

# CERES, the CarboEurope Regional Experiment Strategy in

Les Landes, South West France, May-June 2005.

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### **Capsule summary**

Models and observational strategies of carbon exchange need to take into account synoptic and meso-scale transport for correct interpretation of the relation between surface fluxes and atmospheric concentration gradients.

## **Abstract**

Quantification of sources and sinks of carbon at global and regional scales requires not only a good description of the land sources and sinks of carbon, but also of the synoptic and mesoscale meteorology. An experiment was performed in Les Landes, South West France during May-June 2005, to determine the variability in concentration gradients and fluxes of CO<sub>2</sub>. The CarboEurope Regional Experiment Strategy (CERES, see also <http://carboregional.mediasfrance.org/index> ) aimed to produce aggregated estimates of the carbon balance of a region that can be meaningfully compared to those obtained from the smallest downscaled information of atmospheric measurements and continental scale inversions. We deployed several aircraft to sample the CO<sub>2</sub> concentration and fluxes over the whole area, while fixed stations observed the fluxes and concentrations at high accuracy. Several (mesoscale) meteorological modeling tools were used to plan the experiment and flight patterns.

Results show that at regional scale the relation between profiles and fluxes is not obvious, and is strongly influenced by air mass history and mesoscale flow patterns. In particular we show from an analysis of data for a single day, that taking either the concentration at several locations as representative of local fluxes, or taking the flux measurements at those sites as representative of larger regions would lead to incorrect conclusions about the distribution of sources and sinks of carbon. Joint consideration of the synoptic and regional flow, fluxes and land surface is required for a correct interpretation. This calls for an experimental and modeling strategy that takes into account the large spatial gradients in concentrations and the variability in sources and sinks that arise from different land use types. We briefly describe how such an analysis can be performed and evaluate the usefulness of the data for planning of future networks or longer campaigns with reduced experimental efforts.

## **Introduction**

Adequate quantification of the geographical distribution of sources and sinks of CO<sub>2</sub> is still a major task with considerable implications for both our understanding of the global climate and the possible opportunities to mitigate climate change. Atmospheric measurements of CO<sub>2</sub> 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). The techniques that achieve this (e.g. Gurney *et al.*, 2002) use a globally distributed network of atmospheric concentration observations together with an atmospheric transport model that back calculates an “optimal” source-sink distribution. This inverse modelling technique requires considerable *a priori* information on the assumed source-sink initial patterns, their correlations and errors. Unfortunately, so far, the global inversion approach yields estimates that are not robust beyond the (sub) continental scales (Gurney *et al.*, 2002). In contrast, at the local scale (1 km<sup>2</sup>), direct flux measurements by eddy-covariance techniques (Valentini *et al.*, 2000) 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 and inventory techniques, which allow independent quantification of the average carbon balance of ecosystems, be it also with significant uncertainties (Curtis *et al.* 2002).

These two scales, the global and the local meet at the regional scale. However, how precisely these two scales interact at the regional level is unknown, and it remains a major challenge- both politically in the Kyoto context and scientifically- to quantify the carbon balance at this “missing scale”. The crucial breakthrough in understanding the sub-continental scale carbon cycle may come when plot level measurements of fluxes and

inventories can be aggregated and upscaled in such a way that they match the observed CO<sub>2</sub> concentration or the predictions from inverse models at high spatial resolution. Such a breakthrough requires an understanding of both the role of regional meteorology and land management practices in regulating the fluxes from the land to the atmosphere. This knowledge can be obtained with high intensity experimental campaigns (e.g. Schmitgen *et al.*, 2004, Gerbig *et al.*, 2003, Dolman *et al.*, 2005). This paper describes such an experimental campaign.

The CarboEurope Regional Experiment Strategy (CERES, see also <http://carboregional.mediasfrance.org/index> ) aimed to produce aggregated estimates of the carbon balance of a region that can be meaningfully compared to those from the smallest downscaled information of atmospheric measurements and continental scale inversion results. The key challenge in this experiment is to obtain atmospheric data at high spatial and temporal resolution that can be used to extract information of the surface carbon exchange at similar high resolution. In May-June 2005 we executed a strategically focussed regional field experiment in South West France, Les Landes, to obtain this data. If successful, this will not only lay the foundations for implementing a year long campaign for 2007 with reduced experimental effort, but also for a similar continuous observation network across Europe in the future. It will also allow for integrating carbon observations of different nature such as eddy covariance fluxes, plot and regional scale inventories, remote sensing and atmospheric concentrations. Above all, it will improve our process understanding of the major controls of the emission and uptake of CO<sub>2</sub> at the regional scale. At the global scale such process understanding is often difficult to obtain.

In the past, several regional studies of the carbon fluxes have been conducted, either dominantly based on ground level data and remote sensing (e.g. HAPEX-Mobilhy, André *et al.*, 1986; FIFE, Sellers *et al.*, 1988; BOREAS, Hall *et al.*, 2001), or alternatively focused on atmospheric sampling (e.g. COBRA, Gerbig *et al.*, 2003; CLAIRE-98, Andreae *et al.*, 2001). Gioli *et al.* (2003), Schmitgen *et al.* (2004) and de Arellano *et al.* (2004) describe elements of several pilot experiments that were performed in the framework of the CarboEurope cluster project RECAP. Based on experience from those studies, the regional experiment CERES was planned to combine various types of ground based carbon cycle-related measurements and atmospheric observations with remote sensing to infer a regional carbon budget.

### **Experimental strategy**

The scaling problem between local and global carbon balance studies becomes clearer if one appreciates how large-scale inversion based sink-source estimates, obtained by a limited amount of stations, suffer from a number of errors (e.g. Gerbig *et al.*, 2003). First, measurements from a single location are not necessarily representative of larger regions or model grid cells (“representation errors”). Second, solving for fluxes that do not evenly influence the overall concentration may cause “aggregation errors” (Kaminski *et al.*, 2001). Finally, diurnal and seasonal fluctuations in the boundary layer heights that cause the CO<sub>2</sub> concentration to co-vary with the fluxes are usually poorly represented in large-scale transport models, and cause “rectification errors”. CERES aimed to obtain the data that would better allow quantifications of these errors.

The central methodology of CERES is to make both concentration measurements within and above the boundary layer and to couple those via a modelling/data assimilation framework to the flux measurements at the surface and within the boundary layer. To

achieve this, we instrumented a region near Les Landes forest with ground and air-based measurements at high spatial and temporal resolution. This area was chosen because of the wealth of supporting data that exist from the previous HAPEX-Mobilhy experiment (André *et al.*, 1986) and the vicinity of Météo-France in Toulouse with state of the art forecasting tools. Such a multiple constraint approach has not been tried before at the regional level and the data are thought to give a better understanding of the surface source-sink distributions and allow for a better quantification of the errors listed above.

### **Description of the Experimental area**

The experimental domain covers an area of about 250 by 150 km in South West France. It is bounded to the West by the Atlantic Ocean, the shoreline being almost rectilinear along a NNE orientation. The western half of the domain is dominated by Les Landes forest, of which 80% is included in the Regional Experiment area (Figure 1). The forest is mainly composed of maritime pines (*Pinus pinaster* Ait.). It is a plantation forest that was originally planted to drain the marshlands, managed as a commercial forest, with regular harvests and rotation. Clearings of various size occur which contain agricultural land, mainly maize, but also grassland and pasture (in the southern part of the forest), or other cultivars like vegetables. Close to the west coast, some large ponds occur. Most of this land is covered by cereals, such as maize, with the exception of the Garonne river valley (crossing the domain from SE to NW) where there are fruit trees, and the large “Bordeaux” vineyards, east and north-west of Bordeaux city. There are mostly winter crops towards the South East, whereas summer crops increase towards Les Landes forest.

