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Atmospheric CO_2 modeling at the regional scale: an intercomparison of 5 meso-scale atmospheric models

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Abstract

Atmospheric CO_2 modeling in interaction with the surface fluxes, at the regional scale is developed within the frame of the European project CarboEurope-IP and its Regional Experiment component. In this context, five meso-scale meteorological models participate in an intercomparison exercise. Using a common experimental protocol that imposes a large number of rules, two days of the CarboEurope Regional Experiment Strategy (CERES) campaign are simulated. A systematic evaluation of the models is done in confrontation with the observations, using statistical tools and direct comparisons. Thus, temperature and relative humidity at 2 m, wind direction, surface energy and CO_2 fluxes, vertical profiles of potential temperature as well as in-situ CO_2 concentrations comparisons between observations and simulations are examined. This intercomparison exercise shows also the models ability to represent the meteorology and carbon cycling at the synoptic and regional scale in the boundary layer, but also points out some of the major shortcomings of the models.

1 Introduction

Atmospheric measurements of CO_2, mainly from remote islands, have been a major source of information about the global scale spatial distribution and temporal changes in CO_2 exchange fluxes between ocean-atmosphere as well as land-atmosphere (Tans et al., 1990; Bousquet et al., 1998; Rödenbeck et al., 2003).

However, to retrieve more detailed information of the controlling processes, measurements in the planetary boundary layer over land, have to be made. These measurements show that the spatio-temporal variability, such as derived from aircraft data over continents is very large and exhibits small correlation length scales (e.g. Gerbig et al., 2003). Thus, for any modelling interpretation, high resolution mesoscale models need to be used to resolve this variability. Recent studies have shown the ability of meso-scale models to simulate correctly the surface energy and CO_2 fluxes as well

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as atmospheric CO_2 concentrations (Pérez-Landa et al., 2006; Sarrat et al., 2007; Ahmadov et al., 2007[1]).

This study describes a first intercomparison of CO_2 modeling at meso-scales. This allows the evaluation of the models at the regional scale, as a first step towards inverse regional modeling and sources and sinks retrieval (Lauvaux et al., 2007[2]).

The regional experiment of the European project CarboEurope-IP took place in May and June 2005. The CarboEurope Regional Experiment Strategy (CERES) campaign aimed at measuring and budgeting the atmospheric CO_2. The project is described in detail by Dolman et al. (2006). A dense experimental network represented on Fig. 1, has been deployed in the South-West of France, in Les Landes forest, including 10 surface fluxes stations over several ecosystems (vineyard, maize, wheat, rapeseed, pine forest, fallow). The main sites used in this study are briefly described in Table 1. In the pine forest, the evolution of the Atmospheric Boundary Layer (ABL) was monitored with 3-hourly radio-soundings and a UHF radar. CO_2 concentrations were measured continuously near the Atlantic coast line on the West and above the agricultural area on the East. Four research aircrafts were deployed over the region in order to measure the vertical and horizontal distribution of CO_2 during Intensive Observing Periods (IOPs). Using the full suite of data obtained in CERES provides a stringent test of the models, as we can compare both surface fluxes, boundary layer development and the transport of CO_2 through the domain.

The evaluation of the model behavior is based on simulations of two cases during the different CERES intensive observational periods (IOP2 and IOP4, Dolman et al.,

[1]Ahmadov, R., Gerbig, C., Kretschmer, R., Koerner, S., Neininger, B., Dolman, A., and Sarrat, C.: Mesoscale covariance of transport and CO_2 fluxes: evidence from observations and simulations using the WRF-VPRM coupled atmosphere-biosphere model, J. Geophys. Res., submitted, 2007.

[2]Lauvaux, T. M. U., Sarrat, C., Chevalier, F., Bousquet, P., Laq, C., Davis, K., Ciais, P., Denning, A., and Rayner, P.: Mesoscale inversion: first results from the CERES campaign with synthetic data, Atmos. Chem. Phys., submitted, 2007.

2006). Two contrasting days of the campaign are simulated with the meso-scale models following a precise protocol: the 27 May and the 6 June (hereafter respectively 27 May and 6 June).

27 May is the fourth day of the IOP 2 and is very well documented with 7 aircraft flights. This is a very warm day in an anticyclonic synoptic situation, with temperature reaching 32°C in les Landes. The wind is weak, from South-East in the morning and turning to North-West in the afternoon near the coast because of the sea breeze development.

The second day for simulation is 6 June. It corresponds to the IOP4, the Lagrangian experiment. This has also been well documented with aircraft observations. The day is colder than the 27 May and the North-West wind is homogeneous and regular over the entire domain during all day.

2 Models set-up

Five models are participating in this intercomparison.

The experimental conditions have been briefly described above. All the models are set according the same configuration:

- All models use nested configuration with the resolution set at 2km for the smallest domain (Fig. 1).
- The meteorological variables and surface parameters such as soil moisture are initialized by the ECMWF analysis (the soil water content from ECMWF was compared with the observations taken over 30cm in Table 2).
- Meteorological lateral boundaries conditions are also provided by the ECMWF analysis fields.
- The ECOCLIMAP land cover database (Champeaux et al., 2005) is set as the standard for land cover distribution for all models.

– Sand and clay distributions are taken from the FAO classification.

– Anthropogenic emissions of CO_2 are issued from the Stuttgart University inventory at 10 km hourly resolution.

– Orography and vertical resolution are chosen individually for each model, but are generally taken from similar databases and show no major differences between models.

The models participating in the intercomparison are: the Weather Research and Forecasting model (WRF), Meso-NH and 3 differents versions of Regional Atmospheric Modeling System (RAMS). The models and their set-up are briefly described in the following sections.

