UDC 551.5

S.–E. Gryning[1], *Sc.D.*, **E. Batchvarova**[2], *Sc.D.*, **H. Soegaard**[3], *Prof., Sc.D.*
[1]*Risø National Laboratory DTU, Roskilde Denmark*
[2]*National Institute of Meteorology and Hydrology, Sofia, Bulgaria*
[3]*Institute of Geography and Geology, University of Copenhagen, Denmark*

UPSCALING OF MESOSCALE CO_2 FLUXES IN THE CONVECTIVE BOUNDARY LAYER

Abstract. *A method based on the evolution of the height of the convective boundary layer that has been successfully used for aggregation of sensible heat and momentum fluxes is here applied for aggregation of CO_2 fluxes over Zealand in Denmark. Inputs for the method are vertical profile measurements of CO_2 concentrations, standard measurements of the CO_2 concentration near the ground and successive radio-soundings. The aggregated fluxes of CO_2 represent a combination of agricultural and forest surface conditions.*

Keywords: *Aggregation of fluxes, CO_2, convective boundary layer, vertical profiles.*

1 Introduction

Neither the land nor the sea surface can be considered homogeneous with respect to fluxes of CO_2. The aggregation of CO_2 fluxes over sea and land surfaces is a critical factor when setting up the budget of the sources and sinks of carbon as done in i. e. the context of climate research and integrated assessment models for the environmental status of the sea and land (e. g. [1]). In meteorological models, the individual horizontal grid cells often enclose regions of pronounced inhomogeneities: over land in the vegetation and over the sea in the differential pressure of CO_2 between the air and the sea caused by i. e. biological activity. The estimation of the spatially integrated fluxes is therefore a central issue in a large number of scientific, practical and even political assessments of the role of CO_2 emissions for our present and future climate and environment. A method based on the evolution of the convective boundary layer were suggested by [5] and [3] for aggregation of sensible heat and momentum fluxes over inhomogeneous terrain. Here the method is extended for the aggregation of CO_2 fluxes.

2 Mass balance for CO_2

The aggregated flux of CO_2 can be derived from a mass budget for CO_2. The budget is derived from the surface to the top of the atmospheric boundary layer. The method takes into account the entrainment of air above the boundary layer caused by the growth of the boundary layer, as well as the effect of subsidence and the uptake of CO_2 by the vegetation at the ground. Following [6] and [4] the mass balance reads:

$$\underbrace{h\frac{d\chi_b}{dt}}_{\text{I}} = \underbrace{F_s}_{\text{II}} + \left(\chi_u - \chi_b\right)\left(\underbrace{\frac{dh}{dt}}_{\text{III}} - \underbrace{w_s}_{\text{IV}}\right) \tag{1}$$

where χ is the scalar concentration, F_s is the scalar flux to the surface (positive upward), h is the height of the boundary layer, and w_s is the large scale vertical velocity at the top of the boundary layer caused by convergence or divergence in the large scale flow field. During synoptic high pressure conditions, w_s is negative corresponding to downward motion or subsidence. Subscript b denotes a quantity within the boundary layer, u a quantity in the free air above the boundary layer. The first term in Equation (1) , I, represents the change of mass inside the boundary layer. Term II accounts for the uptake of CO_2 by the vegetation. Term III models the entrainment of CO_2 from air from above the boundary layer caused by the growth of the boundary layer and term IV the effect on the mass budget due to subsidence. Equation (1) can be written as:

$$\frac{d(h\chi)}{dt} = F_s + \chi_u \frac{dh}{dt} - (\chi_u - \chi_b) w_s \tag{2}$$

and reads in discrete form with t_1 and t_2 marking the beginning and end of a time interval:

$$\frac{h_2\chi_{b2} - h_1\chi_{b1}}{t_2 - t_1} = F_s + \chi_u \frac{h_2 - h_1}{t_2 - t_1} - (\chi_u - \chi_b) w_s . \tag{3}$$

Further it can be written as

$$h_1\chi_{b1} = h_2\chi_{b2} - (h_2 - h_1)\chi_u + (\chi_u - \chi_b)(t_2 - t_1) w_s - F_s (t_2 - t_1) . \tag{4}$$

Solving for the flux F_s it reads:

$$F_s = \frac{h_1(\chi_u - \chi_{b1}) - h_2(\chi_u - \chi_{b2}) + (\chi_u - \chi_b) w_s (t_2 - t_1)}{t_2 - t_1} . \tag{5}$$

