9.1 THE JOINT EDDYCOVARIANCE PROJECT (JEP): TOWARDS A STANDARD FOR THE INTERPRETATION OF EDDY-COVARIANCE MEASUREMENTS

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see http://www.met.wau.nl/projects/JEP
for theory, practice, software and discussion on Eddy-Covariance

INTRODUCTION

The eddy-covariance technique (EC) is broadly considered to be today's reference method for the estimation of surface fluxes (Kaimal and Finnigan, 1994). New methods for flux-estimation have to be successful in tests against this method before they are accepted by the micro-meteorological community. Interestingly enough there is no standard recipe for the processing of EC-data. Some of the widely used corrections have been approximated for limited application to Reynolds-averaged data only, whereas with today's technology the use of raw data is common practice and no approximations have to be made. Other corrections are inter-dependent and require an iterative approach and again others are so marginally known that nobody uses them. There is a lot of improvising involved in EC, with the risk of vulnerability to wishful tuning.

In 1998 Henk A.R. De Bruin has started a project to collect the state of the art in eddy-covariance technique, with the aim to set a (continuously developing) standard, to which everybody can refer, contribute and take his recourse. This is done via a discussion forum on the Internet and download sections for a report describing the theoretical and practical details plus a software-package implementing the relevant relations in FORTRAN libraries.

In this presentation we will review how, according to the current state of the JEP-project, measured EC-data should be interpreted. The emphasis will be on new insights, which include: an error-estimate for all derived quantities, iteration-considerations, improved humidity correction for the sonic temperature, oxygen correction for hygrometers and planar fit tilt correction in combination with a correction for flow-distortion.

1. EC BASICS

In the report that can be downloaded from the JEP-site, we start with the energy budget at the surface (figure 1), which consists of (incoming and outcoming, short-wave and long-wave) radiation, fluxes of latent heat and sensible heat, soil heat flux and a crop-term (which is neglected). We use the method outlined by Sun et al. (1995) to integrate the continuity equations for energy and for chemical species. In this way we formulate budget-equations for heat, water vapour, momentum and chemical species over a volume (figure 2) spanned by the surface and the top of the homogeneous transition layer (HTL, a thin layer above the ground, too thin to contain source terms, in which molecular diffusion is transformed into turbulent diffusion). In a second step we extend the budget equation for the HTL to the homogeneous constant flux layer, which allows for the application to samples taken at common measurement heights. Special attention is paid to the definition of the sensible heat flow H (see figure 1). A reference temperature for H is found to be applicable only when there is a temperature jump at the surface. The physical background of the Webb-velocity is discussed (see figure 3). Together with the residual run-mean vertical velocity after a (modified) planar fit correction, (Wilczak et al., 2001) the Webb-velocity leads to a transport of the mean concentration of physical quantities, apart from covariance flux.

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2. RECIPE FOR DATA PROCESSING

After the theoretical section, the report presents the practical steps in EC. The following sequence of steps is suggested to convert sets of raw measured eddy-covariance data into flux-estimates and associated tolerance levels:

1. Before any record of measured data is touched, correction matrix $\overline{\overline{W}}_{\text{dist}}$ for flow distortion by relatively small obstacles (modelled with an ellipsoid) can be calculated via the procedure given by Oost (1991).

2. Raw voltages and bytes are read from file. Known constant delays between the channels are compensated by appropriate shifted reading of the sequences.

3. Synchronized raw data is converted from voltages and bytes into physical quantities with use of known calibration functions. In this calibration step the sonic velocity is corrected for the velocity bias that is estimated by putting the sonic in a closed box and the sonic temperature estimates are corrected for side-wind via the procedure by Liu et al. (2001) (only if this has not yet been done in hardware in de the sonic).

4. In the second iteration of this recipe, the tiltcorrections that were found in the first iteration (see step 10) are applied to the raw data as part of the calibration.

5. In *both* calibration iterations all velocity vectors are corrected for flow-distortion via matrix $\overline{\overline{W}}_{\text{dist}}$ from step 1.

