Stable Boundary Layer Studies in the Arctic

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The main SHEBA ice camp was deployed on the ice in the vicinity of the Canadian Coast Guard ice breaker *Des Groseilliers*, which was frozen into the Arctic ice pack north of Alaska from October 1997 to October 1998.

During this period, the ice breaker drifted more than 1400 km in the Beaufort and Chukchi Seas, with coordinates varying from approximately 74° N and 144° W to 81° N and 166° W.
The SHEBA site was located on Arctic pack ice, which had no large-scale slopes or heterogeneities; the site was a few hundred kilometers from land and thus provided almost unlimited and extremely uniform fetch. For these reasons, the SHEBA flux data are not generally contaminated by drainage (katabatic), strong local advective flows, or orographically generated gravity waves. Thus the SBL observed most often during SHEBA can be characterized as a traditional SBL layer.
The Atmospheric Surface Flux Group (ASFG) deployed a 20-m main micrometeorological tower, two short masts, and several other instruments on the surface located 280 – 350 m from the Des Groseilliers at the far edge of the main ice camp.

Turbulent and mean meteorological data were collected at five levels, nominally 2.2, 3.2, 5.1, 8.9, and 18.2 m (or 14 m during most of the winter).

Each level had a Väisälä HMP-235 temperature/relative humidity probe (T/RH) and identical ATI three-axis sonic anemometers/thermometers (resolution: wind speed 0.01 m/sec; sonic temperature 0.01°C).

An Ophir fast infrared hygrometer was mounted on a 3-m boom at an intermediate level just below level 4 (8.1 m above ice).
The NOAA Arctic Atmospheric Observatory program has been conceived as a broad, interdisciplinary, multiscale program with a core aim of understanding the recent and ongoing, decadal, pan-Arctic complex of interrelated changes in the Arctic. These changes include, among other things, a decline in sea level atmospheric pressure, an increase in surface air temperature, cyclonic ocean circulation, and a decrease in sea ice cover. NOAA is one of eight federal agencies participating in the implementation of IASOA. The primary observation sites are Alert and Eureka, Canada; Barrow, USA; Tiksi, Russia; Ny-Ålesund, Norway; and Summit, Greenland.
Russian Tiksi weather station located in East Siberia (71.6 N, 128.9 E) was established at the Polyarka settlement on August 12, 1932 by the chief management of the northern sea route that began collecting geophysical data. The "Polyarka" observatory is located five miles out of town Tiksi. This is now the location for a new Intensive Arctic Observatory site representing a partnership between the National Science Foundation (NSF), the National Oceanic and Atmospheric Administration (NOAA), and the Russian Federal Service for Hydrometeorology and Environmental Monitoring (Roshydromet). This facility supports the research needs of the International community, across disciplines including supporting Global Atmosphere Watch measurements as well as other climate observations.
Eureka site (80.0 N, 85.9 W) is a long-term research observatory near the coast of the Arctic Ocean (Canadian territory of Nunavut). Eureka was established in 1947 as part of Arctic weather stations network and currently has been identified for enhanced instrumentation to monitor the changing Arctic climate. Beginning in 2004, remote sensors and in-situ instrumentation were installed at Eureka in framework of the SEARCH Program. Turbulent fluxes and mean meteorological data are continuously measured and reported hourly at various levels on a 10-m flux tower. Sonic anemometers are located at 3 and 8 m heights while high-speed Licor 7500 infrared gas analyzer ($\text{H}_2\text{O}$ and $\text{CO}_2$) at 7.5 m height. Turbulent fluxes are based on the eddy-covariance technique. The thermal profile is measured by several slow T/RH sensors and differential temperature pairs at 2, 5 and 10 m heights. Surface characteristics are measured by thermal soil probes, an infrared surface temperature sensor, and a sonic snow-depth sensor.
Eureka, Canada (winter)
Annual cycle of difference of the air virtual potential temperature between 10 m and 6 m levels observed at Eureka (Canadian Archipelago) in 2009. The data are based on 1-hour and 1-day averaging of measurements made at the 10-m flux tower.

