Biogeosciences Discuss., 6, 515–544, 2009
www.biogeosciences-discuss.net/6/515/2009/

Biogeosciences Discussions

Biogeosciences Discussions is the access reviewed discussion forum of *Biogeosciences*

Mesoscale modeling of the CO_2 interactions between the surface and the atmosphere applied to the April 2007 CERES field experiment

C. Sarrat[1], J. Noilhan[1], P. Lacarrère[1], A. J. Dolman[2], C. Gerbig[3], J. A. Elbers[4], O. S. Vellinga[4], B. Gioli[5], F. Miglietta[5], B. Neininger[6], T. Lauvaux[7], P. Ciais[7], M. Ramonet[7], E. Ceschia[8], and J. M. Bonnefond[9]

[1]CNRM-GAME, Météo France, 42 avenue Coriolis, 31057 Toulouse Cedex, France
[2]Vrije Universiteit, De Boelelaan 1085, 1081 HV Amsterdam, The Netherlands
[3]Max Planck Institute for Biogeochemistry, Hans-Knöll-Str. 10, 07745 Jena, Germany
[4]ALTERRA, Droevendaalsesteeg 3, 6708 PB Wageningen, The Netherlands
[5]IBIMET, Via Giovanni Caproni 8, 50145 Firenze, Italia

[6] MetAir, AG, Sonnenberg 27, 6313 Menzingen, Switzerland
[7] LSCE, CEA/Saclay, 91191 Gif-sur-Yvette Cedex, France
[8] CESBIO, 18, avenue Edouard Belin, 31401 Toulouse Cedex 9, France
[9] INRA, B.P. 81, 33883 Villenave d'Ornon Cedex, France

Received: 1 October 2008 – Accepted: 14 November 2008 – Published: 9 January 2009

Correspondence to: J. Noilhan (joel.noilhan@meteo.fr)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

The paper describes a numerical interpretation of the April 2007 CarboEurope Regional Experiment Strategy (CERES) campaign, devotedto the study of CO_2 cycle at the regional scale. The four consecutive clear sky days with intensive observations of CO_2 concentration, fluxes at the the surface and in the boundary layer have been simulated with the Meso-NH mesoscale model. Aircraft observations of CO_2 have been used to identify surface modelling errors and to calibrate the CO_2 components of the surface model. After this calibration, the paper describes a systematic comparison of the model outputs with all the data collected during CERES, in April 2007. As a conclusion, an example of CO_2 budgeting from the mesoscale model is given.

1 Introduction

The April 2007 CarboEurope Regional Experiment Strategy (CERES) campaign offers the opportunity to study the regional variation of CO_2 at the surface and in the boundary layer in response to the regional variability of land use. As compared to previous observations taken in South-Western France 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 previous studies conducted before with the Meso-NH, a mesoscale and Non-Hydrostatic model, for regional atmospheric CO_2 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 4 consecutive days with intensive measurements for which rather steady state anticyclonic conditions prevailed during the full period.

Mesoscale modelling of CO_2, water and energy exchanges in the boundary layer is still a challenging issue despite the previous work by Nicholls et al. (2004); Denning et al. (2003); (Sarrat et al., 2007a,b, 2008). Much remains to be done in order to im-

prove 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 a full interaction between the atmospheric CO_2 and the surface physical processes. Improving these interactions implies a fair simulation of surface CO_2, latent and sensible heat fluxes which control to some extent the CO_2 concentration in the boundary layer. Indeed, CO_2 uptake and evapotranspiration are strongly linked through plant stomatal control and the soil water balance. A correct simulation of daily plant uptake should improve the Bowen ratio which impacts on the atmospheric boundary layer dynamics and possibly on mesoscale circulations. Now, these surface interactions are parametrized and necessitate an accurate calibration of the surface parameters. One of the objectives of the CERES dataset was to provide enough information on surface fluxes and concentration to be able to adjust key surface parameters of the coupled carbon and water cycles in mesoscale model. 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 an instrumented aircraft.

First, the CERES dataset and the atmospheric mesoscale model are described. Secondly, the calibration of the different components of the surface scheme based on preliminary simulation results compared with observations is discussed.

Finally, the ability of the mesoscale model to reproduce the large spatio-temporal variability of CO_2 concentration and fluxes is examined as well as the capacity of the model to be used to estimate the various terms of the regional carbon budget over the pine forest and over an agricultural area.

2 A summary of the CERES April campaign

The CERES 2007 experiment field started on 18, ended on 23 April. 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 19 April offered a clear sky without any clouds. The weak synoptic westerly flow and the high enough temperatures, generated sea breeze development along the Atlantic Ocean coast, especially on 20, 21 and 22 April. In these conditions, the three instrumented aircraft flew twice a day during these 6 consecutives days.

The experimental set-up is detailed in Fig. 1: the 9 surface flux stations were deployed over the representative ecosystems of the area (maize, grassland, sunflower, wheat, coniferous forest). Two tall towers and one "virtual tall tower", monitored continuously the CO_2 concentration near the Altlantic 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 vertical structure of the Atmospheric Boundary Layer (ABL), 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 small 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 flew mainly over the coniferous forest and the Oceanic coast, except on 22 April when its trajectory was near Toulouse.

