7.3 STABLE BOUNDARY-LAYER REGIMES OBSERVED DURING THE SHEBA EXPERIMENT

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1. INTRODUCTION

Determining momentum, heat, and mass exchange in the Arctic is a major challenge for modeling the northern hemispheric circulation and global climate change. Understanding the atmospheric boundary-layer regimes and proper parameterization of the surface fluxes are of obvious relevance for climate modeling, weather forecasting, and other important applications in the Arctic region.

This study uses turbulence data collected over the Arctic pack ice during the Surface Heat Budget of the Arctic Ocean Experiment (SHEBA) from October 1997 to October 1998. Turbulent and mean meteorological data collected at five levels [nominally 2.2, 3.2, 5.1, 8.9, and 18.2 m (or 14 m in winter)] on the 20-m tower are analyzed to examine different regimes of the continuously stable boundary layer (SBL). Detailed descriptions of the data and other relevant information about the SHEBA flux data can be found in Andreas et al. (1999) and Persson et al. (2002).

Observations in the Arctic offer several advantages to studying the structure of the SBL compared to the traditional nocturnal boundary layer measurements in mid-latitudes. At high latitudes, especially during a polar night, long-lived SBLs can reach very stable states. Besides, the Arctic pack ice is a rather uniform flat surface without large-scale slopes and heterogeneity. Thus the obtained data are not contaminated by drainage (katabatic) or strong advective flows.

2. SBL REGIMES IN THE ARCTIC

Eleven months of measurements during the SHEBA campaign cover a wide range of stability conditions, from the weakly unstable regime to very stable stratification. Traditionally SBL regimes are classified into several categories, the weakly stable boundary layer, intermediate (or transition) regime, and the very stable boundary layer (e.g., Mahrt 1999). Note that classifying the SBL into a few states is not universal and is probably an oversimplification.

In the weakly stable boundary layer, the downward heat flux increases with increasing stability parameter, $\zeta \equiv z/L$ (L is the Obukhov length). The traditional Monin - Obukhov similarity theory (MOST) works well in this regime. The maximum of the downward heat flux defines the stability boundary between the weakly stable and transition regimes. According to the SHEBA data shown in Fig.1 (1-hr averaging), the breakdown occurs at $\zeta_m \equiv z_m/L_m \approx 0.05$ (hereinafter subscript m denotes the median value of data measured at five levels, $z_m \approx 6$ m). The value $\zeta_m = 0.05$ corresponds to the median bulk Richardson number $\mathrm{Ri}_{B\ m} \approx 0.01$, and is close to $\zeta \approx 0.06$ for the 10 m data obtained by Mahrt et al. (1998). For $\zeta_m > 0.05$, the downward heat flux, the drag coefficient, and the turbulence intensity decrease rapidly with increasing ζ_m (Fig. 1) due to the

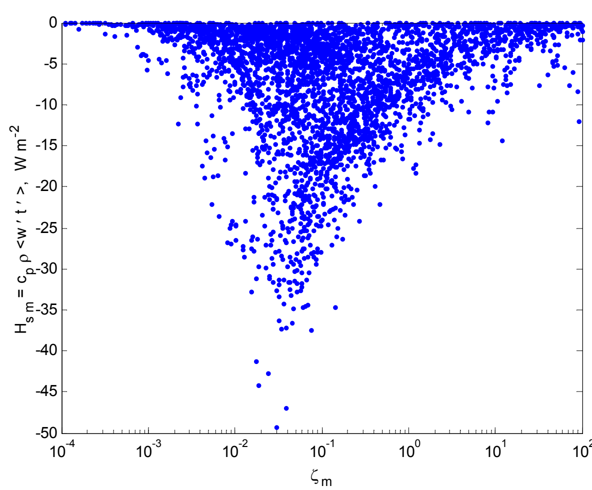

FIG. 1. Median sensible heat flux versus $\zeta_m = z_m/L_m$.

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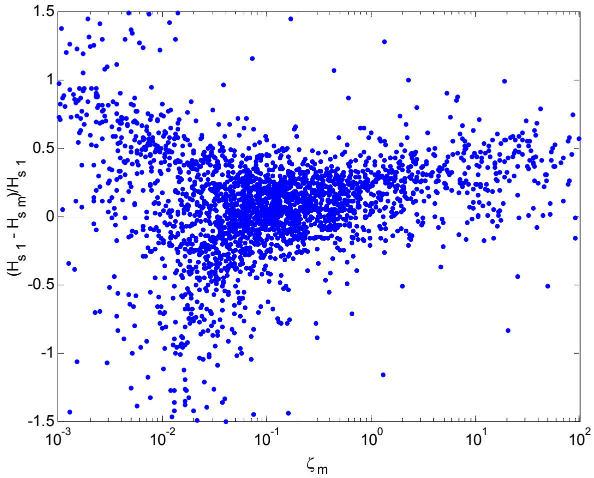

FIG. 2. Vertical divergence of the sensible heat flux.