Zilitinkevich (2002)
Monin-Obukhov Similarity Theory
Surface Scaling

Obukhov (1946), Monin and Obukhov (1954)

Obukhov length: \( L = - \frac{u_*^3 T_v}{\kappa g < w'T_v'>} \)

Monin – Obukhov stability parameter: \( \zeta \equiv \frac{z}{L} \)

Non-dimensional velocity and temperature gradients:
\[
\varphi_m(\zeta) = \frac{\kappa z}{u_*} \frac{dU}{dz}, \quad \varphi_h(\zeta) = \frac{\kappa z}{T_*} \frac{d\theta}{dz}
\]

Non-dimensional standard deviations:
\[
\varphi_\alpha(\zeta) = \frac{\sigma_\alpha}{u_*}, \quad \varphi_\theta(\zeta) = \frac{\sigma_\theta}{\theta_*} \quad (\alpha = u, v, w)
\]
F. T. M. Nieuwstadt (1984, JAS v.41) demonstrated that in the stable boundary layer (SBL) the assumption of height-independent fluxes is not necessary. He thus redefined Monin-Obukhov similarity in terms of local similarity (local scaling) for which the Obukhov length and the flux-profile and flux-variance relationships are based on the local fluxes at height $z$ (i.e., $z$-dependent fluxes) rather than on the surface values.

Z. Sorbjan (1986, BLM v.34; 1988, BLM v.44) argued that the functional forms of the universal functions in the SBL are identical for both surface and local scaling assumptions. Thus, local scaling describes the turbulent structure of the entire SBL.
Stable Boundary Layer Regimes

According to the SHEBA data, stratification and the Earth’s rotation control the SBL over a flat rough surface. Different SBL regimes are described in terms of the Monin-Obukhov stability parameter $(z/L)$, the Ekman number $(E_k)$ that quantifies the influence of the Earth’s rotation, and the bulk Richardson number $(R_{iB})$ that determines the intensity of the turbulence. These three non-dimensional parameters govern four major regimes (see Figure).

Figure shows a schematic diagram of the SBL scaling regimes as functions of the stability and height. Here $z_1 \approx 2$ m (level 1), $E_k \approx 1$, $R_{iB} \approx 0.2$. Dividing lines between the scaling regions are sketched.

Grachev et al. (2005), Boundary-Layer Meteorology, 116(2), 201-235.
Surface-layer scaling regime (weakly stable regime) \( 0 < \zeta < 0.1 \)

This regime is associated with shear stress and sensible heat flux that are approximately constant with height, constant-flux layer (see Figure). The weakly stable boundary layer is governed by traditional Monin-Obukhov similarity theory predictions.

Figure shows the vertical divergence of (a) the downwind stress and (b) the sensible heat flux plotted for period from 31 October 1997 (JD 304) until 21 March 1998 (JD 445, vernal equinox).

Grachev et al. (2005), Boundary-Layer Meteorology, 116(2), 201-235.
Typical (a) stress cospectra (1998 JD 45.4167), and cospectra of the sonic temperature flux (1997 JD 324.5833) for weakly and moderate stable conditions. In (a) $u^*$ decreases with increasing height from 0.134 to 0.08 m/s. Stability parameter increases with increasing height from 0.128 to 1.893. In (b) downward sensible heat flux decreases with increasing height from -1.66 to -0.64 W/m$^2$ (level 1 to level 5). Stability parameter increases with increasing height from 0.096 to 0.533.

Typical cospectra of (a) the momentum flux (JD 355.00, 21 Dec., 1997), and (b) the sonic temperature flux (JD 507.75, 22 May, 1998) in the very stable regime. In (a) the stability parameter is 3 (level 2) and 10.5 (level 3). In (b) the stability parameters increase with increasing height: 1.41, 2.05, 6.34, 8.13 (levels 2–5).

