6.18

INTERPRETATION OF FLUX OBSERVATIONS ALONG THE CABAUW 200 M METEOROLOGICAL TOWER.

Fred. C. Bosveld[1], Erik van Meijgaard[1], Eddy Moors[2] and Cindy Werner[3]

[1] *Royal Netherlands Meteorological Institute, de Bilt, the Netherlands (KNMI).*
[2] *Wageningen University and Research, Wageningen, the Netherlands (WUR).*
[3] *USA-NSF, current affiliation: Geological and Nuclear Sciences, Wairakei, New Zealand.*

Introduction

Present-day atmospheric models for weather forecast and climate prediction typically employ horizontal grid specings from 5 to 50 km, while satellite based observations have pixel sizes of 1 to 10 km. The evaluation of model predicted surface fluxes or the validation of satellite retrieved surface fluxes requires an independent set of observations on comparable horizontal scales. Aeroplane and high tower based eddy-correlation, scintillometry and boundary layer height development are techniques that gives information on the desired scales. All these techniques are hampered with specific problems. Here we concentrate on high tower flux observations performed at the Cabauw 200 m meteorological tower, the Netherlands.

The eddy correlation technique has become a standard method to obtain vertical fluxes in the atmospheric surface layer. Especially for momentum, temperature, humidity and carbon dioxide high quality instruments are commercially available nowadays. Most of the corrections needed to obtain correct fluxes are well documented (e.g. Moncrieff et al., 1997). However, the often observed imbalance in the surface energy budget when using eddy-correlation techniques, remains an outstanding issue (Twine et al., 2000).

In the context of CESAR (*Cabauw Experimental Site for Atmospheric Research)* an observational program including tower fluxes, boundary layer development, scintillometers and soil hydrology is being operated during 2003-2005. Research goals are: 1) the estimation of regional scale fluxes, 2) the nature of the imbalances in the observed surface energy budget, and 3) night time flux estimates of CO2 with the atmospheric budget method at a relatively simple site. This study focuses on two aspects of high tower flux observations. Firstly, the influence of atmospheric advection and the role that atmospheric models may play in estimating this advective influence. Secondly, the desired averaging time and low frequency flux correction.

Fluxes of momentum, sensible heat, latent heat and carbon dioxide are measured at 5, 60, 100 and 180 m height. Additionally, the profiles of wind, temperature, humidity and carbon dioxide are measured. Turbulent fluxes are corrected for density fluctuations. Systematic tilts in the streamlines due to flow obstruction are corrected by performing a rotation of the covariance vectors. High frequency loss due to sensor separation can be shown to be very small, especially at higher levels. No correction is applied. Covariances are calculated on a 10 minute basis by subtracting the mean values of vertical wind and temperature, respectively, from the observed time series. In this study we focus on the temperature flux.

Atmospheric advection

If we try to relate vertical turbulent temperature flux F_{turb} observed at level z to the surface flux F_{surf} defined as the surface flux averaged over the footprint area of the observation (Schmidt, 1994) we have to take into account the rate of change of temperature storage in the profile below the observation level. Here we define the total temperature flux as:

$$F_{tot}(z) = F_{turb}(z) + \frac{d}{dt}\int_{z'=0}^{z} T(z')dz'$$

where T is temperature. For horizontal homogeneous conditions $F_{tot}(z)$ is constant with height and equal to F_{surf} . The relation between elevated flux and surface flux becomes disturbed when there is no horizontal homogeneity. The current definition takes into account variation of fluxes in the upwind terrain, but the storage term sees different footprints depending on height. Moreover the turbulent flux at height z may be disturbed due to the disturbed local gradient in the vertical temperature profile. We call this local advection. A second influence is the large scale advection of air masses with different temperature. This may be related to the development of synoptical systems or to the presence in upwind direction of land surface types (or the sea) with different thermal properties at larger distances to allow for a thorough mixing in the ABL before the air mass reaches the observational point. A change in F_{tot} as derived for different heights is an indication of the presence of advection, local or large scale. The surroundings of the Cabauw site are dominated by grassland which suggests that local advection is relatively small at least for temperature and humidity. Although the presence of the village of Lopik and the river Lek are likely to contribute local advection. For CO2 the situation is more complex since differences in grassland management may contribute to large variations in CO2 sources and sinks in the surroundings. In this study we limit to large scale advection.