3 Modelling configuration

This period of these 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_2 concentration, transported as a passive scalar, which is interactive with the surface carbon flux. The surface energy budget and CO_2 fluxes are computed on-line by the surface scheme, ISBA-A-gs (Noilhan and Planton, 1989; Calvet et al., 1998), including CO_2 assimilation by the vegetation and a simple parametrization of ecosystem respiration, which is dependant on soil temperature. In the surface scheme, the latent heat flux as well as the carbon flux are computed through the same stomatal conductance.

The land cover is from an improvement of the Ecoclimap database at 1 km resolution (Champeaux et al., 2005; Masson et al., 2003) and contains 62 types of cover. For the natural surface (i.e. all surface type except town, sea and lake), a tile approach is used in ISBA-A-gs, in which each 8 km grid cell is divided into patches (bare soil, snow, rock, tree, coniferous, evergreen, C3 crops, C4 crops, irrigated crops, grassland and parks). The energy and CO_2 budgets are calculated for each patch presents into the grid cell and then the resulting fluxes are averaged at the grid scale, according to the fraction occupied by each patch.

The anthropogenic CO_2 emissions are provided by the 10 km inventory of the Stuttgart University (Dolman et al., 2006). The oceanic CO_2 fluxes are parametrized according to Takahashi et al. (1997). In this parametrization, the difference in CO_2 partial pressure between the ocean and the atmosphere has been prescribed.

The simulation is initialized at 18:00 UTC on 18 April 2007 from the ECMWF analysis, both for the surface and the meteorological fields and runs for 5 days. The meteorological lateral boundaries conditions are forced every six hours with the ECMWF analysis. The CO_2 concentration are 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_2 computed with the LMD-Z global assimilation system. Every day, the atmospheric variables as well as CO_2 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_2 respiration which can have a large impact on the simulation of the following day. For instance better results for CO_2 concentration are obtained with an initialization at 18:00 UTC on day J-1 than to start the model at 06:00 UTC on day J, 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_2 surface fluxes through soil respiration and CO_2 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).

4 Further calibration of the surface scheme derived from mesoscale modeling

A first run of Meso-NH was conducted with the same calibration of the surface carbon processes in ISBA-A-gs, performed with the May–June 2005 data set. Comparisons between the aircraft data and the surface stations reveal a large discrepancy between simulated and observed CO_2 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_2 concentration field, showing a minimum of CO_2 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_2 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_2 at low level is underestimated as compared with observations at 500 m, suggesting an underestimation of soil respiration by the model. This behaviour was also confirmed by comparing modelled and observed CO_2 at the Bellegarde tower as well as by comparing the nocturnal CO_2

fluxes at the stations located over winter crops.

(ii) During the afternoon, the modelled CO_2 concentration are 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_2 over the winter crop area (in the other part of the domain the observations do not show such a large model error) was interpreted as a model error in the CO_2 surface fluxes associated to this land cover. Indeed, budget studies for this particular day show that advection was rather low during this period and therefore the atmospheric error in CO_2 can be attributed to CO_2 surface flux error practically in the same area.

Therefore, an improvement of simulated CO_2 fluxes over the crops proved necessary. This was made in two steps. Firstly, the ecosystem respiration for the C3 and C4 crops has been re-calibrated using the 4 flux stations located in the South-Eastern part of the experimental area. The soil respiration parametrization in this version of the ISBA-A-gs surface scheme was really very crude and does not take into account the effect of soil moisture:

$$R_{\mathrm{ECO}} = \mathrm{RE}_{25} \times Q_{10}^{(T_{\mathrm{soil}}-25)/10} \qquad (1)$$

Where T_{soil} is the soil temperature at 20 cm. The RE_{25} parameter corresponds to the ecosystem respiration at 25°C. It was calibrated with the CERES 2005 data with relatively dry soil, in June. For the April campaign the soil wetness was near the field capacity. This was a possible reason for stimulating soil respiration. The calibration with the April data results in an increase of the RE_{25} parameter.

The second step was 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 was slightly higher (around 3 $m^2\,m^{-2}$) in the area west of Toulouse, than the Modis value (less than 2 $m^2\,m^{-2}$) as shows the Fig. 4. On the other hand, the Ecoclimap LAI for C3 was in y good agreement with the field observations (for instance the LAI at the Lamasquère wheat station was 4.25 $m^2\,m^{-2}$, on 25 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, comprises in reality a mixture of crops including some significant fraction of maize. In the original Ecoclimap map, this "Winter Crops" class cover was assumed entirely composed of C3 crops, with high values of LAI. For all of these reasons, the content of the "Winter Crops" class was 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 was made everywhere, in the considered domain of simulation. One of the effect of this modification was to decrease the value of the averaged LAI in the domain, without modifying the LAI associated to the C3 crops. Figure 4 shows the LAI map before and after the Ecoclimap modification. The LAI decrease reaches around 1 $m^2\,m^{-2}$ where the "Winter crops" class is dominant. A new simulation has been run with these two modifications of the ISBA-A-gs surface scheme (soil respiration and composition of the "Winter Crops" class). The effect of course was to increase the soil respiration and to decrease the daytime CO_2 uptake in the "Winter Crops" areas in the mesoscale model. These 2 modifications have a very positive impact as depicted in Fig. 3c and d:

(i) during the morning the simulated CO_2 concentration are high enough to represent the nocturnal respiration and are now closer to the aircraft observation at low level;

(ii) during the afternoon, a significant improvement is shown with better agreement of simulated CO_2 in the ABL with the aircraft.