The equation, however, does not consider the decrease of air pressure as function of height. The effect can be accounted for by introducing the molar density of air ρ (mol m^{-3}) and the CO_2 mixing ratio C (μmol$\cdot$mol^{-1}):

$$F_s = \frac{h_1\rho_{b1}(C_u - C_{b1}) - h_2\rho_{b2}(C_u - C_{b2}) + \rho_u w_s (C_u - C_b)(t_2 - t_1)}{t_2 - t_1} \tag{6}$$

3 Measurements

Micrometeorological measurements including fluxes and concentration of CO_2 were carried out over an agricultural site near Risø (RIMI) and over a beech forest in the centre of Zealand (Lille Bøgeskov). These monitoring stations are part of the CarboEurope network. Figure 1 shows the location of the sites. During an intensive measuring campaign 12-13 June 2006 the measurements were extended with profiles of CO_2 carried out by a research airplane and temperature and wind speed by frequent radio-soundings.

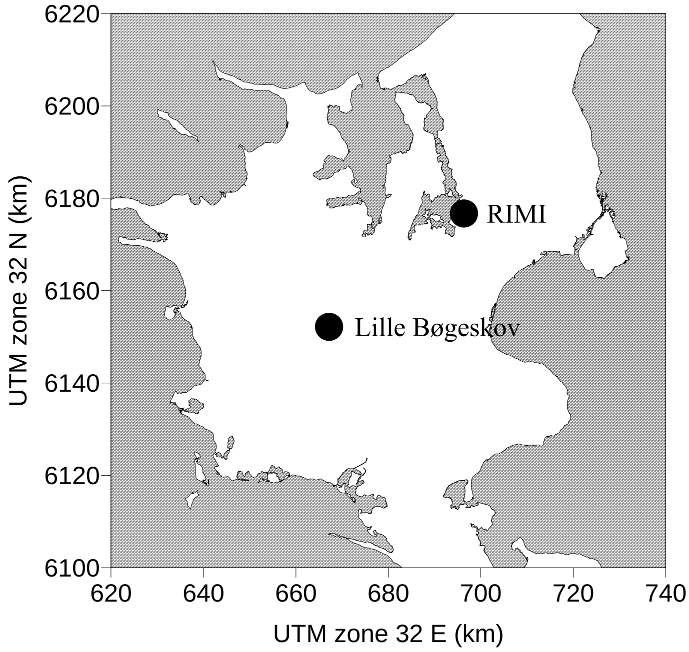

Fig. 1 – The position of the two measuring sites on the island of Sealand, Denmark; RIMI (agricultural) and Lille Bøgeskov (deciduous forest).

The meteorological conditions during the experiment were typical for a well developed large scale high pressure system, low wind speed from varying directions, a cloud free sky and strong insolation resulting in flux around noon of ≈200 Wm^{-2} for the sensible heat and exceeding 300 Wm^{-2} for the latent heat, Fig. 2. In the afternoon the temperature went beyond 25°C. Such conditions give rise to a considerable growth of the boundary layer and are characterized by negligible advection. They are very favorable for the use of budget methods based on the evolution of the convective boundary layer.

