FINAL REPORT

DFG FO 226 / 11-1

Title

Direct measurements of turbulent fluxes in the near-surface environment at high latitudes applying the eddy-covariance method

The Arctic Turbulence Experiment 2006 (ARCTEX-2006) at Ny-Ålesund on Spitsbergen (Svalbard)

Authors

Johannes Lüers[1]
Jörg Bareiss[2]
Thomas Foken[1]

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[1] University of Bayreuth
Department of Micrometeorology
95440 Bayreuth, Germany

[2] University of Trier
Department of Environmental Meteorology
54286 Trier, Germany

1 General information

Final report of a **short application** for a research grant (travel expenses only)

1.1 Applicants

Johannes **Lüers,** Dr. rer. nat.
Scientific assistant
04.06.1966, German
Previous DFG applications: FO 226/11-1

Address (work)

University of Bayreuth
Department of Micrometeorology
D-95440 Bayreuth
Telephone: 0921 / 55 3502
Telefax: 0921 / 55 2366
E-Mail: johannes.lueers@uni-bayreuth.de

Address (private)

Nibelungenstr. 9
D-95444 Bayreuth
Telephone: 0170 / 1840303

Jörg **Bareiss,** Dr. rer. nat.
Scientific assistant
01.08.1966, German
Previous DFG application: BA 2060/02-1&2&3; FO 226/11-1

Address (work)

University of Trier
Faculty VI Geography/Geosciences
Department of Environmental Meteorology
D-54286 Trier
Telephone: 0651 / 201 4621
Telefax: 0651 / 201 3817
E-Mail: bareiss@uni-trier.de

Address (private)

Am Mühlenwäldchen 1
D-55566 Meddersheim
Telephone: 06751 / 96026

Thomas **Foken**, Prof. Dr. sc. nat.
University professor, head of department
01.06.1949, German
Previous DFG application: FO 226/02-1, 10-1, 11-1, 16-1; SPP-1167

Address (work)

University of Bayreuth
Department of Micrometeorology
D-95440 Bayreuth
Telephone: 0921 / 55 2293
Telefax: 0921 / 55 2366
E-Mail: thomas.foken@uni-bayreuth.de

Address (private)

Preuschwitzer Str. 69b
D-95445 Bayreuth
Telephone: 0921 / 7412098

1.2 Topic

Direct measurements of turbulent fluxes in the near-surface environment at high latitudes applying the eddy-covariance method – The Arctic Turbulence Experiment 2006 (ARCTEX-2006)

1.3 Code name

Arctic Turbulence Experiment 2006 (ARCTEX-2006)

1.4 Scientific discipline and field of work

Scientific discipline: Meteorology
Field of work: Boundary-layer meteorology, micrometeorology

1.5 Experiment location and duration

The total field campaign encompasses three weeks: Stay at the French-German Arctic Research Base in Ny-Ålesund (AWI/IPEV) on Spitsbergen (Svalbard) May 2, 2006 to May 20, 2006.

1.6 Application period

May 2006 to April 2007.

1.7 Publications regarding this project

International reviewed publications:

Lüers, J; **Bareiss**, J: The Arctic Turbulence Experiment ARCTEX-2006: Turbulent flux measurements on Svalbard using the eddy-covariance method, laser scintillometry and foot-print analyses. **Journal of Geophysical Research** (in preparation, submission scheduled early summer 2007)

Detailed Work Reports:

The three work reports will be available online at mid of May 2007 (http://www.bayceer.uni-bayreuth.de/mm/de/pub/5407/21697Arbeitsergebnisse.php)

Lüers, J; **Bareiss**, J; **Foken**, T (2007): Direct measurements of turbulent fluxes in the near surface environment at high latitudes applying the eddy-covariance method - The Arctic Turbulence Experiment 2006 at Ny-Ålesund on Spitsbergen (Svalbard) - PART 1: Technical documentation of the ARCTEX-2006 Experiment May, 2nd to May, 20th 2006. Work report University of Bayreuth, Dept of Micrometeorology, **30**, ISSN 1614-8916.

Lüers, J; **Bareiss**, J (2007): Direct measurements of turbulent fluxes in the near surface environment at high latitudes applying the eddy-covariance method - The Arctic Turbulence Experiment 2006 at Ny-Ålesund on Spitsbergen (Svalbard) - PART 2: Near surface measurements during the ARCTEX-2006 Experiment May, 2nd to May, 20th 2006. Work Report University of Bayreuth, Dept of Micrometeorology, **31**, ISSN 1614-8916.

Bareiss, J; **Lüers**, J (2007): Direct measurements of turbulent fluxes in the near surface environment at high latitudes applying the eddy-covariance method - The Arctic Turbulence Experiment 2006 at Ny-Ålesund on Spitsbergen (Svalbard) - PART 3: Aerological measurements during the ARCTEX-2006 Experiment May, 2nd to May, 20th 2006. Work Report University of Bayreuth, Dept of Micrometeorology, **32**, ISSN 1614-8916.

International congresses and meetings

Lüers, J; **Bareiss**, J; **Helbig**, A; **Olesch**, J; **Foken**, T (2007): Direct measurements of turbulent fluxes in the near surface environment at high latitudes applying the eddy-covariance method. The Arctic Turbulence Experiment 2006 at Ny-Ålesund on Spitsbergen (Svalbard) presented at the General Assembly April 2007 of the European Geosciences Union in Vienna (EGU2007) Session AS2.04 - Boundary Layers in High Latitudes: Observations and Modeling, EGU2007-A-02996.

2 Work report and results

2.1 Objectives and goals

Accurate quantification of turbulent fluxes between the surface and the atmospheric boundary layer in polar environments, characterized by frequent stable to very stable stratified conditions, is a fundamental problem in soil-snow-ice-vegetation-atmosphere interaction studies. The observed rapid climate warming in the Arctic requires improvements in the monitoring of energy and matter exchange; accomplished by setting up appropriate (adapted to polar conditions) observation sites to measure turbulent fluxes. To address these problems, it is essential to improve the databases with high-quality in-situ measurements of turbulent fluxes near the surface applying the Eddy-Covariance method.

