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# Mesoscale modelling of the CO<sub>2</sub> interactions between the surface and the atmosphere applied to the April 2007 CERES field experiment

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**Abstract.** This paper describes a numerical interpretation of the April 2007, CarboEurope Regional Experiment Strategy (CERES) campaign, devoted to the study of the CO<sub>2</sub> cycle at the regional scale. Four consecutive clear sky days with intensive observations of CO<sub>2</sub> concentration, fluxes at the surface and in the boundary layer have been simulated with the Meso-NH mesoscale model, coupled to ISBA-A-gs land surface model. The main result of this paper is to show how aircraft observations of CO<sub>2</sub> concentration have been used to identify surface model errors and to calibrate the CO<sub>2</sub> driving component of the surface model. In fact, the comparisons between modelled and observed CO<sub>2</sub> concentrations within the Atmospheric Boundary Layer (ABL) allow to calibrate and correct not only the parameterization of respired CO<sub>2</sub> fluxes by the ecosystem but also the Leaf Area Index (LAI) of the dominating land cover. After this calibration, the paper describes systematic comparisons of the model outputs with numerous data collected during the CERES campaign, in April 2007. For instance, the originality of this paper is the spatial integration of the comparisons. In fact, the aircraft observations of CO<sub>2</sub> concentration and fluxes and energy fluxes are used for the model validation from the local

to the regional scale. As a conclusion, the CO<sub>2</sub> budgeting approach from the mesoscale model shows that the winter croplands are assimilating more CO<sub>2</sub> than the pine forest, at this stage of the year and this case study.

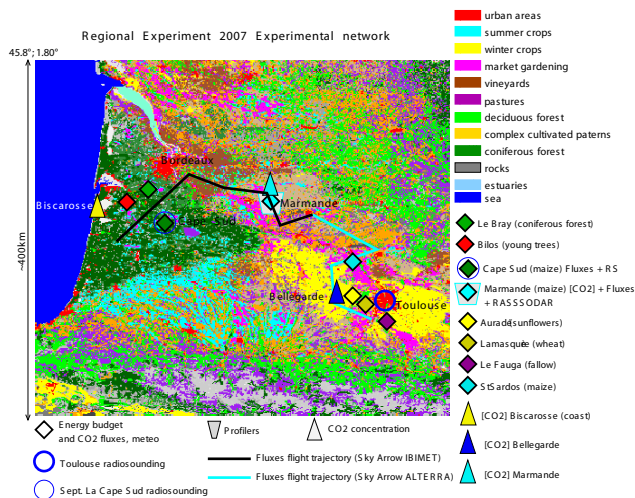
## 1 Introduction

The April 2007, CarboEurope Regional Experiment Strategy (CERES) campaign, described by Dolman et al. (2009), this issue, offers the opportunity to study the regional variation of CO<sub>2</sub> at the surface and in the boundary layer in response to the regional variability of ecosystem fluxes and mesoscale transport processes. As compared with previous observations taken in the same region during CERES 2005 (Dolman et al., 2006), the 2007 dataset was collected during wetter soil conditions and the observations were deployed over a larger domain, reaching the winter crops area around the Toulouse city, as displayed in Fig. 1. The period of sampling was also longer, with 6 consecutive days of measurements.

The previous studies conducted before with the meteorological model Meso-NH for regional atmospheric CO<sub>2</sub> modelling (Sarrat et al., 2007a, b) within the frame of CERES, were concentrated over only one intensive day of measurements. Contrarily, the present study considers 5 consecutive



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**Fig. 1.** Overview of the network deployed during the April 2007 campaign: 9 surface flux stations were deployed for representative land cover types by Alterra, INRA, CESBIO and CNRM institutes. Three towers measuring CO<sub>2</sub> concentration were installed at Biscarosse by LSCE (near the coast), at Marmande by ALTERRA (in the center of the area) and in Bellegarde by LSCE (West to Toulouse). Radio-sounding were made at Toulouse. A RASS-Sodar was installed at Marmande to monitor the vertical structure of the lower part of the atmospheric boundary layer. The solid lines summarize the aircraft trajectories regularly flown by the three-instrumented aircraft: the Western legs were flown by IBIMET Sky Arrow, while the Eastern leg was flown by the Alterra Sky Arrow. The Dimona aircraft flew alternatively the Western or the Eastern trajectories.

days with intensive measurements under rather steady state anticyclonic conditions prevailed during the full period.

Mesoscale modelling of CO<sub>2</sub>, water and energy exchanges in the boundary layer is still a challenging issue despite the previous work by e.g. Nicholls et al. (2004), Denning et al. (2003), Sarrat et al. (2009), b, Pérez-Landa et al. (2007) and Ahmadov et al. (2007). Much remains to be done in order to improve the realism of the carbon and water cycles coupling in the models at the regional scale. For instance, only few mesoscale models are able to simulate the full interactions between atmospheric CO<sub>2</sub> concentration and the surface physical and biochemical processes. Improving these interactions implies a good simulation of surface CO<sub>2</sub>, latent and sensible heat fluxes which control to some extent the CO<sub>2</sub> concentration in the boundary layer. Indeed, CO<sub>2</sub> uptake and evapotranspiration are strongly linked through the plant stomatal control and the soil moisture. A correct simulation of daily plant CO<sub>2</sub> uptake should improve the simulated Bowen ratio, i.e. the surface energy partition between sensible and latent heat ( $B = \frac{H}{LE}$ ). When the magnitude of B is less than one, a greater proportion of the available energy at the surface is transferred to the atmosphere as latent heat than as sensible heat, and the reverse is true for values of B greater

than one. Therefore, the link between CO<sub>2</sub> uptake and B is important because of its impact on the atmospheric boundary layer dynamics and on mesoscale circulations. One of the objectives of the CERES campaigns was to provide enough information on CO<sub>2</sub> surface fluxes and concentration to be able to adjust the key surface parameters of the coupled carbon and water cycles in mesoscale models. This is also the main objective of the present study, which describes the methodology used to calibrate the ISBA-A-gs surface scheme using observations taken at the surface but also taken in the lower part of the atmospheric boundary layer by instrumented aircraft. The originality of this study is to show using a top-down approach, how the atmospheric variables are used to calibrate the surface parameters and what are the feedbacks of these calibrations on the atmosphere.

First, the CERES dataset and the atmospheric mesoscale model are described.

Secondly, the calibration of two land surface scheme ISBA-A-gs parameters, based on preliminary simulation results, and compared with observations is discussed.

Finally, the ability of the mesoscale modelling system to reproduce the large spatio-temporal variability of CO<sub>2</sub> concentration and fluxes across diverse ecosystems is examined as well as the capacity of the model to be used to estimate the various terms of the regional carbon budget over pine forest and agricultural areas, in the studied region.

## 2 A summary of the CERES April campaign

The CERES 2007 experiment field started on the 18th, ended on the 23rd of April 2007. The meteorological conditions were anticyclonic, allowing the temperature to reach 29°C. During this period, low level clouds were often observed in the morning, dissipating in the afternoon with the diurnal warming. Only the 19th of April offered a clear sky without any clouds. The weak synoptic westerly flow and the high temperatures over land, generated sea breeze development along the Atlantic Ocean coast, especially on the 20th, 21st and 22nd of April. In these conditions, the three instrumented aircraft flew twice a day during these 6 consecutive days.