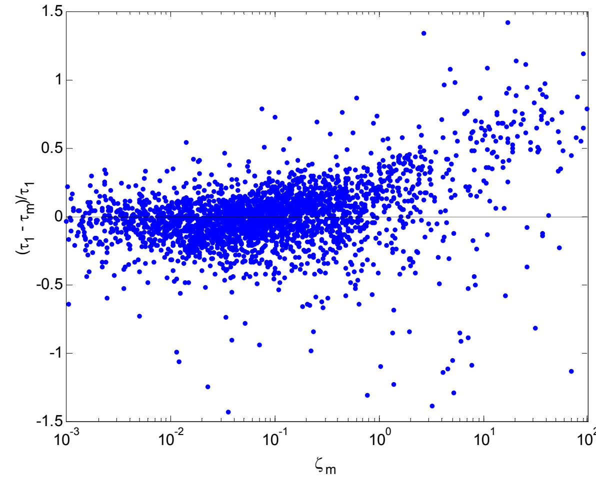

FIG. 3. Vertical divergence of the momentum flux.

buoyancy constraints on the vertical transfer. However, the layer where the turbulent fluxes are constant with height extends beyond this point.

We verified the height-independence of flux assumption underlying MOST. Figure 2 shows a difference of the sensible heat flux measured at level 1 (about 2.2 m above surface), H_{S1}, and the median sensible heat flux, $H_{S\,m}$, normalized by H_{S1} as a function of ζ_m. Similar dependence for the momentum flux is shown in Fig. 3. The greater scatter of points in Fig. 2 for $\zeta_m \rightarrow 0$ is associated with the relatively small and unreliable sensible heat flux in the near neutral conditions (cf. Fig. 1).

According to Figs. 2 and 3 for ζ_m < O(0.1) the momentum flux and the sensible heat flux may be considered constant, independent of height (on the average). Thus a regime for 0 < ζ_m < O(0.1) may be identified as a *constant flux regime*, or the weakly stable case (cf. Mahrt et al. 1998). Traditional surface-layer scaling works well in this regime. According to the measurements over the Greenland ice sheet, traditional MOST is in good agreement with the observations up to $\zeta \approx 0.4$ (Forrer and Rotach 1997).

For ζ_m > O(0.1), the approximation of height-independent fluxes becomes invalid (Figs. 2 and 3). However according to Forrer and Rotach (1997), Mahrt (1998), and Howell and Sun (1999), MOST can be restored in the form of local scaling where the Obukhov length is based on the local fluxes at height z rather than on the surface values. For this reason, this regime may be considered as a *transition local-scaling regime*. The wind shear is large enough to maintain continuous turbulence at all five sonic levels in this regime, and the surface layer does not feel the turning effects of the Coriolis force.

The upper boundary for this regime is defined from the condition when the above approximations fail. Figure 4 shows the difference between wind direction measured at level 5 and 1 as a function of ζ_m (the angle resolution is 1 degree). Observed wind speed structure shows that the turning effects (Ekman-type spiral) cannot be neglected for $\zeta_m \geq$ O(1) (see also Fig. 9). Therefore, ζ_m = O(1) can be considered as an upper boundary for the transition local-scaling regime.

Usually the very stable states, ζ_m > O(1), are associated with light winds and clear skies, especially during a polar night. In such conditions when a diurnal cycle is absent a residual layer, common for a mid-latitude nocturnal SBL, usually will not form. Thus the SBL at high latitudes is not separated from the outer (or Ekman) layer, and it

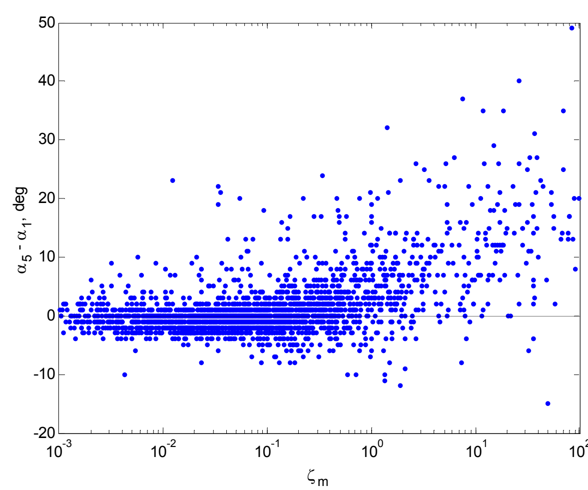

FIG. 4. Difference between wind direction at levels 5 and 1.

