4.7 OBSERVATION OF INTERMITTENT TURBULENCE OVER ARCTIC SEA-ICE

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1. INTRODUCTION

The stable boundary layer (SBL) is less understood compared to the convective boundary layer (CBL) (Mahrt 1999). This is partly due to less available measured data in the SBL. Even less data of long-term measurement is available for the polar regions. Numerical models have difficulties to simulate the climate in the Arctic area. Sea ice is almost permanently present which is unique for the Arctic environment. In mid-latitude areas the diurnal cycle provides a big contribution to the structure of the atmospheric boundary layer (ABL). In the Arctic this diurnal cycle is weak or not present at all.

During Arctic winter the ABL is long-term stably stratified due to no incoming solar radiation and snow covering the warmer ocean. Therefore clouds have more impact on the radiation balance when longwave radiation is reflected to the surface and contribute to warming of the surface. During Arctic summer, melting of ice controls the near surface temperature and results in a larger latent heating near the surface. Energy input from radiation is used to melt ice and snow instead of heating the surface. Energy is lost through freezing of water instead of cooling the surface (Tjernström *et al.* 2004). These processes are specific for Arctic environment and have to be considered in climate models.

Additionally, a lot of elements of the polar SBL (PSBL) are poorly understood like katabatic flow, internal gravity waves, and low level jets (LLJ) (Heinemann 2002; Chimonas 2002; Rees *et al.* 2000). All these processes influence the turbulence in the PSBL. Intermittent turbulence is often observed in the SBL over land (Coulter and Doran 2002; Sun *et al.* 2002; van de Wiel *et al.* 2002) but the origin is still not well understood. For the polar PSBL several studies measured and analysed small scale turbulence (Drüe and Heinemann 2002; Cassano *et al.* 2001; Heinemann 2002; Tjernström *et al.* 2004) but seldom intermittent turbulence was observed. This research focused on the presence of intermittent turbulence in the PSBL and the possible influence of a LLJ.

Three campaigns with the research vessel Polarstern were used to analyse the characteristics of small scale turbulence over sea ice. In total ten flights performed during the ARK-XI (Sept-Oct 1995, East Greenland, Fram Strait), ARK-XII (Jul-Sept 1996, Kara, Laptew, E-Siberian Sea) and ARK-XIX (Mar-Apr 2003, Fram Strait) campaigns were selected for analysing the PSBL.

2. MEASUREMENT SYSTEM AND OBSERVATIONS

In-situ measurements of small scale turbulent fluctuations of wind, temperature, humidity, and turbulent fluxes were made using the Helipod. The Helipod is a 5 meter long probe, carried by a helicopter on a 15 m rope. Measurements are stored at 100 Hz of the 3-dimensional wind vector. Humidity and the air temperature is stored at 20-100 Hz and the surface temperature at 10 Hz. It also records the groundspeed, height, its position, orientation, and attitude by inertial and GPS systems (Bange and Roth 1999; Bange *et al.* 2002).

From the available flight data a few days were selected to analyse. Chosen were the days where flights are made over sea ice without open water. Open leads and polynjas have strong effect on the stratification and can produce large positive sensible heat fluxes (Hartmann *et al.* 2003).

At a specific flight several horizontal legs and a few vertical profiles were flown. Analysing the vertical profiles gave information about the evolution of temperature, humidity, windspeed and wind direction with height (stratification, presence of LLJ). From the horizontal flight legs the turbulent fluxes and the several (co)variances were calculated. Several legs featured intermittent turbulence. Distinguished are these parts of short bursts of energy and continuous weak turbulence which were analysed separately.

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3. CHARACTERISTICS OF THE POLAR BOUNDARY LAYER

The PSBL has some specific characteristics compared to the SBL above land. Temperature and humidity have no diurnal cycle due to the influence of melting ice and snow. The observed temperature gradients near the surface can be related to this process. Temperature gradients at higher altitudes are more likely determined by turbulent eddies. The specific humidity decreased in most cases over the capping inversion. For two analysed cases, the specific humidity increased over the capping inversion. This is unique for the PSBL and indicates that the entrainment zone is a source for boundary-layer moisture. This results also in a presence of high relative humidity in the Arctic atmosphere. Open water between the ice packs can also be a source of continuous supply of moist to the ABL through evaporation. The warm, moist air advection from the ocean over ice results in local mixing and a strong capping inversion appears. This results in a near-neutral or weakly stable surface layer.