Typical raw spectra of (a) the longitudinal wind component and (b) the sonic temperature at four levels (level 3 is missing) for weakly and moderate stable conditions during 14 February 1998 UTC (1998 YD 45.4167). Stability parameter increases with increasing height from 0.128 to 1.893, (levels 1, 2, 4, and 5). The bulk Richardson number also increases with increasing height from 0.0120 to 0.0734 but it is still below its critical value 0.2.

Typical raw spectra of (a) the longitudinal wind component and (b) the sonic temperature at four levels (level 4 is missing) for very strong stable conditions during 21 December 1997 UTC (1997 YD 355.00). For data presented here the stability parameters at levels 2, 3, and 5 are 3, 10.5, and 116.3 (sensible heat flux is missing for level 1). The bulk Richardson numbers at four levels are $R_i_{B1} = 0.0736$, $R_i_{B2} = 0.0839$, $R_i_{B3} = 0.1090$, and $R_i_{B5} = 0.2793$.
Behavior of the bin-averaged downward momentum flux (left panels) and for the sensible heat flux (right panels) for five levels of the main SHEBA tower plotted versus (a) \( \text{Ri} \), (b) \( \text{Rf} \), and (c) \( \zeta = z/L \). Individual 1-hour averaged SHEBA data based on the median fluxes for the five levels are shown as the background x-symbols. The vertical dashed lines correspond to \( \text{Ri} \) and \( \text{Rf} = 0.2 \).
Plots of the bin-averaged spectral slope in the inertial subrange for the spectrum of the (a) longitudinal, (b) lateral, and (c) vertical velocity components and (d) the sonic temperature for five levels versus Ri (left panels) and Rf (right panels). The spectral slopes were computed in the 0.96-2.95 Hz frequency band. Individual 1-hour averaged data for level 3 are shown as the background x-symbols. The vertical dashed lines correspond to Ri & Rf = 0.2. The horizontal dashed lines represent the -5/3 Kolmogorov power law.
Ekman Number

\[ \text{Ek} \equiv -\frac{\langle u'w' \rangle}{2\Omega \sin \varphi \ zU} \]

Difference between wind direction at levels 5 and 1 (individual 1-hr averaged data and bin-averaged medians) as function of
(a) \(\frac{z}{\Lambda}\) (at level 5) and (b) \(\text{Ri}_B\) (level 5 minus surface values). The vertical dashed line in the bottom panel corresponds to a critical Richardson number, \(\text{Ri}_B\), of 0.2.

Dependence of the Ekman number measured at level 5 (individual 1-hr averaged data and bin-averaged medians) as functions of (a) \(\frac{z}{\Lambda}\) (at level 5) and (b) \(\text{Ri}_B\) (level 5 minus surface values). The vertical dashed line in the bottom panel corresponds to the critical Richardson number \(\text{Ri}_B = 0.2\). The horizontal dashed lines correspond to \(\text{Ek} = \text{Ek}_{cr} = 1\).
Evolving Ekman-type spirals during the polar day observed during JD 507 (22 May, 1998) for five hours from 12.00 to 16.00 UTC (4:00–8:00 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).

3D view of the Ekman spiral for 14:00 UTC JD 507 (local time 6 a.m.), 22 May 1998
In very stable case MOST predicts that $z$ ceases to be a scaling parameter:

$$\phi_m(\zeta) = \beta_m \zeta$$
$$\phi_h(\zeta) = \beta_h \zeta$$

A simple linear interpolation between neutral and $z$-less cases:

$$\phi_m(\zeta) = 1 + \beta_m \zeta$$
$$\phi_h(\zeta) = 1 + \beta_h \zeta$$

Plots of (a) $\phi_m$, (b) $\phi_h$, (c) $R_i$, (d) $1/Pr_t$ versus $\zeta = z/L$ from Kansas (1968) experiment (Businger et al. (1971) JAS v. 28(2), 181–189)
Turbulence spectra and cospectra in the SBL
Kaimal et al. (1972), Kaimal (1973), Caughey (1977)