2.1 The WRF model

The Max-Planck Institute for Biogeochemistry ran the Weather Research and Forecasting (WRF) model (Skamarock et al., 2005) for meteorology and CO_2 transport. Biospheric CO_2 fluxes are simulated with a diagnostic model, the Vegetation Photosynthesis and Respiration Model (VPRM, Pathmathevan et al., 2007[3]), using temperature and radiation from WRF, EVI and LSWI satellite indices calculated from MODIS (Moderate Resolution Imaging Spectroradiometer) reflectances. A detailed description of the WRF-VPRM modeling system is given in Ahmadov et al. (2007)[1]. Hereafter, the WRF results from MPI are designated by WRF-MPI.

The main characteristics of the model set-up are :

– The model was run on twwo grids with 2 and 6 km resolution, on two-way nesting mode.

[3]Pathmathevan, M., Wofsy, S., Matross, D., Xiao, X., Dunn, A., Lin, J., Gerbig, C., Munger, J., Chow, V., and Gottlieb, E.: A Satellite-based biosphere parameterization for Net Ecosystem CO_2 Exchange: Vegetation Photosynthesis and Respiration Model (VPRM), Global Biogeochem. Cycles, under review, 2007.

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- Land cover from the USGS land-use (24 classes) and NCEP vegetation fraction data.
- CO_2 concentrations initialized with a homogeneous vertical profile and/or the LMDZ simulations. CO_2 fields from LDMZ were also used for CO_2 boundary conditions.

2.2 The RAMS version from the Vrije Universiteit team

The Amsterdam Vrije Universiteit team ran the RAMS model (Pielke et al., 1992) coupled with the LEAF3 soil/vegetation scheme (Walko et al., 2000). The adaptated version of this model used id the BRAMS-3.2 (Freitas et al., 2005). Their results are referred to as RAMS-AMVU.

A 2-way nesting was applied with grids resolution of 2 and 8 km. The land use is a simplified adaptation of the ECOCLIMAP database where classes have been aggregated.

The Mellor-Yamada turbulence is used. CO_2 sea fluxes are parametrized according to Takahashi et al. (1997).

2.3 The RAMS version from the CEAM team

The CEAM team ran the RAMS (hereafter RAMS-CEAM) model coupled with the LEAF-2 land surface model.

The results concern the meteorology and the surface energy. This model does not simulate the CO_2, neither the surface fluxes nor the atmospheric concentrations.

The land use is a simplified adaptation of the ECOCLIMAP database where classes have been aggregated according to the Vrije University scheme.

2.4 The RAMS version from the ALTERRA team

Hereafter, the results are denoted RAMS-ALTE. The ALTERRA team uses the RAMS model for which the main characteristics are:

- A two nested grid configuration is used at 6 km and 2 km resolution.
- The surface fluxes are simulated with the SWAPS-C surface scheme. There are four tiles per grid box: 1 water + 3 most dominant land cover classes according to ECOCLIMAP. All classes are reclassified to either forest, grassland, urban; The SWAPS-C model parameters have been calibrated for LeBray (forest) and Cabauw (grassland) sites.
- CO_2 initialization and lateral boundaries forcing fields come from the LMDZ global model.
- Anthropogenic emissions are from the University of Stuttgart data sets (at 10 km resolution) and are disaggregated to hourly fluxes from urban pixels only.
- Marine fluxes are parametrized after Takahashi et al. (1997).

2.5 The non-hydrostatic MESO-NH model

Hereafter, the results of this model are noted MNH-CNRM.

The CNRM-Météo-France team ran the meso-scale non-hydrostatic model Meso-NH. The surface scheme ISBA-A-gs (Noilhan et al., 1989; Calvet et al., 1998) coupled on-line includes biospheric CO_2 surface fluxes (assimilation, respiration) as well as the anthropogenic (from the IER 10 km resolution inventory) and the sea fluxes, according to Takahashi et al. (1997). The chosen configuration is a two-way nesting at 2 and 10 km resolution.

The CO_2 concentrations are initialized with a vertical profile homogeneously over the domain. The lateral boundaries conditions for the carbon dioxide impose a zero gradient.

3 Results

All the models have simulated the two cases of the CERES campaign.

Comparisons between models and observations are given here for several variables:

- The temperature and relative humidity observed at the synoptic stations from the Météo-France network: 82 stations allow statistics and calculation of bias and rms for each model.
- The wind direction observed by the aircrafts.
- Surface fluxes of latent and sensible heat, CO_2 fluxes, net radiation at several sites (maize, wheat, pine forest).
- Radio-sounding made in LACS (Landes forest) at 23:00, 05:00, 08:00, 11:00, 15:00 and 17:00 UTC and at 11:00 UTC in TOUL (suburban station). The simulated vertical profiles of potential temperature between 0 and 3000 m are compared with observations.
- The CO_2 concentrations measured by the Piper Aztec and the Dimona aircrafts are compared to the model outputs along the aircrafts trajectories.

3.1 Meteorological variables

The temperature and the relative humidity at 2 m, respectively T2M and HU2M measured at 82 synoptic stations, included in the domain of simulation, are available from the French operational network. The comparisons with the simulations are made for hourly values.

The temporal evolution of the bias for T2m is shown on Fig. 2. There is no clear tendency of a daily cycle in the statistics of bias, although the T2M bias is negative for all models at 00:00 UTC on 27 May. This may be due to a problem in the initialization of the soil temperature. On 6 June, the bias is largely reduced during the night and remains low all day long except for the ALTE version of RAMS.

The Fig. 3 and 4 represents the T2M and HU2M simulated values against the observed ones, respectively for 27 May and 6 June, for all models.

