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Detecting regional variability in sources and sinks of carbon dioxide: a synthesis

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Abstract

The papers of this special issue are put into the context of progress made in experiments and modelling aimed at understanding the carbon balance at regional scale. Mesoscale meteorological effects such as seas breezes and topographically induced flow have the potential to generate significant heterogeneities in the CO_2 concentration fields. This has consequences for the interpretation or inverse modelling, of sources and sinks from these concentrations. Results of experiments executed in South West France in 2005 and 2007 are described and subsequent analysis of modelling results. Overall we conclude that we now have capability to model with mesoscale models realistic CO_2 concentration fields, within the constraint of other model errors, such as in boundary layer characteristics. We show that progress has been made in inverting concentration field at regional scale and indicate the direction of future research efforts.

1 Introduction

The determination of sources and sinks of CO_2 from the terrestrial surface is fraught with difficulties. At small scale, local measurements with eddy covariance towers can indicate a net sink or source (Dolman et al., 2008), at large scale the "inverse" method determines sources and sinks at continental scale, albeit with substantial uncertainty (Stephens et al., 2007). How to link the two methods is subject of an active and growing area of investigations (e.g. Gerbig et al., 2009). The linkage between the local and regional to continental scale is non trivial, and understanding of the processes involved at this scale change is key to improving our capability to determine sinks and sources with reduced uncertainty and at high resolution. Reducing the uncertainty and scale is important to allow credible assessments of emissions and uptake that are relevant to climate treaties such as UNFCCC (United Nations Framework Convention on Climate Change). Reducing the scale is critically important to understand the absolute variation in source and sink strength and attribute specific processes to particular regions, or land use management systems.

At the regional, sub continental scale, loosely defined here as areas of a few hundred kilometres wide and long, CO_2 injected in the atmosphere becomes subject to flow patterns that are sub-grid in the sense of current weather forecasting and climate models. These processes can thus only be represented by the new generation of mesoscale models (Pielke et al., 1992; Nicholls et al., 2004; Denning et al., 2003). Van der Molen and Dolman (2006) were among the first to use these models to address the problems involved in deriving meaningful area mean values of concentration by using a mesoscale model in a spatially heterogeneous area. They showed that mesoscale topographical effects in Central Siberia induced significant perturbations in the mean concentration field that would need to be taken into account when using locally observed concentration values (e.g. as in inversion studies; Gurney et al., 2002). The perturbations were also visible in the experimental record. From a quick analysis on current stations of the global monitoring network they concluded that more than 50% of those could be subject to regional or mesoscale perturbations caused by topography or sea breezes. Further studies (Ahmadov et al., 2007; Sarrat et al., 2007a) corroborated this view and showed that sea-breezes and other meso-scale flows affected the mean concentration and induced significant representation errors (Tolk et al., 2008). Ahmadov et al. (2007) suggested that these spatial effects could be similarly treated as the diurnal and seasonal rectification effects (Denning et al., 1996) in inversions and suggested to call them 3-D rectification effects. Common practice in large scale inversions is to select those data from continuous monitoring stations around noon, so as to suffer little from any mesoscale of diurnal rectification effects. How to extract the correct data when spatial rectification effects occur is less obvious, and would probably depend very strongly on the local and regional monitoring site.

Several experiments in the last few years have started to address the regional spatial variation of atmospheric CO_2 experimentally, for instance the CO_2 Budget and Rectification Airborne study (COBRA, Gerbig et al., 2003); the Cooperative LBA Airborne Regional Experiment (LBA-CLAIRE-98, Andrea et al., 2001). Gioli et al. (2004), Schmitgen et al. (2004), and Vila-Guerau et al. (2004) describe elements of several pilot experiments in Europe. These experiments suggested that regionally large concentrations gradients develop that can only be meaningfully interpreted with high resolution models, Lagrangian or Eulerian. Gerbig et al. (2003) report that atmospheric CO_2 variations occur typically at scales of 10-30 km, and that these need to represent accurately when using the concentration profiles and transects to infer fluxes.

Based on experience from these experimental and modelling studies, the regional experiment CERES (Dolman et al., 2006) 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. This paper describes the set-up of the experiments and the in field conditions of the campaigns with the aim of providing an overview of the instrumentation used and of the data-set. It also aims to bring the papers submitted to this special issue into a coherent context of analysis.

