Boundary Layer Meteorology

Series 4

Introduction

The aim of this series is to practice the analysis of turbulence data. The data are from the *Cabauw Experimental Site for Atmospheric Research* (*CESAR*), The Netherlands (4.926°E, 51.97°N, -0.7 m.a.s.l.) (Monna & Bosveld, 2013; see also https://ruisdael-observatory.nl/cesar/).

In principle, the assignments can be solved in a spreadsheet environment such as Excel. We nevertheless strongly recommend trying to write short programs in *Python*, or *R*.

Important remark: Assignments 1c), 2b), 3d), 4c) and 5 are optional. We encourage you to solve them, but they do not count for the final score!

Assignment 1: Stability (3 points)

Open the file "SurfaceData_Cabauw_05-10-May-2008.txt". The file contains half-hourly data collected between May 5 and May 10, 2008, for the following variables:

- *year* : year
- *month* : month
- *day* : day
- *hour* : decimal hour [UTC]. The given numbers refer to the mid time of each 30-min. interval. Hence, e.g., 11.25 means 11 h 15 min and indicates the 30-minute interval between 11:00 and 11:30.
- *Ta002* : temperature T [°C] at $z = 2$ m
- *U010* : windspeed $\bar{u}_{10}$ [m s^{-1}] at $z = 10$ m
- *ust005* : friction velocity u_* [m s^{-1}] at $z = 5$ m
- *wT005* : kinematic heat flux $\overline{w'T'}$ [m s^{-1} K] at $z = 5$ m.

Missing data are coded as "NaN".

a) Compute the Obukhov length L and display its diurnal cycle (plot L as a function of time of the day). Are your results in line with Fig. 5.21 from Stull (1988) (see below)? Hints: (i) Since we are at sea level, assume $\bar{\theta} \simeq \bar{T}$ when evaluating the buoyancy parameter; (ii) Some of the computed values for L are very large in absolute. Limit the range on the y-axis to -150 to 200 m, as Fig. 5.21 from Stull (1988).

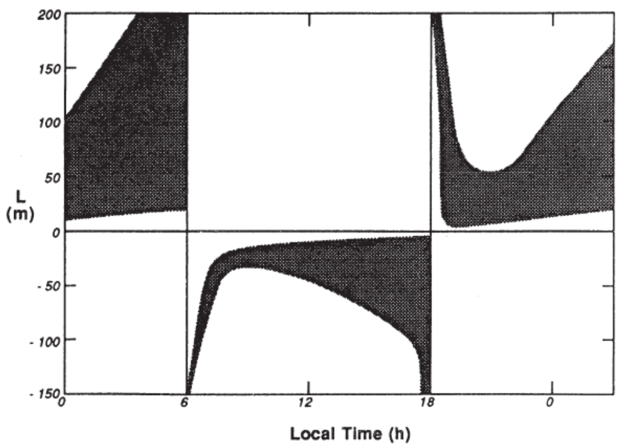

Fig. 5.21: Typical values of Obukhov length (L) over a diurnal cycle (Stull, 1988)

b) When do conditions switch from stable to unstable and, later during the day, from unstable to stable? How are these transition times related to the time of sunrise and sunset? Note that because time is given as UTC, the sun rises at around 4 am and sets at around 7 pm, in early May at Cabauw.

c) (Optional) Examine the effects of mechanical mixing on stability by plotting the absolute value of the stability parameter z/L as a function of the mean wind speed $\bar{u}_{10}$. Which wind-speed range supports conditions close to neutral ($|z/L| < 0.2$)? Hint: it is more convenient to display $|z/L|$ on a log scale. Set the limit on this log scale to between 0.005 and 5.