It is clear, that the inter-model variability is larger for HU2M than for T2M during the two days. Moreover, the scatter for humidity is higher for nighttime than for daytime.

On 6 June, the scatter for temperature and humidity is less important than on 27 May because of a stronger wind that limits the daily variations of temperature and humidity.

In fact, for all models the rms and bias for T2M as well as for HU2M are lower on 6 June than for the 27 May.

3.2 Characterization of the wind direction

At the regional scale, local atmospheric and surface conditions have a strong impact on the atmospheric dynamics. The CO_2 concentration distribution can be largely influenced by regional circulation as sea breeze for example. In fact, this situation is observed on 27 May. During this warm day, the sea breeze is developping along the coast and has been observed by the Dimona flight. Althought, the synoptic situation generates a S-E wind over the cropland, over the forest and along the Atlantic Ocean coast, the wind is from N-W due to the sea breeze development. The comparison between the meso-scale models and the Dimona observations (Fig. 5a) shows that all the models are able to reproduce the sea breeze development.

On 6 June (Fig. 5b), all the models are in good agreement with the observed N-W wind from the Piper-Aztec data, allowing a Lagrangian Experiment Strategy during this day.

3.3 Surface fluxes

Different observed surface fluxes are compared to the simulated fluxes: net radiation (RN), sensible and latent heat (respectively H and LE) as well as the CO_2 flux. Only the RAMS-CEAM model does not simulate the surface flux of carbon dioxide.

Each model has is own CO_2 assimilation scheme (Farquhar type or A-gs type, on-line coupled with the atmosphere or using a diagnostic biosphere such as VPRM in WRF-MPI for example).

Thus, the response of the CO_2 surface flux to the atmospheric forcing presents a variability from one model to the other.

The Fig. 6 represents the 2-D maps of CO_2 fluxes on 6 June at 10:00 UTC for each model. The oceanic fluxes are all from the Takahashi et al. (1997) parametrization (except WRF-MPI with zero oceanic flux) and are of the same order of magnitude. The other areas have quite different fluxes from one model to the other, especially with a positive signal in the North-Eastern part of the domain of the RAMS-ALTE model while the other ones simulate a net sink. These models present also higher negative fluxes (larger uptake) above the cropland than above Les Landes forest, in agreement with the observation of the temporal series of the Fig. 7. This Figure compares the energy budget fluxes and the CO_2 fluxes at several sites: a winter crop, AURA (a), a pine forest, LEBR (b) and a summer crop MARM, (c), on 6 June.

For all models the simulated surface fluxes compare very well to the observed ones at the winter crops stations (AURA), whereas the comparisons are less favorable at the summer crops station especially on 27 May when the temperature is high and the fraction of vegetation is low due to a small development of the summer crops at this period (not shown here).

This day is cloudy in the western part of the domain. The net radiation decreases over the forest, in LEBR. Some models are not able to reproduce the clouds over this station and the net radiation is sometimes overestimated.

For the LEBR site, all models are also able to simulate the energy fluxes, although the latent heat is somewhat overestimated. For the summer crop site, MARM the latent heat flux is overestimated, while the sensible heat flux is overestimated by MNH-CNRM and RAMS-CEAM. One can note that the observed energy fluxes are not in balance in MARM, maybe dure to an underestimation of the observed latent heat flux.

In AURA site, the sky is clear, all models are able to simulate RN and H and SFCO2, LE is overestimated by most of the models.

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In general, all the models simulate relatively well the surface flux of CO_2, particularly in the crop sites, AURA and MARM are simulated better on 6 June than on 27 May, mainly due to a lower LAI and a higher fraction of bare soil on 27 May. Nevertheless, the latent heat flux is often overestimated by most of the models.

3.4 Boundary Layer development

During IOP days, radiosounding (RS) balloons were launched in les Landes forest, at LACS every 3 h. In addition, a radiosounding was launched in Toulouse (TOUL) at 11:00 UTC every IOP days.

The observed and simulated vertical profiles of potential temperature are compared in Fig. 8.

On 27 May, all models underestimate the atmospheric boundary layer height (ABLH), particularly in the TOUL site. Nevertheless, at 11:00 UTC, in TOUL (Fig. 8b), all the models are able to simulate a lower boundary layer height than in LACS (Fig. 8a) as shown in the observations.

On 6 June, the ABLH is very well simulated by RAMS-ALTE. Two models (RAMS-CEAM and RAMS-AMVU) underestimate the potential temperature, whereas two others (MNH-CNRM and WRF-MPI) overestimate the boundary layer height.

The ABL height is a key variable in modeling atmospheric CO_2 since surface fluxes are to first order mixed up to this altitude, causing the atmospheric CO_2 concentration to be underestimated when the ABL is overestimated, and vice versa. The comparisons between the RS and the simulations reveal discrepancies between models and errors on the evaluation of the ABL height despite the agreement between modeled and observed sensible heat fluxes (see Sect. 3.3).

This suggests that some key elementary processes in boundary layer development, as entrainment at the top, may not be well captured by some of the models.

3.5 Atmospheric CO_2 simulation

All models simulate the CO_2 concentrations as a function of the surface fluxes (anthropogenic and biogenic) and the boundary layer dynamics, except the CEAM version of RAMS.

During the CERES campaign the CO_2 concentrations have been measured by aircrafts, above Les Landes forest, the Atlantic Ocean coast or above the agricultural areas.

