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Can we use hourly CO_2 concentration data in inversions? Comparing high resolution WRF-VPRM simulations with coastal tower measurements of CO_2

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Abstract

In order to better understand the effects that mesoscale transport has on atmospheric CO_2 distributions, we have used the WRF model coupled to the diagnostic biospheric model VPRM, which provides high-resolution biospheric CO_2 fluxes based on MODIS satellite indices. We have run WRF-VPRM for the period from 16 May to 15 June in 2005 covering the intensive period of the CERES experiment, using the CO_2 fields from the global model LMDZ for initialization and lateral boundary conditions. The comparison of modeled CO_2 concentration time series against observations at the Biscarosse tower and against output from two global models – LMDZ and TM3 – clearly reveals that WRF-VPRM can capture the measured CO_2 signal much better than the global models with lower resolution. Also the diurnal variability of the atmospheric CO_2 field caused by recirculation of nighttime respired CO_2 is simulated by WRF-VRPM reasonably well. Analysis of the nighttime data indicates that with high resolution modeling tools such as WRF-VPRM a large fraction of the time periods that are impossible to utilize in global models, can be used quantitatively and help constraining respiratory fluxes. The paper concludes that we need to utilize a high-resolution model such as WRF-VPRM to use continental observations of CO_2 concentration data with more spatial and temporal coverage and to link them to the global inversion models.

1 Introduction

There is clear evidence in climate science that the monotonic increase of the atmospheric CO_2 content is caused by the anthropogenic emissions. However one of the challenges in the climate science is the understanding of the mechanisms responsible for removing the anthropogenic CO_2 from the atmosphere. The observations demonstrate that about half of the emitted CO_2 is absorbed by biospheric sinks – the terrestrial biosphere and the ocean (Hansen et al., 2007). There are a number of essential questions related to the biogeochemical cycle of CO_2 to be solved by the scientific community. The modern global coupled atmosphere-biosphere models suggest that, on a global scale, terrestrial ecosystems will provide a positive feedback in a warming world (Heimann and Reichstein, 2008), which makes essential to study the role and evolution of the giant natural carbon reservoirs. The leading questions are first of all the determination and also estimation of processes by which anthropogenic CO_2 is sequestered in the nature. It is also crucial to know the feedback mechanisms between the natural carbon cycle and the global climate system. The attempt to mitigate and also control the greenhouse gas emissions from the different regions and the countries requires estimating their carbon budget which is a big challenge in the atmospheric sciences.

In order to answer the above mentioned questions the atmospheric measurements of CO_2 from global networks are used in combination with inverse analysis to retrieve information on biosphere-atmosphere exchange rates (Tans et al., 1990; Gurney et al., 2002; Law et al., 2002). These approaches were operated based on annual and monthly atmospheric observations. Consequently the flux estimations of such inversion studies were very coarse in both time and space.

Since the estimation of the terrestrial biospheric sources and sinks is an essential task, there is a strong need to deploy continental observation sites. Historically, the dominant fraction of the continental sites was surface stations located on mountains and near coasts. In order to increase the representativeness of measurements sites, tall towers equipped with meteorological and greenhouse gas measurement devices were recently implemented to carry out CO_2 measurements at about 300 m above the ground (Bakwin et al., 1995). However, the location of any continental measurement site close to variable sources is often located in meteorologically complex areas: terrain-induced mesoscale phenomena such as sea-land, (lake, river, forest, etc.) breezes, mountain-valley circulations, urban heat islands etc. make their representation in atmospheric models quite difficult.

It is known that advection and vertical mixing processes are quite complicated over mountains. CO_2 transport over complex topography is strongly influenced by oro-

BGD
5, 4745–4776, 2008

graphic circulations – drainage flows, upslope winds (Sun et al., 2007). However there is a strong need in deployment of mountain stations. This is motivated by their advantages being usually less affected by urban areas compared to surface sites, and also in case of using tall towers over high altitudes one can measure the free tropospheric CO_2 signal during night and even in some cases during daytime. Moreover mountain sites are essential in understanding the role of mountainous regions in the sequestration of carbon. For instance recent estimates show that potentially significant amounts of CO_2 are sequestered by the mountain biomes such as the Rocky Mountains (Schimel, 2002). However it is obvious that such mountain sites are not properly represented in existing global models with typically 2–3° resolution in longitude and latitude.