6. Provisional mean quantities are calculated.

7. Measurements of a slow and stable hygrometer are used to improve the mean value of the (possibly drifted) calibration of the optical hygrometer (usually not used for Licor 7500 hygrometers).

8. Variances and covariances are corrected for linear additive trends.

9. For each run, the mean and (co-)variances of the calibrated quantities are estimated.

10. In the first iteration of this recipe, the effects of misalignment of the set-up on the mean quantities and on the (co-)variances is estimated via either of the following tilt-corrections:

    (a) Classic yaw, pitch and roll-corrections. The assumptions are that the mean velocity per run cannot have a vertical component and that lateral velocity correlations must vanish.

    (b) The Planar Fit Method. This method assumes that the set-up has a stationary misalignment. This misalignment is estimated from the collection of run-mean velocity vectors. The planar fit method can be extended to effectively reproduce the results of the triple-tilt-correction in the former suggestion, with the advantage that now the angles of different runs and of different set-ups are comparable, which was not the case with the yaw, pitch and roll-angles of the triple tilt.

    Both tilt-corrections involve simple matrix-multiplications on the mean quantities and on the (co-)variances. With a modified tilt correction (based on planar fit) we rotate the plane through the collection of run-mean velocities to an inclination that will be horizontal *after* the correction for flow-distortion in step 5 in the second iteration.

11. Now that the tilt-angles are known, all previous steps (except for the first two steps) in this data-reduction recipe are repeated, but now the tilt-corrections are carried out on the raw data.

12. In this second iteration tolerance estimates are generated for both mean quantities and for all (co-)variances. In figure 4 we show how the number of independent samples is estimated for a run of N samples: $N_{\text{indep}} = N_{\text{swap}}/p_{\text{swap}} - 1$, where the probability for two *independent* consecutive samples to have opposite signs is: $p_{\text{swap}} = 2N^{+}N^{-}/N^{2}$. Tolerance for any quantity $\overline{x}$ is estimated to be $\text{Tol}(\overline{x}) = 2\sigma(\overline{x}) = 2\text{RMS}(x')/\sqrt{N_{\text{indep}}}$. To correctly perform tilt-corrections on tolerance estimates, one would have had to record all possible third- and fourth-order correlations. Application of a second iteration eliminates the necessity for tilting of tolerances of covariances, because the tilting is now performed on the raw data.

13. All mean values and (co-)variances which involve the sonic temperature are corrected for humidity effects via modified versions of the relations by Schotanus et al. (1983). This correction is not applied to the raw data in the calibration-process, because in practice the hygrometer may drop out for certain samples or even during (short) periods. Skipping the bad samples of the hygrometer will still permit for the reliable estimation of mean humidity and of covariances with humidity. Therefore humidity corrections which rely on these estimates can still be used, whereas individual samples can no longer be corrected.

14. All (co-)variances involving humidity are corrected for oxygen sensitivity of the optical hygrometer via the procedure by Dijk et al. (2003). The temperature estimates, which are used in the oxygen correction procedure, were corrected for humidity in a previous step. This indicates that the relations for estimation of temperature and of humidity are coupled and should therefore in principle be solved simultaneously. We assume that our decoupled approach, which is first order in the errors involved, will provide sufficiently accurate estimates when these errors are sufficiently small (corrections on corrections are considered to be second order effects and consequently neglected).

15. The models by Moore (1986) and Horst (1999), fitted with the Kaimal et al. (1972)-model spectra, are used to correct (co-)variances for all types of frequency-response errors. Half of the absolute corrections which are made to the covariances are quadratically added to the tolerance estimates which were already made for the covariances.

