Chapter 14
Regional Measurements and Modelling
of Carbon Exchange

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14.1 Introduction

Atmospheric measurements of CO₂ mixing ratios at a number of locations around the
globe have helped significantly to quantify the source–sink distribution of carbon at
the global and sub-hemispheric scales (e.g. Rödenbeck et al. 2003, chapter 3 and 11).
The techniques that achieve this (e.g. Gurney et al. 2002), use a globally distributed
network of atmospheric concentration observations of CO₂ and other trace gasses
together with an atmospheric transport model that back calculates an ‘optimal’
source–sink distribution. So far, this global inversion approach has yielded estimates
of regional sinks and sources at scales of the order of a few hundreds of kilometres.
For example, the distribution of the Northern Hemisphere carbon uptake in longitude
between the oceans, North America, Europe and Asia is subject to many investiga-
tions but also to many uncertainties (e.g. Peylin et al. 2002; Fan et al. 1998). Stephens
et al. (2007) question the common understanding of a large Northern Hemispheric
sink, by comparing modelled profiles against observed ones from a few locations, and
conclude that transport errors in the models may have contributed to putting too much
of the global sink in the Northern Hemisphere transport.

At the local scale (1 km²), direct flux measurements by the eddy covariance
technique (Baldocchi et al. 2001; Valentini et al. 2000, chapter 11) constrain the net
ecosystem exchange (NEE) to within 20%, comparable to the uncertainty estimated
from inverse models (e.g. Janssens et al. 2003). In parallel, intensive field studies
can determine the changes in vegetation and soil carbon stocks using biometric
techniques, which allow independent quantification of the average carbon balance
of ecosystems, albeit also with significant errors (Schulze et al. 2000; Wirth et al.
2002; Curtis et al. 2002). How the two scales, the global and local, interact at the
regional level is unknown. It remains a major challenge to quantify the carbon bal-
ance at this ‘missing scale’. Understanding the link between the local and global
scale will add significant value to the existing local and global networks and will
ultimately help to improve the constraints on the dynamics and vulnerability of the
continental scale carbon balance.

The atmospheric boundary layer (ABL) dynamics play a crucial role in the
transfer of CO₂ between the surface and the troposphere at the regional scale. Two
aspects appear particularly relevant. First, the coupling between CO$_2$, radiation and turbulent fluxes at the surface has important implications for the surface energy balance. The cloudiness in the ABL controls the available solar radiation at the surface, which largely drives the CO$_2$ assimilation during daytime conditions. CO$_2$ assimilation is in turn strongly related to the vegetation transpiration through stomatal control, and hence directly impacts the magnitude of the Bowen ratio. For weak-to-moderate wind conditions, the surface sensible heat flux is the main driver of the development of the diurnal ABL and of the vertical mixing. This affects the CO$_2$ concentration through dilution. It is clearly important to know how strong this dilution effect is, when one is trying to relate atmospheric concentrations to surface sources (e.g. Karstens et al. 2006, chapter 4). The sequence of impacts and feedbacks shows the complexity of the processes involved in the interaction between the surface and the ABL. This complexity is comparable to that of soil moisture and the ABL (e.g. Van Ek and Holtslag 2004). Second, turbulence is the main process for upward transport of air as well as entrainment of tropospheric air at the top of the ABL. The turbulence in the ABL and the entrainment of clean and dry air from the upper free troposphere through the capping inversion are still an area of active research. Little is known of entrainment of CO$_2$ within the ABL and the values for entrainment rates (i.e. the ratio of the flux at the ABL top to the surface one), even for sensible heat flux remain highly speculative.

Recent experimental analyses show how entrainment significantly dries and dilutes the concentration of water vapour and CO$_2$ in the ABL (Vila-Guerau et al. 2004). At nights under weak wind conditions, the stable stratification of the ABL is responsible for the nocturnal accumulation of CO$_2$ close to the surface. Nocturnal inversion layers prevent the vertical mixing, and hence the concentration of CO$_2$ because of surface respiration may increase to high values within a thin atmospheric layer close to the surface (values as high as 10$^3$ ppmv can be observed in forests). This aspect is also very challenging for atmospheric modelling because it requires both refinements of turbulence schemes and a very high vertical resolution. The nocturnal storage of CO$_2$ close to the surface, however, is an initial condition for the CO$_2$ dynamics during the following day, and thus adequate assessment of this starting condition is key to a successful assessment of the daytime behaviour.

As an example of the complexity of boundary layer processes, Fig. 14.1 (Vila-Guerau et al. 2004) shows vertical profiles of fluxes of sensible and latent heat and carbon dioxide measured by an aircraft (Gioli et al. 2004). The graphs show the importance of the entrainment process. By calculating the ratio of the entrainment flux to the surface flux and linearly extrapolating the observed fluxes to the top of the ABL and on the basis of the data collected in the afternoon flights during an experimental campaign in the Netherlands, an indirect estimation of the ratio of the entrainment to the surface flux for the virtual potential temperature, specific humidity and carbon dioxide were obtained. Vila-Guerau et al. (2004) suggest for the case shown in Fig. 14.1 values of 0.6 for sensible heat flux, 0.25 for latent heat flux and 2.9 for the carbon dioxide flux. These values indicate that the turbulent eddies entrain warmer, drier and cleaner (lower concentration of CO$_2$) air from the free