2 Experimental set-up

The central methodology of CERES is to make concentration measurements both 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 the 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. The experimental domain covers an area of about 250 km×150 km in Southwest France. It is bounded to the west by the Atlantic Ocean, the shoreline being almost rectilinear along a north-south orientation. The western half of the domain is dominated by the Landes forest, of which 80% is included in the Regional Experiment area (Fig. 1). The forest is mainly composed of maritime pine (Pinus pinaster Ait.). There are clearings of various size, which contain agricultural land, mainly maize, but also grassland and pasture (in the southern part of the forest), or other cultivars like vegetables. Elsewhere in the domain, the land is covered by cereals, such as maize, with the exception of the Garonne River valley (crossing the domain from southeast to northwest) where there are fruit trees and winter crops, and the large "Bordeaux" vineyards, east and northwest of Bordeaux city. There are mostly winter crops towards the southeast, whereas summer crops increase toward the Landes forest. The northeast corner is a vast, little-cultivated region, mainly composed of woods and pastures. Two major cities are located close to the southeast (Toulouse) and northwest (Bordeaux) corners of the domain. The 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 west-east barrier rising occasionally above 3000-m height. This has a strong influence on the generation of local winds in the domain.

A set of ground-based surface flux measurements, regular radiosoundings, and wind and temperature profilers were installed and aircraft measurements with low flying flux aircraft were also performed. Boundary layer sampling with small aircraft took place and long transects were flown with aircraft sampling concentrations of CO_2 and various other trace gasses (see Dolman et al., 2006 for an extensive description of the experimental layout and the first campaign). Three campaigns were executed to sample the seasonal variation of activity of the land surface from 16 May to 25 June 2005 and in April and September 2007.

Table 1 gives an overview of the experimental activity of these campaigns. The 2007 experimental set-up differs from the 2005 one (as decribed by Dolman et al., 2006). In this case, the CERES 2005 measurements have been completed by an eastern CO_2 concentration tower of 60 m height (Bellegarde-Saint-Marie's tower, near Toulouse), added to the Biscarosse and Marmande towers.

Eight surface stations were measuring continuously the CO_2 and energy surface fluxes, at representative ecosystems of the region (pine forest, young tree, 2 maize, grassland, sunflowers, wheat, fallow).

Radio-soundings were launched during IOP days in Toulouse in April and in September in Toulouse and at La Cape Sud (the central site in the Landes forest, already installed in 2005).

Three aircrafts, the Dimona (from MetAir) and two Sky Arrows (from IBIMET and ALTERRA) were flying over the Landes forest or near Toulouse during IOP days when the meteorological conditions were favourable.

3 Results from CERES experimental campaigns

3.1 Main characteristics of the CERES 2005 campaign

The experimental results of the first campaign are described in more detail by Dolman et al. (2006) and are effectively summarized in Fig. 2 which shows an East-West cross-section over the domain for 27 May (Sarrat et al., 2007a). Several airmasses are respectively enriched and depleted in CO_2. The enrichment comes from high concentrations over the sea with little biological uptake, and the depletion from uptake from winter crops in the area North-West of Toulouse. The different characteristics of these air masses cause a complicated pattern to exist that is not directly related to the flux observed at one of the flux monitoring stations above forest (the Landes) or maize (Marmande). This decoupling of sources, sinks and local profiles can only be resolved when the full 3-D circulation is taken into account (e.g. Sarrat et al., 2007a).

3.2 The 2007 campaigns

The second and third campaign took place in April (from the 18th to the 23rd for 6 days continuously and during 8 days in September (7–8 and from the 10th to the 15th.

During the experimental week of April, anticyclonic conditions prevailed with a weak wind (5 to 10 kts). The mornings were often cloudy, with low level clouds rapidly dissipated, but the sky was clear during the afternoon, allowing warm temperatures (25 to 29°C) and sea breeze development, especially on the 20th, 21st and 22nd of April.

The 7th and 8th of September were rather warm with clear sky, whereas the other September IOP days were more cloudy. Nevertheless, warm temperatures were observed in the experimental area. The wind was weak all the time with variables directions (for instance, from North-East on the 12th and from South-East on the 13th).

In April, the soil water content (W) is nearly at the field capacity (W_{fc}) in the CERES area, except near Toulouse where the soil is dryer. Fig. 3 displays the Soil Water Index (SWI) corresponding to the ratio $SWI=\frac{W-W_{wilt}}{W_{fc}-W_{wilt}}$, where W_{wilt} is the wilting point. In September the soil is dryer (SWI ranging from 0.3 to 0.6 in the experimental zone) than in April but remains normal accordingly to the 1996–2006 mean (not shown here). The Leaf Area Index varied also from April to September as shown in Fig. 4. The Toulouse and Bellegarde-Sainte-Marie area, dominated by winter crops shows a higher LAI in April than in September, with low value at this stage of the year. Conversely, in the western part of the domain and the Landes forest the LAI is higher in September.