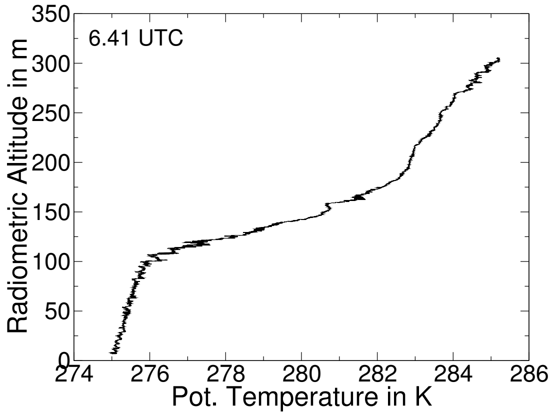

Fig. 1: *Vertical profile of the potential temperature, 30 July, 1996*

Frequently a LLJ is detected in the PSBL. The windspeed is mostly weak and increases aloft to a maximum just below the PSBL top. Almost all vertical profiles (Fig. 1 and 2) analysed from the Polarstern campaigns had the following characteristic ABL structure: Over the first 80-150 m a near-neutral stratification, followed by a strong temperature inversion accompanied by a weak LLJ with a maximum of 6-15 m/s. The profiles which conform to this structure were taken in summer Arctic (July and August) and showed a surface temperature around zero. Two other flight days showed again the same stratified structure

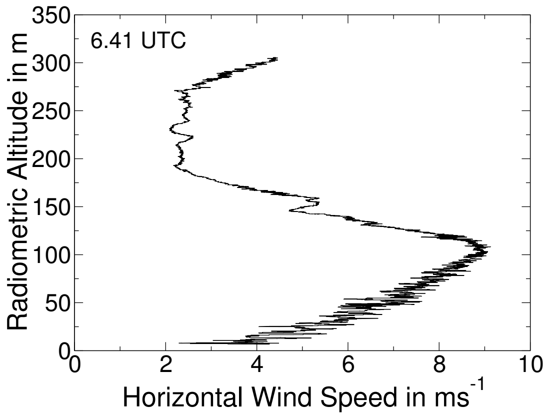

Fig. 2: *Vertical profile of the windspeed, 30 July, 1996*

with a capping inversion at 200 and 350 meter height (respectively taken at 5 Oct.,1995 and 24 March, 2003). Especially the flight at March 24, showed a low surface temperature (-15 to -20^{o} C) and due to less incoming solar radiation a higher SBL was established. The last analysed day showed a complete different structure. At 27 August, 1996, the ABL was stably stratified till 250 meter. At 250 meter a strong LLJ appeared with a windspeed maximum of 22 m/s.

4. LOCAL SCALING

For the unstable boundary layer, turbulence variables are scaled as a function of the BL height (Deardorff 1974). Under stable conditions the vertical motion is restricted and the turbulent eddies cannot extend over the whole BL. The use of the BL height as a scaling factor is not appropriate for stable conditions (Nieuwstadt 1984). Local similarity theory can be considered as an extension of the Monin-Obukhov (M-O) similarity theory above the surface. The local similarity scales are defined analogous to the M-O scales, but depend on local turbulence quantities at the measurement height z instead of surface values. In this section is looked at the possibility to express the PSBL data in terms of the parameter z/Λ, where Λ is the local Obukhov length

$$\Lambda = -\frac{u_L^3}{\kappa(g/T)\langle w'\theta'\rangle} \,. \tag{1}$$

In (1) $u_L = [\langle w'u'\rangle^2 + \langle w'v'\rangle^2]^{1/4}$ is the local friction velocity, κ is the von Kármán constant taken equal to 0.4, g/T is the buoyancy parameter, and $\langle w'\theta'\rangle$ is the vertical sensible heat flux divided by the air density ρ and the heat capacity c_p. The local Obukhov length is proportional to the height were buoyancy first dominates over mechanical production of shear. A positive Λ indicates a stable atmosphere. When Λ is small, z/Λ becomes large and indicates a very stable atmosphere where mechanical turbulence is suppressed by buoyancy and the flow becomes laminair.