For the estimation of the large scale advection we use the Regional Atmospheric Climate MOdel (RACMO) of KNMI. RACMO is a hydrostatic model with dynamics from the HIRLAM model and physics from a GCM (ECHAM4). The model domain is Europe and part of the North Atlantic. The model is run in forecast mode starting from 12:00 UTC the day before the day of interest. ECMWF lateral boundaries are prescribed during the whole forecast period. The lowest three model levels are at approx.

33, 134 and 265 m height. Tendencies are stored for the grid point Cabauw split into the dynamical tendencies (horizontal and vertical advection), the physical tendency and horizontal diffusion. Horizontal diffusion (or computational mixing) is introduced in numerical models to prevent the model from becoming numerically unstable. Horizontal mixing at the grid cell scale occurs in the real atmosphere but the efficiency is an order of magnitude smaller then the diffusion that is needed to keep the model stable. Due to the presence of the North Sea bordering the Netherlands, horizontal diffusion may be significant. We compared two RACMO runs one with a 55 km resolution and one with a 3 times higher resolution. In the 55 km run the Westerly neighbouring grid cell of Cabauw was in the North Sea. In the 18 km run the neighbouring grid cells were all land points. In the low resolution run horizontal diffusion was of the same order of magnitude as horizontal advection. In the high resolution run horizontal diffusion was much smaller then horizontal advection.

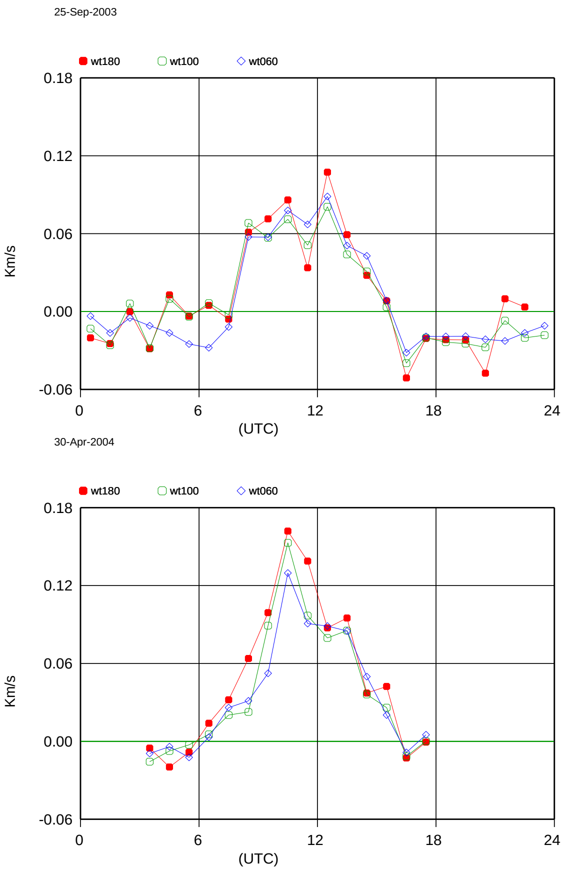

Figure 1 *F_{tot} at 180, 100 and 60 m for two days, 25-Sep-2003 and 30-apr-2004.*

Two contrasting days were selected. Figure 1 shows for two days the observed F_{tot} for the three levels 60, 100 and 180 m. The first day, 25-Sep-2003, with wind speed at 200 m of 6 m/s shows little change in F_{tot} with height during time. The second day, 30-Apr-2004, with wind speed at 200 m of 6 m/s shows significant increase with height during day time. The synoptical situation for both days was anti-cyclonic with South-Easterly winds. The second day showed fronts in the neighbourhood, which were not yet advected over Cabauw, and warmer air upwind over Germany. Figure 2 shows for both days the observed difference in F_{tot} between 180 and 60 m. Also shown is the difference derived from the dynamical tendencies as simulated by RACMO at the second model level. It is found that the model simulates little advection for the first day during daytime and significant advection for the second day. Simulated advection for the second day has the right sign and its value compares well with observations. Although limited in the number of days analysed, this suggests that total flux divergences observed in the lowest 200 m of the atmosphere can be coupled to the occurrence of large scale advection as simulated by an atmospheric model.