The experimental set-up is detailed in Fig. 1: 8 surface eddy-covariance flux stations were deployed over representative ecosystems of the area (maize, grassland, sunflower, wheat, coniferous maritime pine forest). Two tall towers and one short tower, monitored continuously the CO<sub>2</sub> concentration near the Atlantic Ocean coast (Biscarosse), in the center of the domain of interest (Marmande) and at the Eastern edge of the domain, near Toulouse (Bellegarde). A RASS-Sodar was installed in Marmande measuring the first few hundred meters of the Atmospheric Boundary Layer (ABL) vertical structure, for temperature, humidity and wind. Radio-sounding (RS) were launched at 06:00, 12:00 and 18:00 UTC at Toulouse.

Aircraft flux measurements have been provided by two light weight aircraft equipped with MFP (Mobile Flux Platform) systems, referred in the text as IBIMET Sky-Arrow and ALTERRA Sky-Arrow. Aircraft fluxes have been computed from the two aircraft using the same processing software and using at first a spatial length of 2 km; then 2 km data have been spatially averaged to produce fluxes at 8 km length, comparable with model spatial resolution. For a detailed description of the instruments and the methods see Gioli et al. (2004). The two Sky-Arrow flew over the Western track (black line in Fig. 1) or the South track (blue line in Fig. 1) every morning and afternoon, while the Dimona aircraft flew mainly over the coniferous forest and the Oceanic coast, except on the 22nd of April when its trajectory was near Toulouse.

### 3 Modelling configuration

The April period of the CERES experimental days is simulated using the meteorological model, Meso-NH, a non-hydrostatic mesoscale model (Bélair et al., 1998). The model is run with a resolution of 8 km for a large domain of 720 km × 770 km. The atmospheric Meso-NH model includes the CO<sub>2</sub> concentration, transported as a passive scalar, which is interactive with the surface carbon fluxes.

The surface energy budget and CO<sub>2</sub> fluxes are computed on-line, by the surface scheme, ISBA-A-gs (Noilhan and Planton, 1989; Calvet et al., 1998), including CO<sub>2</sub> assimilation by the vegetation and a simple parameterization of ecosystem respiration, which is dependant on soil temperature. In the surface scheme, the latent heat flux as well as the carbon flux are coupled, using the same stomatal conductance.

The physiological stomatal resistance scheme proposed by Jacobs (1994) is employed to describe photosynthesis and its coupling with stomatal resistance at leaf level. In addition, the plant response to soil water stress is driven by a normalized soil moisture factor applied to the mesophyll conductance. The computed vegetation net assimilation can be used to feed a simple growth submodel and to predict the density of vegetation cover. In the application here described, the growth model component is not used.

The ISBA-A-gs surface scheme has been tested against various micrometeorological databases for several vegetation types in off-line mode. It was shown that ISBA-A-gs was able to simulate the water budget and the CO<sub>2</sub> flux correctly (e.g. Habets et al., 1999; Rivalland et al., 2005). The CarboEurope project provides the opportunity to test it again on-line in a mesoscale model.

A particular effort has been made to improve the map of land use in the area, specially for the CERES experiment interpretation. The land cover is issued from the Ecoclimap database at 1 km resolution (Champeaux et al., 2005; Masson et al., 2003), improved through the analysis of the tempo-

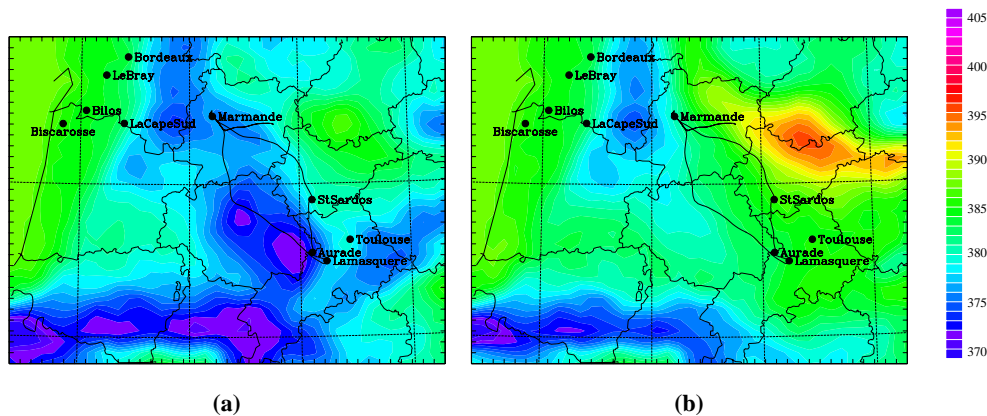
ral SPOT-VEGETATION NDVI profiles from 1999 to 2003. The Ecoclimap database contains 62 types of cover, including winter and summer crops and mixed agricultural parcels. For the natural surface (i.e. all surface type except town, sea and lake), a tile approach is used in the ISBA-A-gs surface scheme, in which each grid cell is divided into a maximum of 12 patches of natural or vegetation types (bare soil, snow, rock, tree, coniferous, evergreen, C3 crops, C4 crops, irrigated crops, grassland and parks). The main surface parameters, as the ecosystem respiration at 25°C, the mesophyll conductance, the root zone depth are fixed for each vegetation type. The energy and CO<sub>2</sub> budgets are calculated for each patch presents into the grid cell and then the resulting CO<sub>2</sub>, momentum, energy fluxes are averaged at the 8 km grid scale, according to the fraction occupied by each patch.

The anthropogenic CO<sub>2</sub> emissions are provided by a 10 km inventory of the Stuttgart University (Dolman et al., 2006). The monthly oceanic CO<sub>2</sub> fluxes are parameterized according to Takahashi et al. (1997). In this parameterization, the difference in CO<sub>2</sub> partial pressure between the ocean and the atmosphere is prescribed.

The dynamical simulation starts at 18:00 UTC (or 20:00 LT) on the 18th of April 2007, from the ECMWF analysis, both for the surface and the meteorological fields. The meteorological lateral boundaries conditions are forced every six hours with the ECMWF analysis. The CO<sub>2</sub> concentration is initialized with a homogeneous vertical profile over the whole domain, while a zero horizontal gradient of concentration is applied at the boundaries of the large-scale domain. In the future, it is planned to couple the system with large scale analysis of CO<sub>2</sub> computed with the LMD-Z global transport model.

Every day, the atmospheric variables as well as CO<sub>2</sub> concentration are re-initialized at 18:00 UTC. This initialization time was found as the best starting time to simulate the nocturnal period and CO<sub>2</sub> respiration which can have a large impact on the simulation of the following day. For instance better results for CO<sub>2</sub> concentration are obtained with an initialization at 18:00 UTC on day D-1 than to start the model at 06:00 UTC on day D, with a homogeneous vertical profile.

The soil moisture is a very important issue for simulating the interaction between the surface and atmospheric processes (Jacquemin and Noilhan, 1990). Soil wetness not only affects the Bowen ratio and the subsequent ABL evolution but also the CO<sub>2</sub> surface fluxes through CO<sub>2</sub> uptake by vegetation. The Soil Wetness Index (SWI) was taken from the ECMWF soil moisture analysis and a particular procedure has been developed to initialize the ISBA-A-gs soil water reservoir. For the April period, the soil reservoirs were close to the field capacity (not shown here).



**Fig. 2.** The simulated CO<sub>2</sub> concentration (ppm) at 16:00 UTC, at the first level of the Meso-NH model (20 m): **(a)** for the first control simulation and **(b)** after calibration of the surface flux model for winter crops. The trajectory followed by the Dimona instrumented aircraft flow between Marmande and the Toulouse region is illustrated with the thin solid line. In the control run, the unrealistic minimum of CO<sub>2</sub> West to Toulouse, in the winter crops area, is clearly seen. After calibration of the surface scheme, this CO<sub>2</sub> anomaly was removed. The grey contours represent the department boundaries.