The primary goals of the ARCTEX-campaign were:

1. continuous measurements of high-resolution (20 Hz) turbulent heat fluxes near the tundra surface using a ultra sonic anemometer (eddy-covariance method) and a ultraviolet krypton hygrometer,
2. continuous measurements of the turbulent sensible heat flux near the tundra surface using the laser scintillometry,
3. measurements of standard meteorological data sampled at 1s intervals using a meteorological gradient tower (6 m and 10 m) and aerological systems (Tethersonde, Radiosonde soundings),
4. pre- and post- processing of high-quality data sets of turbulent fluxes using state of the art flux data quality assessment techniques,
5. understanding of exchange processes and their parameterisation for neutral and stable conditions,
6. validation of commonly used sensible and latent heat flux parameterisations (aerodynamic approach, bulk and gradient method).

2.2 Experiment design

Arctic Turbulence Experiment 2006 (ARCTEX-2006) at Ny-Ålesund (Svalbard) May 2006,
Universities of Bayreuth and Trier, Germany

The map (Figure 1) of Ny-Ålesund (Svalbard) shows the measurement sites during the ARCTEX-2006 campaign. The permanent AWI/IPEV sites used for this study are the 10 m meteorological tower of the Alfred Wegener Institute for Polar- and Marine Research (MT1), the international standardized radiation measurements of the Baseline Surface Radiation Network (BSRN), the WMO 1004 radiosonde launch site (RS) and the temporary AWI tethered balloon launch sites TB1 and TB2. The temporary sites - build up by the Universities of Bayreuth and Trier - are the 6 m meteorological tower (MT2), the eddy-flux measurement complex with sonic anemometer (EF), and the Laser scintillometer pathway (SLS).

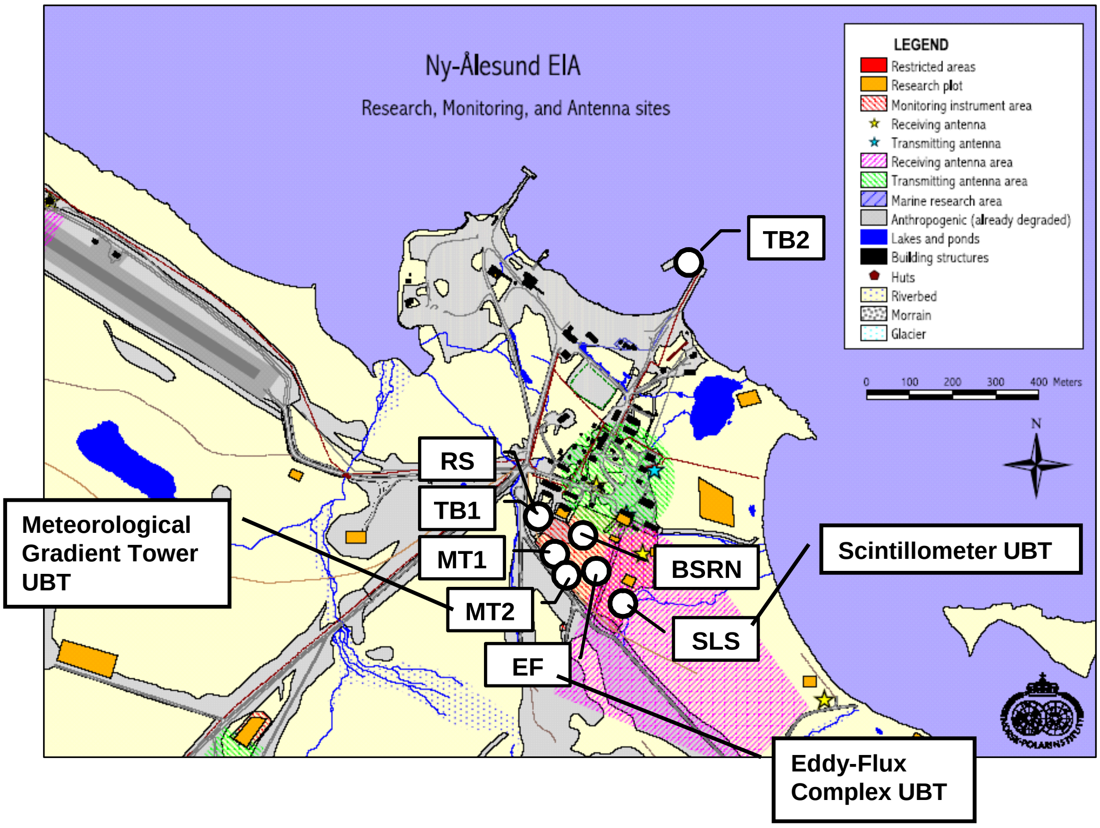


Figure 1: Map of Ny-Ålesund (Svalbard) showing the measurement sites during the ARCTEX-2006 campaign: MT1 (10 m meteorological tower of the Alfred Wegener Institute for Polar- and Marine Research), MT2 (6 m meteorological tower of the University of Bayreuth), EF (eddy-flux measurement complex), SLS (site for scintillometer measurements), BSRN (radiation measurements of the Baseline Surface Radiation Measurements), RS (radiosonde launch site), TB1 and TB2 (tethered balloon launch sites). The base map was kindly provided by the Norwegian Polar Institute.

2.3 Measurements

Table 1 lists the surface and weather conditions during the ARCTEX-2006 campaign. Noteworthy, is the extreme warm period until evening May 7 and the heavy snow-storm at night, May 7 to May 8.

Table 1: Surface and weather conditions during the ARCTEX-2006 campaign.