The NE corner is a vast, little cultivated region, mainly composed of woods and pastures. Two major cities are located close to the SE (Toulouse) and NW (Bordeaux) corners of

the domain. A little less than one million inhabitants live in Toulouse and its suburbs, about one and a half times that of Bordeaux. Given the dominant winds in spring, the domain could be affected by the plumes of the cities. The population of the other cities inside the domain is an order of magnitude lower than that of Toulouse or Bordeaux.

Les Landes forest and the valley of the Garonne river are relatively flat areas, whereas the rest of the domain is mainly composed of gentle hills. Outside the domain, to the South, the Pyrénées mountain range presents a solid W-E barrier rising occasionally above 3000 m height. This has a strong influence on the generation of local winds in the domain. To the East and North-East, the terrain elevates progressively toward the Massif Central, culminating at 1800 m and reaching about 1000 m, 100 km far from the domain.

### **Deployment of instrumentation.**

We installed a set of ground based surface flux measurements, regular radiosoundings and wind and temperature profilers and performed aircraft measurements with low flying flux aircraft. We also performed boundary layer sampling with small aircraft, and flew long trajectories with two research aircraft. Figure 1 shows how the ground-based instruments were deployed geographically. Climatic analysis suggested that dominant winds would be either from the West or the East, therefore we expected to be able to observe modification of the profiles by the land as the airmass progressed east- or westwards. Our design was based to capture this phenomenon with continuous CO<sub>2</sub> concentration measurements on towers near the coast and more inland, and several flux towers scattered in between to sample the different land cover types.

## Ground-based measurements

At the coastal boundary of the domain, near Biscarrosse (Figure 1), a high precision CO<sub>2</sub> instrument, called the CARIBOU, was installed on a 40 m tower. The accuracy of the CO<sub>2</sub> concentration measurement is of the order of 0.1 ppm. We also deployed a 20 m tower near Marmande (Figure 1) with a new low cost device for continuous CO<sub>2</sub> monitoring with intermediate accuracy. In a half-hour cycle up to 6 levels can be sampled. Twice a day, at noon and midnight, a CO<sub>2</sub> calibration gas sample is measured by the analyser to allow a post-correction on the concentrations. Accuracy, after the calibration correction is applied, is better than 1 ppm CO<sub>2</sub>. This accuracy is lower than provided by the CARIBOU system, but because of the large diurnal concentration fluctuations, we hope that this data is of sufficient quality to be used in high resolution atmospheric model inversions.

Fluxes of water, energy and CO<sub>2</sub> were measured using the eddy correlation technique. The basic instruments and methods have been standardised throughout the Euroflux and CarboEurope ecology network (Aubinet *et al.*, 2000). The eddy covariance (EC) system consists of a 3-D sonic anemometer coupled with an open or close path CO<sub>2</sub>/H<sub>2</sub>O InfraRed Gas Analyzers (IRGA). Measurements were obtained above eight different land covers: a vineyard, a pine forest, a clear-cut forest where pine trees have just been resown, maize (3 sites), beans, rape, grassland and above a wheat surface. Table 1 gives an overview of the sites and variables measured.

At three sites (Cape Sud, Marmande and routinely near Cazaux) we obtained continuous information on the wind field within the boundary layer through two UHF and SODAR profilers. The SODAR system near Marmande was extended with a Radio Acoustic Sounder Unit to obtain information on the temperature profile of the lower boundary

layer, typically up to 500-700 m. At Cape Sud we also installed a modified ceilometer laser to detect the height of the boundary layer.

Near Biscarrosse we also obtained FTIR (Fourier Transform InfraRed) measurements of column abundances for a number of trace gases, including CO<sub>2</sub>. These measurements are very useful for future validation of remotely sensed column concentrations of greenhouse gases and the co-location at Biscarrosse with the high precision measurement provides an opportunity to assess the performance of the instrument. The measurement principle of FTIR is based on the characteristic wavelengths of absorption of trace gases. This allows retrieving column densities of several tropospheric and stratospheric gases such as CO<sub>2</sub>, CH<sub>4</sub>, CO, N<sub>2</sub>O, C<sub>2</sub>H<sub>2</sub>, C<sub>2</sub>H<sub>6</sub>, CH<sub>2</sub>O, OCS and various CFCs.

From a site in Les Landes, Cape Sud, radiosondes were launched at 3 hourly intervals during the Intensive Observation Periods (IOP's), while at Toulouse on special days an extra sonde was launched at 12.00 UTC. All the profiles taken at 5, 11, 17 and 23 UTC were sent immediately to the operational weather data system and incorporated into the limited-area, weather assimilation scheme to improve the quality of the analysed and forecast fields in the area. Special constant volume balloons were launched from Cape Sud at particular occasions to sample the atmosphere's temperature and moisture in truly Lagrangian fashion at fixed density levels. The information of the wind patterns and flight path of the balloon was transmitted on some occasions to the pilot of the aircrafts to help them fly in Lagrangian air sampling mode.

### **Airborne measurements**

The advent of small specialized airplanes in the past decade, measuring fluxes at a resolution of a few km and with comparable accuracy to tower fluxes, has greatly increased the possibilities to provide accurate estimates of fluxes in areas of substantial

spatial heterogeneity (Crawford *et al.*, 1996, Gioli *et al.*, 2003). The Sky Arrow, a low and slow flying aircraft, equipped with a state of the art mobile flux platform to measure fluxes of CO<sub>2</sub>, heat, water vapour and momentum was used in the current experiment. We had two Sky-Arrows available, with one equipped with a multi spectral scanner that was used to obtain high resolution NDVI images. The other Sky Arrow flew flux transects among the forest and agricultural areas, typically at 50-100 m above the canopy.

The Piper Aztec (PA23-250) belonging to Météo-France performed continuous measurements of CO and meteorological variables and was equipped with the CONDOR instrument to measure CO<sub>2</sub> concentrations *in situ* at high accuracy. The CONDOR is based on a commercial Non Dispersive Infra Red Analyser (Li-COR 6262) doted with a fast response detector and a high acquisition frequency (1 Hz) that has turned it into a dedicated tool for airborne measurements. This allows it to achieve an accuracy of typically 0.2 ppm. Moreover on board the Piper flask samples were taken for later analysis of trace gases (CO, CH<sub>4</sub>, N<sub>2</sub>O and isotopes (C<sup>14</sup> and C<sup>13</sup>))

The second aircraft used for concentration measurements was the "ECO-Dimona" (DIMO) of MetAir, Switzerland. The DIMO is a small and versatile airborne measuring platform that can carry two underwing-pods with scientific instruments. During CERES, the focus was on the concentrations of CO<sub>2</sub>, CO, H<sub>2</sub>O and NO<sub>2</sub>, and the 3-D-wind in turbulent resolution. For CO<sub>2</sub>, three methods were in use: both a modified LI-6262 (closed path IRGA as described in Schmitgen *et al.*, 2003), and a modified LI-7500 (open path IRGA with a new mounting), plus up to 12 flask samples per flight (also for CO, other substances, and isotopes). The combined accuracy/resolution of this threefold system is 0.2 ppm / 10 Hz. The absolute accuracy of the high-resolution water vapour measurements was supported by a dew point mirror. Additional sensors that were in use

were for O<sub>3</sub>, NO<sub>x</sub>, aerosols (number concentrations of >0.3 and >0.5 μm), and a downlooking hyperspectral scanner (350 to 1050 nm with a parallel looking camera (1 averaged spectrum/photo every 0.7 s)). Operationally, it was important that the crew (pilot plus scientist) could make ad-hoc decisions based on real-time data, and input from the ground (e.g. results of nearby soundings).