Assignment 2: wind profile and friction velocity (3 points)

In this exercise we look at the relationship between mean wind speed and friction velocity. We use the same data as in Assignment 1 and assume that both u_* as well as $\bar{u}_{10}$ were collected within the surface layer. In this case, Monin-Obukhov similarity tells us that:

$$\bar{u}(z) = \frac{u_*}{k}\left\{\ln\left(\frac{z}{z_0}\right) - \psi_m\left(\frac{z}{L}\right)\right\}$$

where k is the von Kármán's constant, z_0 the roughness length and ψ_m is the integral profile function. For unstable conditions ($z/L < 0$), ψ_m is given by:

$$\psi_m\left(\frac{z}{L}\right) = \ln\left[\frac{(1+x)^2}{2}\right] + \ln\left[\frac{(1+x^2)}{2}\right] - 2\,\mathrm{atan}(x) + \frac{\pi}{2}$$

with $x = (1 - 16\,z/L)^{1/4}$. For stable conditions ($z/L \geq 0$), we have:

$$\psi_m\left(\frac{z}{L}\right) = -5\frac{z}{L}$$

Tasks:

a) Plot u_* against $\bar{u}_{10}$ and fit a linear model (you can do it by eye if you are not familiar with implementing linear regression in a programming environment). How large are the slope and intercept? Based on this model, what would be a rule-of-thumb for estimating u_* given measurements of $\bar{u}_{10}$? How does this estimate compare to a quick and dirty evaluation of the log wind profile (i.e., without consideration of the effects of stability)? Assume $z_0 = 0.02$ m.

b) (Optional) Use the expression of the diabatic wind profile above to compute an estimate of the friction velocity (denote this estimate by $\tilde{u}_*$ or another meaningful symbol) for all measurements of the month. Assume, as in a), $z_0 = 0.02$ m. Plot $\tilde{u}_*$ versus u_*. Do the data points scatter around the 1:1 line, as expected for a proper choice of the stability functions and roughness length?

Assignment 3: time series, distributions, and moments (4 points)

Download the file "Cabauw_TimeSeries_09May2008_05000530_rotated.txt", which includes time series of the wind components and of the temperature collected at Cabauw on May 9, 2008, between 05:00 and 05:30 UTC, at $z = 3$ m above ground. The temporal resolution is 0.1 s (i.e., the data were collected at 10 Hz frequency), and there are 18'000 entries in the record. For your convenience, the wind velocity data have already been rotated into the mean wind.

The columns in the file refer to the following variables:

- *yyyy* : year
- *mm* : month
- *dd* : day
- *MIN* : minute
- *SEC* : second
- *u* : longitudinal wind component (in [m s^{-1}])
- *v* : lateral wind component (in [m s^{-1}])
- *w* : vertical wind component (in [m s^{-1}])
- *T* : absolute temperature (in [K])

a) Plot the time series of u, v, w, and T and estimate by eye the order of magnitude of the turbulent fluctuations in each series. Hint: we are not interested in something like $u' \approx 0.235$ m s^{-1}, but rather in $u' \sim \mathcal{O}(0.1$ m s$^{-1})$.

b) Calculate for each variable mean and standard deviation (over the full length of the record). Do the results for $\bar{v}$ and $\bar{w}$ (rounded to at most 2 digits after the comma) verify the assertion that we are in streamwise coordinates? Do the results for σ_u, σ_v, σ_w, and σ_T validate your guess of the order of magnitude of the turbulent fluctuations in a)?

c) What is the turbulence intensity in the mean wind direction? What is the turbulent kinetic energy, TKE, for this 30 min interval? Is the value you obtain in the range of those displayed in Fig. 6.1. of the Lecture Notes? (Hint: the data used here refer to a time of the day around the transition from stable to unstable conditions in the early morning).

d) (Optional) Estimate the friction velocity, $u_* = \left(\overline{u'w'}^2 + \overline{v'w'}^2\right)^{1/4}$, the kinematic heat flux $\overline{w'\theta} \cong \overline{w'T'}$ and the Obukhov length L. Furthermore, evaluate σ_w/u_*. Does the value of z/L, where (in this exercise) $z = 3$ m, confirm that the data were collected under approximately neutral conditions? How close are the value of σ_u/u_*, σ_v/u_* and ,σ_w/u_* to the standard estimates $\sigma_u/u_* = 2.5$, $\sigma_v/u_* = 1.9$ and $\sigma_w/u_* = 1.3$ (cf. Series 3)?