May 3 to May 5	wet melting snow over ice, larger snow free spots (bare soil, tundra), surface melt water, some rain fall and partly cloudy, Arctic Haze event, extremely warm, temp. range +3 °C to +8 °C
May 6 to May 8	storm and heavy snowfall, heavy snowdrift; overcast weather, extreme warm (+8 °C) until begin of 2nd storm May 7, 18 h CET and temp. drop of more than 16 K (–10 °C)
May 9 to May 11	fresh snow cover (predominantly sunny weather, temp. range –5 °C to –2 °C)
May 12 to May 14	ongoing snowdrift, snow cover depleting, at 13th pm temp. around zero Degree °C, (predominantly overcast or partly cloudy weather, temp. range –4 °C to 0 °C)
May 15 to May 16	ongoing snowdrift, some snow free spots, at ground thin ice layers (predominantly sunny or partly cloudy weather, temp. range –4 °C to –1 °C)
May 17 to May 19	melting snow over ice, some snow free spots (bare soil, tundra), light to moderate rain and/or snowfall (17th and 18th, temp. range –2 °C to +1 °C)

The installed instrumentation on the monitoring area south-east of Ny-Ålesund - maintained by the ARCTEX-Team - were:

(**EF**) Eddy-Flux measurement complex, Eddy-Covariance, (Univ. of Bayreuth):

- CSAT3, ultra sonic anemometer (Campbell Scientific, Inc., U.S.A.)
- KH20, ultraviolet krypton hygrometer (Campbell Scientific, Inc., U.S.A.)
- CR23X, data logging system (Campbell Scientific, Inc., U.S.A.)
- Control system (Mini-ITX)

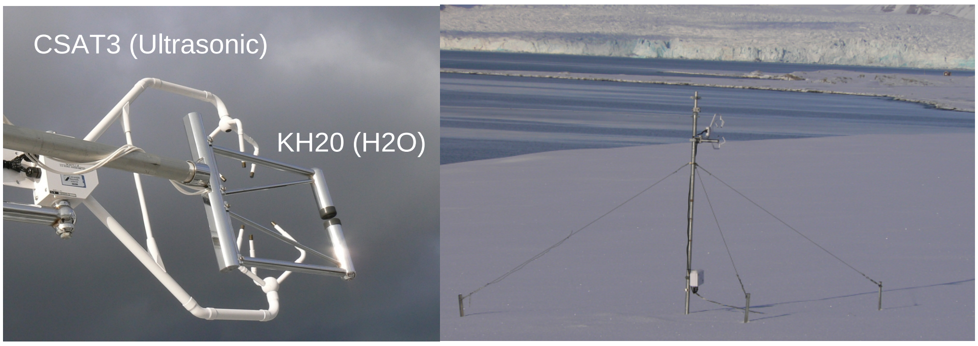
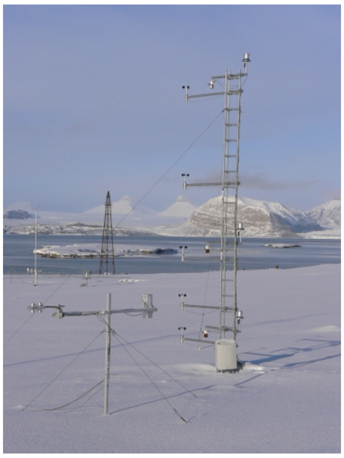


Figure 2: Eddy-Flux measurement complex (EF) of the Univ. of Bayreuth, monitoring area south-east of Ny-Ålesund (Svalbard), ARCTEX-2006 campaign.

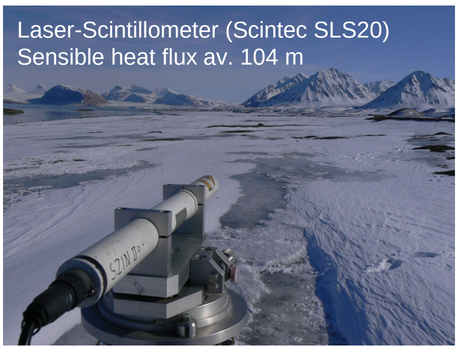
(**MT2**) Flux-gradient measurement complex, bulk / gradient methods, (Univ. of Bayreuth):



- Meteorological tower (6 m)
- Cup anemometers at 5 different heights above displacement height
- Electrically ventilated thermometers at 3 different heights above displacement height
- CNR1 net radiometer (Kipp & Zonen, Delft, Netherlands)
- KT 15.82D, infrared thermometer (Heitronics, Germany)
- Data logging system (Vaisala-logger)

Figure 3: Flux-gradient measurement complex, 6 m tall meteorological gradient-tower and radiation measurement (MT2) of the Univ. of Bayreuth, monitoring area south-east of Ny-Ålesund (Svalbard), ARCTEX-2006 campaign.

(**SLS**) Laser Scintillometer, Scintec SLS20, (Univ. of Bayreuth):



- Sensor path length 104 m
- Average sensor path height above ground level 1.5 m

Figure 4: Laser Scintillometer, Scintec SLS20 (SLS) of the Univ. of Bayreuth, monitoring area south-east of Ny-Ålesund (Svalbard), ARCTEX-2006 campaign.

Due to a malfunction of the Campbell CR23X data logger we were regrettably not able to run the KH20, ultraviolet krypton hygrometer to measure the water vapor turbulent fluctuations. Consequently, we were unable to obtain any latent heat fluxes directly during the ARCTEX-2006 campaign.

2.4 Flux data quality assessment and quality control

The turbulent fluxes were pre- and post-processed with the internationally standardized QA/QC software package TK2, developed by the Department of Micrometeorology, University of Bayreuth (Mauder and Foken, 2004). The software package TK2 is based on 15 years of experiences. It was developed to calculate turbulent fluxes automatically for several international micrometeorological experiments since 1989. TK2 is capable of performing all of the post processing of turbulence measurements producing quality assured turbulent fluxes for a station automatically in one single run. It includes all corrections and tests, which are state of science (i.e. detection of spikes, application of Planar Fit method for coordinate transformation, determination of the time delay between sensors) and a quality assessment. The latter following a procedure proposed by Foken and Wichura (1996) and further developed by Foken et al. (2004). Two quality tests were applied to the flux data. The Steady State test is designed to detect non steady state conditions, which are an assumption of the eddy covariance method. This test compares a 30-minute covariance with the arithmetic mean of the six 5-minute co-variances in this 30-minute interval. The agreement between both values is a measure of steady state conditions. The second test is based on the flux-variance similarity, which means that the ratio of the standard deviation of a turbulent parameter and its turbulent flux is nearly constant or a function, e.g. of the stability. These normalized standard deviations are called Integral Turbulence Characteristics (ITC). This test compares measured integral turbulence characteristics with modeled ones (Foken, 2004). The agreement between both values is a measure of well-developed turbulence. To check the sensible heat flux, models for normalized standard deviations of the vertical wind velocity *w* and sonic temperature *Ts* were applied.