There are two basic ways to sample the concentration of CO<sub>2</sub> in the atmosphere: Eulerian (grid based) and Lagrangian (airmass following). Information of the weather forecast and detailed trajectory modelling (e.g. Lin *et al.*, 2003) were used to determine exact flight patterns. The footprint, or surface influence, for a given measurement time and location was derived with adjoint transport models that were driven by assimilated meteorological fields from the ECMWF and Aladin (Météo-France) mesoscale weather analysis. The Stochastic Time Inverted Lagrangian Transport model (STILT) was used to extract this footprint information so that up to five days in advance we could plan our flights.

### **Quality Control and Assessment**

Special attention was given to obtain the CO<sub>2</sub> concentration measurements as reliable and accurate as possible. CO<sub>2</sub> concentrations were measured on ground stations, on towers and on board airplanes, both *in situ* and with flask samplings. Variations in CO<sub>2</sub> concentrations, as large as several tens of ppm or even more, were observed both on horizontal distances of tens of km or, at a given place, during the course of the day. Although the absolute accuracy of the various instruments is able to capture such variability, to calculate the CO<sub>2</sub> budgets at a timescale of a whole (or several) day(s) and over the whole area would require a much better accuracy because of the averaging involved. This is the reason why we executed a more precise quality control and quality

assessment procedure. Given that the CARIBOU system was our most accurate system (0.1 ppm), we calibrated our other instruments against this instrument on a single day towards the end of the campaign. On every profile performed by the Piper Aztec, 3 or 4 flasks were filled at various levels inside and above the boundary layer, to *a posteriori* evaluate the functioning of the continuously measuring CONDOR system. A total of 110 flasks were used, the major part of them above the Marmande area (where the RASS/SODAR was installed) or over the ocean, close to the shoreline where the CARIBOU system was set up. The DIMO aircraft also used 40 flasks to post-calibrate its closed-path Licor system. The Piper-Aztec, Sky Arrow and DIMO also flew several paired common profiles, above Marmande and/or Cape Sud. This full intercomparison between all systems is currently underway. Finally, as for the eddy correlation calculations, each group used its own software, but for post processing we decided to use single software to analyze all data, so as to provide a consistent analysis.

### **First results**

A 6-week period in the spring of 2005 (from 05/16/05 to 06/25/05) was chosen for high intensity observations of boundary layer development and flux aircraft for enhanced spatial sampling. When the weather forecast and footprint modeling suggested good days for flying the aircraft, an Intensive Observation Period was called. Table 2 gives an overview of the days when an Intensive Observational Period was announced. During IOP's we attempted to fly as many instruments as we could, executed an intensive radio sonde program with launches at 5, 8, 11, 14, 17 and 23 UTC and flew when possible one or two Lagrangian balloons. In total we obtained about 21 days of intensive measurements. Starting problems with the instrumentation meant that the first IOP contained somewhat less data coverage than the later ones. Figure 2 shows time series of

CO<sub>2</sub> concentration at Biscarrosse and meteorological observations for the full experimental period, with the IOP's also indicated.

## **IOP-2**

We present some preliminary results from the second IOP that lasted from 24 to 27 May. During this period there was a strong anticyclonic situation over the area with very weak variable winds. Figure 3 presents the boundary-layer structure during the last day of the IOP. Particularly noteworthy is the very deep (1.7 km) boundary layer that develops over the forest during the day. It is topped by a very sharp inversion that is accompanied by a strong humidity decrease, where above 1.7 km a very dry layer of air has developed. This high final boundary-layer depth appears to be facilitated by a quick development through the residual boundary layer of the previous day in the early part of the afternoon.

Figure 4a,b show an image obtained from the DIMO flight on the afternoon of 27 May. Figure 4c shows the flight plan. The aircraft tried to intercept the constant volume balloon that was released, so as to obtain a perfect Lagrangian flightpath. The main advantage of this type of sampling is that any changes in the airmass can be attributed directly to fluxes encountered by the airmass from the ground or overlying air, as it travels along its path. In figure 4a and 4b the concentration of CO<sub>2</sub> and temperature along the flight path are shown. The aircraft took off at Saucats airport, and flew south to intercept the balloon at release near Cape Sud, then westwards to the coast, after which it flew south for 100 km to fly inland along a north east line to Marmande. After Marmande it flew west towards the coast, intercepting the balloon. CO<sub>2</sub> concentrations vary along the flight track between from 375 to 385 ppm in the boundary layer, with the highest concentration close to the ocean surface. The lowest concentrations are observed

over the agricultural area. Because the winds were weak and variable, we expect that most of this variation is related to different uptake and emission regimes of the land surface. If this is true, the agricultural areas in the East part of the flight would be a larger sink than the forest in the West. Our surface flux measurements over Les Landes Forest for this day and the previous show a relatively high uptake rate, while our flux station in Marmande shows small net CO<sub>2</sub> fluxes (e.g. Figure 5). These latter observations were obtained over an area of growing maize, that had large parts of soil exposed to the air and produced relatively high respiration. Our crop sites towards the South-East showed indeed fluxes of comparable magnitude as the forest fluxes. In fact, analysis of the land cover shows that towards the South-East of the domain the crops are large winter crops that already have high CO<sub>2</sub> uptake rates, while the summer crops are still having low rates (Figure 1).

The Sky Arrow measures latent and sensible heat and this allows us to investigate the energy balance characteristics of the land surface at regional scale. Figure 6 shows the sensible, latent heat and CO<sub>2</sub> flux at noon observed by the Sky arrow. We show data from 24 May, because the flights above forest and agriculture were executed around the same time. On 27 May we do not have these nearly simultaneous flights available. Two things call for attention. The sensible heat flux over the forest is larger than over the agricultural areas, whereas latent heat fluxes are more similar. At the agricultural areas the Bowen ratio is close to 1 during IOP-2, for the forests it is closer to 1.5. The high sensible heat flux above the forest is likely to be the major cause for the extremely high boundary-layer depths observed during this day. The CO<sub>2</sub> fluxes over the forests are also much larger than in the agricultural areas, but comparable to those over the vineyards. Thus the observed high concentration of CO<sub>2</sub> over the forest is not directly correlated with the flux, as the CO<sub>2</sub> flux is high, suggesting that the air over the forest area would be

more depleted in CO<sub>2</sub> than observed. Latent heat flux correlates with the CO<sub>2</sub> flux over the forest but not over the agricultural area (Fig.6b), suggesting that soil evaporation of arable land was contributing to the overall flux more than plant transpiration. In fact, areas planted with maize appear to act as a source of CO<sub>2</sub>, as maize still is in the early stages of development.

The trajectories and footprints obtained by STILT may provide some further insight into this apparent discrepancy between fluxes and concentrations. Figure 7 shows the footprint calculations for the locations of Biscarrosse and Marmande using the Aladdin forecast of 12.00 UTC on 26 May. The footprint of Marmande is lying in a mostly westerly direction, in strong contrast to the Biscarrosse footprint that is strongly North-South oriented. In fact, the air sampled by the DIMO over Les Landes forest suggests that CO<sub>2</sub> rich air is advected northward along the coast, while air sampled near Marmande is strongly depleted in CO<sub>2</sub> because it moved over active vegetation areas in the South-East. Taking either the concentration at Biscarrosse or Marmande as representative of local fluxes, or taking the flux measurements at those sites as representative of larger regions would thus lead to incorrect conclusions. Clearly joint consideration of the synoptic and regional flow, fluxes and land surface is required for a correct interpretation. The significant difference of the Biscarrosse to the Marmande footprint, given that the distance is only 100 km, indicates a high variability of the synoptic flow that requires mesoscale modeling to properly resolve the observed tracer gradients. This was what CERES was aimed to achieve.

The data obtained during CERES is not only suited for three dimensional interpretation, but because we applied several novel techniques, we also collected data that are very

useful for furthering our process level understanding, such as the FTIR near Biscarrosse and cheap concentration measurements (Marmande tower).