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

CERES 2007 provided an 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, of course, is the steady state atmospheric conditions experienced during the period, allowing some reduction of uncertainties in measurements through the repetitive sampling of similar conditions.

In the following, a summary of comparison with surface flux stations, CO_2 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 stations with representative land cover: a grassland site at Saint-Sardos, a pine forest site at Le Bray station, a wheat site at full development at the Lamasquère station and a bare ground site (just sown by maize) at the Cape Sud site. Figure 5 shows a comparison of simulated and observed sensible and latent heat and CO_2 surface fluxes at all the four sites. The modelled fluxes correspond to the patch within the grid box, which is similar to the station, respectively a grassland, a pine forest and C3 and C4 crops. This is an important aspect of the ISBA-A-gs implementation with the tiling approach. Generally, the comparison 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_2 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; Jacquemin and Noilhan, 1990). However, the daytime CO_2 flux is slightly underestimated by the model. Conversely, at the Lamasquère wheat site, the Bowen ratio is very much lower and around 0.3 with very high values of daytime evapotranspiration picking at 400 Wm^2 around noon. Again, the turbulent fluxes are fairly reproduced by the model. Again, the CO_2 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 shows also low value of the Bowen ratio due to high soil evaporation and very weak CO_2 fluxes because the fraction of vegetation is very low.

5.2 Comparison with observed CO_2 concentration at the tower sites

Additional validation at the regional scale is provided by the comparison of CO_2 observed and simulated at the three towers (Fig. 6). At Marmande, the observations show a very large daily variation of CO_2 (up to 200 ppm the fourth day!) with a large accumulation during the night and values around 380 ppm during the day. The modelled CO_2 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_2, near the surface, otherwise, the nocturnal concentration are underestimated.

Indeed, the 2005 CERES results showed that very large CO_2 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 in level of observation and modeling. At the Biscarosse coastal site, the daily variation is remarkably reduced as compared with inland 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 behaviour cannot be resolved explicitly with the 8 km resolution used in the present mesoscale simulation.

At the Bellegarde inland station, the observations are taken at a higher level than the first 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_2 fluxes

One original point of view of this analysis, was to examine the ability of the mesoscale model to reproduce the spatio-temporal variation of CO_2 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_2 fluxes all along the track.

A summary of the comparison of simulated and observed fluxes by the Alterra Sky Arrow along the Eastern flight track is given in the Fig. 7. The comparison is provided for the 4 consecutive days lasting on 19 April. Here, only the results for the afternoon flights are given where the link between evapotranspiration and CO_2 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_2 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 in assimilation in the late afternoon which is well captured by the mesoscale model. Conversely, on 20 and 21 April both observations and the model show a slight increase of assimilation around noon with an averaged value close to $-10\,\mu\text{mol}\,\text{m}^{-2}\,\text{s}^{-1}$.

Comparison with the IBIMET Sky Arrow (Fig. 8) allows to evaluate the model in the 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, in agreement with the Bray flux tower. On the other hand, the simulated assimilation is significantly higher than the observations, notably in the morning flight. However, the simulation are more in agreement with the aircraft observations over the forest. Again, we observe significant horizontal variations of the measured CO_2 flux which are not reproduced at all by the model, probably because of the coarse model resolution of 8 km.

5.4 Comparison with the radio-sounding in Toulouse

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

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 forecasted, even if some bias in the potential temperature can be noted below 2000 m on 22 and 23 April.

6 Discussion

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_2 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 tall towers, a radio sounding site and 3 instrumented aircraft were fully operational every day. The Meso-NH atmospheric mesoscale model coupled with the ISBA-A-gs surface scheme is used for the interpretation of the data and to improve our understanding on the coupling of water and carbon fluxes at mesoscale in response to the variability of land use.

In April, the soil wetness was close to the field capacity and evapotranspiration was not (or little) controlled by soil water availability. A particular effort have been made to improve the map of land use in the area. Therefore, the Ecoclimap dataset has been updated by improving the crops mapping using five years of NDVI Vegetation data. The classification algorithm (Champeaux et al., 2005) takes full advantage of the seasonal and inter annual change 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, and by winter and summer crops in the Eastern part, and well known Bordeaux vineyards in the Garonne valley. These main four vegetation types form large areas relatively homogeneous (for instance in the case of the winter crops area East to Toulouse) overs 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_2 concentration. The improved land cover map has been introduced in Meso-NH. Futhermore, a particular procedure has been developed to reinitialized the surface and atmospheric fields every day at 18:00 UTC.

A preliminary run with no calibration of the surface scheme revealed that an unrealistic minimum of CO_2 concentration was simulated East of Toulouse, corresponding to mixed agricultural area dominated with winter crops in full development. This minimum was not observed by the SA aircraft flying above the area at 100 m height. These model errors were attributed to a two low soil respiration and a two high vegetation cover 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 was compared very favourably with CO_2 monitored by the instrumented aircraft. Indeed, the method described in this study shows how an instrumented aircraft can be used to optimise simulated CO_2 surface fluxes by adjusting simulated CO_2 concentration with aircraft observations in the lower part of the boundary layer.

