

Theme of the Year Workshop 3 at NCAR Geophysical Turbulent Phenomena



Turbulence Measurements for Surface-Layer Micrometeorological Studies over Sea and Sea-Ice

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Physics of air-surface interactions and coupling to ocean-ice/atmosphere BL



Aspects:	 Emphasize surface fluxes Similarity Scaling Bulk Flux Parameterizations Surface/subsurface processes Improve Observing Technologies Flux climatologies 	
Applications:	 Model lower BC (PBL, Meso, NWP, GCM) Ocean budgets (stress, heat, waves, sea-ice) Carbon budgets Pollution deposition (particle, ozone) Cloud microphysics (aerosol source, DMS) Atmos Propagation (Cn², ducting, extinction) Hurricane intensity 	



Flux Definitions



Sensible Heat :
$$H_s = \rho_a c_{pa} \overline{w'T'}$$

Latent Heat : $H_l = \rho_a L_e \overline{w'q'}$
Stress : $\vec{\tau} = \rho_a \overline{w'u_x'}\hat{i} + \rho_a \overline{w'u_y'}\hat{j}$
Rain Heat : $H_p = c_{pw} P(T_s - T_{wet})$

 $BuoyAir: F_b = H_s / \rho_a c_{pa} + 0.61T H_l / \rho_a L_e$ $BuoyWater: F_b = -\alpha g H_{net} / \rho_w c_{pw} + \beta g(E - P)$ $Gas Exchange: F_x = \overline{w'r_x'}$ $Particle Exchange: F_n = \overline{w'n(r)'} - w_g \overline{n(r)} + \overline{w_s'n(r)'}$



Present Status of Surface Flux Parameterizations



Turbulent Fluxes: Bulk Parameterization Mean correlation of turbulent variables represented in terms of mean flow variables – wind speed, surfaceto-air variable difference

$$\begin{split} &Met \ Flux: \overline{w'x'} = C_x U(X_s - X_r) = C_x U\Delta X\\ &Gas \ Flux: \overline{w'x'} = k_x \alpha_x \Delta X \qquad \alpha = sol.\\ &Particles: F_{deposition} = -V_d(r) \overline{n(r)};\\ &F_{source} = F(f_{whitecap}, U, u_*, wave breaking, slope) \end{split}$$







- Near-surface in situ
 - Sonic anemometer/thermometer
 - IR fast hygrometer, fast CO2
 - Chemilum. Fast ozone, DMS
 - High quality mean T, q, Ts
 - Eppley solar/IR radiometers
 - Surface waves
- Boundary Layer/column
 - Ceilometer
 - Wind profiling radar
 - Rawindsonde
 - Microwave radiometer
 - Doppler cloud radar



Rugged, High Speed, Accurate Sensors for Eddy Covariance Measurements



Unbelievable Number of Dirt Effects

- Motion corrections
- Contamination by salt, ship exhaust, sea gulls, ...
- Flow distortion (Ship, tower, other sensors)
- Sensor separation, time delays, decorrelation, frequency response, path averaging,...
- Surface boundary conditions (currents, ocean/snow gradients)
- Extreme cold, icing, frost formation, fog/rain impact
- Poor signal to noise, weak stratified turbulence
- Sensor-variable crosstalk (Webb, motion, chemical)
- Artificial (self-) correlation



Turbulence Measurements from Ships















Ship Motion Corrections



Power spectra of raw and corrected vertical velocities. GasexIII 2008, JD76, hour 12



Time series of w measured, ship's vertical motion and final w'. GasExIII 2008, JD76, hour

"Observing the Turbulent Atmosphere: Sampling Strategies, Technology and Applications", May 28-30, 2008, Boulder CO



Sample Dirt/Crosstalk Effects









Log Frequency

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Flux at the End of a Long Tube





Sample Tube Filter Effects







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Historical perspective on turbulent fluxes: Typical moisture transfer coefficients



FIG. 3. Humidity coefficients (C_E) for the ten selected schemes under neutral or slightly unstable conditions as a function of the wind speed (u_{10}) at an altitude of 10 m. Scheme acronyms are given in Table 1.



Algorithms of UA (solid lines), COARE 2.5 (dotted lines), CCM3 (short-dashed lines), ECMWF (dot-dashed lines), NCEP (tripledot-dashed lines), and GEOS (long-dashed lines).