### **Lessons learned and outlook**

CERES has provided a wealth of data that on its own could prove useful, but should be particularly useful as a comprehensive dataset to narrow down uncertainties in regional carbon balance estimation. It provides considerable insight into the large variability of spatial CO<sub>2</sub> fields (10-20 ppm over 200 km) and the strong diurnal range in the boundary layer that can approach 100 ppm as observed during night at the Marmande tower. The interpretation of this data requires insight into the synoptic scale variation of boundary layer properties and flow patterns. Without appreciation of this 3-D context of the relation between surface fluxes and atmosphere we could not understand some of the patterns we observed from the aircraft. It is exactly this 3-D context that has limited the usefulness of 1-D inversions such as the convective boundary layer technique (Styles *et al.*, 2002, Lloyd *et al.*, 2001, Laubach and Fritsch, 2002).

Atmospheric mesoscale models have been powerful tools to study regional exchange of water and energy (Noilhan and Lacarrere, 1995). This development has been further taken up in CarboEurope, so that non-hydrostatic mesoscale models are now used to simulate the surface-atmosphere exchange of CO<sub>2</sub> at resolutions comparable to that of flux aircraft and single flux towers (e.g. 1-2 km). For such limited area transport models, the boundary conditions come from atmospheric coarser scale models used in the Continental Integration Component (<http://www.carboeurope.org>). CERES intends to use both forward and backward modelling tool to simulate the CO<sub>2</sub> fields as well as estimate the regional source and sink distribution. During the execution of the experiment the availability of the Meso-NH model (Belair *et al.*, 1997), running

operationally without CO<sub>2</sub> fields, assisted already in adjusting flight plans depending on the predicted boundary-layer heights and wind fields of the model.

Inverse methods for determining surface CO<sub>2</sub> fluxes have been used in first attempts at high-resolution regional scales both in the USA and in Europe (see for instance Gerbig *et al.*, 2003, Lin *et al.*, 2004, Ronda *et al.*, 2005). For a previous CarboEurope winter campaign in the Netherlands, for instance, we were able to considerably narrow down uncertainty in regional fossil fuel emissions, indicating not only the strength of the method, but also its usefulness to check fossil fuel emission inventories. Good transport models however, are fundamental to the success in inversions of the concentration observations to obtain sink-source distributions (Peylin *et al.*, 2002). The data of the boundary-layer soundings and profilers will be extremely useful to quantify possible errors in the transport or structure of the boundary layer. This is an essential difference from the global scale synthesis inversion methods that have been used in the past, since in the regional models development and structure of the boundary layer plays a key role in determining the diurnal and spatial variation in CO<sub>2</sub> concentrations. Initial comparisons with Meso-NH output suggest that the modelled boundary layer depths compared well with our observations. We have started a model intercomparison for two days of the campaign, in which we will analyse model performance and further assess the capability of the mesoscale models to adequately represent transport at the mesoscale.

A further primary requirement to successfully use high resolution meso-scale models for Bayesian CO<sub>2</sub> inversion of sources and sinks is the existence of accurate *a priori* flux distributions and high resolution spatially and temporally distributions of fossil fuel sources. Such a high resolution emission map was obtained by downscaling the regional estimates to 6-hourly timesteps and 1 km resolution. Realistic mapping of the surface

fluxes relies on information on land cover, and surface biophysical parameters (LAI, albedo) that can be obtained from high resolution (e.g. Landsat, Spot, Aster) and high repetitiveness (e.g. Vegetatio, Modis, Meris) spaceborne images. Because data was obtained on surface fluxes for a variety of land cover types, we expect to narrow uncertainties in flux parameterizations considerably. The atmospheric meso-scale transport models are fitted with land surface packages (SVAT) and are excellent tools to act as a host platform for data assimilation of field and model data, similar to the use in for instance past field experiments like HAPEX-MOBILHY that focussed on water and energy exchange only, e.g. Bougeault *et al.* (1991).

Estimating regional, sub-national carbon exchange for protocol verification purposes also requires upscaling in time, as the carbon cycle is a combination of slowly interacting processes in soils and biomass with very fast ones in meteorology (e.g. Körner, 2003). CERES so far has been mainly concerned with the fast interaction, but we wish to be able to extrapolate to larger time scales. This calls for a concise modelling strategy on how to extrapolate the regional estimates to long time scales, relevant to the Kyoto protocol (>5 years). The best approach would seem to use models of biological processes and fossil fuel emission that are constrained by parameters which are optimized from data obtained during campaigns like CERES. Our intention is to analyse the current data set carefully with the aim to identify a minimum observational strategy for a regional long term approach. For 2007, such a strategy in the same region is planned to obtain a full year's carbon balance with a similar high spatial and temporal resolution as in the current experiment. A 20 year high resolution dataset of weather variables at 8 km resolution is available to extrapolate even further back in time, to account for changes in land management and cropping techniques (Habets *et al.*, 1999) .

CERES has shown that it is feasible to obtain a consistent data set of surface and air borne observations of the fluxes and concentrations of CO<sub>2</sub>. The availability of operational forecast tools has greatly helped our planning up to the point that we only had to cancel one flight due to bad weather conditions. We were also able to update flight plans on the basis of the predictions of the mesoscale model. The data obtained during CERES are only a first step to improve our understanding of the interaction between land use and the carbon cycle at the regional scale. After an initial period of analysis the data will be made available to interested partners. More information on the experiment and progress of the analysis can be found on <http://carboregional.mediasfrance.org/index>.

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		BS	CZ	BL	LB	CS <sub>maize</sub>	CS <sub>beans</sub>	CO	MR	FR	AF	MB	SS	LF	AU	LM	
		Site															
<u>Parameter</u>																	
Meteorology	Pressure		•	•	•		•		•	•	•	•	•	•	•	•	
	Temperature	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	
	Canopy temperature														•	•	
	Moisture	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	
	Incoming radiation		•	•	•	•	•	•	•	•	•	•	•	•	•	•	
	Light interception														•	•	
	Net radiation			•	•	•	•	•	•	•	•	•	•	•	•	•	
	Wind	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	
	Rain	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	
	Concentration	•		•	•	•	•	•	•				•	•	•	•	
CO <sub>2</sub>	PPFD <sup>1</sup>			•	•	•		•						•	•		
	Soil emission													•	•		
Soil	Temperature			•	•		•		•	•	•	•	•	•	•		
	Moisture			•	•		•		•	•	•	•	•	•	•		
	Soil heat flux			•	•		•					•	•	•	•		
	Sensible heat flux			•	•	•	•	•	•			•	•	•	•		
Eddy flux	Latent heat flux			•	•	•	•	•	•			•	•	•	•		
	Momentum flux			•	•	•	•	•	•			•	•	•	•		
	CO <sub>2</sub> flux			•	•	•	•	•	•			•	•	•	•		
	Ozone flux					•	•							•	•		
	NO <sub>x</sub> flux						•								•		

Table 1. Summary of ground flux sites with variables observed during the full campaign. Abbreviated site names and location can be found on Figure 1. <sup>1</sup> Photosynthetic photon flux density