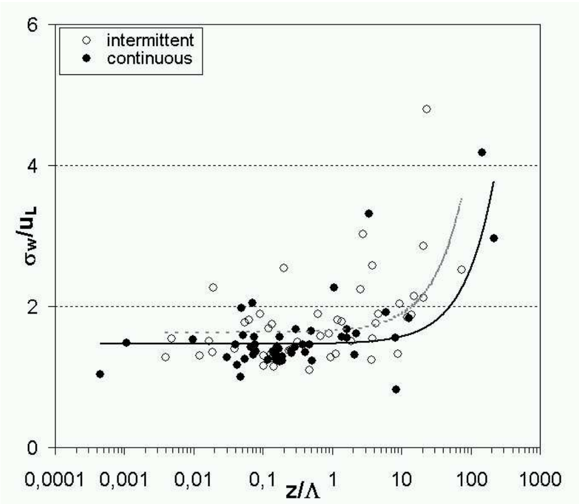

Fig. 3: *Standard deviation of the vertical wind velocity normalised with local friction velocity*

Assumed is that the small scale turbulence in the PSBL can be described by dimensionless groups of the variances and covariances. The standard deviation of the vertical wind velocity (σ_w) normalised with the local velocity scale (u_L) is shown in Fig. 3 as a function of z/Λ. For values of z/Λ < 5, σ_w/u_L is reasonable constant at 1.5 and therefore independent of z/Λ. For higher stabilities the σ_w/u_L increases and is no longer z-less. This is in agreement with other studies (Brooks *et al.* 2003; Pahlow *et al.* 2001; Spieß *et al.* 2004).These higher stabilities are only found in the upper BL, above 120 meters. The normalised variances of the horizontal velocities show more scatter but also a constant value is found for z/Λ < 5 (Fig. 4 and 5). The σ_u/u_L is constant at 3.0 and σ_v/u_L is constant at 3.2.

In contrary, the standard deviation of the temperature, normalised with the local temperature scale (σ_θ/θ_L), shows a constant value for z/Λ > 0.05 (Fig. 6). Under very stable conditions, σ_θ/θ_L becomes independent of height.

In Fig. 3 to 5 the data points are distinguished by intermittent and continuous turbulent parts. The solid line represents the linear trend through the continuous turbulence data points. The dotted grey line is a linear fit through the intermittent turbulence data points. For higher stabilities, where the standard deviations of wind are no longer z-less, the intermittent turbulence data points show a quicker increase. This can be due to the small number of data points at higher stability or there is difference between the behaviour of the intermittent and continuous flow. The original local scaling theory (Nieuwstadt 1984) considered some simplifications of the stable conditions. Several terms are neglected: horizontal advection terms (assuming horizontal homogeneity), the local time change and the Coriolis terms (these time scales are much larger then the turbulence time scale) and the transport terms (assuming that turbulent transport is small under stable conditions). While local scaling is not valid for higher stabilities, at least one of these assumptions is incorrect (Brooks *et al.* 2003).

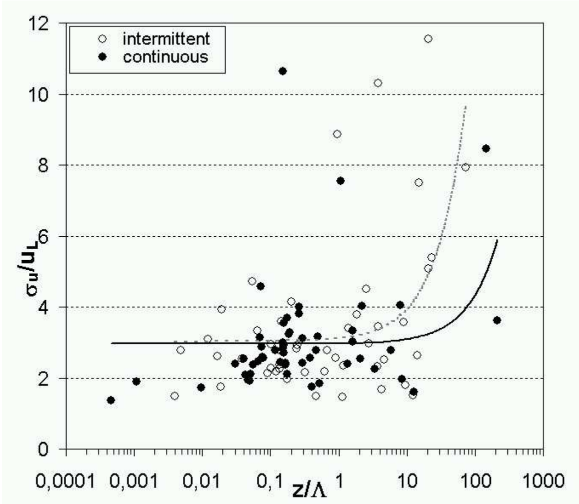

Fig. 4: *Standard deviation of the horizontal u-wind velocity normalised with local friction velocity*

