EAS 572 Assignment 2 (15%) 2007

Tables (1-5)[1] give various micrometeorological statistics observed (22 May 2003) at Ellerslie (Alberta), during a windbreak experiment[2]. Cup anemometers and shielded, ventilated thermocouples measured the vertical profiles of mean cup windspeed ("S") and mean temperature[3] on a mast standing in the (by assumption, horizontally-homogeneous) flow upwind of its disturbance by a windbreak. The mean profile data (Tables 1, 2) suffice to determine the MOST scaling parameters for each interval, however in addition a 3-dimensional sonic anemometer at $z = 2$ m on the mast provides an *independent* and direct estimate of the MOST scales, by manipulation of the statistics it provides (Tables 4, 5). A wind vane on the mast provided the mean wind direction ("θ") in the compass convention.

The porous plastic windbreak, whose height and resistance coefficient were $h = 1.25$ m, $k_r = 2.4$, was erected in a straight line oriented N-S. A perpendicular (W-E) transect of cup anemometers standing at $z/h = 0.5$ measured the effect of the windbreak on the mean flow, at streamwise locations $x/h = (-15, -1, 2, 4, 6, 10, 20)$, with the lowest cup anemometer on the mast providing the reference windspeed $S_0 \equiv S(x = -15h, z = h/2)$.

Task 1: Surface-layer parameters from mean profiles

For each 15 min interval, analyse the mean profile data on the mast to provide the friction velocity u_*, the temperature scale T_*, the Monin-Obukhov length L, and the sensible heat flux density[4] Q_H (you will need to write a computer program to do this: the general outline of a method is given below). Plot at least two of the given mean profiles alongside your corresponding theoretical profiles (i.e. those implied by your derived u_*, T_*). Also plot (on one graph) the complete set of mean wind profiles, normalizing each profile using the "reference velocity" S_0 provided by the lowest cup anemometer on the mast. Deduce the surface roughness length z_0.

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[1] These data are also available in electronic form by downloading a file from the class web site.

[2] For details, see Wilson (2004; J. Applied Meteorol. Vol. 43, 1149-1167)

[3] Or more precisely, mean temperature *differences* ("$\overline{T} - \overline{T}_{ref}$") relative to a reference temperature at $z = 0.34$ m.

[4] The mean temperature T_0 during this period was about 20° C, and for the purpose of calculating the density ρ_0 you may assume the atmospheric pressure $p = 93$ kPa.

Task 2: Surface-layer parameters from the sonic anemometer

From the sonic data compute alternative estimates u_*^s, T_*^s, L^s and mean wind direction $\beta_s = \arctan(V/U)$ (correct for the orientation of the sonic frame, ie. add 90^o). Comment on the measured values of $\sigma_u/u_*, \sigma_v/u_*, \sigma_w/u_*$ in the context of MO similarity theory.

Task 3: Analysis of shelter effectiveness

Plot the raw transects (Table 3) of windspeed $S(x)$ across the windbreak, and also normalized transects $S(x)/S_0$. Estimate for each interval the fractional wind reduction $\Delta S/S_0 \equiv 1 - S/S_0$ at the location of minimum mean windspeed, and plot this parameter against mean wind direction and against the stability parameter h/L. Compare with the value $k_r/(1+2k_r)^{0.8}$ expected in neutral, perpendicular flow.

Appendix: Profile Fitting Method

Create the set of measured differences $\Delta S_z{}^m = S_z - S_{ref}$, $\Delta T_z{}^m = T_z - T_{ref}$ (etc.) where S_{ref} is the windspeed at a reference height, such as $z = 0.62$ m. To each of these differences there correspond (for any guess of the scales u_*, T_*) theoretical differences $\Delta S_z{}^t = (S_z - S_{ref})^t$ (etc.) that may be calculated from the Monin-Obukhov similarity profiles. Your scales should be optimal in the sense that they minimize the dimensionless residual:

$$\begin{aligned} R &= \frac{\sum_1^{N_S} (\Delta S^m - \Delta S^t)^2}{\delta S^2} \\ &+ \frac{\sum_1^{N_T} (\Delta T^m - \Delta T^t)^2}{\delta T^2} \end{aligned}$$