One of the limitation probably is 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_2 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 made such a procedure more difficult to be applied. In such area, maybe that operating a CO_2 tall tower for several months would be a better mean to adjust surface fluxes using mesoscale inversion of CO_2 (see Lauvaux et al., 2008b). 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. The mesoscale modelling results show a very high level of realism to reproduce the surface CO_2 fluxes for contrasted vegetation types as well as the Bowen ratio and the CO_2 fluxes in the lower part of the boundary layer. The Bowen ratio was lower than one in the Eastern part of the area, consistently with soil wetness close to the field capacity. However, a slightly higher value was observed and simulated over the Landes Forest, in response with stomatal control of transpiration by the pine trees. However, some discrepancies with the aircraft CO_2 fluxes were found in the Western part with observations lower than the simulation, while simultaneous observations and simulation of the Bowen ratio were matching surprisingly well.

Finally, the simulation of the CO_2 concentration at the 3 surface towers was satisfactorily, with the classical limitations due to the model spatial resolution. At the sea coast, the horizontal 8 km resolution of the model was too weak to simulate accurately the possible small scale circulations revealed by the observations at Biscarosse. On the other hand, the vertical resolution of the model (first model level at 20 m) was too coarse to be able to reproduce the nocturnal accumulation of CO_2 close to the ground as monitored at Marmande. However, the mesoscale model showed a very good potential to simulate the daily cycle of CO_2 at the 2 Eastern continental towers.

All these comparisons show the general excellent quality of the mesoscale model to reproduce the main characteristics of the carbon cycle under these anticyclonic weather conditions. However, the mesoscale model can be evaluated only in the instrumented part. Indeed, a large fraction in the South, encompassing the Pyrénées range, is not covered by the network. It seems to the authors that the unique way to improve

the CO_2 survey for the whole area should be to develop a tower network, sufficiently dense to be able to detect CO_2 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 is given to show how the mesoscale model can then be used to estimate a regional CO_2 budget for representative land covers of the area understudy. Day, 19 April is chosen, a day flown by the Dimona aircraft between Marmande and Biscarosse, through La Cape Sud in Les Landes (aircraft trajectories are displayed in Fig. 10a). Model comparison with CO_2 observations along the aircraft track was excellent (see Fig. 10b).

Two domains were selected to estimate the diurnal budget of CO_2 during the day (between 10:00 and 16:00 UTC). The 2 boxes centred over the Landes area (FOREST box) and centred around Marmande (CROPLAND box) are shown Fig. 10a. The CO_2 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_2 budget: the variation of CO_2 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_2 in the ABL during the day is mostly dominated by the turbulent tendency, associated with the plant uptake. The averaged value of CO_2 assimilation is higher at the CROPLAND box than over the FOREST one. In the FOREST box, horizontal advection of rich CO_2 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_2 transport from the forested area.

Such a budget approach is being 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 shows the good capacity of the Meso-NH mesoscale model to reproduce the regional spatio-temporal variation of CO_2 concentration, intensively observed during the CERES 2007 experiment.

The analysis shows how an improvement of the surface scheme can be deduced from comparisons between the simulated atmospheric parameters and the aircraft observations.

Particularly, the same methods will be applied to the September data set which is characterized by drier soil conditions and maturing maize crops.

Acknowledgements. The authors would like to thank all the CERES teams for providing the data and to the pilots of the 3 aircrafts based at the wonderful Villeneuve-Sur-Lot airport hosted by Mr. Moustache. Thanks also to the CNRM colleagues who were involved in the experiment field, the Météo France forecaster of the CDM31 for providing excellent meteorological assistance. CERES 2007 was founded by the CarboEurope-IP's Regional component.

The publication of this article is financed by CNRS-INSU.

References

Bélair, S., Lacarrère, P., Noilhan, J., Masson, V., and Stein, J.: High-resolution simulation of surface and turbulent fluxes during HAPEX-MOBILHY, Mon. Weather Rev., 126, 2234–2253, 1998. 519

Calvet, J.-C., Noilhan, J., Roujean, J.-L., Bessemoulin, P., Cabelguenne, M., Olioso, A., and Wigneron, J.-P.: An interactive vegetation SVAT model tested against data from six contrasting sites, Agr. Forest Meteorol., 92, 73–95, 1998. 520

Champeaux, J., Fortin, H., and Han, K.-S.: Spatio-temporal characterization of biomes over South-West of France using SPOT/VEGETATION and Corine Land Cover datasets, IGARSS'05 Proceedings, 2005. 520

Denning, S., Nicholls, M., Prihodko, L., Baker, I., Vidale, P.-L., Davis, K., and Bakwin, P.: Simulated variations in atmospheric CO_2 over a Wisconsin forest using a coupled ecosystem-atmosphere model, Global Change Biol., 9, 1241–1250, 2003. 517

Dolman, A., Noilhan, J., Durand, P., Sarrat, C., Brut, A., Butet, A., Jarosz, N., Brunet, Y., Loustau, D., Lamaud, E., Tolk, L., Ronda, R., Miglietta, F., Gioli, B., Magliulo, E., Esposito, M., Gerbig, C., Körner, S., Galdemard, P., Ramonet, M., Ciais, P., Neininger, B., Hutjes, R., Elbers, J., Warnecke, T., Landa, G., Sanz, M., Scholz, Y., and Facon, G.: CERES, the Carboeurope Regional Experiment Strategy in les Landes, South-West France, May–June 2005, BAMS, 87(10), 1367–1379, 2006. 517, 520

Gioli, B. a. F. M., Martino, B. D., Hutjes, R. A., Dolman, H. A. J., Lindroth, A., Schumacher, M., Sanz, M., Manca, G., Peressotti, A., and Dumas, E. J.: Comparison between tower and aircraft-based eddy covariance fluxes in five european regions, Agr. Forest Meteorol., 127, 1–16, 2004. 519

Jacquemin, B. and Noilhan, J.: Validation of a land surface parameterization using the HAPEX-MOBILHY dataset, Bound.-Lay. Meteorol., 52, 93–134, 1990. 521, 524

Lauvaux, T., Uliasz, M., Sarrat, C., Chevallier, F., Bousquet, P., Lac, C., Davis, K. J., Ciais, P., Denning, A. S., and Rayner, P. J.: Mesoscale inversion: first results from the CERES campaign with synthetic data, Atmos. Chem. Phys., 8, 3459–3471, 2008a.