#### 4 Further calibration of the surface scheme derived from mesoscale modelling

A first run of Meso-NH was conducted with the same calibration of the surface CO<sub>2</sub> flux processes in ISBA-A-gs, performed with previous data set. Comparisons between the aircraft data and the surface stations reveal a large discrepancy between simulated and observed CO<sub>2</sub> concentration in the ABL and close to the surface, for a large area near Toulouse. This area appears very clearly in Fig. 2a, representing the simulated CO<sub>2</sub> concentration field and showing a minimum of CO<sub>2</sub> South-West of Toulouse. This is an area mainly covered by winter crops. This area was flown by the Dimona aircraft. A comparison of CO<sub>2</sub> observed and simulated at the exact time and location of the aircraft is shown Fig. 3. The results of the first run for the morning (Fig. 3a) and afternoon flights (Fig. 3b) reveal significant differences:

(i) During the morning, the modelled CO<sub>2</sub> at low level is underestimated as compared with observations at 500 m, suggesting an underestimation of soil respiration by the model. This behavior is confirmed by comparing modelled and observed CO<sub>2</sub> at the Bellegarde atmospheric measurement tower as well as by comparing the nocturnal CO<sub>2</sub> fluxes at the stations located over winter crops.

(ii) During the afternoon, the modelled CO<sub>2</sub> concentration is strongly reduced close the surface while aircraft observations do not show such a reduction at low levels.

This large error in the computed boundary layer CO<sub>2</sub> over the winter crop area (in the other part of the domain the observations do not show such a large discrepancy) is interpreted as a model error in the CO<sub>2</sub> surface fluxes associated to this land cover. Indeed, budget studies for this particular day show that CO<sub>2</sub> advection is rather low during this period and the atmospheric error in CO<sub>2</sub> can be mostly attributed

to CO<sub>2</sub> surface flux error practically in the winter crops area south-west of Toulouse.

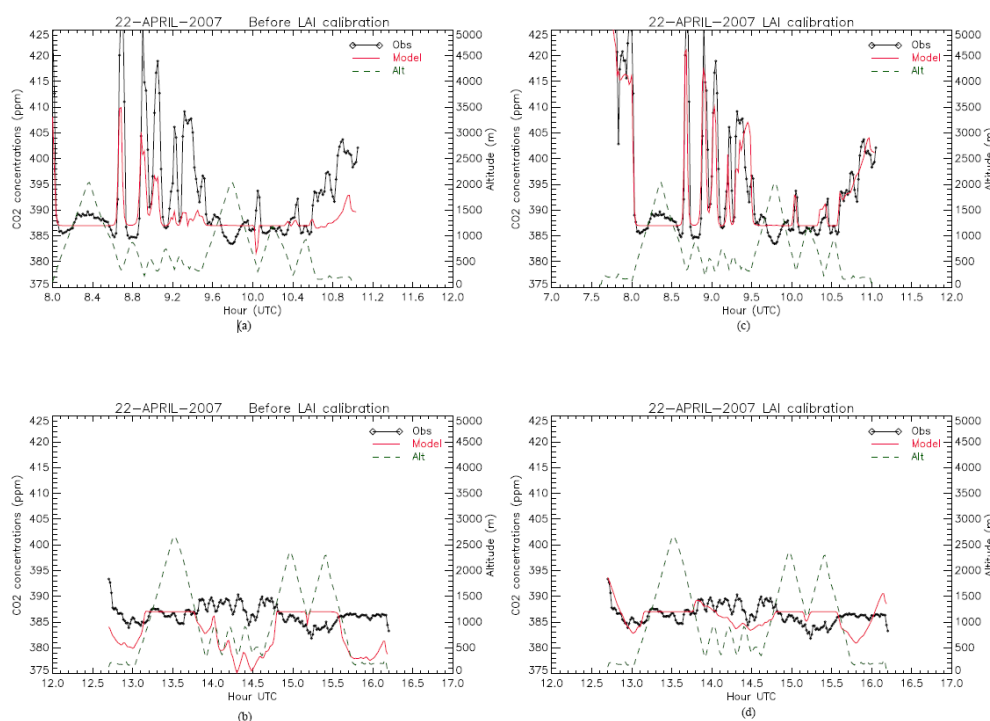
Therefore, an improvement of simulated CO<sub>2</sub> fluxes over the croplands in Toulouse region proved necessary. This is made in two steps. Firstly, the ecosystem respiration for the C3 and C4 crops are re-calibrated using the 4 flux stations located in the South-Eastern part of the experimental area. The soil respiration parameterization in this version of the ISBA-A-gs surface scheme is rather simple and does not take into account the effect of soil moisture:

$$R_{\text{ECO}} = RE_{25} \times Q_{10}^{(T_{\text{soil}} - 25)/10} \quad (1)$$

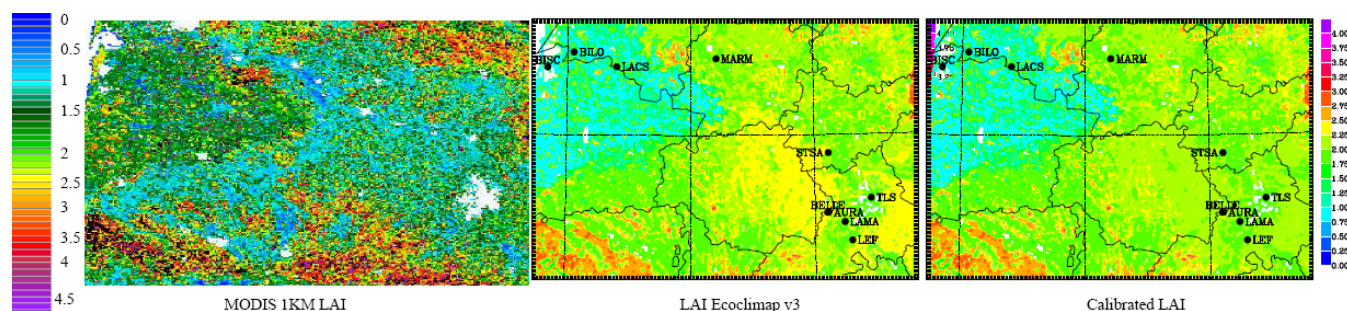
Where  $T_{\text{soil}}$  is the soil temperature at 20 cm. The  $RE_{25}$  parameter corresponds to the ecosystem respiration at 25°C. It is calibrated with the CERES 2005 data for relatively dry soils, in June 2005. For the April 2007 campaign, in contrast, the soil wetness was near the field capacity. This is a possible reason explaining a higher soil respiration. Calibration of the  $RE_{25}$  which was done for the previous campaign under dry conditions does not work here and the  $RE_{25}$  has to be increased for the present simulation, for the winter and summer crops vegetation types.

The second step is a slight modification of the Ecoclimap land cover database. A comparison of Ecoclimap LAI with Modis LAI observed at the same period revealed that the Ecoclimap LAI is slightly higher (around 3 m<sup>2</sup>.m<sup>-2</sup>) in the area west of Toulouse, than the Modis value (less than 2 m<sup>2</sup>.m<sup>-2</sup>) as shows the Fig. 4. On the other hand, the Ecoclimap LAI for C3 is in y good agreement with the field observations (for instance the observed LAI at the Lamasquère wheat station was 4.25 m<sup>2</sup>.m<sup>-2</sup>, on the 25th of April). Further comparison with data from the French Agricultural agency suggests that the area west of Toulouse, mainly classified as “Winter Crops” in the Ecoclimap database,





**Fig. 3.** Comparisons of simulated and observed CO<sub>2</sub> concentration along the aircraft trajectory during the morning (a–c) and afternoon flights (b–d) on the 22nd of April. The altitude of the flight is given by the green dotted line. The modelled CO<sub>2</sub> has been interpolated in space (same latitude, longitude, altitude) and time at the exact location of the Dimona aircraft. The model results correspond to the control run (a–b) and after the calibration (c–d).