In addition to the single high precision "tall" tower at Biscarosse of the 2005 campaign, a second one was operated near the town of Bellegarde-Sainte-Marie. Figure 4 shows the diurnal cycle of the measurements at the two towers, with a CO_2 maximum observed during the night due to the accumulation of CO_2 in the night-time boundary layer as a result of anthropogenic and biospheric emissions. At Bellegarde the diurnal cycle is much more pronounced in April (22 ppm vs 10 ppm) than in September. This is most likely due to strong diurnal land uptake through biospheric activity in April linked to a higher LAI compared to September, but also to a strong nocturnal respiration due to the soil water content, higher in April than in September, favouring the soil microbiological activity. The diurnal pattern of Biscarosse shows less seasonal variation, as it is more influenced by the CO_2 from the marine sources. The amplitude of the diurnal cycle at Biscarosse is higher in September compared to April (13 ppm vs 8 ppm), as a result of the summer photosynthetic activity of the Northern Hemisphere.

This is consistent with the April Dimona flights (Fig. 6) over the western part that revealed an east–west CO_2 gradient with higher values at low levels over the crops and the Landes forest than near the ocean coast. Most of the flights show that this gradient remains in the afternoon, although the regional differences are reduced because of the boundary layer vertical mixing. Higher values of CO_2 concentrations over land at this time of the year is probably related to relatively high value of soil respiration (wet conditions), low value of CO_2 uptake and reduced vertical mixing in the atmospheric boundary layer.

In April, the Sky Arrow IBIMET flew horizontal transects in the western part of the domain, the measurement methodology is described by Miglietta et al., 2009. The Fig. 7 shows the fluxes of sensible and latent heat and CO_2 observed at 100 m above ground by the aircraft. One can note the systematically high value of CO_2 uptake by the vineyards whereas the CO_2 fluxes over the forest is relatively weak. The evapotranspiration is high probably because of a high contribution of the soil evaporation in the total latent heat.

The radiosounding analysis shows a large difference of observed Boundary Layer (BL) height between April and September, possibly as a response of the reduction of soil moisture availability. In fact, the mean BL height in April in Toulouse reaches 1000m while in September in the Landes forest, the BL height often reaches 2000m, late afternoon (not shown here).

4 Modelling

4.1 Forward modelling

Early modelling results of the CERES campaign were compared and analysed by Sarrat et al. (2007b). They compared five different meso-scale models with various settings and versions to see how they represented the atmospheric carbon dioxide. The complex spatial distribution as well as the temporal evolution of CO_2 in interaction with the surface fluxes was realistically simulated compared to the aircraft observations. This raised hope that the mesoscale models may provide adequate transport of CO_2 and other tracers at high resolution.

The dynamic parameters at the synoptic scale (temperature and relative humidity at 2 m) but also at the local scale (potential temperature at various sites), were also validated. All models were able to simulate the surface meteorology reasonably well. Nevertheless, some discrepancies with observations were also noted such as a cold bias in the initial temperature at 2 m. This could have been due to an error in the initialization.

Also, the boundary layer height modeling, as a key process in meso-scale modeling, still showed some divergence from the observations. The importance of entrainment at the top of the boundary layer was earlier noted Vila-Guerau et al. (2004). The latent heat flux is often overestimated by most of the models, indicating some issues with the land surface schemes, particularly related to soil moisture.

Ahmadov et al. (2007) and Sarrat et al. (2007) presented new simulations of specific events of the campaigns. Ahmadov et al. (2007) highlighted the complexity of the three dimensional structure that arises from mesoscale flows. They introduced WRF-VPRM as a new modeling system that couples a diagnostic biosphere model, a high-resolution emission inventory, and realistic boundary conditions from a global CO_2 transport model with a weather forecasting model in order to simulate fluxes and concentrations of CO_2 at high spatial and temporal resolution. They applied the modeling tool for two different days of the CERES 2005 regional experiment, with different conditions in both meteorology and biospheric activity. Due to its high spatial resolution the model captured mesoscale transport processes such as the sea-land breeze circulation. Although the exact magnitude and direction of the sea breeze circulation was not always simulated perfectly, the main flow patterns were. They concluded that measurements made at coastal stations do not always see large-scale representative CO_2 signals in onshore air flows, but that in cases of a sea breeze circulation the spatio-temporal patterns show a strong mesoscale character. This conclusion echoes the conjecture made by van der Molen and Dolman (2007) that some of the data used in large scale inversions may be subject to what we could call “mesoscale rectification effects”.