Lauvaux, T., Pannekoucke, O., Sarrat, C., Chevallier, F., Ciais, P., Noilhan, J., and Rayner, P. J.: Structure of the transport uncertainty in mesoscale inversions of CO_2 sources and sinks using ensemble model simulations, Biogeosciences Discuss., 5, 4813–4846, 2008b. 529, 530

Masson, V., Champeaux, J., Chauvin, F., Mériguet, C., and Lacaze, R.: A global database of land surface parameters at 1 km resolution for use in meteorological and climate models, J. Climate, 16, 1261–1282, 2003. 520

Nicholls, M. E., Denning, A. S., Prihodko, L., Vidale, P.-L., Baker, I., Davis, K., and Bakwin, P.: A multiple-scale simulation of variations in atmospheric carbon dioxide using a coupled biosphere-atmospheric model, J. Geophys. Res., 109, D18117, doi:10.1029/2003JD004482, 2004. 517

Noilhan, J. and Lacarrère, P.: Gcm gridscale evaporation from mesoscale modelling, J. Climate, 8, 206–223, 1995. 524

Noilhan, J. and Planton, S.: A simple parametrization of land surface processes for meteorological models, Mon. Weather Rev., 117, 536–549, 1989. 520

Pérez-Landa, G., Ciais, P., Sanz, M. J., Gioli, B., Miglietta, F., Palau, J. L., Gangoiti, G., and Millán, M. M.: Mesoscale circulations over complex terrain in the Valencia coastal region, Spain - Part 1: Simulation of diurnal circulation regimes, Atmos. Chem. Phys., 7, 1835–1849, 2007, http://www.atmos-chem-phys.net/7/1835/2007/.

Sarrat, C., Noilhan, J., Lacarrère, P., Donier, S., Lac, C., Calvet, J.-C., Dolman, A., Gerbig, C., Neininger, B., Ciais, P., Paris, J., Boumard, F., Ramonet, M., and Butet, A.: Atmospheric CO_2 modeling at the regional scale: Application to the CarboEurope Regional Experiment, J. Geophys. Res., 112, D12105, 2007a. 517

Sarrat, C., Noilhan, J., Dolman, A. J., Gerbig, C., Ahmadov, R., Tolk, L. F., Meesters, A. G. C. A., Hutjes, R. W. A., Ter Maat, H. W., Prez-Landa, G., and Donier, S.: Atmospheric CO_2 modeling at the regional scale: an intercomparison of 5 meso-scale atmospheric models, Biogeosciences, 4, 1115–1126, 2007b. 517

Sarrat, C., Noilhan, J., Lacarrère, P., Masson, V., Ceschia, E., Ciais, P., Dolman, A., Elbers, J., Gerbig, C., and Jarosz, N.: CO_2 budgeting at the regional scale using a Lagrangian experimental strategy and meso-scale modeling, Biogeosciences Discuss., 5, 2931–2957, 2008, http://www.biogeosciences-discuss.net/5/2931/2008/. 517

Takahashi, T., Feely, R., Weiss, R. F, Wanninkhof, R. H., Chipman, D. W., Sutherland, S., and Takahashi, T. T.: Global air-sea flux of CO_2: An estimate based on measurements of sea-air pCO_2 difference, Proc. Natl. Acad., 94, 8292–8299, 1997.

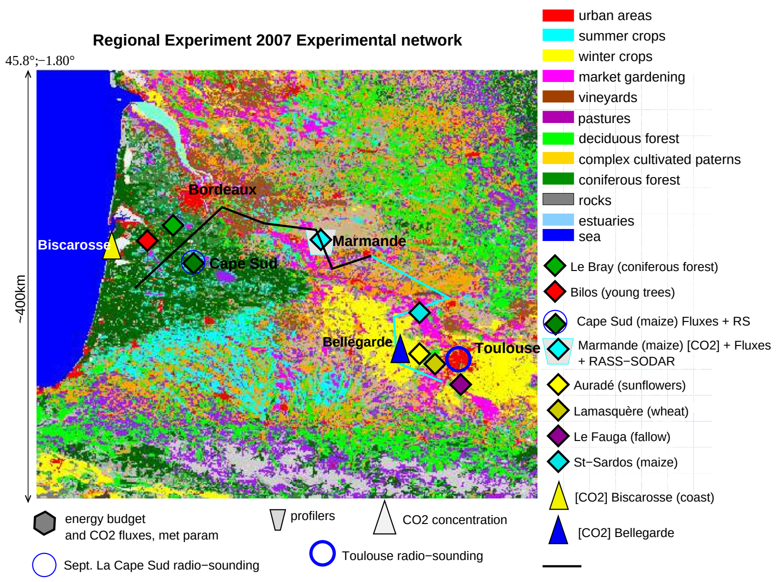

Fig. 1. Schematising of the network deployed during the April 2007 campaign: 9 surface flux stations were deployed for representative land cover types by Alterra, INRA, CESBIO and CNRM institutes. Three towers measuring CO_2 concentration were installed at Biscarosse (near the coat), at Marmande (in the center of the area) and in Bellegarde (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 SA, while the Eastern leg was flown by the Alterra SA. The Dimona aircraft flew alternatively the Western or the Eastern trajectories.