**Fig. 4.** Maps of LAI in April : from MODIS (left), the original (middle) and the corrected Ecoclimap database (right).

comprises in reality a mixture of crops including some significant fraction of maize. In the original Ecoclimap map, this “Winter Crops” class cover is assumed entirely composed of C3 crops, with high values of LAI. For all of these reasons, the content of the “Winter Crops” class is changed by reducing the C3 winter crop from 100 to 60 % and assuming that 40 % is covered by C4 crops, which mainly corresponds to bare ground at this stage of the year. This modification of the composition of the “Winter Crops” class is made everywhere, in the considered domain of simulation. One of the effect of this modification is to decrease the value of the

averaged LAI in the domain, without modifying the LAI associated to the C3 crops. Fig. 4 shows the LAI map in April, before and after the Ecoclimap modification. The LAI decrease reaches around  $1 \text{ m}^2 \text{ m}^{-2}$  where the “Winter Crops” class is dominant.

A new simulation is run with these two modifications of the ISBA-A-gs surface scheme (soil respiration rate and LAI of the “Winter Crops” class). The effect is to increase the soil respiration and to decrease the daytime CO<sub>2</sub> uptake in the “Winter Crops” areas in the mesoscale model. The simulated CO<sub>2</sub> concentration is increased everywhere winter crops are

cultivated as shown on Fig. 2b. One can observe high concentration north of the FAGR site, where the residual nocturnal respiration is probably dragged into the diurnal ABL.

These 2 modifications have a very positive impact as depicted by Fig. 3c and d:

- (i) during the morning the simulated CO<sub>2</sub> concentration are high enough to represent the nocturnal respiration and are now closer to the aircraft observations at low level;
- (ii) during the afternoon, a significant improvement is shown with better agreement of simulated CO<sub>2</sub> in the ABL with the aircraft.

## 5 A detailed validation of the five-day mesoscale simulations against in situ data

CERES 2007 provided a unique opportunity to examine the ability of the mesoscale model to simulate the various components of the energy, water and carbon cycles against in situ data.

One of the interest is the anticyclonic atmospheric conditions experienced during the period, allowing some reduction of uncertainties in measurements through the repetitive sampling of similar conditions, particularly with weak advection.

In the following, a summary of comparisons with surface flux stations, CO<sub>2</sub> observations at the 3 tower sites, with aircraft fluxes and radio-soundings is provided.

### 5.1 Comparison with observed surface fluxes

We present a selection of surface eddy covariance flux stations with representative land cover: a grassland site at Saint-Sardos (noted STSA, in Fig. 5a), a pine forest site at Le Bray station (noted LEBR in Fig. 5b), a wheat site at full development at the Lamasquère station (noted LAMA, in Fig. 5c) and a bare ground site (just sown by maize) at the Cape Sud site (noted LACS, in Fig. 5d). Fig. 5 shows the comparisons of simulated and observed sensible and latent heat and CO<sub>2</sub> surface fluxes at all the four sites. The modelled fluxes correspond to the patch within the grid box, which is similar to the station vegetation type. This is an important advantage of the ISBA-A-gs implementation with the subgrid tiling approach. Generally, the comparisons show a fair agreement between modelled and observed fluxes for the 4 sites. It is important to recall that all these fluxes are computed interactively by the model and that the evapotranspiration is computed with the same stomatal conductance used to compute the CO<sub>2</sub> assimilation during the day. For the pine forest, the agreement is particularly good with a Bowen ratio larger than one, in response to strong stomatal reduction of evaporation even with wet soil conditions (see Noilhan and Lacarrère, 1995). However, the daytime CO<sub>2</sub> flux is slightly underestimated by the model. Conversely, at the Lamasquère wheat site, after calibration of the model, the Bowen ratio is lower and around 0.3 with very high values of daytime evapotranspiration peaking

at 400 W.m<sup>-2</sup> around noon. The turbulent water and energy fluxes are fairly reproduced by the model. The CO<sub>2</sub> uptake is slightly underestimated and the nocturnal positive respiration relatively well simulated. The last case for the Cape Sud maize site mainly constituted of bare ground in April shows also a low value of the Bowen ratio due to high soil evaporation and very weak CO<sub>2</sub> fluxes because the fraction of vegetation is very low.

### 5.2 Comparison with observed CO<sub>2</sub> concentration at the tower sites

Additional validation at the regional scale is provided by the comparisons of CO<sub>2</sub> observed and simulated at the three atmospheric towers (Fig. 6). At Marmande, the observations show a very large daily variation of CO<sub>2</sub> (up to 200 ppm the fourth day!) with a large accumulation during the night and rather constant values around 380 ppm during the day. The modelled CO<sub>2</sub> concentration shows a similar daily cycle but with a reduced variation, particularly during the night. Only during the second night, the model is able to accumulate such high concentration of CO<sub>2</sub>, near the surface, otherwise, the nocturnal concentration are underestimated.

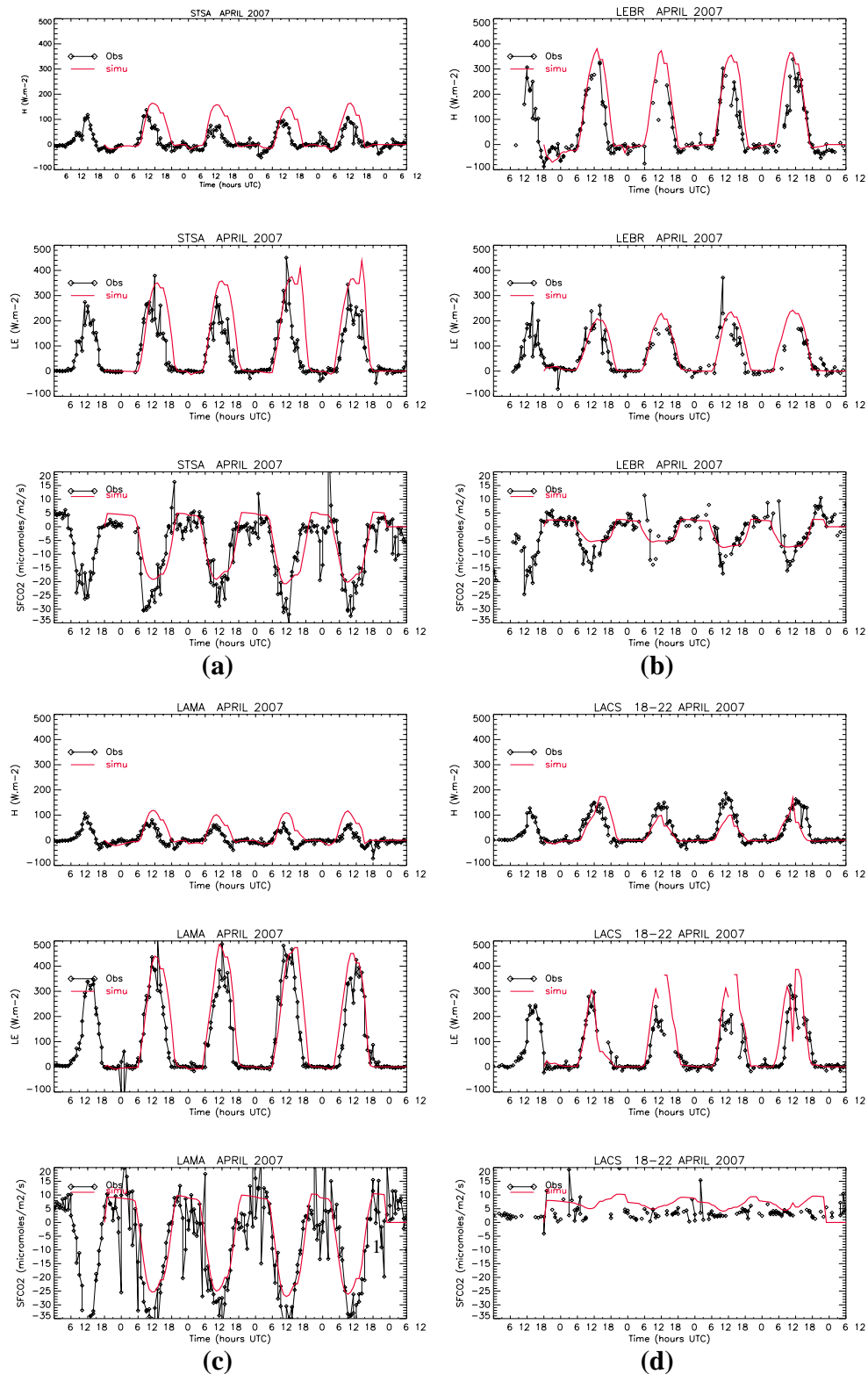
Indeed, the 2005 CERES results already showed that very large CO<sub>2</sub> vertical gradient occurred at nighttime in the first layers close to the ground. The discrepancies during the day are more difficult to explain since vertical mixing should limit the impact of the differences between observation and modelling.