Assignment 4: turbulence spectra (4 points)

Download the file "Cabauw_SpecDens_09May2008_05000530.txt", which includes (one-sided) spectral densities of the wind velocity components for the 30 min. interval between 05:00 and 05:30 UTC on May 9, 2008 (the same 30 min.-interval of Assignment 3). To compute the spectral densities, the data were processed following the guidelines given in Kaimal and Finnigan (1994, Ch. 7). The columns in the file refer to the following variables:

- *freq* : the natural frequency (f in [s^{-1}])
- *Su* : the spectral density for the longitudinal wind component (S_u in [m^2 s^{-1}])
- *Sv* : the spectral density for the lateral wind component (S_v in [m^2 s^{-1}])
- *Sw* : the spectral density for the vertical wind component (S_w in [m^2 s^{-1}])

a) Verify that the integrals of S_u, S_v and S_w are equal (to within $\pm$15%) to variances you computed in Assignment 2, i.e., that:

$$\int_0^\infty S_u(f)\, df \;=\; \sigma_u^2, \qquad etc.$$

Use the trapezoidal rule to evaluate numerically the integrals:

$$\int_0^\infty S_u(f)\, df = \sum_{i=2}^{N} \frac{1}{2}\left(S_{u,i} + S_{u,i-1}\right)(f_i - f_{i-1}), \qquad etc.$$

where $N = 9000$ is the total number of entries in the file.

b) Assuming surface layer scaling (z = 3 m) and neutral conditions ($\phi_\varepsilon \cong 1$), plot the spectra in non-dimensional form (cf. Eq. (7.33) and Figs. 7.4 and 7.5 in the lecture notes of Chapter 7, p. 9 ff.).

c) (<u>Optional</u>) Compare your results with the empirical models for neutral conditions proposed by Olesen et al. (1984):

$$\frac{f\,S_u(f)}{u_*^2} = \frac{n\,S_u(n)}{u_*^2} = \frac{79\,n}{1 + 263\,n^{5/3}}$$

$$\frac{f\,S_v(f)}{u_*^2} = \frac{n\,S_v(n)}{u_*^2} = \frac{13\,n}{1 + 32\,n^{5/3}}$$

$$\frac{f\,S_w(f)}{u_*^2} = \frac{n\,S_w(n)}{u_*^2} = \frac{3.5\,n}{1 + 8.6\,n^{5/3}}$$

For which of the wind velocity components and for which frequency range do you find the largest systematic departure between data and model?

Assignment 5 (optional): inertial and dissipation subranges

Consider again the datafile "Cabauw_SpecDens_09May2008_05000530.txt" and your solution to Assignment 4b).

a) Looking at your plots, at which frequency (roughly) would you set the lower limit of the inertial subrange (i.e., the transition from the energy-input to the inertial subrange)? Verify your answer by plotting the ratios of the spectral densities, S_v/S_u and S_w/S_u, and looking for the frequency at which the ratios start to fluctuate within ±30 % of the theoretical value of $4/3$.

b) Using the spectral densities for u, S_u, estimate the mean dissipation rate of TKE, ε [m^2 s^{-3}]. As shown in the lecture notes (Ch. 7, p. 9), invoking Kolmogorov's first hypothesis, within the inertial subrange (and only there!) we have:

$$f\, S_u(f) = \alpha \left(\frac{2\pi\, f}{\bar{u}}\right)^{-2/3} \varepsilon^{2/3}$$

where $\alpha = 0.55$. (Hint: consider only frequencies well within the inertial subrange.)

c) Evaluate the Kolmogorov time scale τ_K (Chapter 7, p. 9) using your estimate of the dissipation rate in 5b) and infer the corresponding frequency ($f_K = 1/\tau_K$). Do the data in the file used for this exercise extend into the dissipation range? Hint: How does the highest frequency in the record compare to your estimate of the Kolmogorov frequency? Use $1.53 \cdot 10^{-5}$ m^2 s^{-1} for the molecular viscosity of air.

References

Kaimal, J. C., and J. J. Finnigan., 1994: Atmospheric Boundary Layer Flows: Their Structure and Measurement. Oxford University Press, Oxford, 289 pp.

Monna, W., and F. Bosveld, 2013: In Higher Spheres – 40 years of observations at the Cabauw Site. KNMI-Publication 232, De Bilt, 56 pp.

Olesen, H. R., S. E. Larsen, and J. Højstrup, 1984: Modelling velocity spectra in the lower part of the Planetary Boundary Layer. Boundary-Layer Meteorology, 29, 285-312.

Stull, R. B., 1988: An Introduction to Boundary Layer Meteorology. Kluwer Academic Publishers, Dodrecht, 666 pp.