On 27 May, as shown on Fig. 9a, the Dimona aircraft flew over the forest and over the cropland. Many vertical profiles have been performed during this flight (see altitude of flight on Fig. 9b). The CO_2 in-situ observations, on Fig. 9b show a strong gradient up to 15 ppmv between the cropland and the forest. This gradient is due to a combination of a strong assimilation by the winter crop and a recirculation of nocturnal respired CO_2 in the sea-land breeze pattern (Sarrat et al., 2007; Ahmadov et al., 2007[1]). All the models are able to reproduce this gradient and especially the low concentrations measured over the eastern part of the flight related to a high assimilation of CO_2 over the agricultural area.

During the same day, the Piper Aztec aircraft made vertical profiles above the forest and the cropland, in the morning and the afternoon. These vertical profile provide information on the ABL height and the CO_2 concentrations in and above the ABL. The Fig. 10 shows the height of the ABL as a function of CO_2 in the both sites. It shows that the observed CO_2 concentrations decrease in the ABL when the ABL height increases. This decrease is related to CO_2 vertical mixing in the layer but also to photosynthesis activity which depletes the ABL, off set by entrainment at the top of the ABL. The decrease is also more visible in MARM site (cropland) than is LACS (forest) although the ABL height is smaller. All the models are able to reproduce this general trend.

On 6 June a North-West regular wind prevailed and allowed a "Lagrangian Experiment", based on in-situ aircraft measurements. This experiment deals with the in-flow air sampling in the morning (near the oceanic coast line) and the sampling of the same air mass downstream the forest a few hours latter, depending on the wind speed and the air mass displacement, as shown on the Fig. 11 (see also Sarrat et al., 2007b[4]).

The time series of CO_2 concentrations measured by the Piper-Aztec aircraft are compared to the simulations along the aircraft trajectory. The observed concentrations in the morning (Fig. 11a) are rather constant and regular along the flight, between 382 and 383 ppmv, independently of the altitude. The simulations give also constant concentrations except for WRF-MPI that occasionally overestimates the CO_2 at low altitude. In the afternoon flight, (Fig. 11b), downstream the forest, the observed concentrations are lower, except above the ABL, principally due to net assimilation of carbon dioxide by the ecosystem. The WRF-MPI and RAMS-ALTE models tend to overestimate the afternoon concentrations, despite good CO_2 surface fluxes shown in Sect. 3.3. RAMS-AMVU underestimates the concentrations when the aircraft is at low altitude, in relation with its tendency to overestimate the assimilation fluxes (Sect. 3.3). RAMS-AMVU also exaggerates the vertical extent of CO_2 depletion. This depletion above 1 km originates above mountain ranges outside the CERES domain, and is then advected to within the domain (not shown here).

However, the simulations are in reasonable agreement with the observations, showing the air mass depleting with CO_2 while it moves across the forest.

In general, the regional models are able to simulate with reasonable accuracy the larger scale atmospheric CO_2 concentrations, despite some remaining discrepancy at smaller spatial and temporal scale.

4 Conclusions

Two contrasting golden days of the CERES campaign have been selected and simulated by 5 meteorological meso-scale models. A protocol of simulation was applied in

[4]Sarrat, C., Noilhan, J., Lacarrère, P., Donier, S., Dolman, A., Ciais, P., Butet, A., and Masson, V.: CO_2 budgeting at the regional scale using a lagrangian experimental strategy and mesoscale modeling, Geophys. Res. Let., submitted, 2007a.

order to run as much as possible a common framework:

- A similar inner domain of simulation at 2km resolution was used.
- Meteorological variables are initialized and forced at the lateral boundaries by the ECMWF model as well as the surface initialization.
- the ECOCLIMAP land cover served as the main land cover map.

For these two days some comparisons between the models and the observations have been performed in order to evaluate the outputs of the meso-scale modeling. These comparisons include:

- The meteorological variables: temperature and relative humidity at 2m. The hourly data are provided by 82 meteorological stations data allowing rms and bias calculation for each models.
- The surface fluxes of net radiation, sensible and latent heat fluxes, CO_2 surface flux, measured by eddy correlations at several sites.
- The potential temperature in the boundary layer measured during radio-soundings in the forested central site.
- The CO_2 concentrations observed during the aircrafts flights above the Atlantic coast, the forest and the cropland.

All these comparisons showed the ability of meteorological meso-scale models to represent the atmospheric carbon dioxide distribution satisfactory, in general agreement with the observations. The complex spatial distribution as well as the temporal evolution of CO_2 in interaction with the surface fluxes are realistically simulated compared to the aircrafts observations. This raises 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 2m) but also at the local scale (potential temperature at various sites) have previously been validated in confrontation with the respective observations. All the models are able to simulate the surface meteorology reasonably well. Nevertheless, some discrepancies are pointed out in this study: a common cold bias in the initial temperature at 2 m appears in this intercomparison. This may be due to an initialization problem, that has to be improved. Also, the boundary layer height modeling, as a key process in meso-scale modeling, still causes some discrepancy. Particularly, the entrainment at the top of the boundary layer has to be checked as a key process in CO_2 modeling (Vilá-Guerau et al., 2004). The latent heat flux is often overestimated by most of the models. The uncertainties are still high, compared to what would be required for really accurate inversion calculations. The critical points listed above are related to each other and must be examined in order to improve the simulation before to go further in regional modeling. In fact, with the present set up, it is difficult to distinguish between differences caused by (1) determination of the surface fluxes of CO_2; (2) determination of the atmospheric transport of CO_2. A numerical experiment imposing common surface fluxes to all models could be usefull for the interpretation of the results, for the future.

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Table 1. Surface fluxes stations description.