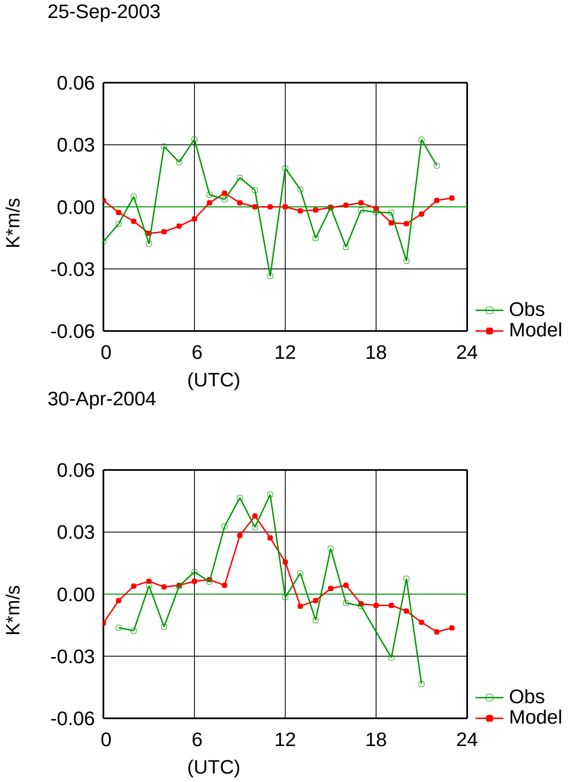

Figure 2 *F_{tot} difference between 180 and 60 m for two days from observations and model prediction.*

Averaging time

Having established that for 25-Sep-2003 case large scale advection is negligible, we turn to the issue of low frequency contribution to the turbulent flux (Vickers and Mahrt, 2003). Common practice in calculating eddy-correation fluxes is to define a time interval and to subtract mean quantities from the original time series. The result is that flux contributions on time scales longer than the chosen averaging time are negected. The time interval is chosen long enough that a statistical meaningfull result is obtained and short enough to resolve the desired features over the day. For observations at heights of 5 to 10 m, typical values are 10 to 30 minutes. Low frequency losses are typical a few percent depending on wind speed and stabilty.

Going to higher levels the whole co-variance spectrum shifts to the low frequency side. Also the characteristics of the turbulence may change due to the presence of organised thermal under convective conditions. Organised motions on the meso-scale are also more likely to have a significant contribution at higher levels in the atmospheric boundary layer then close to the ground.

Here we investigate this further by calculating the eddy covariance's for larger time basis than the original 10 minutes, e.g. 20, 30 and 60 minutes. Fluxes on a larger time basis <*wt*> can be reconstructed from a series of *N* 10 minute time based values $<wt>_n$, when also the 10 minute average vertical wind speed $<w>_n$ and temperature $<t>_n$ are retained:

$$< wt > = \tfrac{1}{N}\sum_{n=1}^{N} < wt >_n$$

$$+ \tfrac{1}{N}\sum_{n=1}^{N} < w >_n \cdot < t >_n - < w > \cdot < t >$$

where <*w*> and <*t*> are the average vertical wind speed and temperature over the entire interval of *N* 10 minute intervals. Figure 3 shows hourly values of F_{turb} for the three observational heights and for the time bases 10, 20, 30 and 60 minutes. As expected F_{turb} decreases with height especially in the morning. It is observed that going to longer time bases the hour to hour variation increases. Hour to hour variations for the 60 minute time basis are much larger then the changes in global radiation suggests. Table 1 lists the average fluxes for the period 8:00-16:00 UTC for each level and each time basis. The numbers show that the systematic contribution of long time scales to the turbulent flux is in general relatively small.

Discussion and conclusions

This paper describes a limited attempt - only two days are analysed - to interpret high tower flux observations for estimating regional scale fluxes. In contrast to eddy correlation measurements at low heights horizontal advection and low frequency flux contributions may play a dominant role here. The issue of advection is addressed by calculating the dynamic tendencies with an operational atmospheric model. An encouraging result is that for two contrasting days observations and model show qualitatively the same results. This analysis will be extended to incorporate humidity and CO_2. Advection of CO_2 behaves differently from temperature and humidity since the latter two can change in the atmosphere through absorption of radiation and condensation/evaporation. But, of course, also the sources and sinks at the earth surface have quite different distributions. To apply the method for CO_2 a model has to be used that incorporates sources, sinks and transport of CO_2. Such a model for the Dutch situation based on the meso-scale model RAMS is under development at WUR.