At the Biscarosse coastal atmospheric station, the daily variation is remarkably reduced as compared with inland Marmande observations. Differences between model and observations are seen during the day and a better agreement is generally found during the night. Simulations performed with a higher resolution showed that the small scale circulation around the Biscarosse tower are very complex during these anticyclonic conditions where local advection developments are governed by sea and land breezes. Such behavior cannot be resolved explicitly with the 8 km resolution used in the present mesoscale simulation.

At the Bellegarde inland atmospheric station, the concentration is measured at 60 m, almost the third model level, explaining lower observed values at night. In general, the agreement during the day is fair particularly during the third day of comparison.

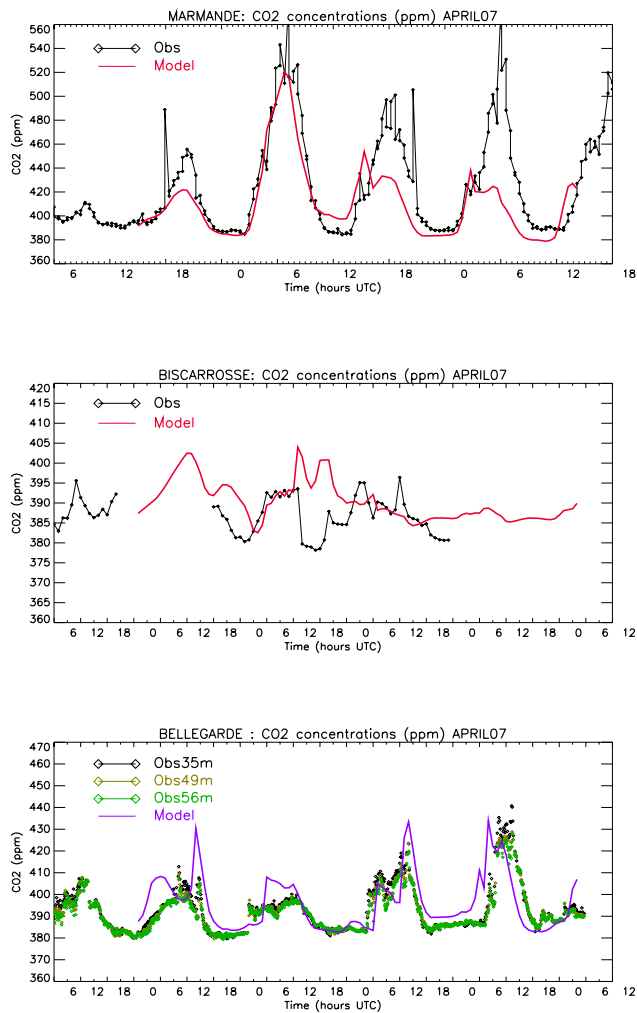
### 5.3 Comparison with aircraft energy and CO<sub>2</sub> fluxes

One originality of this analysis was to examine the ability of the mesoscale model to reproduce the spatio-temporal variation of CO<sub>2</sub> observed by a unique set of observation in the ABL with the 3 instrumented aircraft. Indeed, the 2 small Sky Arrow aircraft allow to fly at low altitude, below 200 m and to measure the energy and CO<sub>2</sub> fluxes all along the track.



**Fig. 5.** Comparisons of latent and sensible heat fluxes and CO<sub>2</sub> flux at several surface stations: **(a)** at a grassland site (STSA=Saint-Sardos), **(b)** at a coniferous forest (Le Bray), **(c)** at a winter crop site (LAMA=Lamasquère), and **(d)** at a maize site (LACS=La Cape Sud). See Fig. 1 for details.





**Fig. 6.** Comparisons of CO<sub>2</sub> concentration at Marmande, Biscarosse and Bellegarde towers.

A summary of the comparison of simulated and observed fluxes by the ALTERRA Sky Arrow along the Eastern flight track, mainly over cropland, is given in the Fig. 7. The comparison is provided for the 4 consecutive days from the 19th of April. Here, only the results for the afternoon flights are given where the link between evapotranspiration and CO<sub>2</sub> uptake is strong. The comparison shows a fair and surprisingly good agreement between the observed and simulated Bowen ratio for the four days. The Bowen ratio is around 0.5 and relatively stationary in space and time and is in agreement with observations at the flux stations. The comparison with the CO<sub>2</sub> fluxes can be also considered as satisfactorily although the observations are more scattered than for the Bowen ratio. On 19 April observations show a decrease of the Net Ecosystem Exchange (NEE) in the late afternoon, when the respiration becomes comparable to assimilation. The trend is well captured by the mesoscale model. Conversely, on 20 and 21 April both observations and the model

show a slight increase of NEE around noon with an averaged value close to  $-10 \mu \text{mol m}^{-2} \text{s}^{-1}$ .

Comparisons with the IBIMET Sky Arrow fluxes (Fig. 8) allow to evaluate the model in the forested Western part of the domain on 19 April. Again, the modelled and observed Bowen ratio are in good agreement although the observations show significant horizontal variations which are not simulated. It is difficult to know the level of realism of these horizontal variations of the Bowen ratio. Also, this figure shows relatively clearly a higher value of the Bowen ratio around 1 over the forest, compared to the bowen ratio measured by the ALTERRA Sky Arrow over the cropland. This is in agreement with the Bray flux tower. On the other hand, the simulated NEE is significantly higher than the observations, notably in the morning flight. However, the simulations are more in agreement with the aircraft observations over the forest. Again, we observe significant horizontal variations of the measured CO<sub>2</sub> flux which are not reproduced at all by the model, probably because of the coarse model resolution of 8 km. In all the cases, the model tends to overestimate the NEE measured by aircraft.

#### 5.4 Comparison with the radio-sounding in Toulouse

The ABL height was monitored at Toulouse, several times a day. Radio-sounding were launched the synoptic hours, at 06:00, 12:00 and 18:00 UTC.