	IOP	Weather conditions	Aircraft operations				Soundings			LB <sup>1</sup>	Remarks
			PIPER	DIMO	Sky Arrow Flux	Sky Arrow RS	Toulouse (UTC)	<sup>2</sup> Z <sub>i</sub> (m) at 17.00 UTC	LCS (UTC)		
18-20 May	IOP 1	Anticyclonic 19-20 May clear skies	1 profile, 2 LesLandes 36 flasks		12 flux flights		19, 20 May 11.00		18 May: 6, 18 19,20 May: 5,8,11,14,17		Initial problems with CONDOR Best day: 19 May
23-27 May	IOP 2	Anticyclonic, clear skies, weak winds	5 LesLandes, 1 LesLandes- Toulouse. 72 flasks	6 flights, mostly Lagrangian. 60 flasks	10 flux flights	4 RS flights	24-27 May 11.00	1100-1900	23 May :17 24-26 May : 5,8,11,14,17,23 27 May :5,8,11,14,17	4	Intercomparison profiles flown. Best day :27 May
31 May-2 June	IOP 3	Fair weather, high clouds, NE-E winds	2 LesLandes 18 flasks		6 flux flights	3 RS flights	31 May-2 June: 11.00	1600-2000	31 May: 5,11,17,23 1 June: 5,8,11,14,17,23 2 June: 5,11,17		Best day: 1 June
6 June-10 June	IOP 4	Anticyclonic weak winds W-NE to NE	4 LesLandes and 1 Lagrangian 47 flasks	2 Lagrangian 21 flasks	12 flux flights	6 RS flights	6-10 June: 11.00	1300-1800	6 June: 5,8,11,14,17 7 June: 5,11,14,17,23 8 -9 June: ,8,11,14,17,23 10 June: 5,8,11,14,17	7	Intercomparisons and tracking of Bordeaux plume Best days: 6,8 June
14-15 June	IOP 5	Westerly flow	2 Lagrangian 18 flasks	2 Lagrangian 24 flasks			15-16 June: 11.00	1000-1200	14 June: 5,8,11,14,17 15 June: 5,11,14,17		Best day: 15 June
18-22 June	IOP6	Anticyclonic very hot	3 Les Landes 28 flasks		6 flux flights	3 RS flights			19 June: 5,11,17		Best day 19 June

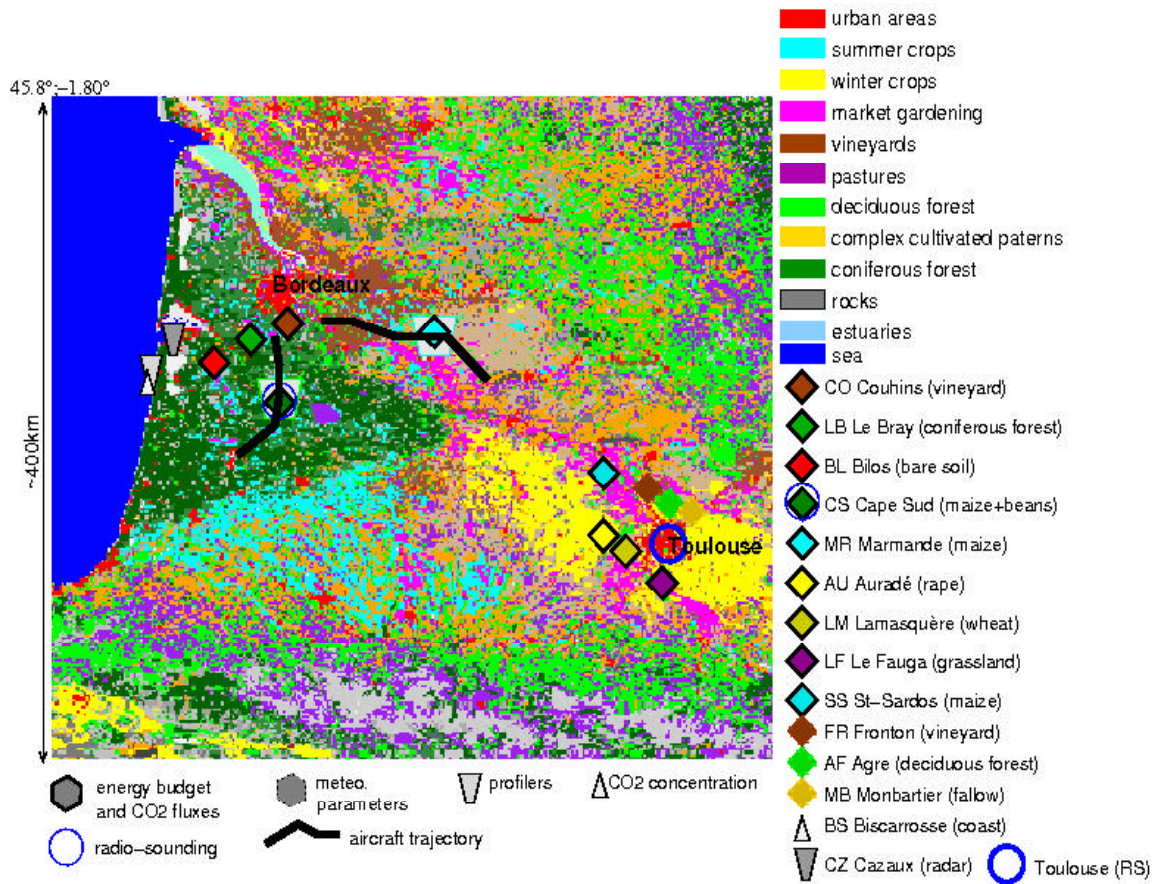
Table 2. Summary of operations during Intensive observational periods (IOP) <sup>1</sup> Lagrangian Balloon, <sup>2</sup> Height of the mixed layer.