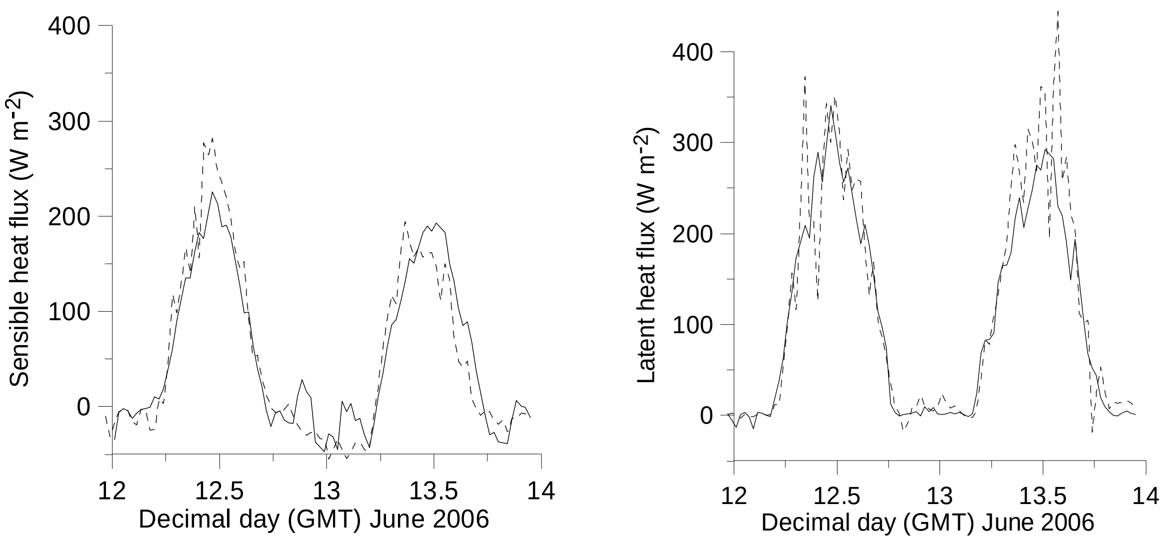

Fig. 2 – Illustration of the sensible and latent heat fluxes on 12 and 13 June 2006 at RIMI.

In order to derive the aggregated flux of CO_2 to the surface from Eq. (1) the development of the boundary layer, the vertical velocity w_s of the air as well as the concentration of CO_2 above the boundary layer, and the concentration of CO_2 near the ground should be known as function of time.

The height of the boundary layer at the RIMI site was determined by simultaneously considering several parameters in the radiosonde profile such as jumps in the temperature, wind-direction, wind-speed and humidity. Interpolation of the height of the boundary layer was performed by use of a formula for the height of the boundary layer (for details see [2] and [5]).

The measured and interpolated heights of the boundary layer are illustrated in Fig. 3.

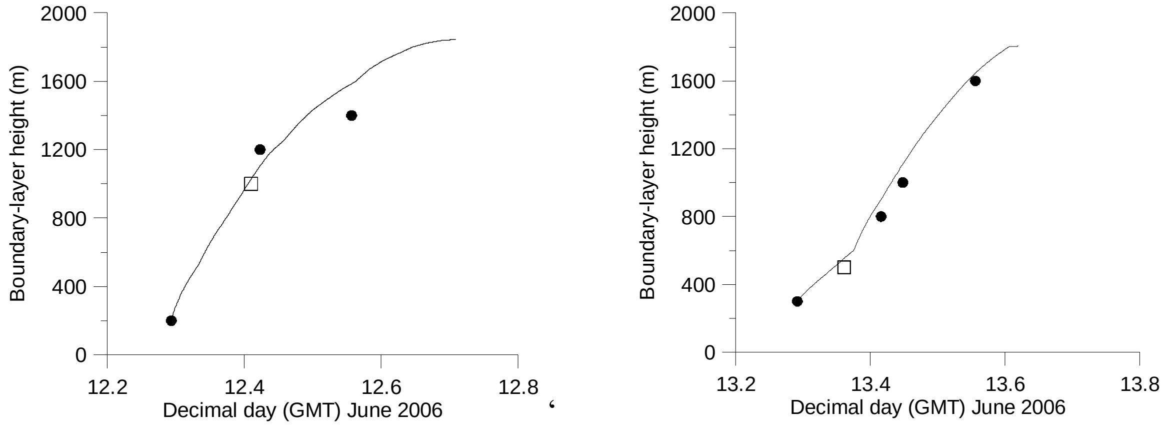

Fig. 3 – Interpolated height of the boundary layer on 12 and 13 June 2006. Radiosonde measurements are shows as bullets, airplane measurements by squares. Left panel 12 June and right panel 13 June 2006.

The height of the atmospheric boundary layer can also be detected in the vertical profiles of the CO_2 concentrations that were measured by the airplane, Fig. 4. On both days it can be seen that the CO_2 concentration inside the boundary layer is about 365 ppm and approximately constant with height. On 12 June a jump of 5 ppm in the CO_2 concentration