5. INTERMITTENT TURBULENCE

Intermittent turbulence is characterised by short bursts of energy intervened with periods of weak turbulence. In the PSBL on several flights, intermittent turbulence was observed. The processes how intermittent turbulence is generated and under what conditions are not clear (Mahrt 1999). Several studies demonstrate that the NBL is strongly affected by mesoscale atmospheric disturbances which also influences the intermittency dynamics (Coulter and Doran 2002; van de Wiel *et al.* 2002; Poulos and Burns 2003).

To find the origin of the observed intermittent tur-

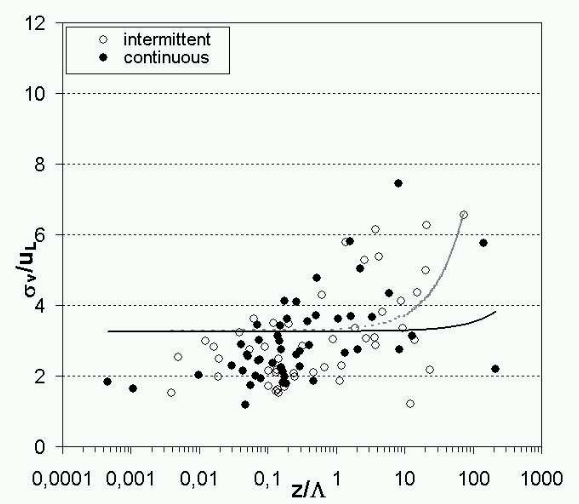

Fig. 5: *Standard deviation of the horizontal v-wind velocity normalised with local friction velocity*

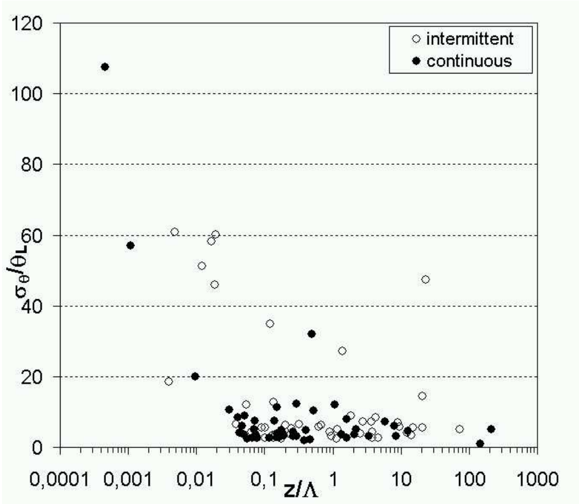

Fig. 6: *Temperature standard deviation normalised with local temperature scale*

bulence in the PSBL, first the influence of a present LLJ is analysed. The role of a LLJ and the shear layer below the jet in generating downward turbulent fluxes in the NBL was analysed in a few studies (Banta *et al.* 2002; Sun *et al.* 2003). They found that the wind maximum of a LLJ is most likely responsible for the production of shear and the generation of turbulence between the LLJ and the surface.