Following this work Ahmadov et al. (2008) show how only the mesoscale models as WRF are able to simulate well the diurnal course of CO_2 concentrations. Lower resolution models are not quite capable of following the mesoscale perturbations caused by local topography and mesoscale dynamic processes. They ran WRF-VPRM for the period covering the intensive period of the CERES experiment, using the CO_2 fields from the global model LMDZ for initialization and lateral boundary conditions. The comparison of modeled CO_2 concentration time series against observations at the Biscarosse tower and against output from two global models – LMDZ and TM3 – clearly revealed that WRF-VPRM can capture the measured CO_2 signal much better than the global models with lower resolution. Also the diurnal variability of the atmospheric CO_2 field caused by recirculation of nighttime respired CO_2 is simulated by WRF-VRPM reasonably well. Analysis of the nighttime data indicates that with high resolution modeling tools such as WRF-VPRM a large fraction of the time periods that are impossible to utilize in global models, can be used quantitatively and help constraining respiratory fluxes.

Tolk et al. (2008) used the mesoscale modeling system RAMS (Pielke et al., 1982) to determine the errors that arise from neglecting the 3-dimensional nature of the flow. They defined the representation error in relation to the values of CO_2 concentration in a 2 km resolution run with the mean value at a coarser resolution of 10, 20, 50 and 100 km. They found that representation errors could be caused by variations in topography, specific mesoscale circulations such as sea breezes and flux variability of the land surface. During the day, the sea breeze, leading to a small band of convergent flow where large errors arose, caused the largest representation errors. At night unresolved topography in the low resolution runs caused substantial errors due to accumulation of respired CO_2.

Ter Maat and Hutjes (2008) use the RAMS model setup to simulate CO_2 concentration fields in the Netherlands. They show how variability in land cover, agriculture versus urban, and the proximity of the ocean (North Sea) affect the regional distribution of CO_2.

The April 2007 campaign was simulated with the meso-scale model Meso-NH (Sarrat et al., 2007). This study shows how aircraft observations of CO_2 concentration are used to identify surface modeling errors and to calibrate the CO_2 components of the surface model, particularly the LAI. They show also the improvement of the atmospheric CO_2 simulation highly dependent of the on-line coupled surface scheme and its characteristics such as LAI.

4.2 Inversion modelling

The previous section has made clear how spatially complex patterns of CO_2 distribution can arise as a result from mesoscale atmospheric perturbations. Filtering out these perturbations from observational data has been the norm when site data is used in large scale inversions (e.g. Gurney et al., 2006). However as, for instance suggested in Ahmadov et al. (2008) and Gerbig et al. (2009), the variability in atmospheric concentration could also be used to put realistic constraints on surface inversions at regional scale. The prime requirement for this to the successful is a good simulation of the 3-D flow fields. However when this is achieved the issue of adequate data, adequate a priori fields still remains.

Lavaux et al. (2008) studied the characteristics of a statistical ensemble of mesoscale simulations in order to estimate the model error in the simulation of CO_2 concentrations. Their ensemble consisted of ten members and a reference simulation. The ensemble

of simulations was used as the initial and boundary conditions for meso-scale model simulations. The resulting ensemble represents then the model dependence to the boundary conditions. The variance of the ensemble was estimated over the domain, with associated spatial and temporal correlations. On the horizontal plane, the calculated variance of the ensemble followed the discontinuities of the mesoscale structures during the day, but remained locally driven during the night. This corresponds with the analysis of Tolk et al. (2008) who found similar covariance. In the vertical, the surface layer variance showed large correlations with the upper levels in the boundary layer (>0.6), down to 0.4 with the low free troposphere. Large temporal correlations were found during the afternoon (>0.5 for several hours), that was reduced during the night.

Using the ensemble to back calculate the fluxes, they found that the posterior error reduction on the inverted CO_2 fluxes showed the predominance of the temporal over the spatial correlations when using tower-based CO_2 concentration observations.