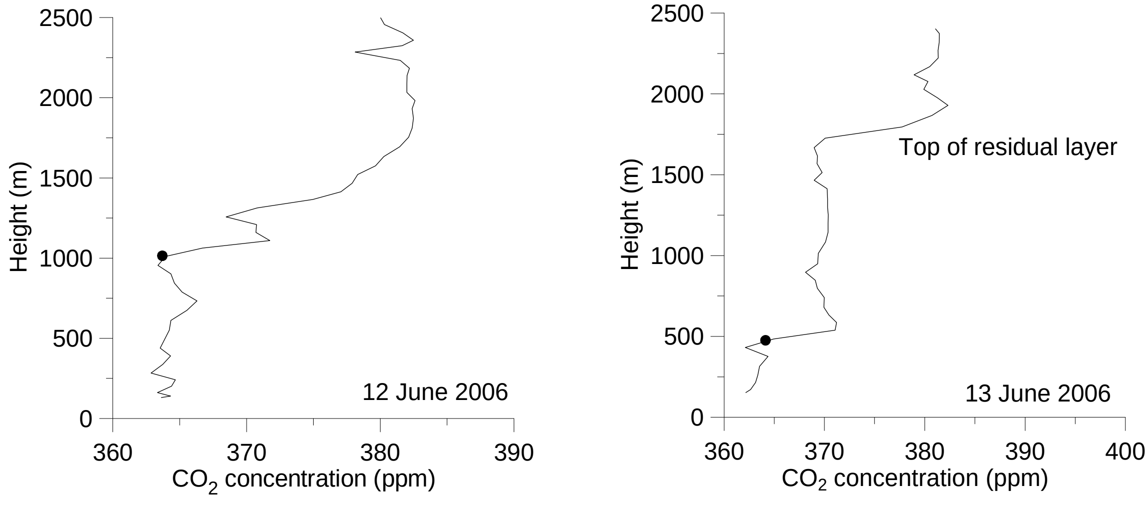

Fig. 4 – Profiles measured by the aircraft near the RIMI site of CO_2 concentration on 12 June at 09:50 and 13 June at 08:40 GMT. The height of the boundary layer is shown by a bullet, it is estimated to be 1000 and 500 meters respectively. Left panel 12 June and right panel 13 June 2006.

at 500 meters height marks the top of the growing boundary layer. On 13 June a jump in the CO_2 concentration at 1000 meters indicates the top of the boundary layer. It can be seen that the next jump takes place at about 1700 m which marks the top of the residual layer (top of boundary layer from the foregoing day). Above the residual layer the CO_2 concentration is about 380 ppm. The smaller concentration inside the boundary layer is caused by uptake of CO_2 by the vegetation. The boundary layer heights on both days are in agreement with the estimate from the radiosonde measurements, Figure 3.

4 Aggregated CO_2 fluxes

Using the above parameters the aggregated fluxes were determined by Equation (2). The results are shown below, Figure 5.

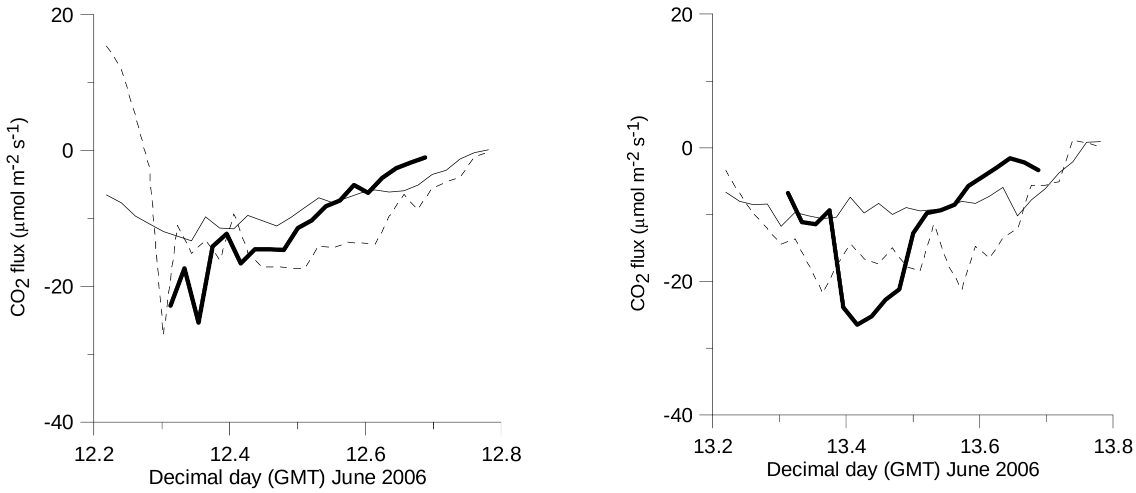

Fig. 5 – Measured CO_2 fluxes near the surface at RIMI/wheat (thin solid line), Lille Bøgeskov/deciduous forest (thin dashed line), and the regional CO_2 fluxes from the boundary layer method (thick solid line). Left panel 12 June and right panel 13 June 2006.