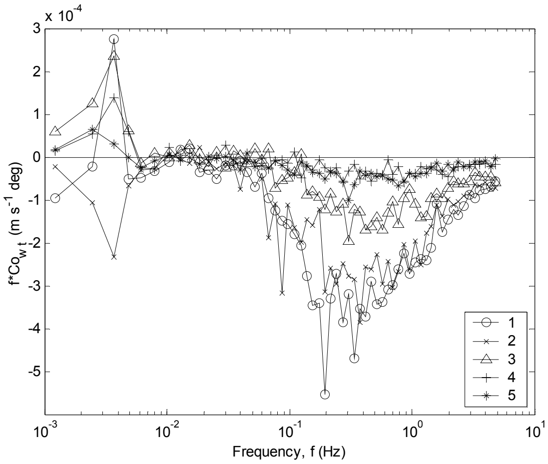

FIG. 5. Cospectra of the temperature flux at five levels, JD 324.75, $\zeta_2 \approx 6.2$ (level 2), $\zeta_3 \approx 24.2$ (level 3).

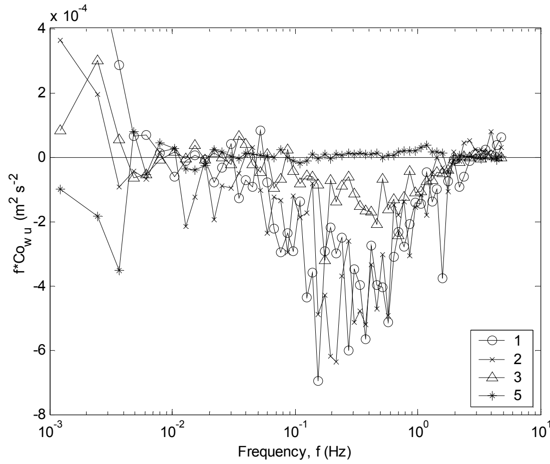

FIG. 6. Stress cospectra at four levels (level 4 is missing), JD 355.0, $\zeta_2 \approx 3$ (level 2), $\zeta_3 \approx 10.5$ (level 3).

can reach very stable states. With formation of an Ekman spiral at ζ_m > O(1), the near-surface turbulence is affected by the Coriolis parameter and the Brunt-Väisälä frequency of the outer flow (non-local scaling parameters) as well as the surface stress and the buoyancy flux (local scaling parameters). This state can be treated as by the *transition non-local scaling regime*.

The non-local theory for the SBL without the effect of the earth's rotation has been derived by Zilitinkevich and Calanca (2000). In this regime, the surface layer (continuous turbulence) may be very shallow (< 5 m). We observed a layered structure with weak turbulence near the surface (usually 2–3 lowest sonic levels) and collapsed turbulence (no turbulence) above (1–2 upper sonic levels). Some typical cases of the SBL structure in this regime are shown in Figs. 5 and 6. As stability increases, turbulence decays and vertical fluxes vanish (Figs. 7 and 8). However, the stress decays faster than the heat flux (Figs. 7 and 8). According to our data the uw-covariance falls as a parabolic function since both w' and u' approach zero. At the same time the heat flux decreases as a linear function since only $w' \to 0$, while t' is small but is still a finite value due to the strong temperature gradient. Thus, small but still significant heat flux and negligibly small stress characterize this situation (Figs. 7 and 8). The critical Richardson number limits the transition regime. According to Fig. 7 the critical value of $\mathrm{Ri}_{\mathrm{B}\,m}$ is about 0.2.

In the SBL where $\mathrm{Ri}_{\mathrm{B}\,m} \gtrsim 0.2$ (ζ_m > O(10)), the basic state is associated with near-zero fluxes and the strong influence of the earth's rotation. This regime can be treated as the *supercritical stable regime* (by definition) or the very stable regime. However, even in the very stable regime some intermittent turbulence persists. Turbulence in this regime can be generated by shear associated with the low level jet. We observed situations when the strongest turbulence is detached from the surface

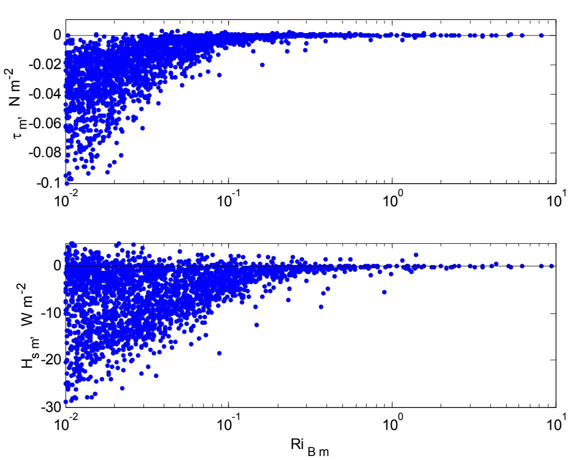

FIG. 7. Behavior of the stress and the heat flux near the critical Richardson number as function of $\mathrm{Ri}_{\mathrm{B}\,m}$.