- Observations in the SBL have shown that properly normalized spectra and cospectra can be represented by a series of universal curves based on the Monin-Obukhov scaling:

\[
\frac{n \cdot S_\alpha (n)}{\sigma^2_\alpha} = \frac{0.164 \cdot f / f_o}{1 + 0.164 \cdot (f / f_o)^{5/3}} \quad \alpha = u, v, w, \theta
\]

\[
\frac{n \cdot C_{\alpha w} (n)}{<\alpha'w'>} = \frac{0.88 \cdot f / f_o}{1 + 1.5 \cdot (f / f_o)^{2/3}} \quad \alpha = u, \theta
\]

Normalized (a) spectra of \(w, v, u, \theta\) and (b) cospectra of \(uw, w\theta,\) and \(u\theta\) plotted versus \(f/f_o\) based on the Kansas (1968) data (Kaimal et al. (1972) Q. J. Roy. Meteorol. Soc., v.98(417), 563–589).
"Kansas-type" local z-less scaling was questioned
Current extensive datasets

- Local z-less scaling has been brought into question by recent measurements:
  - Forrer and Rotach (1997)
  - Howell and Sun (1999)
  - Yagüe et al. (2001, 2006)
  - Pahlow et al. (2001)
  - Cheng and Brutsaert (2005)
  - Baas et al. (2006)
  - Grachev et al. (2005, 2007)

Plots of (a) $\phi_m$ & $\phi_h$ versus $\zeta = z/L$ from CASES-1999 experiment (Baas et al. (2006) J. Atmos. Sci., 63(11), 3045–3054) and (b) $\sigma_u/u^*$ versus $\zeta = z/L$ (Pahlow et al (2001) Boundary-Layer Meteorol. 99(2), 225–248)
Non-Dimensional Vertical Gradients
"The SHEBA parameterizations"

\[ \varphi_m \text{ SHEBA} = 1 + \frac{a_m \zeta (1 + \zeta)^{1/3}}{1 + b_m \zeta} = 1 + \frac{6.5 \zeta (1 + \zeta)^{1/3}}{1.3 + \zeta}, \]

\[ \varphi_h \text{ SHEBA} = 1 + \frac{a_h \zeta + b_h \zeta^2}{1 + c_h \zeta + \zeta^2} = 1 + \frac{5 \zeta + 5 \zeta^2}{1 + 3 \zeta + \zeta^2}, \]

where \( a_m = \beta_m = 5, b_m = a_m/6.5, a_h = \beta_h = 5, b_h = 5, \) and \( c_h = 3. \)


In particular, these parameterizations are used in the SHEBA bulk flux algorithm by Andreas et al. (2010a, b)
Saving the z-less concept

- Basu et al. (2006) revisited the data used by Pahlow et al. (2001) and applied rigorous quality control to this and some other datasets to remove non-turbulent effects. Their analysis supported the validity of z-less stratification for $\sigma_u/u^*$. 
- Mahrt (2007) analyzed extensive eddy-correlation datasets to examine the influence of non-stationarity of the mean flow on the flux-gradient relationships for $\zeta < 1$. However, even for stationary cases, the function $\varphi_m(\zeta)$ increases more slowly than the linear prediction in the range $0.6 < \zeta < 1$.
- Hong et al. (2010) nevertheless supported the validity of z-less stratification only up to $\zeta \sim 0.5$ by applying the Hilbert-Huang transform to separate turbulent signals from non-turbulent motions.
- These contradictory results indicate that the validity of z-less stratification is still an open question that requires further clarification.