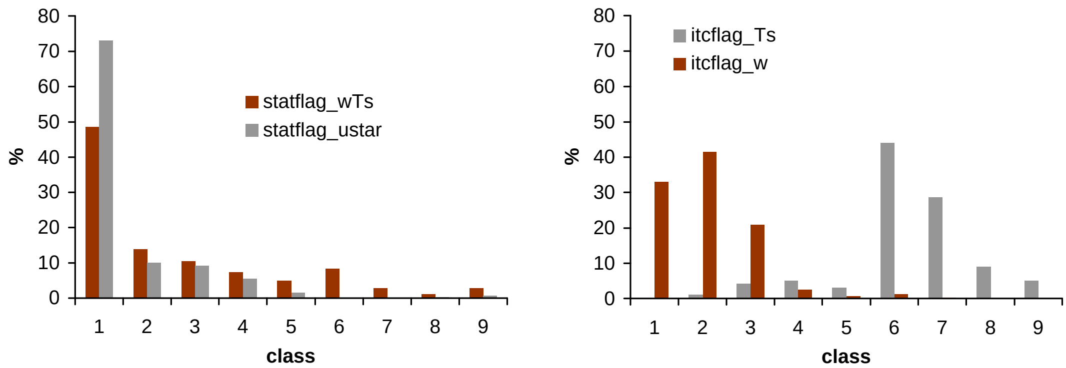


Figure 5: Left: Steady State test. Right: Integral Turbulence Characteristics test. Flux data obtained May 7 to May 19, 2006, monitoring area south-east of Ny-Ålesund (Svalbard), ARCTEX-2006 campaign. Vertical wind velocity (*w*), sonic temperature (*Ts*) and friction velocity *u** (ustar) and buoyancy fluxes (*wTs*).

The Steady State test (Figure 5 left) during ARCTEX shows high quality conditions (classes 1 to 3) for 92 % of all *u** and 73 % of all buoyancy fluxes (*wTs*). But as expected the ITC-test (Figure 5 right) especially regarding temperature results in more or less bad flags. This is mostly due to the marked intermittence pattern of the sensible heat flux typical for Polar Regions (longer periods without turbulence interrupted by rapid and acute turbulent conditions) and due to limitations regarding the relation of standard derivation and flux caused by neutral conditions (Thomas and Foken, 2002). Class 1 to 3 represent highest quality data and can be used for fundamental research, such as the development of parameterizations. The class 4 to 6 can be used for the calculation of monthly or annual sums for continuously running systems. Class 7 and 8 are used only for orientation. Data of class 9 should be excluded.

2.5 Results

These direct measurement data (Campbell CSAT3 sonic anemometer, KH20 krypton hygrometer, and Sintec SLS20 laser scintillometer) obtained during the first Arctic Turbulence Experiment (ARCTEX-2006) in May 2006 at the French-German Arctic Research Base in Ny-Ålesund (AWI/IPEV) on Spitsbergen (Svalbard) allowed a comparison with simulated results from simple flux gradient-parameterizations used today to force atmosphere-ocean-ice models. In addition, the results of this pilot study shows the problematic of direct measurements in a polar environment (e.g. snow drift through the sensor path ways) under rough weather conditions as well as they reveal that the misestimating of sensible heat fluxes can result from inaccurate measurements or calculation of the surface temperature and inaccurate treatment of the neutral and stable conditions (e.g. intermittency, gravity waves) in the bulk parameterization.

The comparison between measured - sonic-anemometer (Eddy-Covariance, *Ecv*) and a Laser-scintillometer (*SLS*) - and modeled sensible heat flux using the approach of Jouko Launiainen & Bin Cheng, 1995 (*Turbflx*) proves overall a relatively good agreement but significant discrepancies occur e.g. at heavy snow storm events (night of May 7 to May 8 until 6 o'clock) like shown in Figure 6 resulting in misleading heat fluxes determined by the sonic-anemometer (*Ecv*) due to too heavy snow-drift through the sensor-pathways.

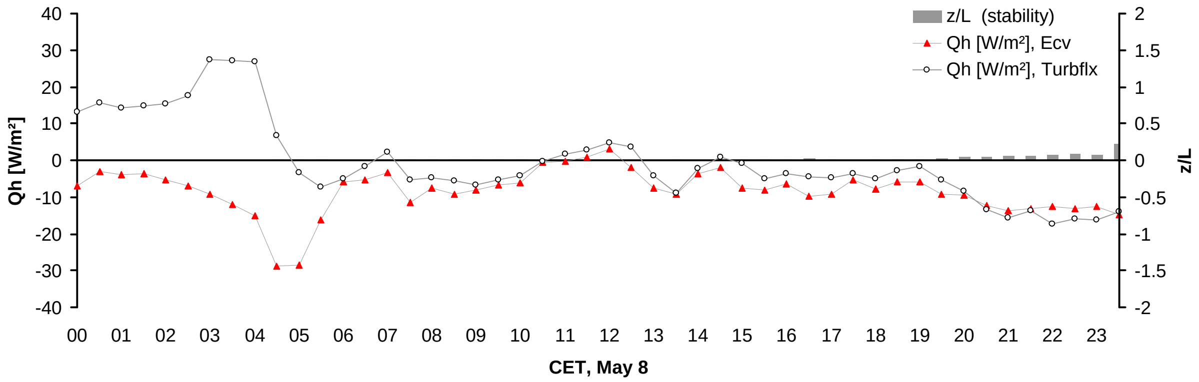


Figure 6: Comparison between measured - Campbell-CSAT3 sonic-anemometer (2.25 m above snow cover, Eddy-Covariance, *Ecv*) - and modeled sensible heat flux (*Qh*) using the approach of Jouko Launiainen & Bin Cheng, 1995, modified by Lüers and Bareiss (*Turbflx*: calculation of the bulk transfer coefficients using the Obukhov stability parameter *z/L* and a set of universal functions in respect to different stability conditions). Ny-Ålesund (Svalbard), ARCTEX-2006 campaign, May 08, 2006.