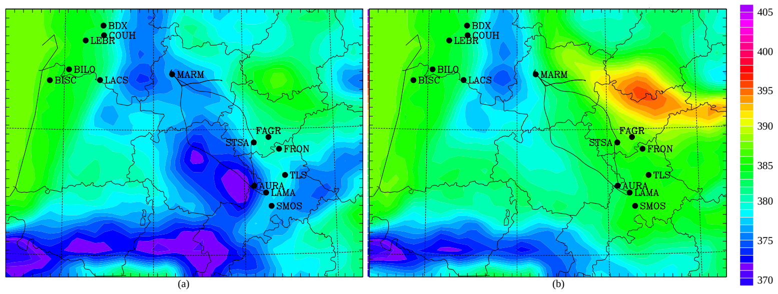

Fig. 2. The simulated CO_2 concentration at the first level of the Meso-NH model: **(a)** for the preliminary (or control) simulation and **(b)** after calibration of the surface scheme for winter crops. The trajectory followed by the Dimona instrumented aircraft flown between Marmande and the Toulouse region is illustrated with the thin solid line. In the control run, the minimum of CO_2 East to Toulouse, in the winter crops area, is clearly seen. After calibration of the surface scheme, this CO_2 anomaly was removed.

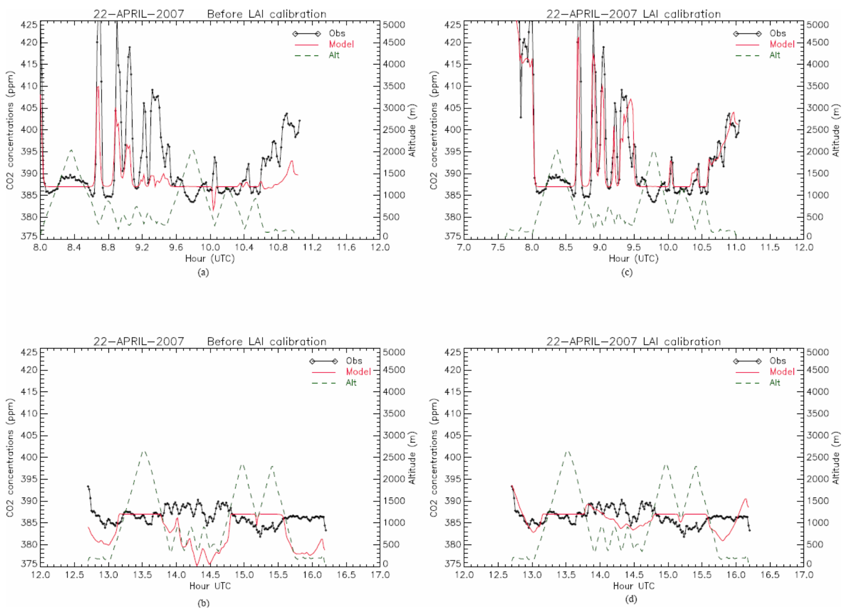

Fig. 3. A comparison of simulated and observed CO_2 concentration along the aircraft trajectory during the morning (**a–c**) and afternoon flights (**b–d**) on 22 April. The altitude of the flight is given by the green doted line. The modelled CO_2 has been interpolated in space (same latitute, longitude, 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).

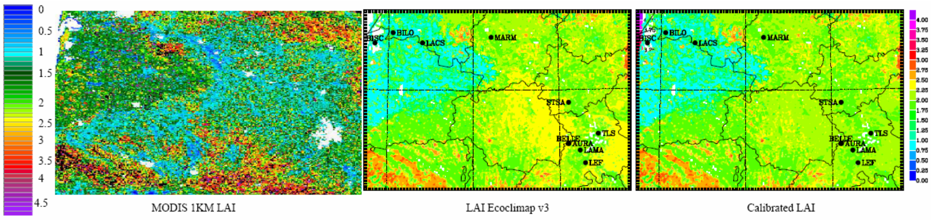

Fig. 4. Maps of LAI in April: from MODIS (left), the original (middle) and the corrected Ecoclimap database (right).