In a further study, Lavaux et al. (submitted) use observations of the CERES campaigns to derive correction on a priori fluxes modeled by the ISBA-A-gs (Calvet et al., 1998). They used concentration measurements from the two tall towers in CERES 2007 to derive a correction for the fluxes, which were then subsequently validated by observations from eddy covariance towers and an aircraft (Gioli et al., 2006). They found a significant error reduction compared to the prior estimates of land surface fluxes. This error reduction also applied to the time evolution of the fluxes, which was corrected by the inversion.

5 Discussion and conclusion

The CERES experiment and associated modeling has generated a considerable advance in our understanding of variations in CO_2 concentration at the regional scale. The papers in this special issue bear witness to that. Also, the availability of a considerable amount of experimental data had made it possible to add to the existing effort, such as shown by Rascher et al. (2009). They performed airborne measurements of solar induced fluorescence in combination with extensive ground-based quantification of leaf- and canopy-level processes in support of ESAs Candidate Earth Explorer Mission, FLEX (see http://www.congrex.nl/09c01/SP1313-4_FLEX.pdf). During three measurement periods in 2007 structure and functional characteristics over 20 different types of vegetation in the Landes region were extensively characterized. On the larger spatial scale, the aim of this campaign was to test if fluorescence can be detected from airborne platforms and if this remote sensing signal can be used to improve estimates of plant mediated exchange on the mesoscale. For that purpose a canopy fluorescence was quantified from three airborne platforms: (i) a hyperspectral spectrometer that was installed on an EcoDimona delivered fluorescence in the oxygen A band along transects during 12 day courses, (ii) the prototype airborne sensor AirFLEX was installed in a Seneca aircraft quantified fluorescence in the oxygen A and B bands and (iii) the first employment of the high performance spectro-imager HYPER delivered spatially resolved and multi-temporal transects across the whole region. Additionally, high resolution geolocated hyperspectral data cubes along the whole optical spectrum, including the thermal region were gathered with an AHS sensor. Both sensors were operated jointly in a C-212-200 airplane. Several transects and flight lines were successfully recorded during the three measurement periods.

Similar experimental progress has been obtained by Miglietta et al. (2009) who used aircraft flux data for the validation of a simple bulk formulation for sensible heat ad latent heat (see also Fig. 7). The availability of repeated transect flights over both forest and agricultural land greatly improved the feasibility of such a test.

In virtually all the studies in the special issue data is used from eddy covariance measurements from the backbone network of flux sites (Jarosz et al., 2009).

One of the key question that formed the origin of the CERES campaigns was how much variability there is present in the atmospheric CO_2 signal and how much of this variability can be explained by mesoscale processes and the interaction of the land surface with the atmosphere. As documented in Dolman et al. (2006) the variability can be large and substantial, and can only be understood when mesoscale processes such as sea breezes, differences in land surface uptake patterns and 3-D flow fields are coupled together. The progress in developing and testing the meso-scale models that carry CO_2 has much been improved (e.g. Sarrat et al., 2007; Ahmadov et al., 2008; Tolk et al., 2008). These models are now capable to realistically simulate diurnal patterns of carbon uptake and the associated atmospheric variability. Further progress in this area can be expected when the mesoscale models, probably with dynamical phenology models incorporated, will start to tackle questions of regional variability at seasonal time scales.

In fact, the observation that the source areas of receptor points like tall towers vary strongly dynamically, suggest that analysis of the mesoscale flow field around tall towers is a real critical item in a quality assessment of these towers (e.g. van der Molen and Dolman, 2006; Gerbig et al., 2009). Progress in using the modelled flow fields with observed concentration in a regional inversion framework has been slow, but significant (e.g. Lavaux et al., 2009). Further work using several techniques such as MLEF (e.g. Peters, et al., 2008) or Lagrangian tracer models (Lin et al., 2004) is needed to show the viability of this approach at regional scale.

Overall the papers in this special issue show how the combination of a highly dense observation network, coupled with advanced mesoscale atmospheric models leads to fruitfull analysis. During the experiment novel techniques such as Langrangian (constant pressure) balloons were used to track airmasses. As already noted, in the 2007 campaigns the experiment was extended to include several new remote sensing techniques from aircraft. Without an integrated experiment such as CERES, these innovations would not have been possible.