## Figure captions

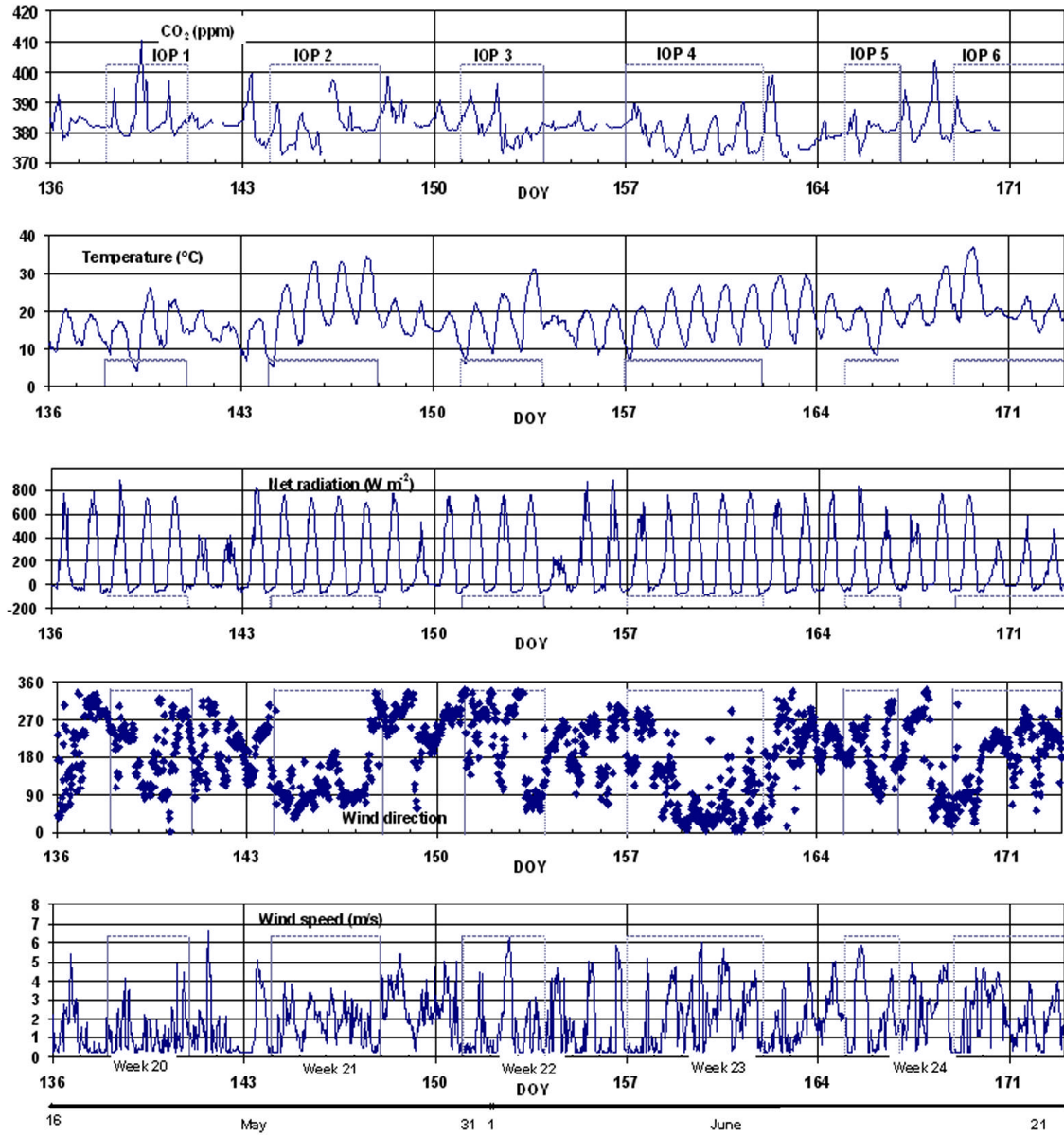
- Figure 1. Land cover map at 250m resolution for the experimental domain in the south west region of France showing the different location of summer and winter agricultural crops (classification by A. Champeaux, *et al.*, 2005). Also shown are the locations of the ground-based observation sites of surface fluxes and boundary layer. Flight tracks indicate the path flown by the Sky Arrow flux aircraft for agriculture and forested regions.
- Figure 2. Time series of CO<sub>2</sub> concentration (top panel), temperature (second), net radiation (middle panel), wind direction (second lowest) and windspeed observed near the Biscarrosse tower. Also shown are the periods when Intensive Observation Periods were held.
- Figure 3. Development of Potential temperature on 27 May from the radiosondes launched at Cape Sud.
- Figure 4. DIMO flight 27 May 3. Figure 4a contour plot of CO<sub>2</sub> concentration against distance flown, 4b, contour plot of potential temperature against distance flown, 4c the flight track. Red color codings indicate agricultural (summer crops) areas, black forested areas and blue the sand dunes of the coast line.
- Figure 5. Surface fluxes for 27 May 2005. 5a. Fluxes of NEE above Le Bray in Les Landes forest and maize in Marmande. 5b. Net radiation, latent and sensible heat above the forest of le Bray. 5c. Net radiation, latent and sensible heat above maize in Marmande.
- Figure 6. Sky Arrow observations of 24 May 2005: fluxes of sensible and latent heat and CO<sub>2</sub> observed at 50-100 m altitude (a) over the agricultural area, (b) over the forests. The fluxes are not yet corrected for flux divergence. Figure 6c illustrates the relation between CO<sub>2</sub> flux and evaporation for the agricultural and forest areas.

Figure 7. Stilt forecast of the concentration footprints based on Aladin on 26 May 12.00 hr. forecast., The strong N-S footprint is for the measurement at Biscarrosse, the more inland footprint pictures the source are of the Marmande observations.