Here $\delta S, \delta T$ are the estimated characteristic uncertainties in windspeed and temperature difference; assume values $\delta_S = 0.05$ m s^{-1}, $\delta_T = 0.1$ °C. In the present case the number of velocity differences is $N_S = 3$ and $N_T = 2$. The simplest computational approach is to use a nested loop: scan through all combinations of u_*, T_* covering a physically reasonable range, say, $0.05 \leq u_* \leq 0.5$ m s^{-1} (with interval 0.01) and -5 K $\leq T_* \leq 0$ (with interval 0.01).

Please note that in unstable stratification the temperature profile can be represented as

$$\overline{T}(z) - \overline{T}(z_0) = \frac{T_*}{k_v} \left[\ln \frac{z}{z_0} - \psi_h\left(\frac{z}{L}\right) + \psi_h\left(\frac{z_0}{L}\right) \right]$$

where $\psi_h = 2\ \ln\left[\frac{1}{2}\ \left(1 + {\phi_h}^{-1}\right)\right]$. Dyer and Bradley (1982; BLM Vol. 22, 3-19) recommended $\phi_h(z/L) = (1 - 14\, z/L)^{-1/2}$.

Table 1: Profiles of (uncorrected) 15 min mean cup windspeed $[\mathrm{m\,s^{-1}}]$ in an undisturbed ASL, Ellerslie (AB), 22 May, 2003 (on all tables, end times are given in Local Standard Time). Measurements have been rounded to nearest 0.01 $\mathrm{m\,s^{-1}}$. The cup anemometers should be assumed to have overestimated the mean speed by 8%, and each value should be corrected accordingly.

			HEIGHT	
t_{end}	0.62 m	1.57 m	3.07 m	5.02 m
1600	3.33	4.04	4.49	4.84
1615	3.24	3.98	4.47	4.83
1630	2.83	3.43	3.80	4.10
1645	3.31	4.09	4.66	5.07
1700	2.52	3.11	3.46	3.73
1715	3.48	4.37	4.95	5.38
1730	2.28	2.82	3.16	3.43
1745	2.94	3.62	4.07	4.43
1800	3.17	3.92	4.46	4.84
1815	2.71	3.40	3.88	4.26
1830	2.29	2.90	3.30	3.62
1845	2.36	2.94	3.35	3.67

Table 2: Profiles of 15 min mean temperature difference [K] in an undisturbed ASL, Ellerslie (AB), 22 May, 2003. Negative entries imply the upper level is cooler than the lower (reference) level, implying unstable stratification.

t_{end}	1.31 m (-) 0.34 m	4.25 m (-) 0.34 m
1600	-0.84	-1.40
1615	-0.92	-1.53
1630	-0.85	-1.34
1645	-0.67	-1.14
1700	-0.80	-1.18
1715	-0.57	-0.92
1730	-0.23	-0.33
1745	-0.22	-0.34
1800	-0.15	-0.20
1815	-0.0074	0.017
1830	0.24	0.42
1845	0.31	0.52

Table 3: Transects of mean cup windspeed (rounded to nearest 0.01 m s^{-1}) at $z = 0.62$ m ($z/h = 0.5$) along a perpendicular to the windbreak, spanning $-15 \leq x/h \leq 20$. The mean wind direction (θ) was measured in the upwind, undisturbed flow (a westerly, exactly normal to the windbreak, has $\theta = 270^{\mathrm{o}}$). Measurements made at Ellerslie (AB), 22 May, 2003. Note: the cup anemometers should be assumed to have overestimated the mean speed by 8%, and each value should be corrected accordingly.