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Table 1. Observations made during the three CERES campaign

Types of Observations	May–June 2005	April 2007	September 2007
Number of IOP days	22 days	6 days	8 days
RS	128 RS +11 BVC	19 RS	22 RS
	Toulouse + La Cape Sud	Toulouse	Toulouse+La Cape Sud
Piper-Aztec:	23 flights	0	0
[CO_2] and dynamic			
Dimona:	10 flights	3 flights South	3 flights South
[CO_2] and dynamic	8 flights Landes	8 flights Landes	
Sky Arrow Ibimet	52 flights	11 flights	4 days
Flux measurements			of measurements
Sky Arrow Alterra	0	11 flights	7 days
Flux measurements			of measurements
Sky Arrow Isafom	15 flights	0	0
CO_2 conc. towers	2	3	3
	Biscarosse,	Biscarosse,	Biscarosse,
	Marmande	Marmande,	Marmande,
		Bellegarde	Bellegarde
Flux Stations	10	8	8

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Detecting regional variability of carbon dioxide

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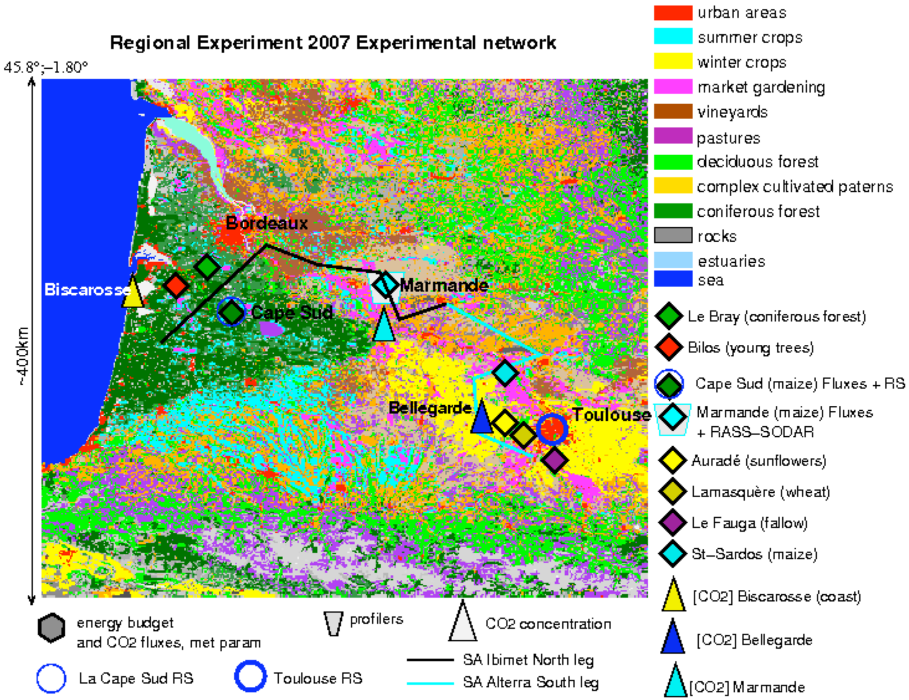

Fig. 1. The CERES Experimental set-up during the April and September 2007 campaigns.

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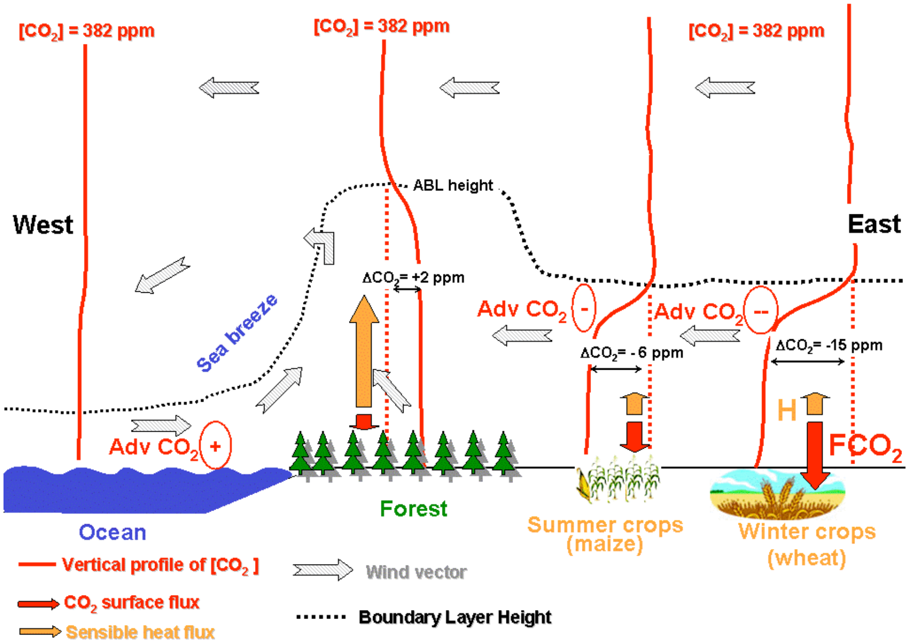