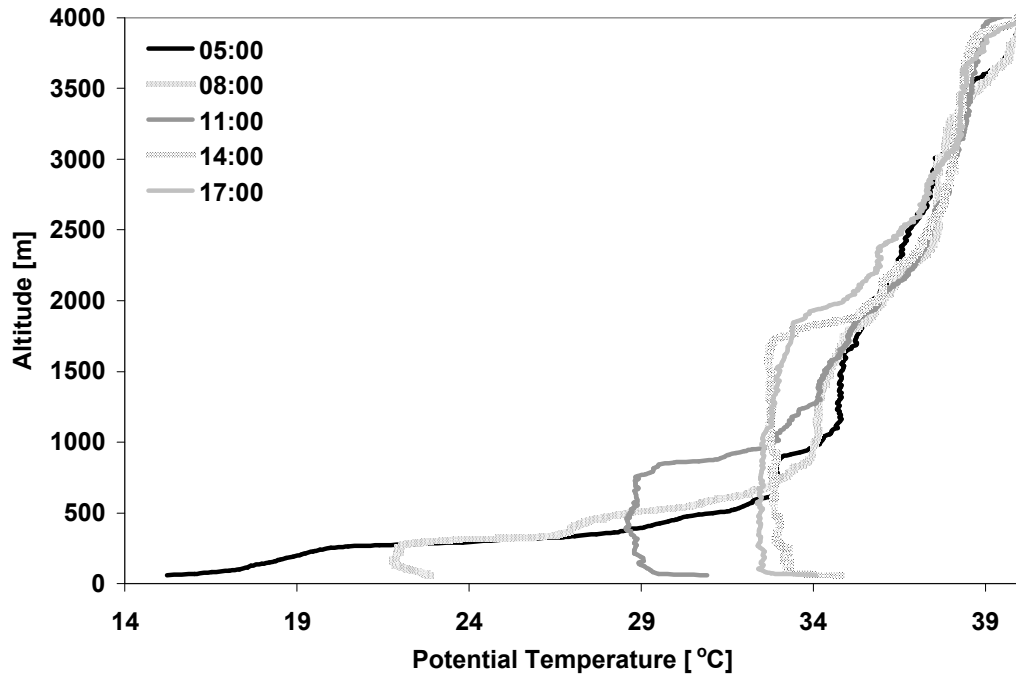
**Figure 1**



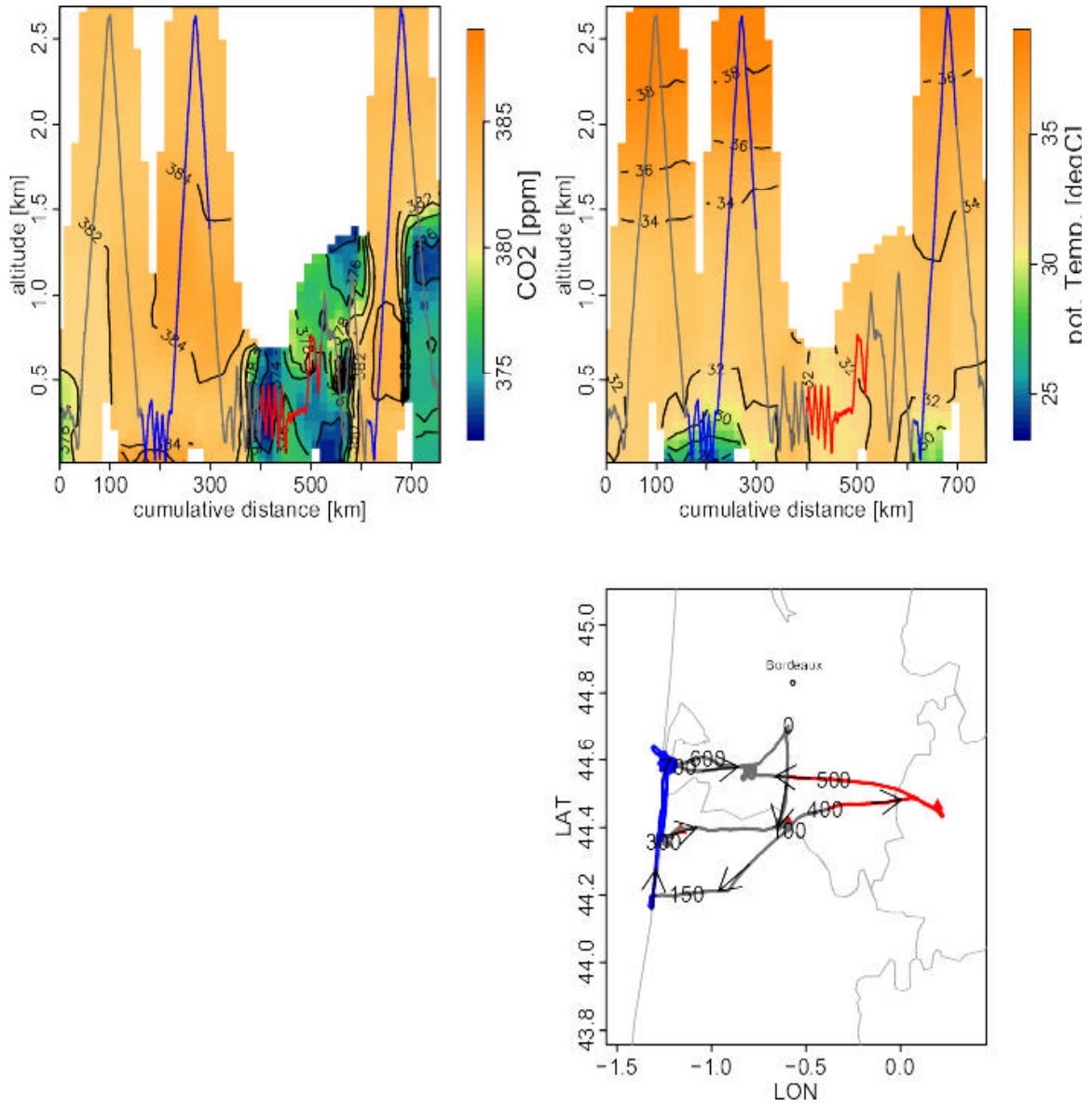
**Figure 2**



**Figure 3**

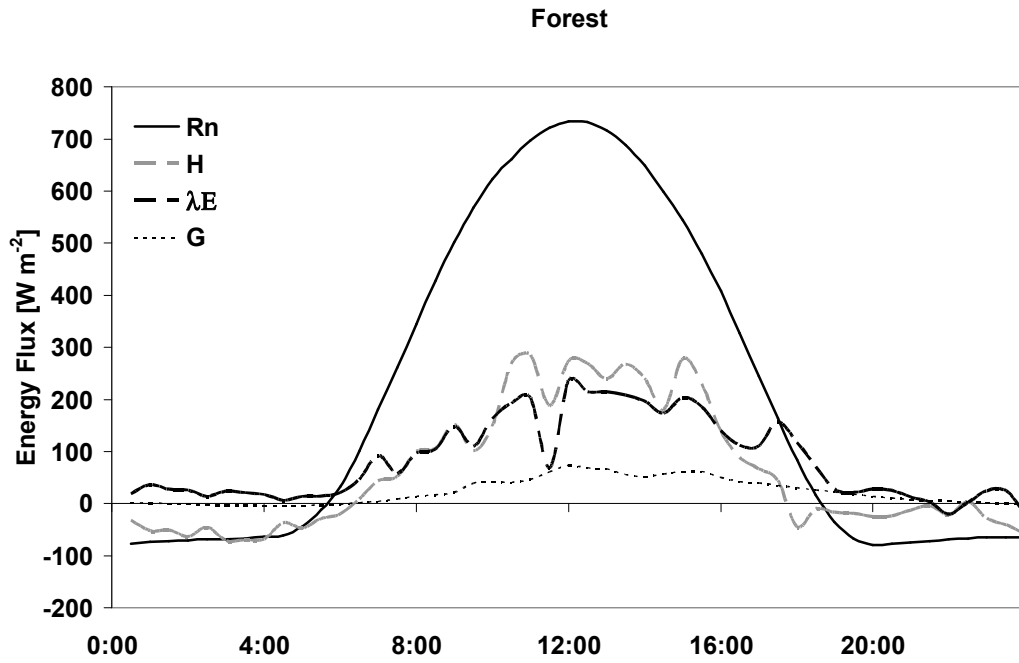


**Figure 4**

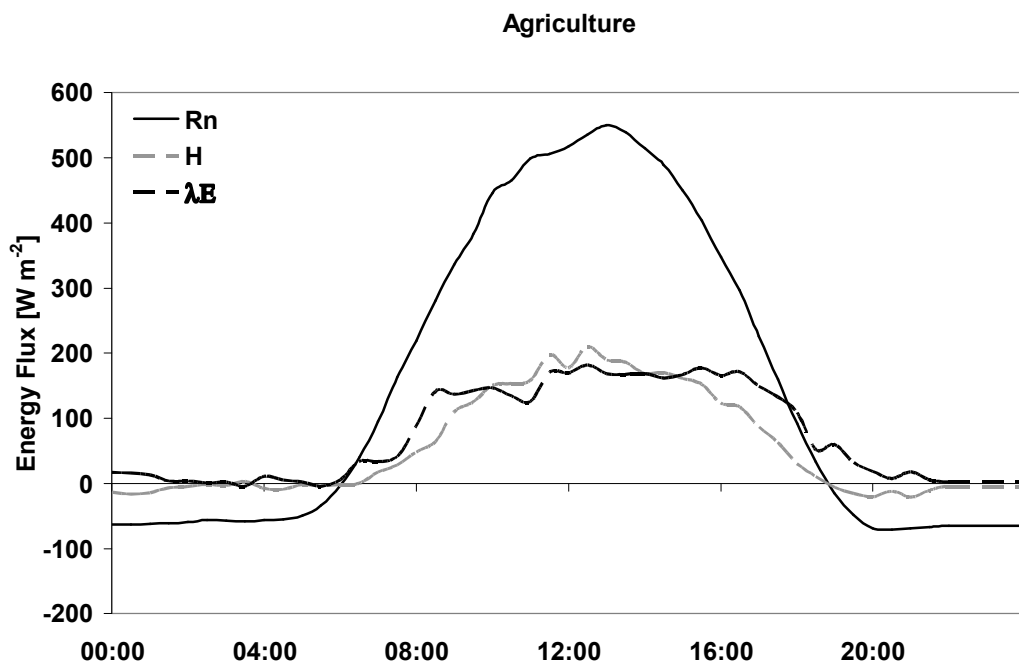


**Figure 5**

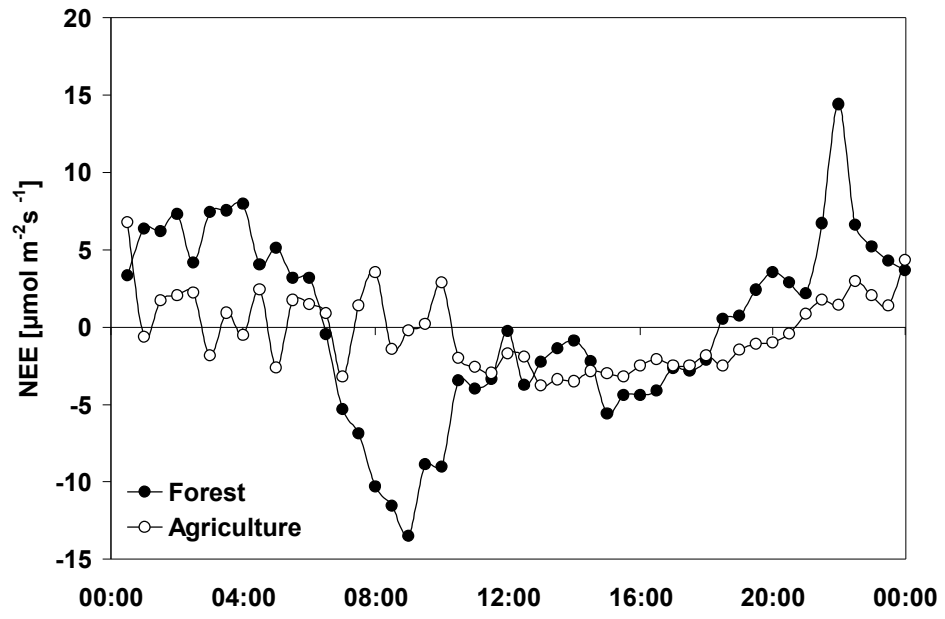
a.



b.