Sketch of $\varphi_m$ & $\varphi_h$ versus $\zeta = z/L$ based on the current data revealing the level-off of $\varphi_m$ & $\varphi_h$ (Hong (2010) APJAS v. 46(1))

Bin-averaged values of $\varphi_m$ versus $\zeta = z/L$ for stationary and non-stationary cases (Mahrt (2007) BLM 125(2), 245–264)

$\varphi_m = 1 + 5\zeta$
The bin-averaged $\phi_m$ (left panels) and $\phi_h$ (right panels) for five levels of the main SHEBA tower plotted versus $\zeta = z/L$ (a) for the original data, (b) in the subcritical regime when prerequisites $Ri < R_{icr}$ and $Rf < R_{fcr}$ with $R_{icr} = R_{fcr} = 0.2$ have been imposed on the data, and (c) in the supercritical regime when prerequisites $Ri > R_{icr}$ and $Rf > R_{fcr}$ have been imposed on the data.

Grachev et al. (2013), Boundary-Layer Meteorology, 147(1), 51 - 82.
Scaling Systems

Local Scaling

- The Pi theorem used in MOST provides only a general methodology, and the choice of the primary governing variables is not unique. In fact, Nieuwstadt (1984) deprived the turbulent fluxes of their “privileged role” and paved the way to construct a local similarity theory in the SBL based on governing variables other than the fluxes.

- Monin and Obukhov (1954)

\[ \tau, \ H, \ \beta \implies L = \frac{\tau^{3/2}}{\kappa \beta H}, \ u_* = \sqrt{\tau}, \ \theta_* = \frac{H}{\sqrt{\tau}} \]

- Smeets, Duynkerke, Vugts (2000, BLM v.97)

\[ \sigma_w, \ H, \ \beta \implies L_{wH} = \frac{\sigma_w^3}{\kappa \beta H}, \ U_{wH} = \sigma_w, \ \theta_{wH} = \frac{H}{\sigma_w} \]


\[ \sigma_w, \ N, \ \beta \implies L_{wN} = \frac{\sigma_w}{N}, \ U_{wN} = \sigma_w, \ \theta_{wN} = \frac{\sigma_w N}{\beta} \]

\[ \sigma_\theta, \ N, \ \beta \implies L_{\theta N} = \frac{\beta \sigma_\theta}{N^2}, \ U_{\theta N} = \frac{\beta \sigma_\theta}{N}, \ \theta_{\theta N} = \sigma_\theta \]
Dougherty-Ozmidov Scaling System
The $N$-$\varepsilon$ scaling: Dimensional analysis

• The $N$-$\varepsilon$ scaling $N, \varepsilon, \beta \implies L_{N\varepsilon} = \sqrt{\frac{\varepsilon}{N^3}}, U_{N\varepsilon} = \sqrt{\frac{\varepsilon}{N}}, \theta_{N\varepsilon} = \sqrt{\frac{\varepsilon N}{\beta}}$

$N = \sqrt{\beta \frac{\partial \theta}{\partial z} = \sqrt{-g \left( \frac{\partial \rho}{\partial z} \right)}}/\rho$ is the Brunt-Väisälä frequency (or buoyancy frequency)

• According to Buckingham’s Pi theorem, any properly scaled statistics of the small-scale turbulence are universal functions of a stability parameter defined as the ratio of a reference height $z$ and the Dougherty-Ozmidov length scale:

$$\xi = z / L_{N\varepsilon}$$

• Non-dimensional relationships for $dU/dz$, momentum flux, and temperature flux

$$Ri = \psi_R(\xi), \quad \frac{\tau N}{\varepsilon} = \psi_m(\xi), \quad \frac{\beta H}{\varepsilon} = \psi_h(\xi)$$

• Non-dimensional relationships for standard deviations of wind speed components, temperature, turbulent viscosity and thermal diffusivity

$$\frac{\sigma_a}{\sqrt{\varepsilon / N}} = \psi_a(\xi), \quad \frac{\sigma_i \beta}{\sqrt{\varepsilon N}} = \psi_t(\xi), \quad \frac{K_m N^2}{\varepsilon} = \psi_{Km}(\xi), \quad \frac{K_h N^2}{\varepsilon} = \psi_{Kh}(\xi)$$
Dougherty-Ozmidov universal functions
SHEBA data

Left panels: Plots of the non-dimensional turbulent viscosity versus (a) the Dougherty-Ozmidov stability parameter; (b) the gradient Richardson number, $Ri$. Right panels: Plots of the bin-averaged non-dimensional turbulent thermal diffusivity versus (a) the Dougherty-Ozmidov stability parameter; (b) the flux Richardson number, $Rf$.