Fig. 2. Schematic description of the main physical processes along a vertical west-east cross section on may-27 around 14:00 UTC: the high ABL above the pine forest is due to a high sensible heat flux. The CO_2 concentration slightly increases in the ABL due to advection of CO_2 by the sea breeze and because of a small CO_2 surface flux. The ABL height decreases over the eastern crops where the sensible heat is weak. The CO_2 concentrations in the ABL decreases remarkably over the winter crops area characterized by a high assimilation rate. Over the summer crops, despite a relatively small assimilation rate, the CO_2 concentration remains low due to horizontal advection of poor CO_2 air mass from the southeast (Sarrat et al., 2007).

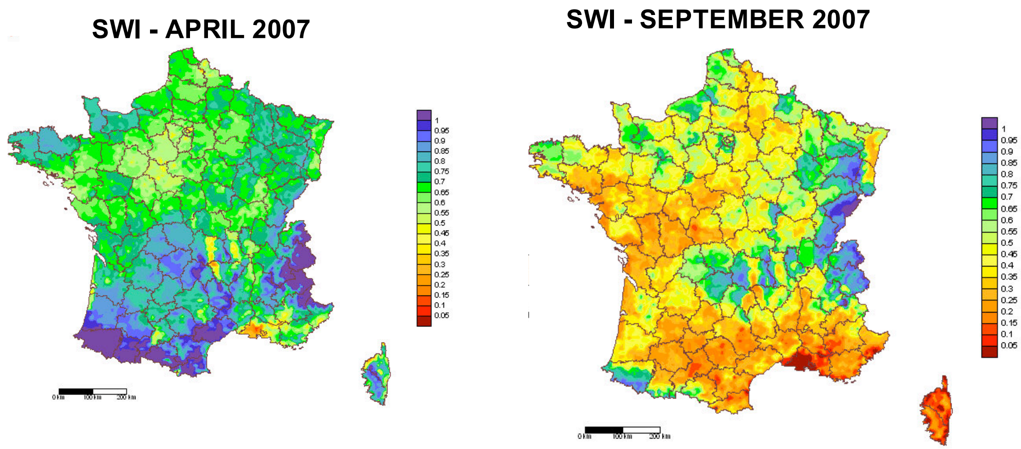

Fig. 3. Soil Wetness Index in April (left) and September (right) 2007, computed from the SIM hydrometeorological model (Habets et al., 2008).

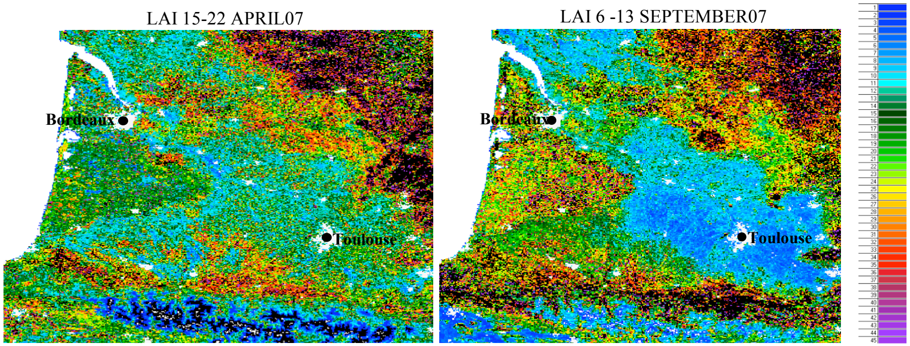

Fig. 4. Leaf Area Index (LAI) at 1km resolution from the remote sensing captor MODIS, for the April campaign (left) and the September campaign (right).