To analyse the occurrence of intermittent turbulence found in the PSBL, first a global index of the horizontal flights was made. Using the vertical profiles of the PSBL (Helipod data) the horizontal flights were classified with stratification strength ($\Delta\theta/\Delta z$), change of horizontal windspeed with height ($\Delta u_{hor}/\Delta z$) and the distance relative to the LLJ (z/z_{LLJ}). Fig. 7 shows that near the LLJ (z/z_{LLJ} between 0.7 and 1.3) most flights appear to have turbulence with an intermittent character. But due to less data points at LLJ level, no hard conclusion can be made. The blue dots represent the legs flown at 27 August, 1996 in a stable stratification with a strong LLJ of 22 m/s. Close to the surface the turbulence was continuous (blue dots), at 50 meter weakly intermittent (light blue dots) and just below the LLJ stronger intermittent (open blue dots). Above the LLJ, where the stratification decreased a bit, the turbulence had a weaker intermittent character again. It looks that for this case the strong shear below the LLJ contributed to the intermittent character of the generated turbulence. The green dots represent the flights at 5 Oct., 1995 and 24 March, 2003. Below the LLJ the stratification was near-neutral. The legs close to the surface showed mostly continuous turbulence (green dots) and aloft, near the LLJ, weak intermittent turbulence (light green dots). Notable are a few legs close to surface (15-30 m) which showed intermittent turbulence (open green dots). These legs belong to the flight in March when the surface temperature was much lower compared to the other analysed days. It is most likely that some local surface processes produced these short bursts of energy. The black dots represent flight legs from July-August 1996. It seems that the most cases with continuous turbulence were found closer to the surface and in weaker stratification. No cases with continuous turbulence were found close to the LLJ. But the general conclusion that intermittency occurs more often under strong stable stratification can not be made.

The windshear obvious had a big influence on the generation of turbulence in the SBL. Fig. 8 shows the windshear related to the stratification strength. The blue dots represent again data measured on 27 August, 1996, while the green dots indicate data measured on 5 Oct., 1995 and 24 March, 2003. The black dots represent data measured at flights during July-August 1996. No systematic dependence on the state of turbulence was found. The data from intermittent turbulence could not be distinguished from continuous turbulence. But, when $\Delta\theta/\Delta z$ was strong enough in comparison with $\Delta u_{hor}/\Delta z$, it seems that more cases of intermittent turbulence appea-

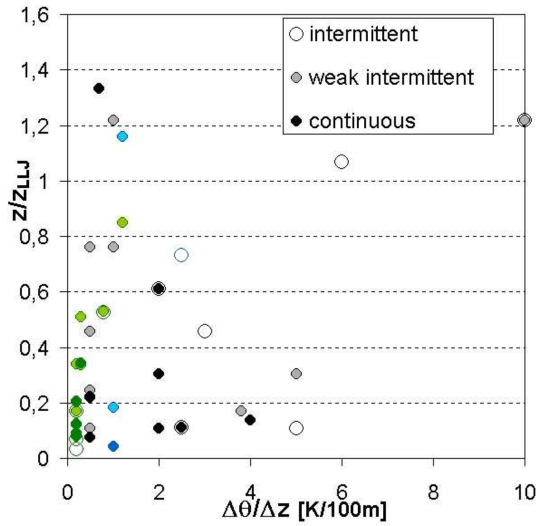

Fig. 7: *Stratification as function of the relative distance to the LLJ*

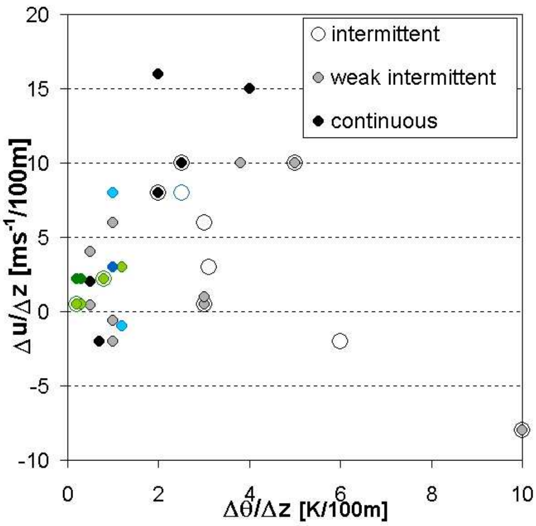

Fig. 8: *Stratification as function of the windshear*

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6. OUTLOOK

Mesoscale motions are important for the very stable case, partly because the turbulence is weak. In this research these motions are not yet taken in account. In contrary to turbulent fluxes, mesoscale motions are not related to the local wind shear and the temperature stratification. To investigate the influence of the characteristic turbulence timescale under stable conditions, first the turbulent and mesoscale motions have to be separated using the cospectral gap. The next step is to analyse mesoscale disturbance over a larger area (instead of locally) to characterise the flow and understand their influence on intermittent turbulence in the PSBL.

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