Name	Acronym	Type of site	Location
La Bray	LEBR	Pine forest	East – forest
La Cape Sud	LACS	Summer crops (maize and beans)	East – forest
Auradé	AURA	Winter crop	East of the domain
Marmande	MARM	Summer crops	Middle of the domain
Toulouse	TOUL	Suburban place	East of the domain

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Table 2. Comparisons between the measured volumetric soil moisture (WG, $m^3 m^{-3}$) and the ECMWF analysis. Note that no precipitation occurred since the soil water measurement in MARM (18 May) and the day 27 May of the simulation.

	WG_{MARM} on 19 May $m^3 m^{-3}$	WG_{LACS} on 18 May $m^3 m^{-3}$	WG_{AURA} on 27 May $m^3 m^{-3}$
OBS	0.31	0.12	0.25
ECMWF on may 27	0.25	0.13	0.27

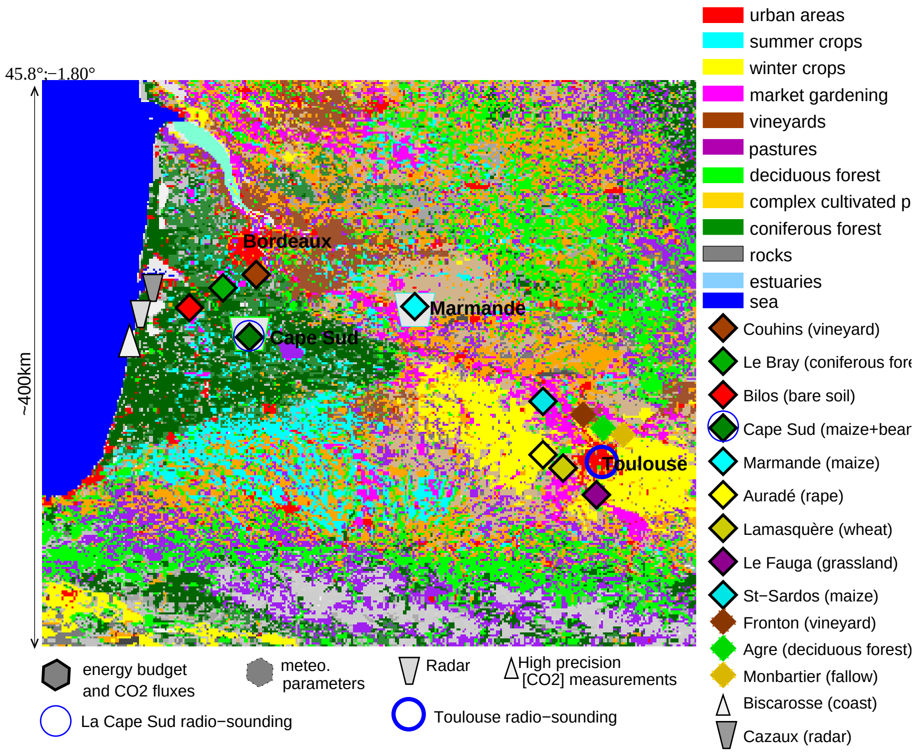

Fig. 1. Map of the experimental network that corresponds approximatively to the domain of simulation at 2 km.

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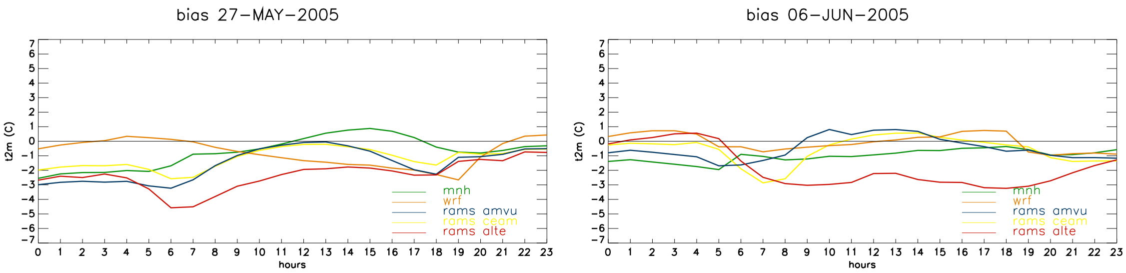
Intercomparison of meso-scale atmospheric CO_2 models

C. Sarrat et al.



(a) (b)

Fig. 2. Temporal evolution of the bias calculated for each model for the temperature at 2m (T2M) on **(a)** 27 May and **(b)** 6 June.