The both above scatter plots of Figure 7 show this snow-drift effect by comparing measurement (*Ecv*) and model (*Turbflx*) but the right one without the snowstorm period May 6 to May 8 resulting in a much better correlation. The below scatter plots show the direct relations between sonic-anemometer and scintillometer measurements and a typical underestimation of the fluxes determined by the anemometer.

The same effect occurs when using model results (*Turbflx*) instead of values measured by the sonic-anemometer.

Further comparisons using the measurements of our micrometeorological gradient tower and a set of different parameterizations of flux gradient approaches like Louis (1979), Ebert and Curry (1993), Handorf et al. (1999) or Zilitinkevich et al. (2002) are in work and will be published 2007.

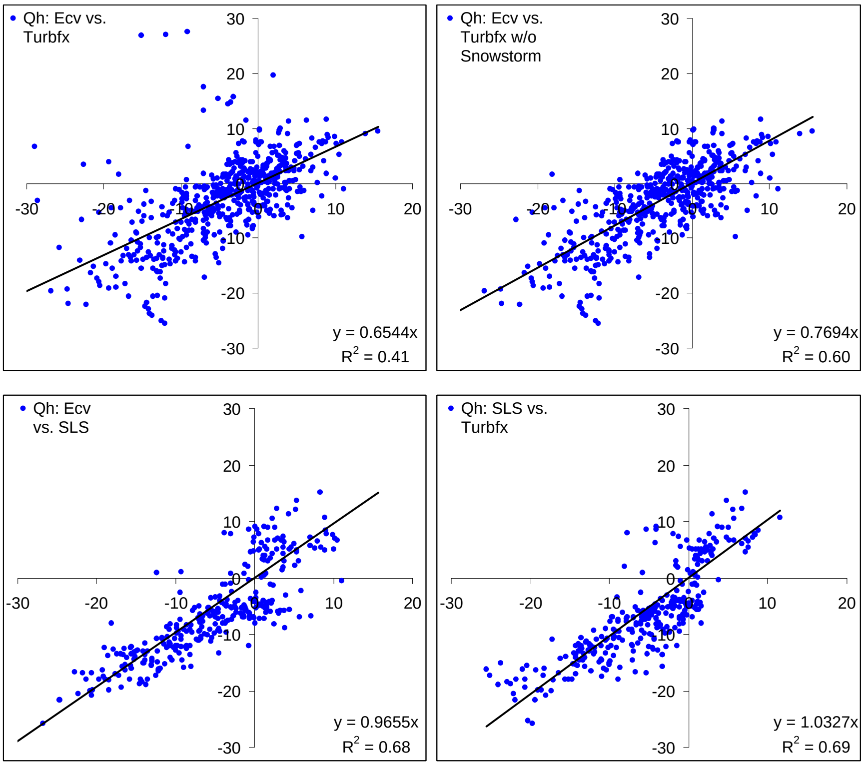


Figure 7: Scatter plots: Comparison between measured sonic-anemometer (*Ecv*) and Laser-scintillometer (*SLS*) and modeled (*Turbflx*) sensible heat flux (*Qh*). Flux data Ny-Ålesund (Svalbard), ARCTEX-2006 campaign, May 05 to May 19, 2006.

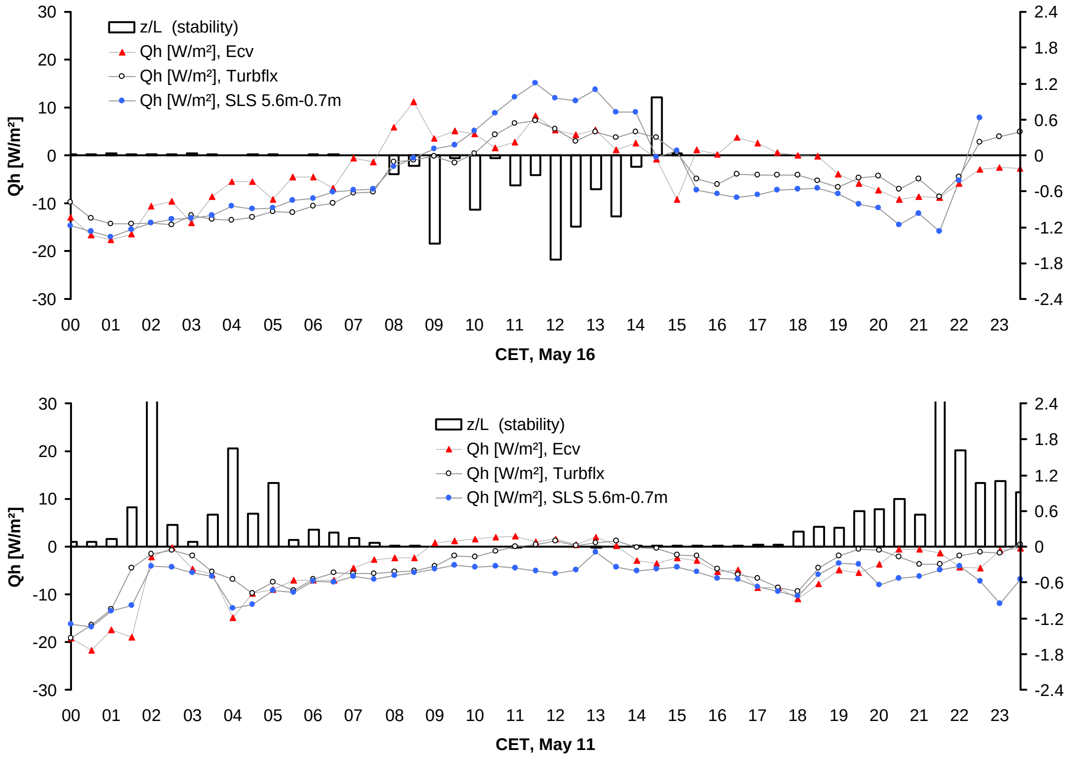


Figure 8: Comparison between measured - Campbell-CSAT3 sonic-anemometer (2.25 m above snow cover, Eddy-Covariance, *Ecv*) and a Scintec SLS20 Laser-scintillometer (*SLS*, 104 m pathway) - and modeled sensible heat flux (*Qh*) using the approach of Jouko Launiainen & Bin Cheng, 1995, modified by Lüers and Bareiss (*Turbflx*: calculation of the bulk transfer coefficients using the Obukhov stability parameter *z/L* and a set of universal functions in respect to different stability conditions). Ny-Ålesund (Svalbard), ARCTEX-2006 campaign, May 11 and May 16, 2006.