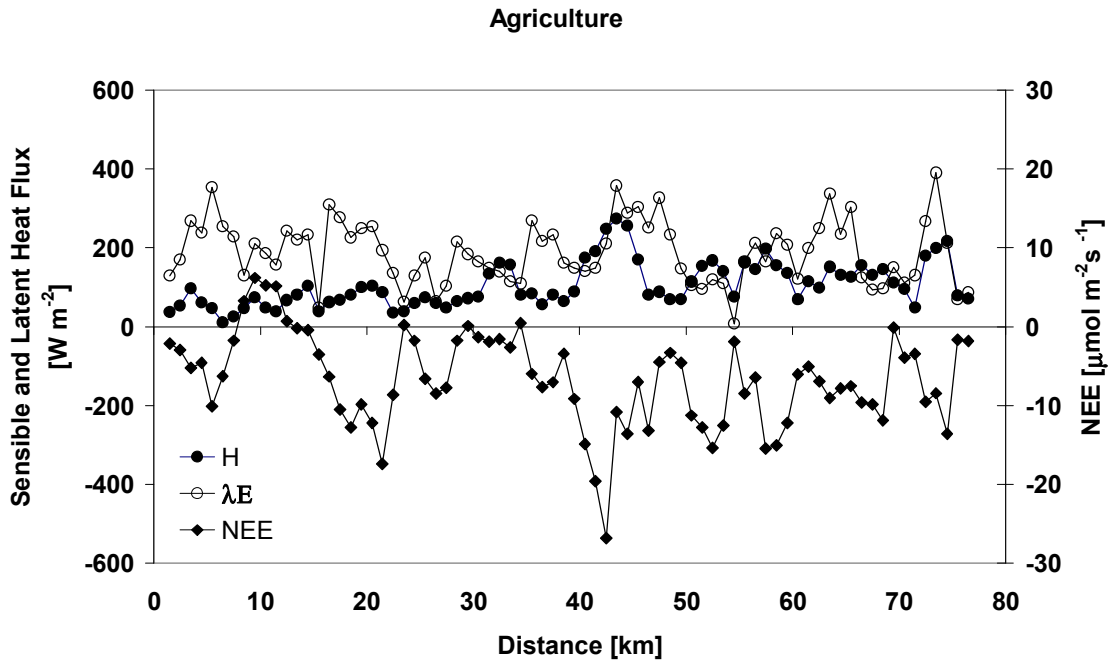


c.

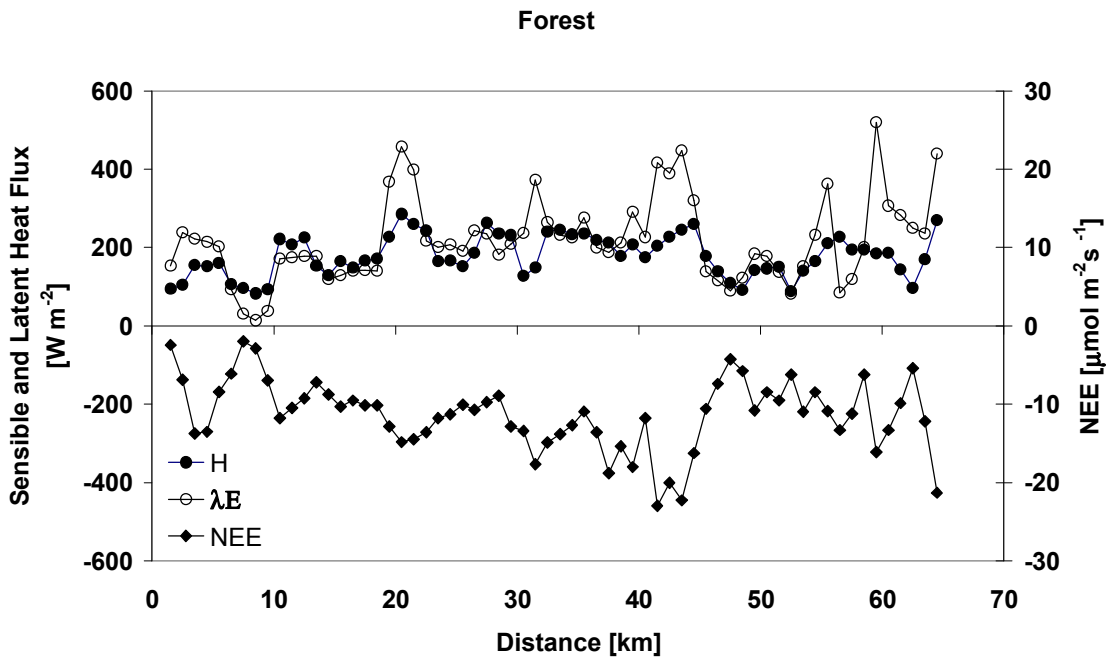


**Figure 6**

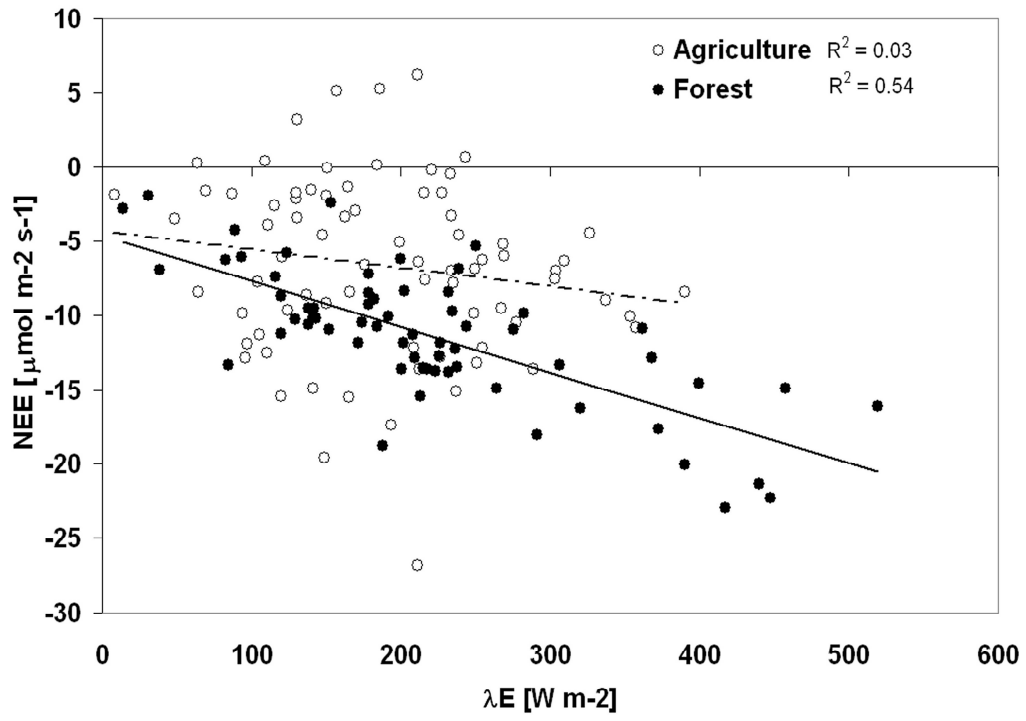
a.



b.



c.



**Figure 7**

ALAD 052714, receptor at Biscarosse and Marmande  
file used:052612; receptor xsec length: 50 km;