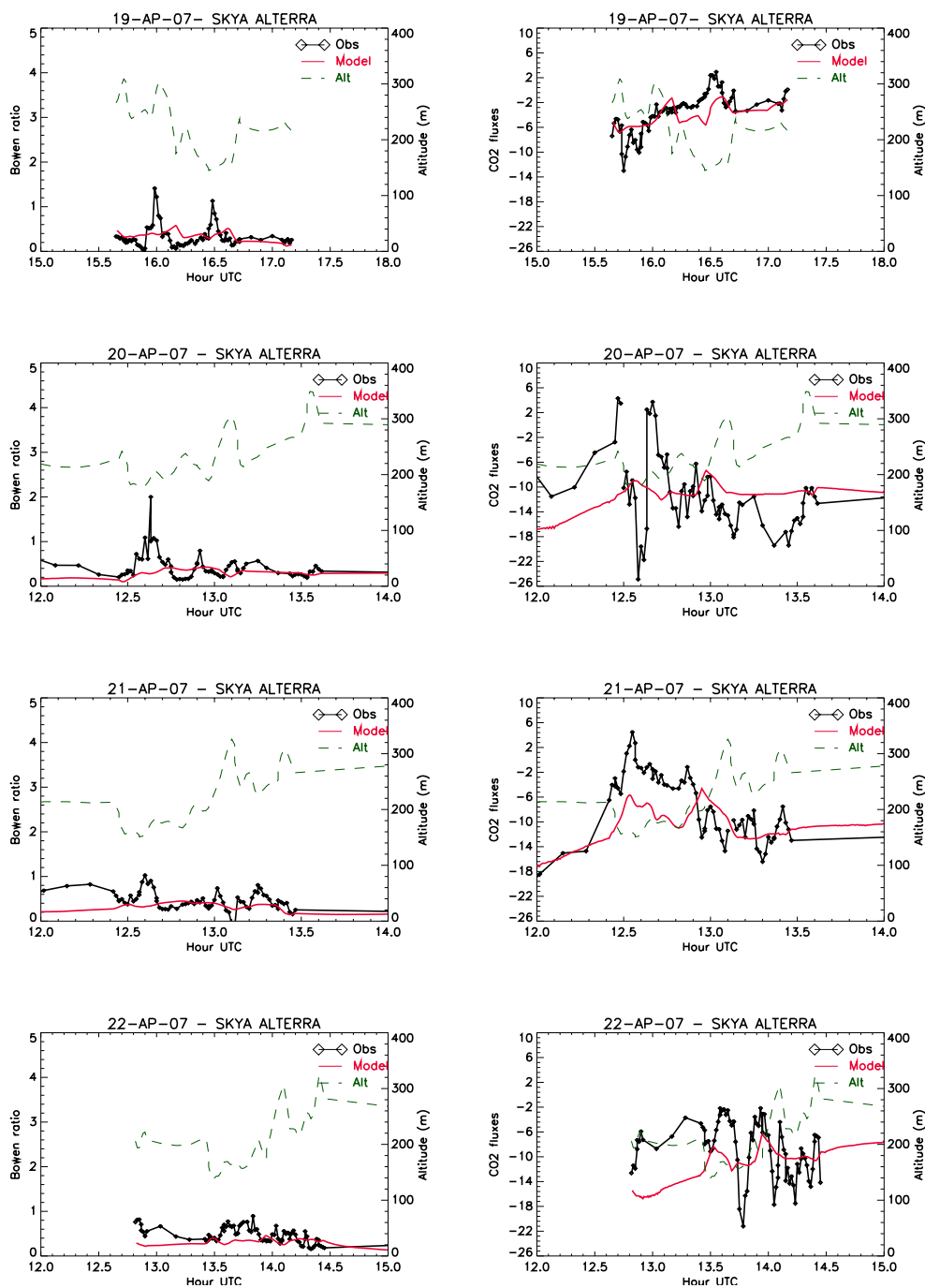
This is an important issue for the CO<sub>2</sub> concentration representation in the model since the ABL height determines the concentration vertical mixing and the entrainment at the ABL top.

The Fig. 9 shows the comparisons of the potential temperature measured by these radio-sounding launched at 12:00 UTC with the vertical profiles from the model.

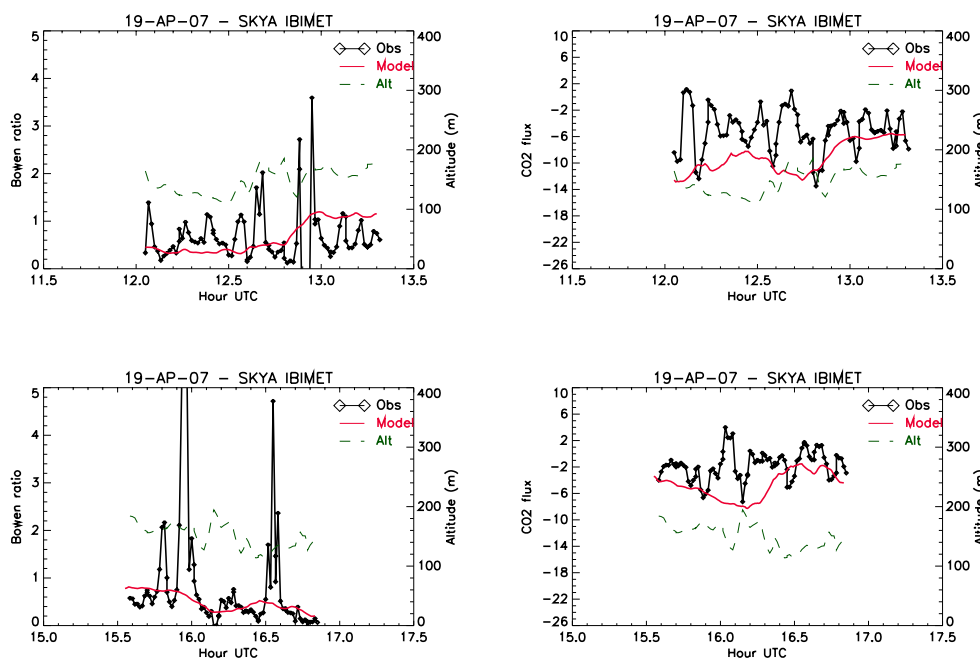
For the 4 days, the height of the ABL is correctly simulated, even if some bias in the potential temperature can be noted below 2000 m on 22 and 23 April.

## 6 Discussion

As described in the Sect. 4, preliminary Meso-NH run with no calibration of the surface scheme reveals an unrealistic minimum of CO<sub>2</sub> concentration simulated East of Toulouse, corresponding to mixed agricultural area dominated with winter crops in full development. This minimum was not observed by the DIMONA aircraft flying near Toulouse. This model error is attributed to a too low soil respiration (involving too low CO<sub>2</sub> concentration in the early morning, Fig. 3a) and a too high vegetation uptake in the winter crops area as revealed by a comparison of LAI between Ecoclimap and Modis (Fig. 4). After calibration of soil respiration and adjustment of the vegetation cover in the area of winter crops, a new simulation is compared very favorably with CO<sub>2</sub> monitored by the instrumented aircraft. Indeed, the method



**Fig. 7.** Comparison of observed and simulated Bowen ratios (left panels) and CO<sub>2</sub> fluxes,  $\mu\text{mol m}^{-2} \text{s}^{-1}$  (right panels). The Bowen ratio and the CO<sub>2</sub> fluxes are observed by the Alterra Sky Arrow flying the Eastern leg, on the 19th, 20th, 21st and 22nd of April. The altitude of the flight is given by the green dotted line. The comparisons are made at the exact location of the Dimona aircraft: the same latitude, longitude, altitude and time in the model.