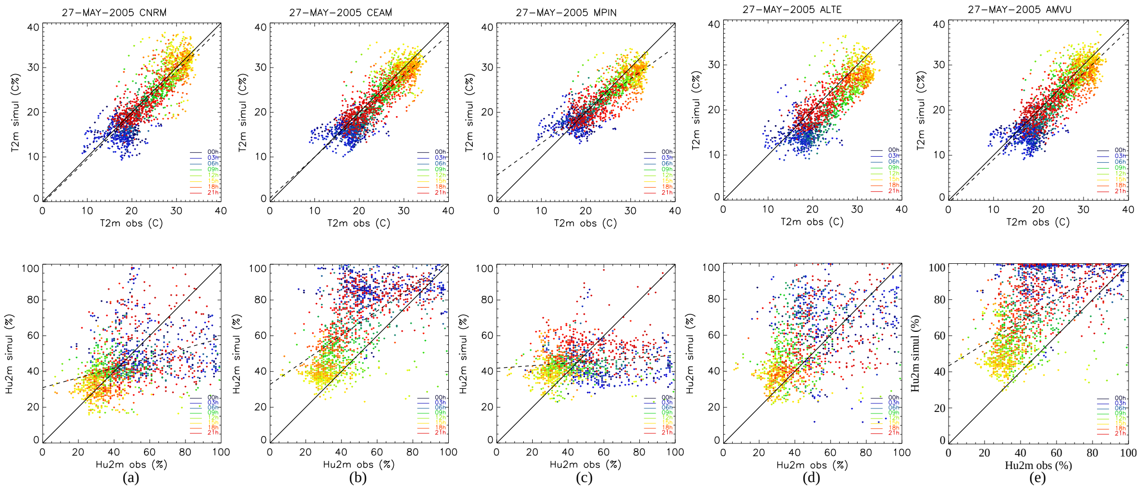


Fig. 3. Temperature at 2 m and relative humidity at 2 m simulated vs observed for each model. Each point represents one hour for one station, i.e. 82 stations ×24 h on 27 May. **(a)** MNH-CNRM, **(b)** RAMS-CEAM, **(c)** WRF-MPI, **(d)** RAMS-ALTE, **(e)** RAMS-AMVU.

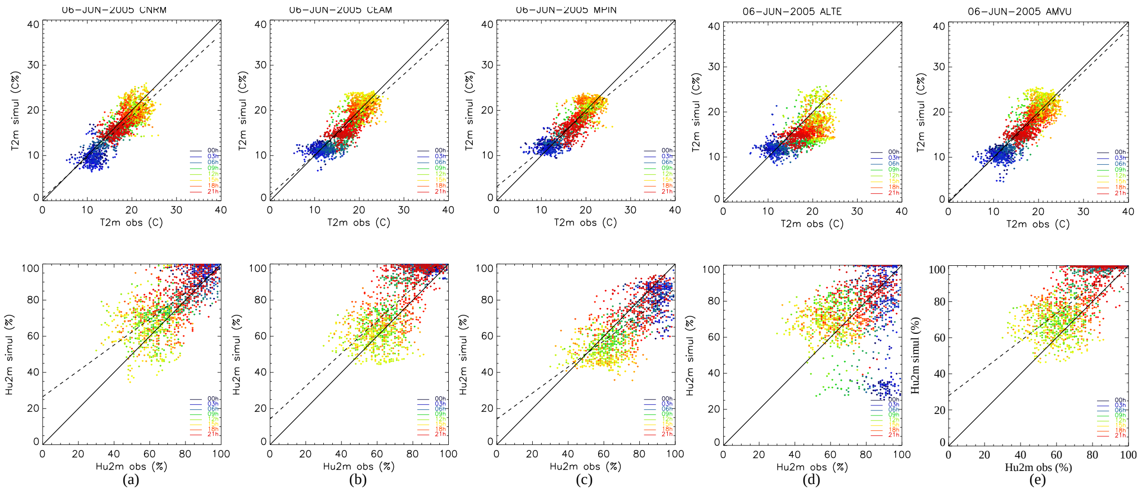


Fig. 4. Temperature at 2 m and relative humidity at 2m simulated vs observed for each model. Each point represents one hour for one station, i.e. 82 stations ×24 h on 6 June. **(a)** MNH-CNRM, **(b)** RAMS-CEAM, **(c)** WRF-MPI, **(d)** RAMS-ALTE, **(e)** RAMS-AMVU.

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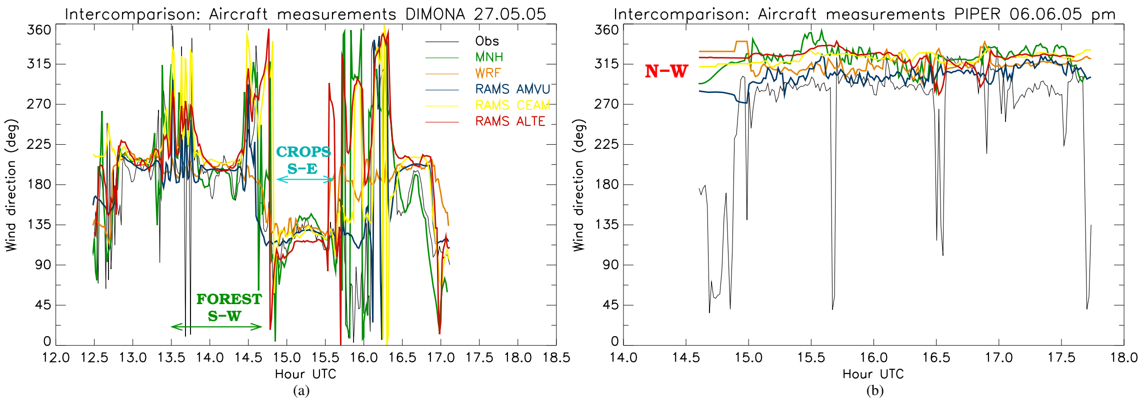

Fig. 5. Wind direction comparison sbetween the simulations and the observations: **(a)** from the Dimona aircraft on 27 May; **(b)** from the Piper-Aztec on 6 June.