The issue of long time scales contributing to the turbulent flux is investigated by constructing turbulent flux estimates with longer time bases from the original 10 minute time based fluxes. It is observed that the hour to hour variation increases when going to longer time bases. On the average the long time scale contributions appears to be small for this day. This suggests that the long time scales merely induce noise through the statistical nature of turbulence. If this result proves to be more general then for this single day we might better search for a method to correct the 10 minute based turbulent flux estimates as is normally done for low height flux observations on the basis of surface layer scaling theory. Other parameters like boundary layer height may come into play here.

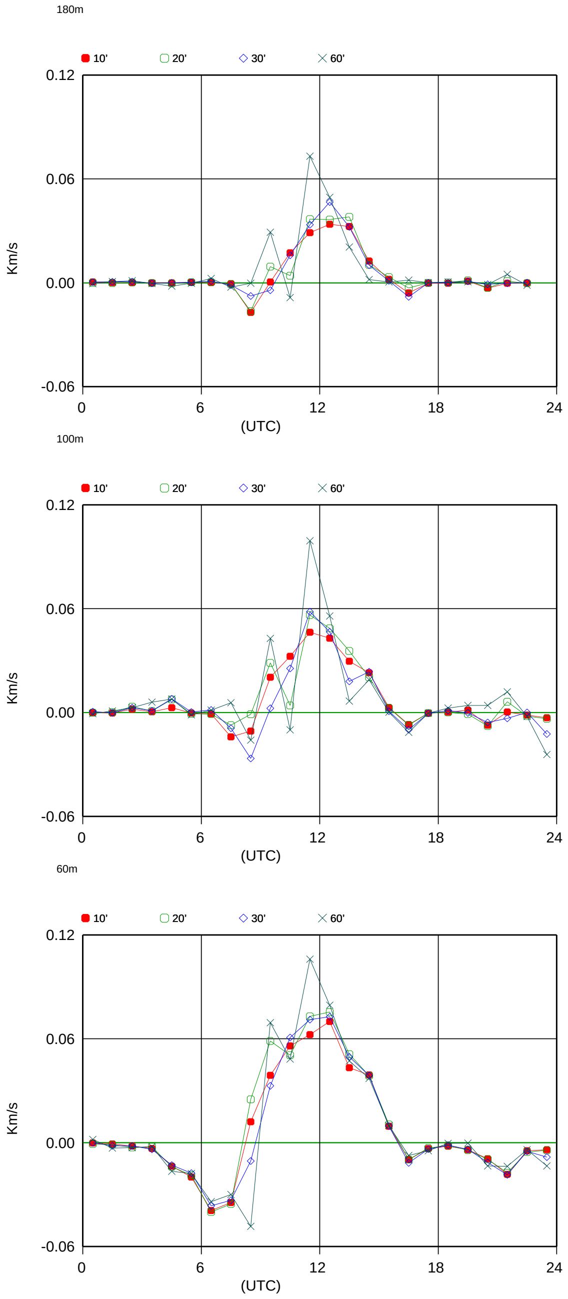

Figure 3 F_{turb} with different time basis for turbulent part of the flux at 180, 100 and 60 m. (from top to bottom)

Table 1 Average values of temperature flux (K·m/s) at 25-Sep-2003 between 8:00-16:00 UTC, total flux and turbulent flux with different time basis for three heights.

height	F_{tot}	F_{turb} →	10’	20’	30’	60’
180 m	0.057		0.014	0.015	0.016	0.021
100 m	0.051		0.023	0.024	0.019	0.025
60 m	0.056		0.041	0.048	0.041	0.044

References

Moncrieff J. B., J. M. Massheder, H de Bruin, J. Elbers, T. Friborg, B. Heusinkveld, P. Kabat, S. Scott, H. Soegaard and A. Verhoef (1997). A system to measure surface fluxes of momentum, sensible heat, water vapour and carbon dioxide. *Journal of Hydrology* **188-189**, 589-611.

Schmid H. P. (1994). Source areas for scalars and scalar fluxes*. Boundary layer meteorology*, **67**, 293-318.

Twine T.E., W.P. Kustas, J.M. Norman, D.R. Cook, P.R. Houser, T.P. Meyers, J.H. Prueger, P.J. Starks and M.L. Wesely (2000). Correcting eddy-covariance flux underestimates over a grassland. *Agric. And Forest Meteorology*, **103**, 279-300.

Vickers D. and L. Mahrt (2003). The cospectral gap and turbulent flux calculations. *J. Atm. Oc. Techn.*, **20**, 660-672