16. The Webb-velocity (Webb et al., 1980) is added to the direct estimate for the mean vertical velocity.

17. Surface fluxes are estimated from the mean values and (co-)variances at measurement height δz. For scalars ξ with density ϱ_ξ, e.g. water vapour: $F(\varrho_v) \equiv E$, surface friction τ and sensible heat flow H:

$$\begin{aligned} F(\varrho_\xi) &= \overline{w'\varrho_\xi'}\big|_{\delta z} + \overline{w}\ \overline{\varrho_\xi}\big|_{\delta z}\,, \\ \tau &= -\,\overline{\varrho}\,\overline{w'u'} - \overline{u}\,E \\ H &= c_p\,\overline{\varrho}\,\overline{w'T'}\Big|_{\delta z} + \overline{J}_{rz}\Big|_{\delta z} - \overline{J}_{rz}\Big|_{0} \end{aligned}$$

    Radiation divergence terms $\overline{J}_{rz}\Big|_{\delta z}$ and $\overline{J}_{rz}\Big|_{0}$ should be available from additional peripheral measurements conducted during each run.

18. Tolerance levels are estimated for the surface fluxes. All surface fluxes have a term dependent on mean velocity $\overline{w}$. Even when the mean vertical velocity is rotated out with a tilt-correction, then a statistical error in $\overline{w}$ remains. This error expresses how well one can expect to eliminate the mean vertical velocity of other runs with the tilt-angles of this particular run. Here the number of eddies plays a role: the largest turbulent structures will be horizontally oriented. This implies that fluxes which depend on horizontal velocities (e.g. horizontal transport terms) will tend to have larger tolerances than fluxes which depend on vertical velocity (the ground fluxes).

3. SOFTWARE LIBRARY ECPACK

We have written an open source fortran library, named ECPack, containing all relevant EC-routines and an interface to raw measurements stored in NetCDF-format. ECPack can be downloaded for free from the JEP-site http://www.met.wau.nl/projects/JEP/index.html, together with the report that explains the theory and all practical steps. The library has been split into functionally different groups of routines (mathematics, corrections, general physics, IO, NetCDF). From the name of a routine one can see to which group it belongs. For each separate step in the data-processing, there is a 'vanilla'-routine that does nothing more than that particular step, with a minimum of required parameters. With a set of integrated routines one can take collections of steps in the data-processing in one call. The separate routines can easily be added by people to their existing programs to incorporate new functionality. The integrated routines, with a sample program, give an efficient tool for the processing of EC-data.

4. THE DISCUSSION FORUM

The implementations of the routines in ECPack and the theory in the report are open for improvement, criticism and suggestions for new methods. To facilitate discussion, we have opened a forum at the JEP site, where all eddy-covariance related topics can be discussed.

5. CONCLUSIONS

We hereby invite you to visit the JEP site. Either to download the report and associated fortran routines. Or to contribute to the debate on the forum. Have you already programmed a method that does not yet form a part of ECPack? Or do you think that your implementation is better? Please stand up! Only with your input, we can come to a reference in eddy-covariance that is open to the whole community!

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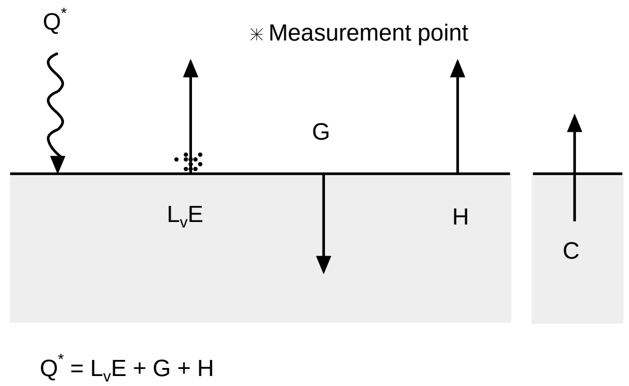

FIG. 1: Energy balance at the surface consists of one incoming term (net radiation Q^*) and three outgoing terms (latent heat L_vE, soil heat flux G and sensible heat H). Convection C *through* the surface does not contribute to the energy balance *at* the surface. Consequently only the conductive heat transfer is of interest for the sensible heat flux.