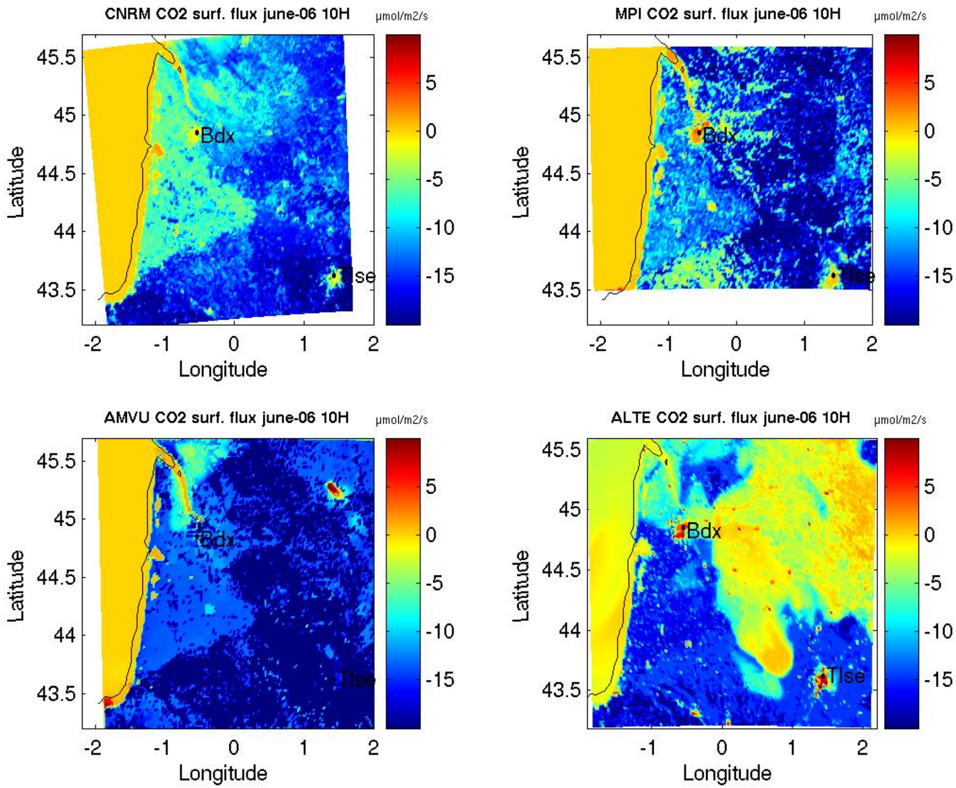

Fig. 6. CO_2 surface fluxes at 10:00 UTC on 6 June by the differents models.

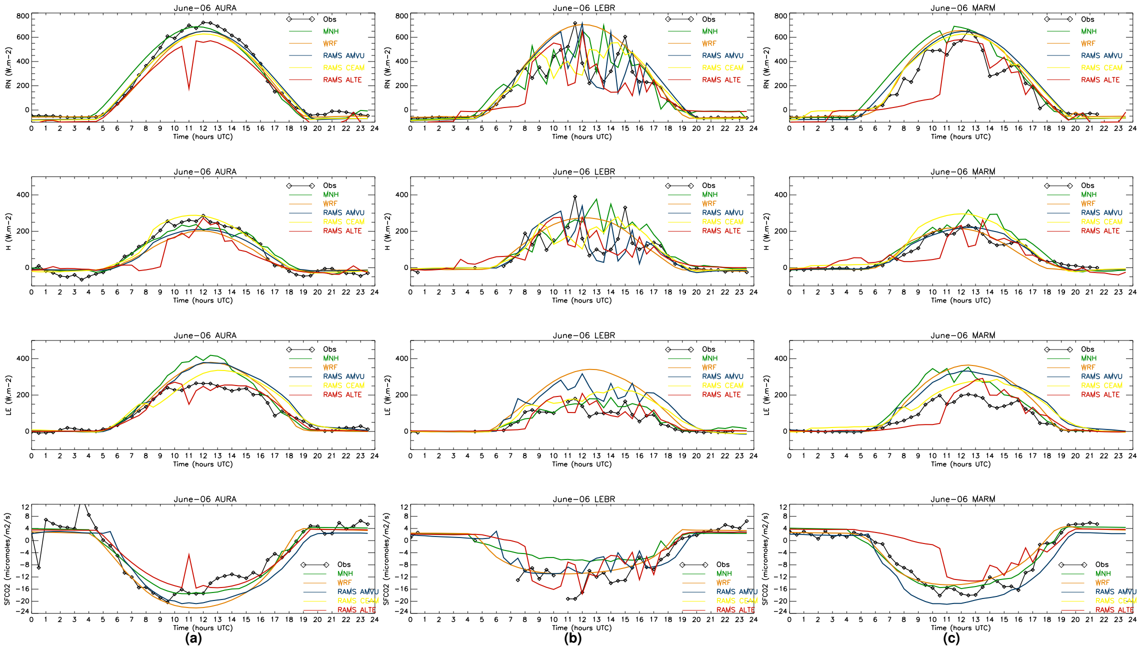

Fig. 7. Time series of surface fluxes, RN, H, LE and CO_2 on 6 June: **(a)** AURA (wheat); **(b)** LEBR (pine forest); **(c)** MARM (maize).

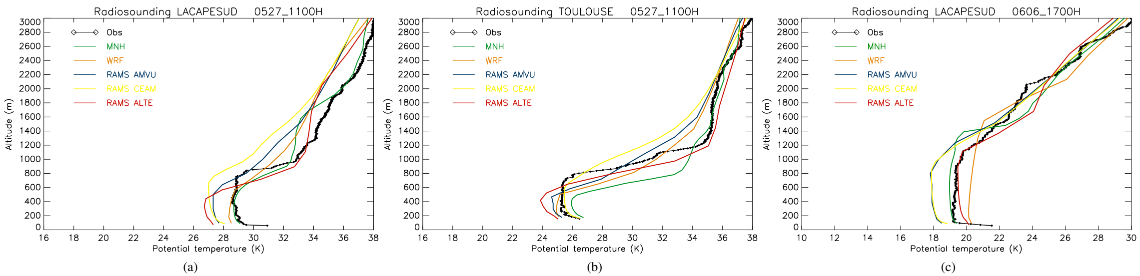

Fig. 8. Vertical profiles of potential temperature observed by radio-soundings and simulated on 27 May at 11:00 UTC **(a)** in LACS (forested site); **(b)** in TOUL (eastern); **(c)** on 6 June at 17:00 UTC.