					x/h			
t_{end}	θ	-15	-1	2	4	6	10	20
1600	305	3.33	2.79	1.86	1.89	2.17	2.52	2.98
1615	299	3.24	2.77	1.89	1.73	1.95	2.42	2.83
1630	280	2.83	2.40	1.53	1.49	1.65	2.07	2.48
1645	283	3.31	2.82	1.83	1.66	1.86	2.35	2.94
1700	269	2.52	2.09	1.31	1.20	1.38	1.83	2.27
1715	281	3.48	3.00	1.88	1.67	1.91	2.55	3.34
1730	307	2.28	2.00	1.30	1.30	1.49	1.87	2.16
1745	302	2.94	2.45	1.59	1.55	1.69	2.14	2.56
1800	288	3.17	2.60	1.59	1.43	1.59	2.14	2.69
1815	278	2.71	2.20	1.31	1.17	1.31	1.75	2.35
1830	287	2.29	1.89	1.22	1.18	1.36	1.66	2.15
1845	313	2.36	2.06	1.36	1.31	1.55	1.89	2.13

Table 4: Velocity statistics (MKS units) from the sonic anemometer at $z = 2.00$ m on the upwind mast. The sonic was 'facing' west, thus when $v = 0$ wind direction is 270°. In principle, the statistics should be rotated into a frame for which $\overline{w} = 0$, but we shall neglect this step. All components of the Reynolds stress tensor $R_{ij} \equiv \overline{u_i' u_j'}$ can be computed from the given data.

t_{end}	$\overline{\sqrt{u^2+v^2}}$	$\overline{u}$	$\overline{v}$	$\overline{w}$	$\overline{uu}$	$\overline{vv}$	$\overline{ww}$	$\overline{uv}$	$\overline{uw}$	$\overline{vw}$
1600	3.8911	3.0302	1.8369	0.02797	11.091	5.3169	0.13858	5.0236	0.00715	0.00728
1615	3.8344	3.1779	1.7024	0.01642	11.959	5.1048	0.13379	5.9387	-0.00238	-0.00505
1630	3.3915	2.8322	0.87041	-0.00192	10.261	3.3805	0.11158	3.2606	-0.02209	-0.0007
1645	4.062	3.4954	0.80817	0.02067	13.94	3.9946	0.14443	2.6813	0.00212	-0.00099
1700	3.1466	2.8657	-0.24558	0.01233	10.099	1.5816	0.12456	-0.95182	0.00265	-0.00165
1715	4.2673	3.9732	0.889	0.08001	17.588	2.7315	0.18221	3.7178	0.18194	0.05048
1730	2.8478	2.2395	1.5841	0.00487	5.6528	3.1505	0.06604	3.596	-0.03078	-0.00674
1745	3.4946	2.8851	1.5797	0.00889	9.6414	3.6841	0.09758	4.4309	-0.00306	-0.03642
1800	3.8828	3.5494	1.0493	0.00491	13.572	2.4648	0.10391	3.7716	-0.0565	-0.01844
1815	3.4068	3.1655	0.17019	0.00166	11.066	1.4712	0.09773	0.04456	-0.04546	0.0385
1830	2.9145	2.464	0.94502	-0.00898	6.6746	2.576	0.06216	2.6348	-0.04173	-0.02076
1845	2.8312	2.0503	1.8399	-0.00517	4.6244	4.0064	0.0528	3.8413	-0.03112	-0.04291

Table 5: Temperature and heat flux statistics (MKS units) from the sonic anemometer at $z = 2.00$ m on the upwind mast. From these data the eddy heat fluxes can formed as, for example, $\overline{u'T'} = \overline{u\,T} - \overline{u}\,\overline{T}$.

t_{end}	$\overline{T}$	$\overline{T\,T}$	$\overline{u\,T}$	$\overline{v\,T}$	$\overline{w\,T}$
1600	20.023	401.4	60.634	36.547	0.66429
1615	19.97	399.2	63.45	33.994	0.42466
1630	19.837	393.96	56.439	17.35	0.054
1645	20.231	409.62	70.755	16.312	0.49237
1700	20.062	402.79	57.626	-5.0379	0.31351
1715	20.499	420.5	81.243	18.17	1.7131
1730	19.9	396.24	44.506	31.641	0.12985
1745	20.043	401.8	57.865	31.548	0.19873
1800	20.189	407.65	71.591	21.223	0.12048
1815	20.132	405.33	63.711	3.424	0.03931
1830	19.917	396.71	49.127	18.883	-0.1858
1845	19.849	394	40.716	36.55	-0.11142