Self-Correlation and Outlier Problem

Plots of the bin-averaged turbulent Prandtl number (bin medians) as functions of (a) Ri, (b) Rf, and (c) (bin means) during the 11 months of the SHEBA measurements.

"Hybrid" Similarity Theory

The bin-averaged $\phi_m/\phi_w$ for five levels of the main SHEBA tower plotted versus $\zeta = z/L$ (a) for the original data, (b) in the subcritical regime when prerequisites $\text{Re} < \text{Re}_{cr}$ and $\text{Re} < \text{Re}_{cr}$ with $\text{Re}_{cr} = \text{Re}_{cr} = 0.2$ have been imposed on the data, and (c) in the supercritical regime when a prerequisites $\text{Re} > \text{Re}_{cr}$ and $\text{Re} > \text{Re}_{cr}$ have been imposed on the data. The function $\phi_m/\phi_w$ is not affected by the self-correlation.
Self-correlation & "Hybrid" MOST for $\varepsilon$

Self-correlated plots

Fair plots
The bin-averaged and the hourly data (the background yellow symbols) of the non-dimensional universal functions for the standard deviations of scalars: (a) air temperature, (b) air humidity, and (c) carbon dioxide plotted versus Monin-Obukhov stability parameter $z/L$ observed at the Tiksi site during 2012-2014. The horizontal dashed lines correspond to (a) 2.0, (b) 2.7, and (c) 2.7.

The bin-averaged and the hourly data (the background yellow symbols) of the non-dimensional universal functions for the horizontal scalar fluxes: (a) $u'^t$, (b) $u'^q$, and (c) $u'^c$ plotted versus Monin-Obukhov stability parameter $z/L > 0$ (stably stratified ABL) observed at the Tiksi site during 2012-2014. The horizontal dashed lines correspond to (a) -2.4, (b) -2.7, and (c) -2.7.
Measurements of atmospheric turbulence made at the U.S. Army Corps of Engineers Field Research Facility (FRF) located on the Atlantic Ocean near the town of Duck, North Carolina, during the CASPER Program (October-November 2015) are used to study air-sea/land coupling in the FRF coastal zone.
Monin-Obukhov Functions in the Coastal Zone vs. $z/L$

Pier Tower (3 levels), YD 281–313 (Oct 8–Nov 9, 2015)
Conclusions

- Polar Regions can be considered as ideal meteorological "laboratories" for studying the stable boundary layer (SBL). At high latitudes, stable conditions are long lasting and can reach very stable and quasi-stationary states. Besides, the Arctic pack ice is a rather uniform, flat surface without large-scale slopes. The almost unlimited and extremely uniform fetch provides an opportunity to isolate many physical processes.

- This study surveys early results and presents new findings of measurements in the SBL made over the Arctic pack ice during SHEBA and at two terrestrial long-term research observatories located at Eureka (Canadian Archipelago, 80.0°N) and Tiksi (East Siberia).

- An overview of the SBL regimes, flux-profile relationships, critical Richardson number, turbulent Prandtl number, and other parameters is given. The traditional Monin-Obukhov approach and its limits of applicability, z-less scaling, self-correlation, and alternative local scalings are discussed based on the data collected in the Arctic.

- In addition, according to our data collected in the coastal zone, $\phi_w$ and $\phi_e$ are less sensitive to assumptions underlying MOST and they are more or less consistent with the classical MOST predictions. At the same time, the statistical dependence of $\phi_m$ and $\phi_h$ on $\zeta = z/L$ in the coastal zone appears weak, if not non-existent.
Thank you Holland!