In Figure 8 both days show two typical patterns under polar day conditions (24 h sunshine). Neutral conditions at “day time” and stability at “night time” (May 11) and vice versa weak turbulent exchange around noon (intermittence) and neutral conditions during low sun positions (May 16). The latter seems matchable to known diurnal pattern observed in the mid-latitudes like Central Europe (inversion at night-times and well developed turbulence at daylight). But as the ITC-test (Figure 5 right) proves the turbulence characteristics regarding the temperature doesn’t match very well. Reasons are strong intermitted pattern of the turbulent temperature fluctuation, advection or even short periods of free convection around midday. Such an exemplary pattern is shown in Figure 9 and Figure 10, predominantly occurring during the transition period between winter and spring under typical polar atmospheric stratification conditions of the near surface boundary layer. During few minutes around noon melting conditions and a more or less developed turbulent mixing occurs.

The duration of such an intermitted mixing period of course depends on the surface conditions (fully, partly snow covered, or snow free) as well as the weather conditions during the warming period of the Arctic spring season.

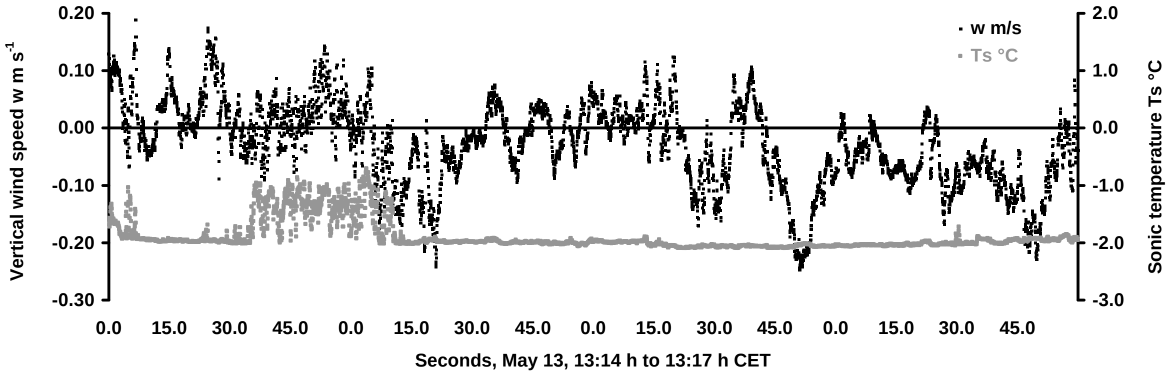


Figure 9: High frequency (20 Hz) raw data sensible heat flux measurements of the eddy-flux complex of the Univ. of Bayreuth (vertical wind velocity *w* and sonic temperature *Ts*), Ny-Ålesund (Svalbard), ARCTEX-2006 campaign, May 13, 13:14 h to 13:17 h CET, 2006: Typical intermittent pattern of *Ts* at noon.

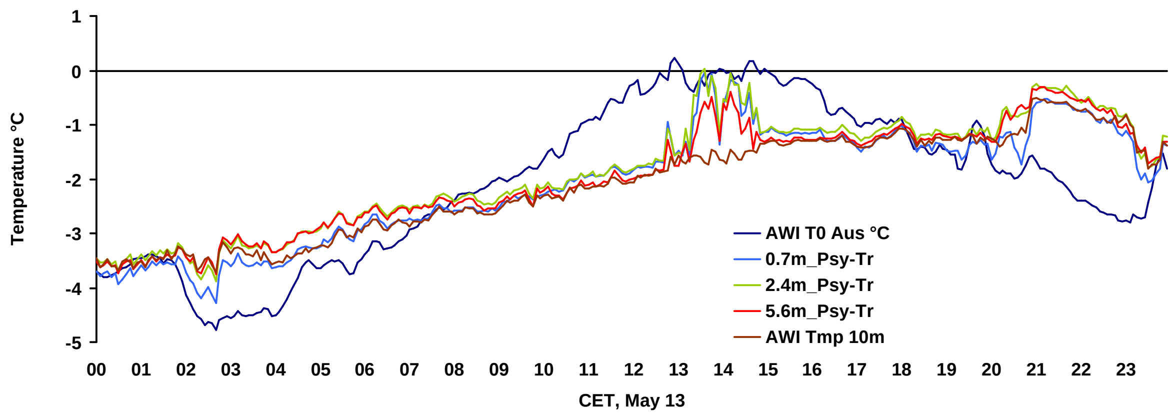


Figure 10: Vertical temperature profile same day as Figure 9 (May 13), measured at the micrometeorological tower of the University of Bayreuth. (*AWI T0 Aus* = surface temperature, snow cover, derived from measurements of the outgoing long wave radiation BSRN-Station Ny-Ålesund; *Psy-Tr* = ventilated air temperature different heights, Univ. Bayreuth, *AWI Tmp* = air temperature at 10 m height, AWI).

This intermittency of the turbulent temperature and water vapor fluctuation results to significant errors by calculating the regarding sensible and latent heat fluxes if only using the standard eddy-covariance method implemented in most software-packages like our own TK2-routins.

Maybe a more accurate way is the application of the conditional sampling or conditional average method (Thomas and Foken, 2007; Antonia, 1981) - meanly related to coherent structures - to detect and extract quantitative information about the flux contribution of this short - but unlike the coherent structures - more or less unstructured mixing events.