COARE MODEL HISTORY



- 1996 Bulk Meteorological fluxes $(k_u = u^*C_d)$
 - Update 2003 (8000 eddy covariance obs)
 - Oceanic cool skin module molecular sublayer
- 2000 CO2
- 2004 DMS
- 2006 Ozone



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Results from 13 Cruises in 8 years





Air-Sea transfer coefficients as a function of wind speed: latent heat flux (upper panel) and momentum flux (lower panel). The red line is the COARE algorithm version 3.0; the circles are the average of direct flux measurements from 12 ETL cruises (1990-1999); the dashed line the original NCEP model.



Observations Normalized by Model





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Cruise Tracks



TexAQS 2006



Leg 1: from July 27 to August 18

Leg 2: from August 21 to September 10

Stratus 2006



October 13 to October 25



Deposition velocity versus Friction velocity

TexAQS 2006

STRATUS 2006



"Observing the Turbulent Atmosphere: Sampling Strategies, Technology and Applications", May 28-30, 2008, Boulder CO



GASEX-I, GASEX-II, and DMS Field Programs: Difference in CO2 and DMS from Solubility-Bubble Effect







Measurement over Sea Ice Surface Heat

Budget of the Arctic Ocean Experiment (SHEBA)



• 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 ice station drift from October 2, 1997 until October 9, 1998.

The SHEBA camp

The Des Groseilliers and C-130



ASFG Instrumentation



• 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.

• 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).





Typical Turbulent Spectra

for weakly and moderate stable (left) and very stable (right) conditions



10¹

10¹

10⁰

 10^{0}



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 $Ri_{B1} = 0.0736$, $Ri_{B2} = 0.0839$, $Ri_{B3} = 0.1090$, and $Ri_{B5} = 0.2793$

10⁻¹

Frequency, f (Hz)

 10^{-1}

Frequency, f (Hz)



Typical Turbulent Cospectra

for weakly and moderate stable (left) and very stable (right) conditions





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/m² (level 1 to level 5). Stability parameter 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).



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 (Ek) that quantifies the influence of the Earth's rotation, and the bulk Richardson number (Ri_B) that determines the intensity of the turbulence. These three nondimensional 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), Ek_{cr} ≈ 1 , Ri_B ≈ 0.2 . Dividing lines between the scaling regions are sketched.





Ekman Surface Layer





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



Profile Functions versus *z* / *L*





Plots of φ_m against (*a*) the surface stability parameter, z_n/L_l , and (*b*) the local stability parameter, z_n/L_n , for five levels (n = 1-5). The green dashed line represents $\varphi_m = l + \beta \zeta$ with $\beta = 5$, the blue dashed-dotted line is based on the Beljaars and Holtslag (1991) formula, and the black dotted line is the Cheng and Brutsaert (2005) parameterization. The red solid line is the SHEBA parameterization. Individual 1-hourr averaged data based on the median fluxes for the five levels are shown as the background x-symbols.



Plots of φ_h against (*a*) the surface stability parameter, z_n/L_l , and (*b*) the local stability parameter, z_n/L_n , for five levels (n = 1-5). The green dashed line represents $\varphi_h = l + \beta \zeta$ with $\beta = 5$, the blue dashed-dotted line is based on the Beljaars and Holtslag (1991) formula, and the black dotted line is the Cheng and Brutsaert (2005) parameterization. The red solid line is the SHEBA parameterization. Individual 1-hourr averaged data based on the median fluxes for the five levels are shown as the background x-symbols.



The SHEBA Profile Functions



- Non-dimensional velocity gradient:
- Non-dimensional temperature gradient:

$$\varphi_{m}(\zeta) = \frac{\kappa z}{u_{*}} \frac{dU}{dz} = 1 + \frac{a_{m} \zeta (1+\zeta)^{1/3}}{1+b_{m} \zeta} \equiv 1 + \frac{6.5\zeta (1+\zeta)^{1/3}}{1.3+\zeta} \equiv \varphi_{m \text{ SHEBA}}$$
$$\varphi_{h}(\zeta) = \frac{\kappa z}{T_{*}} \frac{d\theta}{dz} = 1 + \frac{a_{h} \zeta + b_{h} \zeta^{2}}{1+c_{h} \zeta + \zeta^{2}} \equiv 1 + \frac{5\zeta + 5\zeta^{2}}{1+3\zeta + \zeta^{2}} \equiv \varphi_{h \text{ SHEBA}}$$