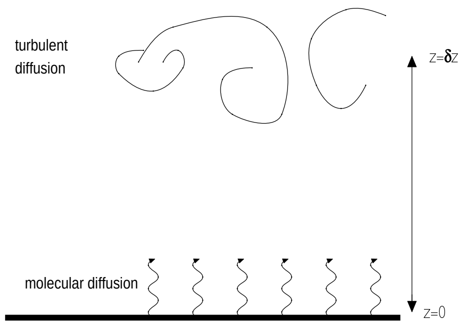

FIG. 2: Thin layer adjacent to the surface over which budget equations are integrated

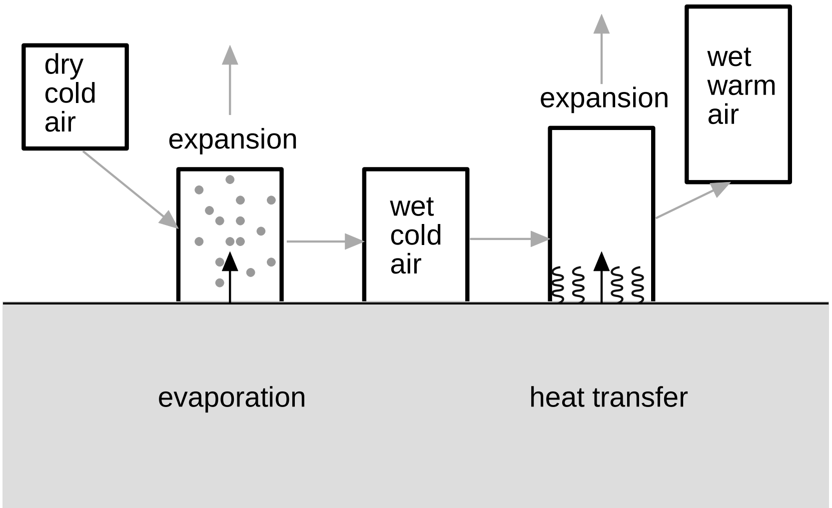

FIG. 3: Induction of mean vertical (Webb-)velocity via exchange with the surface of water vapour and heat

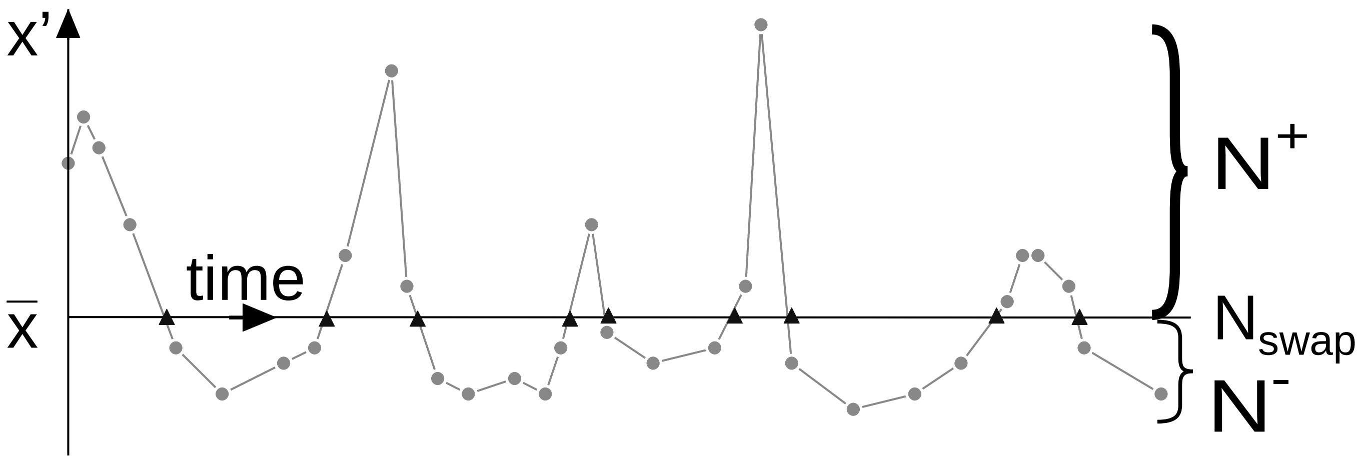

FIG. 4: Root-counting of fluctuations in oversampled data with a skew distribution