Another problem caused by the predominantly neutral or stable atmospheric stratification occurs, dealing with the Laser-scintillometer technique. To decide if the heat flux direction is positive (unstable conditions) or negative (stable conditions), the use of the Obukhov stability parameter *z/L* obtained by the sonic-anemometer is in our case not very helpful due to the indifferent situation most of the time. Taking into account the average scintillometer Laser-beam height above ground of 1.5 m, the use of the temperature gradient between the measurement heights of 2.4 m and 0.7 m above ground obtained by our meteorological gradient tower was our first assumption. But further analysis shows that the use of the temperature difference between 5.6 m and 0.7 m yields to the best fit.

During the ARCTEX-2006 campaign additional aerological soundings (Tethersonde and Radiosonde observations, Table 2 and Table 3) were performed and are available for analysis of the vertical structure and dynamics of the boundary layer and polar troposphere to help to find appropriate flux parameterizations.

Table 2: Radiosonde start times at the Ny-Ålesund station (79° N, Svalbard, Kongsfjorden) during the ARCTEX-2006 campaign.

Date	Time (UTC)
01 May to 09 May 2006	1100 UTC
10 May 2006	1200 UTC to 2300 UTC
11 May 2006	0000 UTC to 1700 UTC
12 May to 20 May 2006	1100 UTC

Table 3: Tethersonde start times at the Ny-Ålesund station (79° N, Svalbard, Kongsfjorden) during the ARCTEX-2006 campaign.

Date	Time (CEST)	Location	Maximum altitude
03 May 2006	1500 to 2300	Observatory	1200m
09 May to 10 May 2006	1400 to 0100	Observatory	1200 m
10 May 2006	0200 to 2200	Observatory	700 m
16 May 2006	1400 to 1800	Harbor	330 m

To understand the lower atmospheric circulation pattern around the Kongsfjord the two examples shown in Figure 11 represents first a typical cyclone passage (Figure 11 above) moving moist (and warm) air masses form southern directions to Spitsbergen connected with a heavy snowstorm event (up to 30 m s^{-1}) shortly before passage of the cold front resulting in a relatively high boundary layer up to 3000 m. And second (Figure 11 below) a typical redirection of northern winds (clear and dry air) into the main wind direction south-east at ground level canalized alongside the shoreline of the Kongsfjord connected with the usual height of the boundary layer in May around 1000 m.

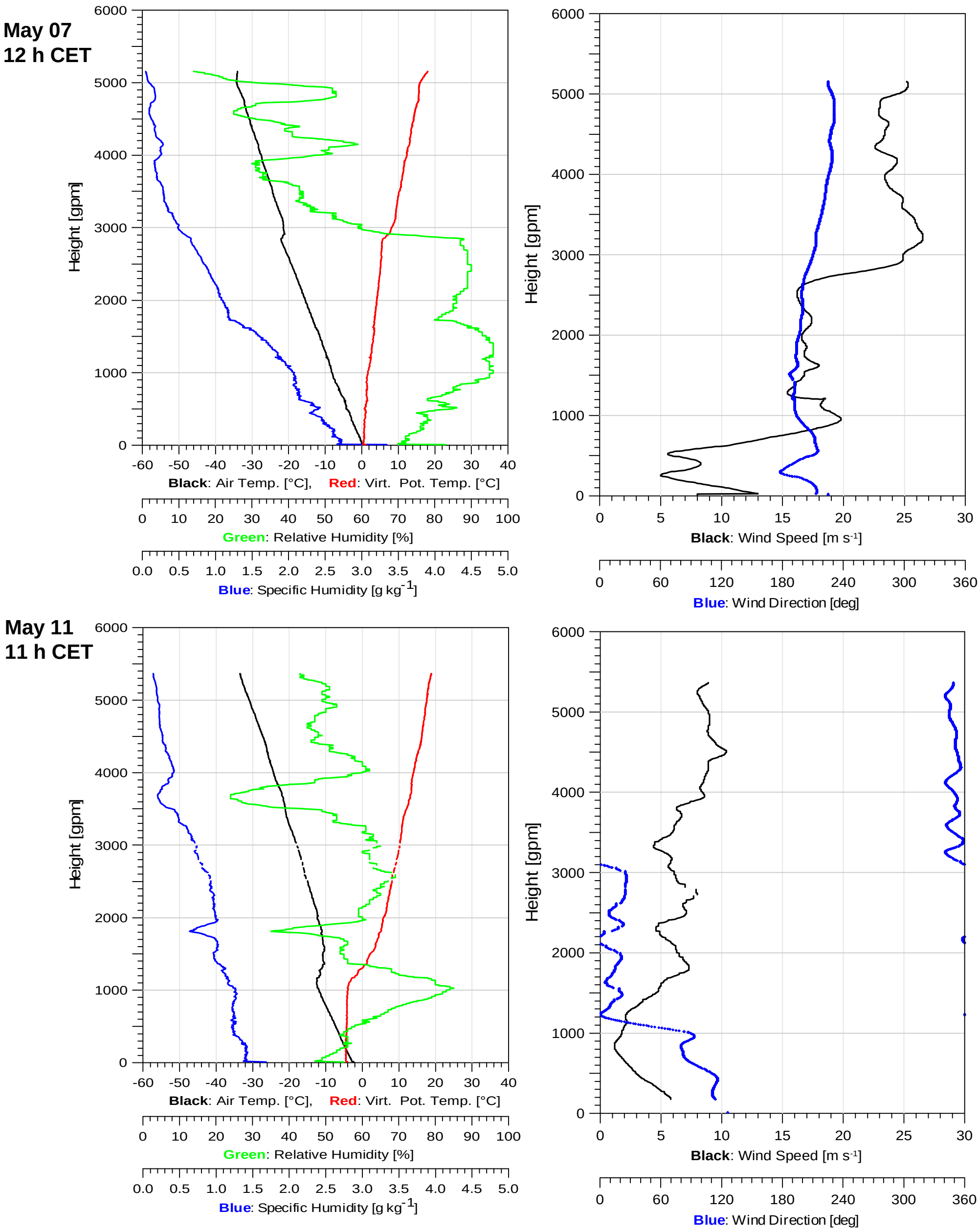


Figure 11: May 7, 11:48 h CET (above) and May 11, 11:01 h CET (below), 2006, radiosonde observation at Ny-Ålesund, Svalbard (WMO 1004) operated by the Alfred Wegener Institute for Polar and Marine Research. Radiosonde type RS90-AG, Vaisala, inc. GPS-based wind receiving options. Vertical profile of the polar troposphere during a heavy snowstorm event (above) and a typical redirection of winds alongside the shoreline of the Kongsfjord (below).