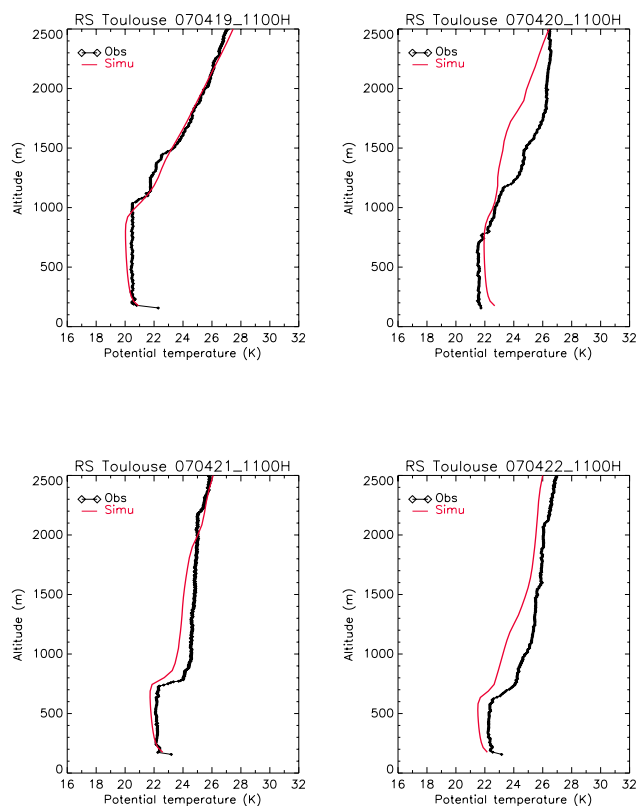
**Fig. 8.** Same as Fig. 7. Observations were taken by the Ibimet Sky Arrow instrumented aircraft, flying the Western leg twice a day. The comparisons are given for the 19th of April. The flight altitude is given by the green dotted line. The comparisons are made at the exact location of the Dimona aircraft: the same latitude, longitude, altitude and time in the model.

described in this study shows how an instrumented aircraft can be used to optimize simulated CO<sub>2</sub> surface fluxes by adjusting simulated CO<sub>2</sub> concentration with aircraft observations in the lower part of the boundary layer. To our point of view, such a link between errors in CO<sub>2</sub> concentration within the ABL and errors in the surface processes modelling proved the interest of using a mesoscale approach to simulate the daily coupling between the carbon and water cycles.

One of the limitations is probably related to the size of the land use type to which this correction can be attributed. If the area considered is too small or made of small patches, it will be difficult to identify the land cover responsible of the poor estimation of CO<sub>2</sub> concentration. On the other hand, an area sufficiently large (e.g. tens of km) and dominated by one type of crop, would be more suitable for correction since the size of the area will affect primarily the ABL dynamics and therefore the corrections could be simplified. In the CERES domain, these four large areas are the pine forest, the winter (wheat) and summer (maize) crops and the Bordeaux's vineyards areas.

The South-Eastern of the CERES domain is more patchy and associated with topographical features that makes such a procedure more difficult to be applied. In such area, probably that operating a CO<sub>2</sub> tall tower for several months would be a better mean to adjust surface fluxes using mesoscale inversion of CO<sub>2</sub> (see Lauvaux et al., 2008a).

Following the calibration of the surface scheme, the results of the mesoscale simulation have been carefully compared with the CERES observations for the 5 consecutive days. Comparing to aircraft observations, the mesoscale model results show a good level of realism to reproduce the CO<sub>2</sub> fluxes for contrasted land cover as well as the Bowen ratio in the lower part of the boundary layer. The Bowen ratio is lower than one, in the Eastern part of the domain, consistent with soil wetness close to the field capacity. However, a slightly higher value is observed and simulated over the Landes Forest, as a response of the transpiration stomatal control by the pine trees. Nevertheless, some discrepancies with the aircraft CO<sub>2</sub> fluxes are found in the Western part with observations lower than the simulation, while simultaneous observations and simulation of the Bowen ratio are matching well. At the local scale, the model represents well the surface energy balance, but underestimate the NEE. A probable reason for the underestimation of the NEE by the model is that the simulated assimilation depends on the LAI and does not take into account the assimilation by the total Photosynthetic Area Index (PAI) (including stems, ears, leaves...). In fact, a recent study, by Hoyaux et al. (2008) shows that for winter crops the stem assimilation rate equal to 63% of the leaf assimilation. The comparisons at the surface fluxes stations are also difficult because of the spatial variability of the ecosystem and the problem of representativeness of a 8 km grid cell.



**Fig. 9.** Radio-sounding launched at Toulouse site every day of the IOP at 11:00 UTC, compared to the simulated vertical profile of potential temperature (C).

The aircraft observations are taken at a scale more suitable for comparison with the mesoscale model.

Finally, the simulation of the CO<sub>2</sub> concentration at the 3 surface towers is satisfactorily, with the classical limitations due to the model spatial resolution. At the sea coast, the horizontal 8 km resolution of the model is too coarse to simulate accurately the possible small scale circulations, as sea breeze, revealed by the observations at Biscarosse. On the other hand, the vertical resolution of the model and possibly the nocturnal stable ABL (first model level at 20 m) is too coarse to be able to reproduce the nocturnal accumulation of CO<sub>2</sub> close to the ground as monitored at Marmande. However, the mesoscale model, coupling Meso-NH and ISBA-A-gs shows a good potential to simulate the daily cycle of CO<sub>2</sub> at the 2 Eastern continental towers.

All these comparisons show the general good quality of the mesoscale model to reproduce the main characteristics of the regional carbon cycle under anticyclonic weather conditions. The mesoscale model can be evaluated only in the instrumented part. Indeed, a large fraction in the South, encompassing the Pyrénées range and in the North of the domain are not covered by the network. It seems to the authors that the unique way to improve the CO<sub>2</sub> survey for the whole

area should be to develop a tower network, sufficiently dense to be able to detect CO<sub>2</sub> regional variation related to the land use. The design of such a network in connection with inverse mesoscale modelling is an issue which has been already attempted in this area (see Lauvaux et al., 2008b).

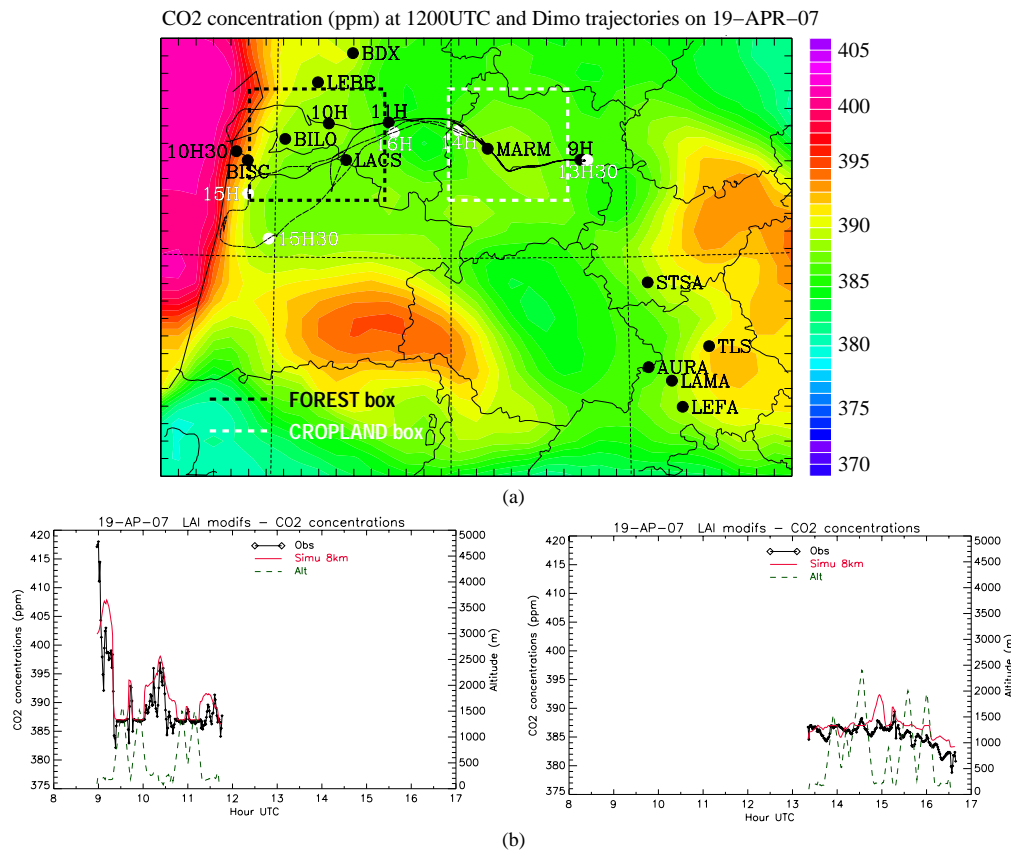
Before concluding the paper, a last example shows how the calibrated mesoscale model can be used to estimate a regional CO<sub>2</sub> budget for representative land covers of the area. The 19th of April is chosen, a day flown by the Dimona aircraft between Marmande and Biscarosse, through La Cape Sud in the Landes forest (aircraft trajectories are displayed in Fig. 10a). Model comparison with CO<sub>2</sub> observations along the aircraft track is excellent (see Fig. 10b).

