To derive absolute values the sensors have to

be calibrated for ambient conditions of density, temperature and humidity. Because there is very little knowledge from literature about CTA measurements at low densities we have started our own laboratory studies within a vacuum chamber. Due to the high measurement resolution it is possible to measure the turbulent spectrum in the stratosphere down to the viscous subrange. As far as we know this was not done before. The calculated spectra correspond to the theoretical expected behavior of turbulence in the inertial and viscous subrange. By fitting a spectral model to our measured spectra we determine the inner scale and therewith the energy dissipation rate. We also confirm the earlier observations from soundings in the 1980s which show thin turbulent layers with sharp dividing boundaries.
In future further balloon soundings shall be performed in Kühlungsborn. Additionally a second BEXUS launched of our CTA sensor together with a high-resolution temperature sensor is planned for October 2009. Thus it would be possible to compare wind and temperature fluctuations in the stratosphere.

ACKNOWLEDGMENTS

We thank SNSB (Swedish National Space Board) and DLR (German Aerospace Center) for the possibility to be part of the BEXUS 6 payload. We thank our colleague Torsten Köpnick (IAP) for his support in hardware development and Olle Persson (SSC), Olga Suminska and Dörte Petzsch for their support during the BEXUS launch campaign.

REFERENCES

[1] O. M. Phillips. The generation of clear-air turbulence by the degradation of internal waves In *Proceedings of the International Colloqium "Atmospheric turbulence and radio wave propagation"*, pages 130–138, Moscow, 1967.

[2] J. Barat. Some characteristics of clear-air turbulence in the middle stratosphere. *J. Atmos. Sci.*, 39:2553–2564, 1982.

[3] J. Barat, C. Cot, and C. Sidi. On the measurement of turbulence dissipation rate from rising balloons. *J. Atmos. Ocean. Techn.*, 1:270–275, 1984.

[4] F.-J. Lübken. On the extraction of turbulent parameters from atmospheric density fluctuations. *J. Geophys. Res.*, 97(D18):20385–20295, 1992.

[5] M. Rauthe, M. Gerding, and F.-J. Lübken. Seasonal changes in gravity wave activity measured by lidars at mid-latitudes. *Atmos. Chem. Phys.*, 8(22):6775–6787, 2008.

[6] D. E. Lilly, D. E. Waco, and S. I. Adelfang. Stratospheric mixing from high-altitude turbulence measurements. *J. Appl. Meteor.*, 13:488–493, 1974.

[7] M. Gerding, A. Theuerkauf, O. Suminska, T. Köpnick, and F.-J. Lübken. Balloon-borne hot wire anemometer for stratospheric turbulence soundings. *ESA SP-671*,..., 2009

[8] F.-J. Lübken, 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(D11):20369–20384, 1993.

[9] W. Heisenberg. Zur statistischen Theorie der Turbulenz. *Z. Phys.*, 124:628–657, 1948.