It can be seen that the aggregated flux of CO_2 in broad terms follows the behavior of the flux of CO_2 measured at RIMI (wheat) and Lille Bøgeskov (deciduous forest). It is promising to see that the aggregated flux is comparable not only in size but also in the general diurnal (daytime) cycle of CO_2 fluxes at RIMI and Lille Bøgeskov. It can be noticed from Figure 5 that the integrated downward CO_2 flux over the beech forest during daytime is larger than over grassland indicating the important role of forest as a carbon sink.

5 Discussion

The required information for use of the boundary layer method is 1) measurements on the concentration of CO_2 at the surface, 2) vertical profiles of CO_2 concentration in order to estimate the jump in concentration at the top of the boundary layer, 3) information on the growth of the boundary layer.

Measurements of the CO_2 concentration are standard at many places. The jump of the CO_2 concentration at the top of the atmospheric boundary layer can be measured by airplanes, but the development of a CO_2 sensor that could be attached to a radiosonde and sensitive enough to measure the structure of the CO_2 profile would constitute a major scientific breakthrough for research in CO_2 aggregation. The growth of the boundary layer can be obtained from wind speed and temperature profiles obtained by radio-soundings when they are performed frequently enough to provide a reasonable detailed structure of the development of the boundary layer. Alternatively data from remote sensing techniques can be used.

The method is applicable at meteorological conditions such that a convective boundary layer is well developed and advection is negligible. These conditions are typical for a large scale high pressure systems, where the heat fluxes are usually high resulting in a rapid growth of the boundary layer and a well defined top, the wind speeds are low from varying directions and consequently advection is generally negligible.

Acknowledgements. The study was supported by the Danish Research Agency (Sagsnr 21-04-0499). The work is related to activities of authors within COST728, COST732 and COST735.

References

1. *Baldocchi, D. and R. Valentinini* (2004) Geographic and Temporal Variation of Carbon Exchange by Ecosystems and their Sensitivity to Environmental Pertubations. In C.B. Field and M.R. Raupach (eds). The Global Carbon Cycle, Scope 62. Island Press, pp. 295–316.
2. *Batchvarova, E. and S.-E. Gryning* (1991) Applied Model for the Growth of the Daytime Mixed Layer. Boundary-Layer Meteorol., 56, pp. 261–274.
3. *Batchvarova, E., S.-E. Gryning, C.B. Hasager*. (2001) Regional fluxes of momentum and sensible heat over a sub-arctic landscape during late winter. Boundary-Layer Meteorol., 99, pp. 489–507.
4. *Denmead, O.T., M.R. Raupach, F.X. Dunin, H.A. Cleugh and R. Leuning* (1996) Boundary layer budgets for regional estimates of a scalar. Global Change Biol., 2, pp. 255–264.
5. *Gryning, S.E. and E. Batchvarova.* (1999) Regional Heat Flux over the NOPEX Area Estimated from the Evolution of the Mixed Layer. Agric. For. Meteorol., 98–99, pp. 159–168.
6. *Levy, P.E., A. Grelle, A. Lindroth, M. Mölder, P.G. Jarvis, B. Kruijt and J.B. Moncrieff* (1999) Regional-scale CO_2 fluxes over central Sweden by a boundary layer budget method. Agric. For. Meteorol., 98–99, pp. 169–180.

Уточнение расчетов мезомасштабных потоков CO_2 в конвективном пограничном слое атмосферы

Аннотация. *Метод, основанный на учете эволюции высоты конвективного пограничного слоя атмосферы и успешно использованный для интеграции потоков импульса и тепла, в данной работе применяется для интеграции потоков CO_2 над островом Зеландия в Дании. Исходными данными для данного метода являются вертикальные профили измеренных концентраций CO_2, стандартная информация об измеренных концентрациях CO_2 вблизи поверхности земли и данные радиозондирования за последовательные сроки. Суммарные потоки CO_2 воспроизводят комбинированные условия, включающие условия над сельскохозяйственными угодьями и подстилающей поверхностью лесного массива.*

Ключевые слова: *интеграция потоков, CO_2, конвективный пограничный слой атмосферы, вертикальные профили.*