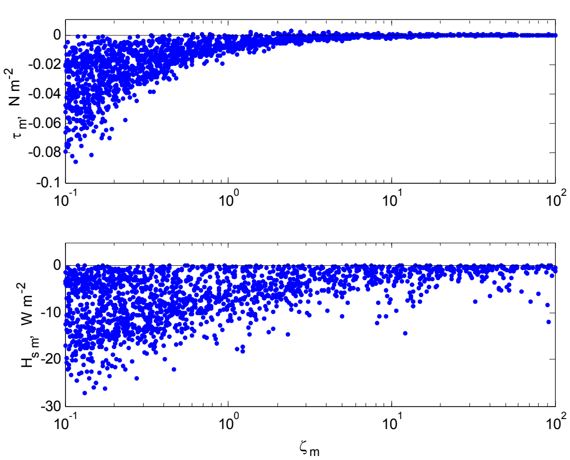

FIG. 8. Same as Fig. 7 but plotted against $\zeta_m = z_m/L_m$.

(levels 4–5) while the turbulence adjacent to the surface (levels 1–3) collapses. This is, thus, an upside-down SBL. In the very stable regime, the fluxes and variances may be contaminated by internal gravity waves with periods of several minutes (see Figs. 5 and 6). The occurrence of the above features is a common phenomenon in the SBL (e.g. Smedman 1988; Mahrt 1999). However, the very stable regime in the Arctic is often affected by the turning effects of the Coriolis force even near the surface. The Ekman spiral for wind observed in the very stable regime during SHEBA is shown in Fig. 9. In this case turbulence collapses at all five levels. Similar surface wind veering was observed by Lettau et al. (1977) in the Antarctic. Note the opposite wind spiral signs in the Northern (SHEBA data) and Southern (Lettau et al. 1977) Hemispheres.

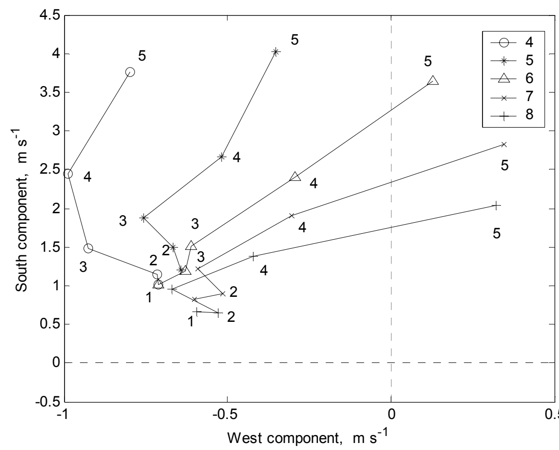

FIG. 9. Evolving Ekman-type spirals during JD 142 (1998) for five hours from 4 to 8 a.m. local time (see the legend). Markers indicate ends of wind vectors at levels 1 to 5 (1.9, 2.7, 4.7, 8.6, and 17.7 m).

3. CONCLUSIONS

The structure of the SBL is discussed based on the SHEBA data. The vertical flux divergence, influence of the earth's rotation, and the critical Richardson number govern four major regimes:

I. $0 < \zeta_m <$ O(0.1). The *constant flux regime* (or weakly stable regime) is associated with approximately constant (in the vertical) shearing stress and the sensible heat flux. The weakly SBL is governed by the traditional MOST predictions.

II. O(0.1) $< \zeta_m <$ O(1). In the *transition local-scaling regime* the approximation of height-independent fluxes becomes invalid. However, the flow is insensitive to the earth's rotation and turbulence is more or less continuous. In this regime MOST seems adequate, but similarity theory should be redefined in terms of local similarity, when L is based on the local fluxes at height z (cf. Forrer and Rotach 1997).

III. O(1) $< \zeta_m <$ O(10). In the *transition non-local scaling regime* MOST appears to break down. In this regime fluxes vary with height, and the wind structure is influenced by surface friction, temperature gradient, and the outer (or Ekman) layer (cf. Zilitinkevich and Calanca 2000).

IV. $\mathrm{Ri}_{B\ m} \gtrsim 0.2$ ($\zeta_m >$ O(10)). The *supercritical stable regime* (or very stable regime) is associated with collapsed turbulence and the strong influence of the earth's rotation. Observed wind speed structure shows features of the Ekman spiral even near the surface (cf. Lettau et al. 1977).

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