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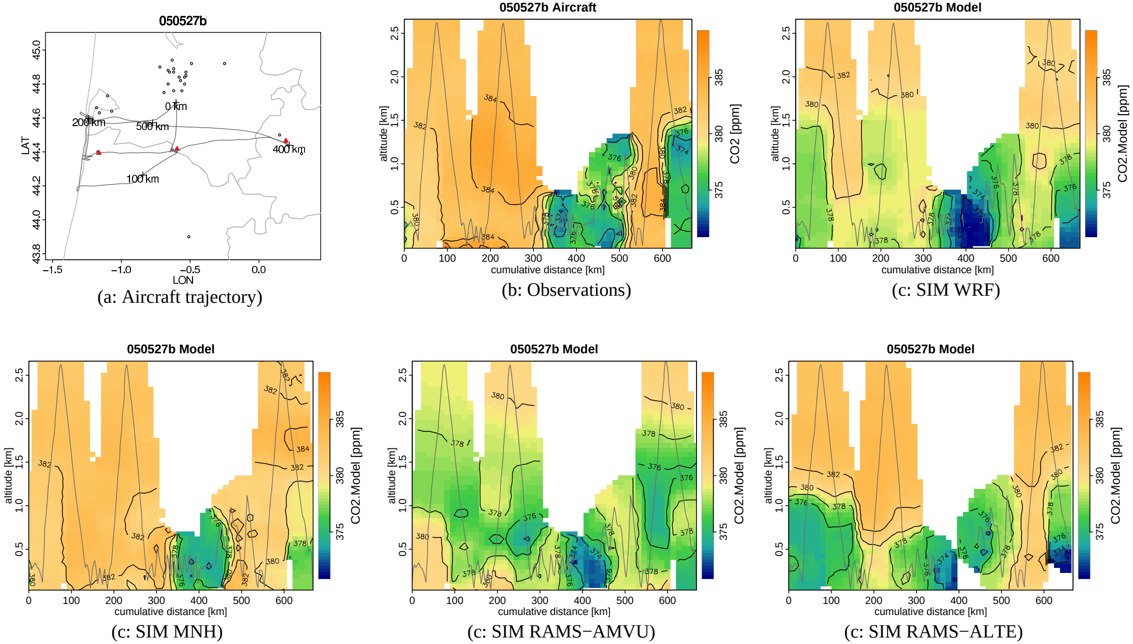

Fig. 9. CO_2 concentrations observed and simulated along the aircraft trajectory represented on **(a)**; the observations are displayed on **(b)**.

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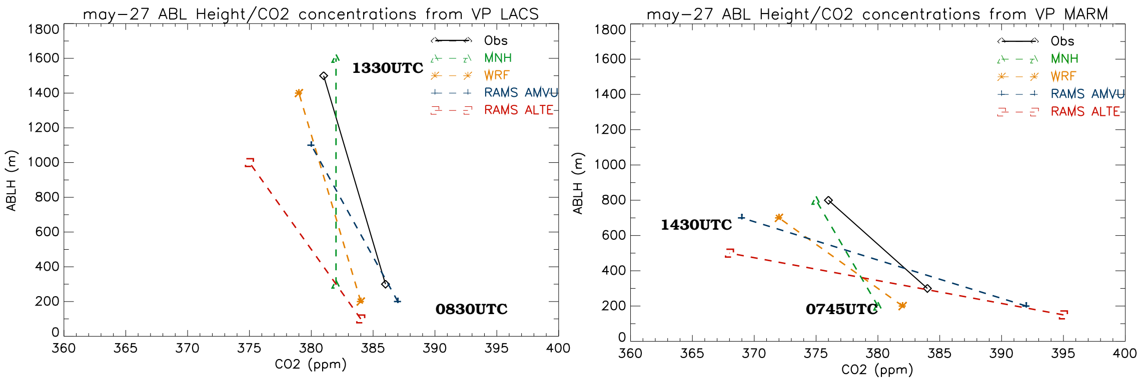

Fig. 10. HCLA as a function of CO_2 concentrations in the ABL in LACS (left panel) and in MARM (right panel).

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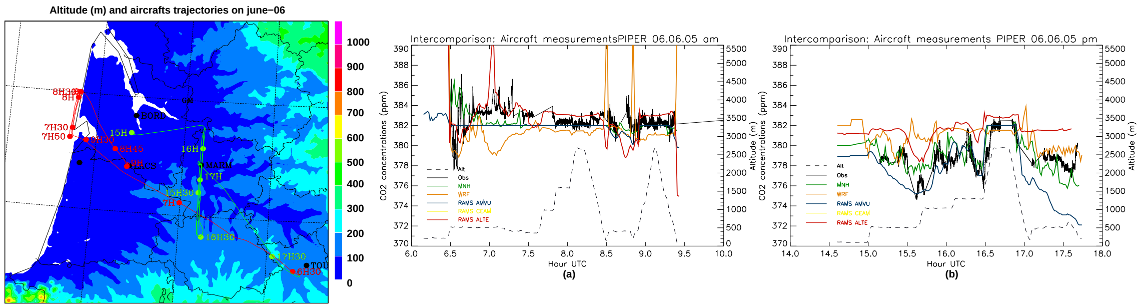

Fig. 11. Altitude of the domain with aircraft trajectories: red = morning fight and green = afternoon flight. Times series of CO_2 concentrations observed by the Piper-Aztec aircraft and simulated in the morning **(a)** and in the afternoon **(b)**. The dashed lines represent the altitude of flight.