where $a_m = a_h = 5$, $b_m = a_m / 6.5$, $b_h = 5$, and $c_h = 3$

• The integral form of φ_m :

$$\Psi_{m \text{ SHEBA}}(\zeta) = -\frac{3a_m}{b_m}(x-1) + \frac{a_m B_m}{2b_m} \left[2\ln\frac{x+B_m}{1+B_m} - \ln\frac{x^2 - xB_m + B_m^2}{1-B_m + B_m^2} + 2\sqrt{3} \left(\arctan\frac{2x-B_m}{\sqrt{3}B_m} - \arctan\frac{2-B_m}{\sqrt{3}B_m}\right) \right]$$

• The integral form of φ_h :

$$\Psi_{h \text{ SHEBA}}(\zeta) = -\frac{b_{h}}{2}\ln(1+c_{h}\zeta+\zeta^{2}) + \left(-\frac{a_{h}}{B_{h}}+\frac{b_{h}c_{h}}{2B_{h}}\right) \left(\ln\frac{2\zeta+c_{h}-B_{h}}{2\zeta+c_{h}+B_{h}}-\ln\frac{c_{h}-B_{h}}{c_{h}+B_{h}}\right)$$

where $x = (1+\zeta)^{1/3}$ $B_m = [(1-b_m)/b_m]^{1/3}$ $B_h = \sqrt{c_h^2 - 4} = \sqrt{5}$

• Coefficients a_m and a_h are determined from the asymptotic behaviour of φ_m and φ_h for $\zeta \to 0$; the ratio a_m/b_m and coefficient b_h are derived from the asymptotic behaviour of these functions at $\zeta \to \infty$. Note that $\varphi_m \to = (a_m/b_m)\zeta^{1/3}$ and $\varphi_h \to I + b_h = 6$ as $\zeta \to \infty$. Coefficient c_h is derived by our visually fitting the data.



Turbulent Prandtl number





Plots of the bin-averaged medians of the turbulent Prandtl number based on the local fluxes (n = 1-5) as functions of (a) z_n/L_n and (b) Ri_B. The dashed-dotted line in the upper panel is derived from the Beljaars and Holtslag (1991) formula, and the dotted line is based on the Cheng and Brutsaert (2005) parameterization. The vertical dashed line in the lower panel corresponds to the critical Richardson number, Ri_{B cr} = 0.2. Individual 1-hour averaged data based on the median fluxes for the five levels are shown as background crosses.



Self-correlation: the turbulent Prandtl number



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. The vertical dashed lines correspond to the critical Richardson number 0.2. Individual 1hr averaged data based on the median fluxes for the five levels are shown as background crosses. It is found that Pr. increases with increasing stability if Pr, is plotted versus gradient Richardson number, Ri; but at the same time, Pr, decreases with increasing stability if Pr, is plotted versus flux Richardson number, Rf, or versus z/L. This paradoxical behaviour of the turbulent Prandtl number in the SBL derives from the fact that plots of Pr, versus Ri (as well as versus Rf and z/L) for individual 1-hr observations and conventional binaveraged values of the individual quantities have built-in correlation (or self-correlation) because of the shared variables.





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Self-correlation: the von Kármán constant



Another notable example of self-correlation is the suggestion that the von Kármán constant, κ , depends on the roughness Reynolds number, Re_{*}. Andreas et al. (2006) found recently that artificial correlation seems to explain the tendency for κ to decrease with increasing Re^{*} in the atmospheric surface layer (i.e., Frenzen and Vogel, 1995a, 1995b; Oncley et al., 1996). According to Andreas et al. (2006) the von Kármán constant is, indeed, constant at 0.38–0.39.

The stability-corrected SHEBA and Ice Station Weddell values of the von Kármán constant are plotted against measured values of the roughness Reynolds number. The plot also shows tendencies and roughness Reynolds number ranges for the κ values that McKeon et al. (2004), Frenzen & Vogel (1995a), and Oncley et al. (1996) deduce.



The stability-corrected von Kármán constants are plotted against corresponding estimates of the roughness Reynolds number from our bulk flux algorithm. The lines show the least-squares fits of the Ice Station Weddell data, the SHEBA data, and the combined set.