Two sub-domains are selected to estimate the diurnal budget of CO<sub>2</sub> during the day (between 10:00 and 16:00 UTC). The 2 boxes centered over the Landes area (FOREST box) and centered on Marmande (CROPLAND box) are shown Fig. 10a. The CO<sub>2</sub> budget is computed by the mesoscale model at each grid point, for each grid level and then averaged horizontally. Figure 11 gives the vertical profiles of the various terms of the horizontally averaged CO<sub>2</sub> budget: the variation of CO<sub>2</sub> between 10:00 and 16:00 UTC, the total advective tendency (horizontal and vertical advections are summed) and the turbulent tendency (e.g. the divergence of the vertical turbulent flux). Both budgets show that the depletion of CO<sub>2</sub> in the ABL during the day is mostly dominated by the turbulent tendency, associated with the plant uptake. The averaged value of CO<sub>2</sub> assimilation is higher at the CROPLAND box than over the FOREST one. In the FOREST box, horizontal advection of CO<sub>2</sub> rich oceanic air compensates slightly the surface assimilation at the lowest level. The vertical profile for the CROPLAND box exhibits a positive advection near the top of the ABL which is associated to inland CO<sub>2</sub> transport from the forested area.

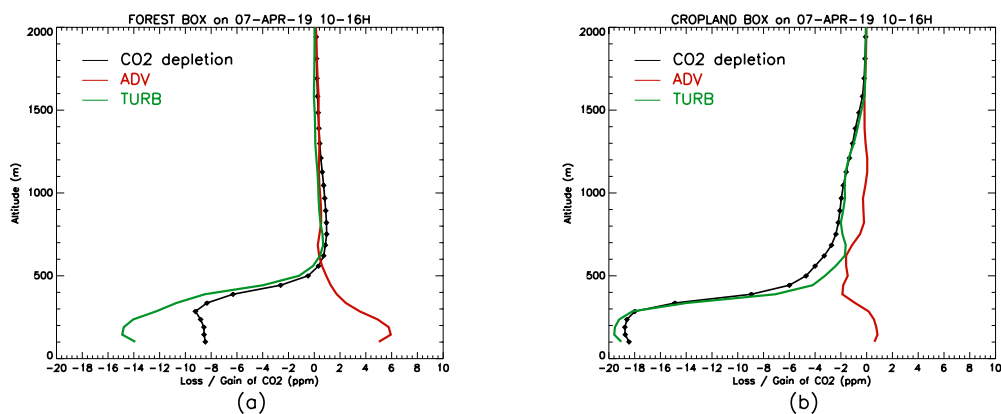
Such a budget approach is developed to interpret the whole data set and by considering domain variables in size and time of the day (nighttime period versus daytime).

## 7 Conclusions

This study tries to take full advantage of the very rich CERES dataset on April 2007 to improve and to understand a mesoscale simulation of the water, energy and CO<sub>2</sub> fluxes exchanges between the surface and the atmospheric boundary layer. Another large interest of the data set is that the period of observation covers 5 consecutive days with relatively steady state large scale conditions: anticyclonic, weak synoptic winds, clear sky except for the last days in the Western part of the domain and over the Pyrénées mountains. The experimental effort can be considered as relatively unique since 8 flux stations, 3 towers measuring atmospheric CO<sub>2</sub> concentration, a radio sounding site and 3 instrumented aircraft were fully operational every day. In April, the soil wetness was close to the field capacity and evapotranspiration was



**Fig. 10.** (a) Meso-NH field of CO<sub>2</sub> concentration at 12:00 UTC on the 19 April at the first level of the model (20 m), with the two aircraft trajectories, the morning one (solid black line and black hours) and the afternoon one (dashed line with white hours); (b) comparisons between Meso-NH CO<sub>2</sub> concentration (red) and aircraft observations (black), for the morning flight (up) and the afternoon flight (down). The comparisons are made at the exact location and hours point in the model. The black and the white rectangles represent respectively the FOREST and the CROPLAND boxes in which are averaged the numerical budget displayed in Fig. 12.



**Fig. 11.** Vertical profiles of the several budget terms calculated by Meso-NH and averaged over the FOREST box (a) and the CROPLAND box display in Fig. 11. For the both boxes, the budget is calculated between 10:00 and 16:00 UTC. The black profile represents the difference of CO<sub>2</sub> concentration between the two instant of integration, the red profile represents the advective tendency (horizontal plus vertical advections) and the green profile represents the turbulent tendency.



not (or little) controlled by soil water availability. The Ecolimap land cover dataset has been updated by improving the crops mapping using the full advantage of the seasonal and inter annual change over 5 years of NDVI to distinguish 62 vegetation types in the area. As already discussed in Sarrat et al. (2007a) and Dolman et al. (2006), the area is characterized by a very large extensive maritime pine forest in the Western part, by winter and summer crops in the Eastern part, and the well known Bordeaux vineyards in the Garonne valley. These main four vegetation types form large areas relatively homogeneous over tens of km. Therefore, the surface fluxes associated to each large zone can affect the ABL dynamics and develop mesoscale circulations involving a large horizontal variability in atmospheric CO<sub>2</sub> concentration.

The Meso-NH atmospheric mesoscale model coupled with the ISBA-A-gs surface scheme proved to be a good numerical tool for the interpretation of these 5 consecutive days of data and to improve our understanding on the coupling of water and carbon fluxes at mesoscale in response to the variability of land use. This model is also able to reproduce the regional spatio-temporal variation of CO<sub>2</sub> concentration, intensively observed during the CERES 2007 experiment.

Additionally, the analysis shows how an improvement of the surface scheme can be deduced from comparisons between the simulated atmospheric CO<sub>2</sub> and the aircraft observations.

The aircraft observations of CO<sub>2</sub> concentration as well as energy and CO<sub>2</sub> fluxes appear in fact, as relevant data to be exploited in the mesoscale model, in order to calibrate the surface parameters, to validate the results but also to help to the understanding of the interactions surface-atmosphere at the regional scale.

For this period of the year, the CO<sub>2</sub> budgeting atmospheric approach shows that daytime NEE is higher over the winter cropland than over the maritime pine forest. Similar methods will be applied to the September data set which is characterized by drier soil conditions and maturing maize crops.

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