A closer look to the dynamics of the boundary layer offers the aerological data obtained by the tethered balloon system described by Figure 12. The gradually stronger gradient of the potential temperature profile during the afternoon until midnight describes the transition from a more neutral to a strong stable stratification in line with our near surface eddy flux measurements at a similar situation at May 11 shown in the above plot of Figure 8.

In accordance, the vertical profiles of the humidity proves a more or less better mixing around afternoon until 6 o'clock pm and a sudden stabilization afterwards and the drop down of the boundary layer resulting in an air mass separation below the inversion (entrainment) layer (moister air) and above (drier air).

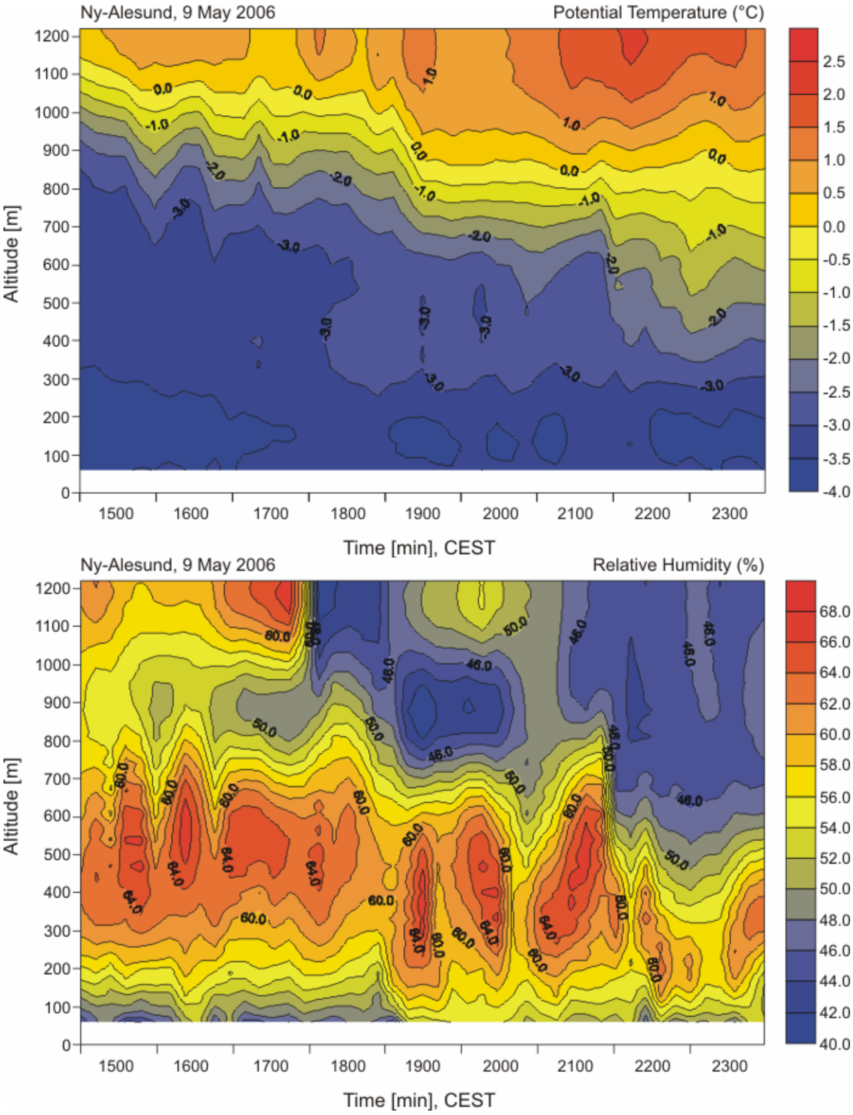


Figure 12: Hovmoeller plots (time/height) of potential temperature (above) and relative humidity (below) measured by six Vaisala tethersondes (TSS111) connected to a tethered balloon system used as a tower to measure atmospheric conditions at 6 levels (up to 1200 m) simultaneously, Ny-Ålesund (Svalbard), ARCTEX-2006 campaign, May 09, 15:00 to 23:59 CEST, 2006.

2.6 Cited literature

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2.7 Cooperation with other scientists at the Ny-Ålesund research facilities

a) Base personnel

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b) Vertical structure of ABL

Dr. M. Maturilli, Anne Theuerkauf (Tethersonde observations) and Jürgen Graeser (Radiosonde), all of them: AWI.

c) Surface radiation data (BSRN) and meteorological date

Dr. Andreas Herber (AWI) and his team.

2.8 Additional cooperation's

Close and long time cooperation with different Departments of the Alfred Wegener Institute for Polar and Marine Research in Bremerhaven (Dr. Christian Haas) regarding sea ice and fast ice and Potsdam (Prof. Dr. Klaus Dethloff, Dr. Annette Rinke) regarding regional atmospheric modeling; Cooperation with Dr. Veniamin Perov, Swedish Meteorological and Hydrological Institute (SMHI), Norrköping, regarding the HIRLAM project (development and maintenance of a numerical short-range weather forecasting system for operational use); Long time cooperation with Prof. Dr. H. Eicken (Geophysical Institute of the University of Alaska, Fairbanks, U.S.A.) and with Dr. S. Gerland vom Norsk (Polar Institut, Tromsø, Norway).

Signatures

Dr. Johannes Lüers
(University of Bayreuth)

Dr. Jörg Bareiss
(University of Trier)

Prof. Dr. Thomas Foken
(University of Bayreuth)