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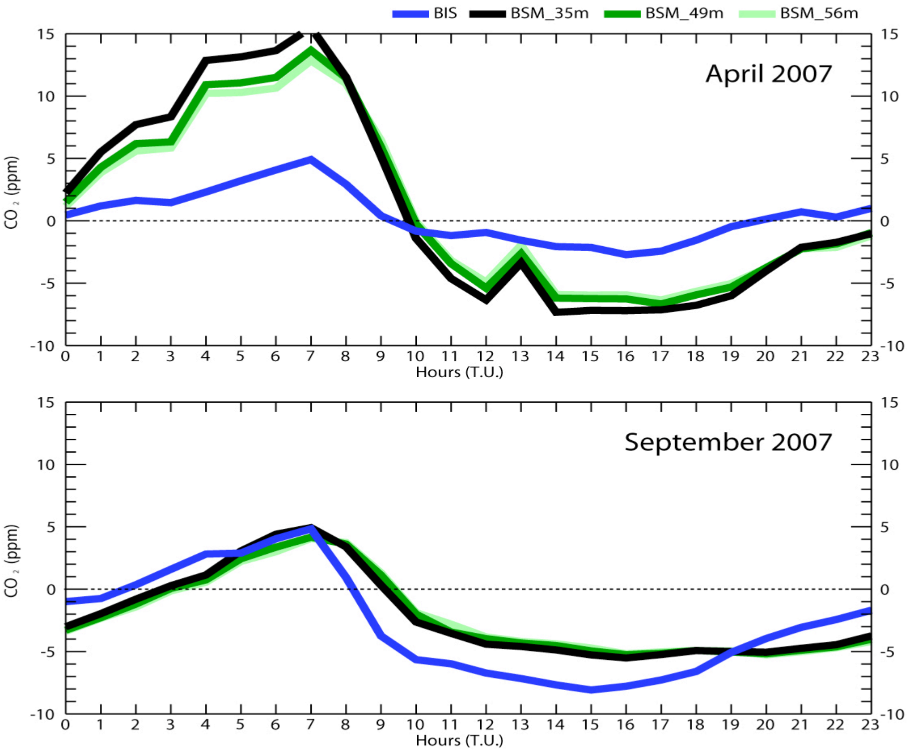

Fig. 5. Mean CO_2 concentration measured at the Biscarosse tower (blue) and at the Bellegarde-Sainte-Marie tower at different height (green and black), during the April (above) and September (below) 2007 campaigns (data provided by LSCE).

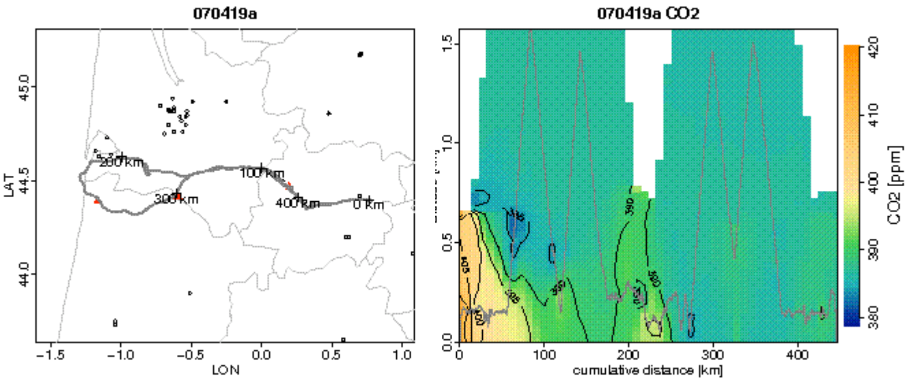

Fig. 6. Dimona trajectory (left) on the 19th of April over the croplands, the Landes forest and the ocean, and the vertical cross section of the CO_2 concentration measured as the function of the distance flown by the aircraft (right).

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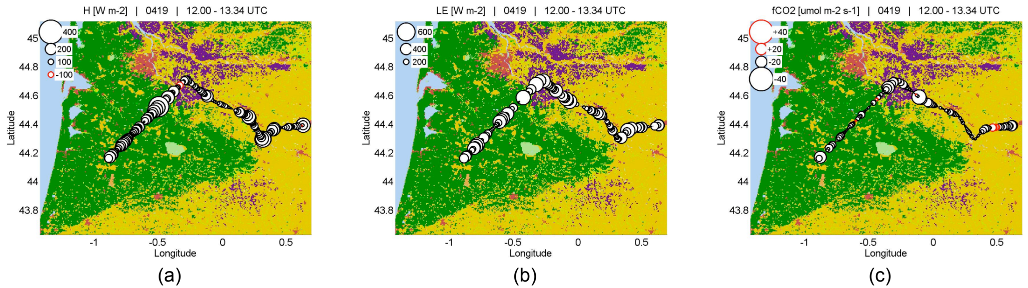

Fig. 7. Sky Arrow Ibimet measurement of sensible heat flux **(a)**, latent heat flux **(b)** and CO_2 flux **(c)** (data provided by IBIMET, Gioli, Miglietta).

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