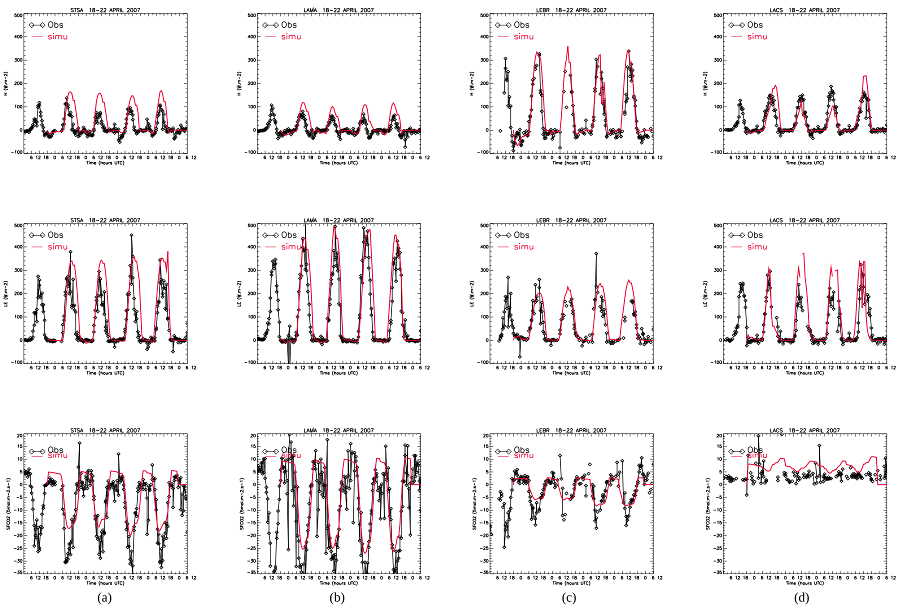

Fig. 5. Comparisons of latent and sensible heat fluxes and CO_2 flux at several surface stations: **(a)** at a grassland site (Saint-Sardos), **(b)** at a winter crop site (Lamasquère), **(c)** at a coniferous forest (Le Bray) and **(d)** at a maize site (La Cape Sud).

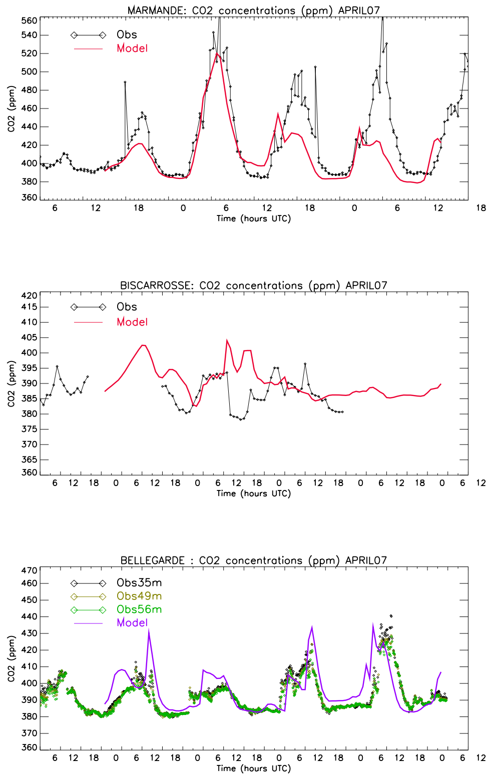

Fig. 6. Comparisons of CO_2 concentration at Marmande, Biscarosse and Bellegarde towers.

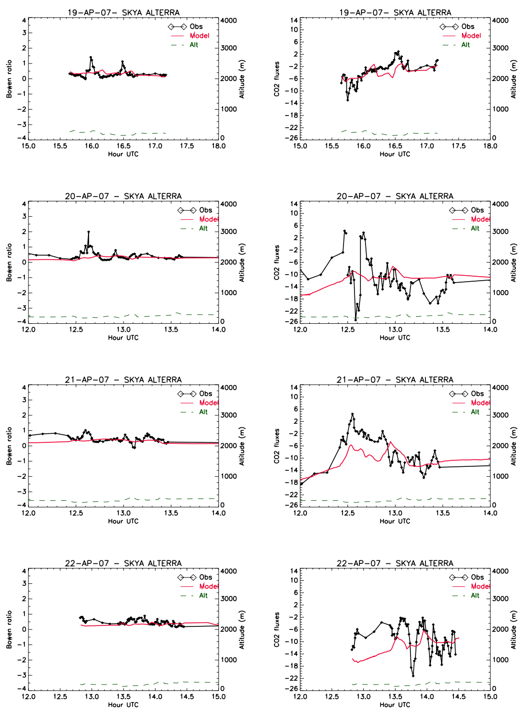

Fig. 7. Comparison of observed and simulated Bowen ratios (left panels) and CO_2 fluxes, μmol m^{-2} s^{-1} (right panels). The Bowen ratio and the CO_2 fluxes are observed by the Alterra Sky Arrow flying the Eastern leg, on 19, 20, 21 and 22 April. The altitude of the flight is given by the green doted line. The comparisons are made at the exact location of the Dimona aircraft: the same latitute, longitude, altitude and time in the model.

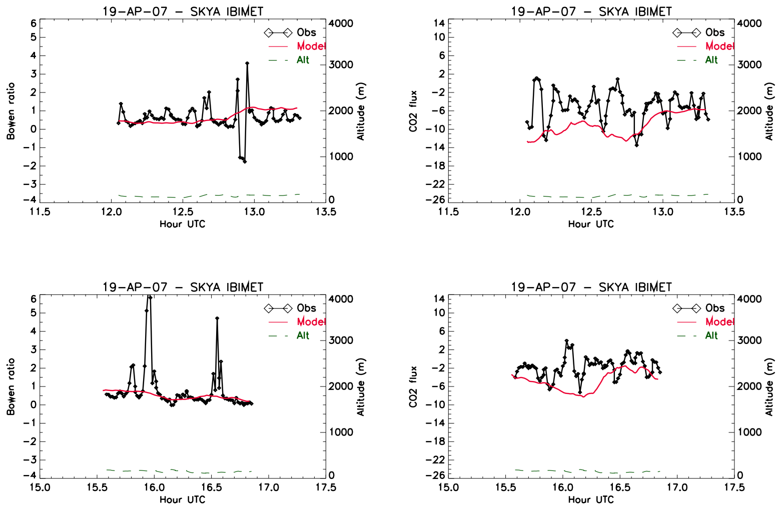

Fig. 8. Same as Fig. 7. Observations were taken by the Ibimet Sky Arrow instrumented aircraft, flying the Western leg twice a day. The comparisons are given for 19 April. The altitude of the flight is given by the green doted line. The comparisons are made at the exact location of the Dimona aircraft: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

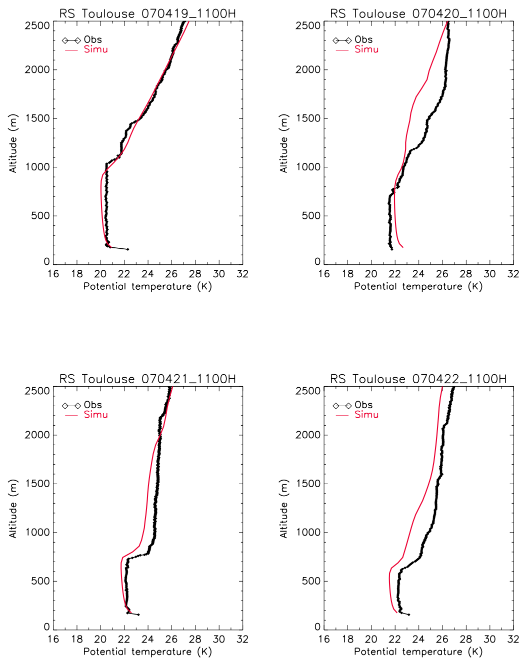

Fig. 9. Radio-sounding launched at Toulouse site every day of the IOP at 11:00 UTC, compared to the simulated vertical profile of potential temperature (C).

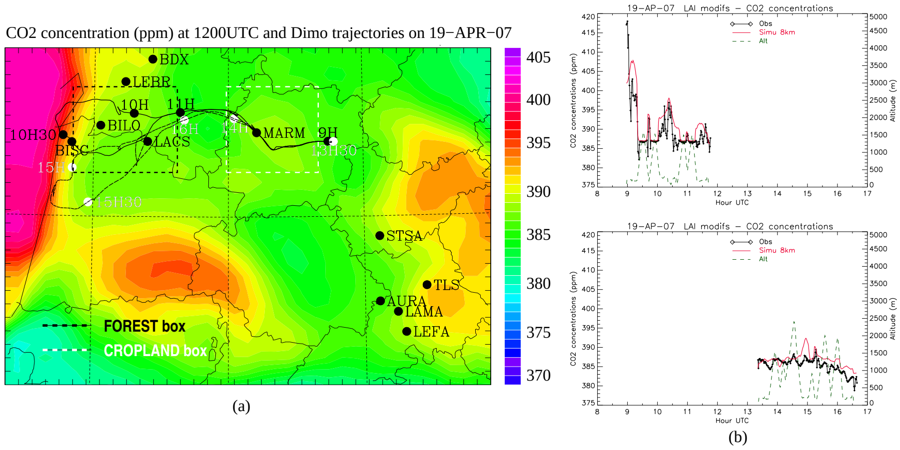

Fig. 10. (a) Meso-NH field of CO_2 concentration at 12:00 UTC on the 19 April at the first level of the model, with the two aircraft trajectories, the morning one (solid black line and black hours) and the afternoon one (dashed line with white hours); **(b)** comparisons between Meso-NH CO_2 concentration (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 respectevely the FOREST and the CROPLAND boxes in which are averaged the numerical budget displayed in Fig. 12.

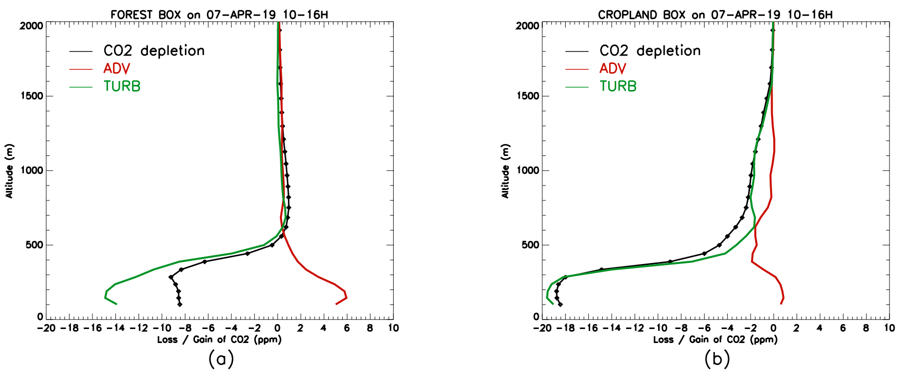

Fig. 11. Vertical profiles of the several budget terms caculated by Meso-NH and averaged over the FOREST box **(a)** and the CROPLAND box **(b)** displayed in Fig. 11. For the both boxes, the budget is calculated between 10:00 and 16:00 UTC. The black profile represents the difference of CO_2 concentration 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.