Mesoscale effects generated by land surface heterogeneity and complex topography are usually on the subgrid scales of current generation transport models used in inversions. In addition high resolution models are able to capture more accurately the front passing time and related effects at the site. The accurate simulation of front passing time at the measurement station is crucial since this may lead to strong jumps in CO_2 concentration (Wang et al., 2007). Further, in a model with coarse resolution the complex boundary layer structures and thus the vertical profiles of CO_2 over heterogeneous land cannot be adequately resolved. The mesoscale flows and mixing in the atmosphere are strongly correlated with short term variability of biospheric CO_2 fluxes, since they are both driven by the same mechanism, solar radiation. Hence inappropriate representation of the atmospheric transport on mesoscales may lead to significant biases in biospheric sources and sinks derived from inverse modeling. Thus all these effects can only be addressed with high resolution mesoscale simulations that include CO_2 fields in order to bridge the gap between the measurements and the inversion models.

The strong deterioration of the CO_2 inversions due to transport model deficiencies are proven in some studies (Lin and Gerbig, 2005; Gerbig et al., 2008b). In these studies uncertainties in advection and vertical mixing from ECMWF and ETA meteorological models are quantified and then linked to resulting errors in CO_2 inversions. The transport deficiencies become especially critical when trying to invert high space/time resolution of fluxes as compared to monthly fluxes on large regions for which data limitation is probably larger (Gurney et al., 2002). A comprehensive validation of the different global (TM3, LMDZ) and regional (HANK, DEHM, REMO) offline transport models were done by Geels et al. (2007) for several European tall towers and mountain stations. The intercomparison study revealed the remarkable improvement of the CO_2 concentration simulation by regional models with horizontal resolutions down to 50 km compared to the coarser global models. The author team (Geels et al., 2007) concluded several important results from this intercomparison work to be considered by the inversion community.

- Both global and regional scale models fail to reproduce phasing of daily cycles as well as absolute concentrations observed at high-altitude stations due to complex meteorology and poor representation of the high elevation in the models.
- All the models have difficulties to simulate correctly the height of the planetary boundary layer (PBL) which has substantial influence on the concentration levels at the stations. Especially nighttime mixing is very uncertain in the models.
- The vertical CO_2 profile is difficult to simulate, especially near the ground due to the surface exchange. The recommendation is therefore to emphasize the use of tower data in inverse studies.

The two latter results are also supported by (Stephens et al., 2007), who showed that annual-mean vertical CO_2 gradients calculated from measurements taken during midday are inconsistent with those simulated by global models. These results impose severe limitations on the usability of the continental CO_2 concentration observation data for inversions. Hence a huge amount of valuable measurement data – from mountain stations, but also from low budget near-surface stations and short towers which could be densely deployed, cannot be used in the inversions so far. As a result, the CO_2

inversions performed by the TransCom 3 inversion community down-weighted continental observations, assuming that the data contained too much "noise" (Gurney et al., 2004; Wang et al., 2007). Moreover one may add also coastal stations to the above mentioned "difficult sites" list (Riley et al., 2005). These all severely reduce the number of continental sites used in inversions to constrain continental fluxes.

Another problem is the requirement of strict temporal data selection in inversions. Global CO_2 inversions usually use only afternoon hourly or even averaged values. Nighttime data or measurements taken during morning and evening hours are not used for most of the continental sites. Some of the inversion studies involve further filtering for day to day variability of the CO_2 observation data to remove the "noise". This leads to losing the information about diurnal cycle of biospheric signals containing information on biospheric processes – respiration and photosynthesis, where for instance using nighttime data would make possible to constrain respiration fluxes. Thus it would be an obvious gain to use the full time series of continuous data for the inversion rather than only afternoon values. Using high-frequency concentration data would also be very useful for regional scale inversions which also could assist to close the gap between top-down and bottom-up estimations.

As pointed out by (Gerbig et al., 2008b) there are several ways to mitigate the shortcomings of current inversion systems associated with uncertainties in transport representation of the meteorological fields used for the global inversion models. One of the promising solutions would be to apply transport models which significantly better reproduce these processes. There are very few studies addressing this problem by involving high-resolution atmosphere-biosphere models. Several mesoscale modeling systems are currently used to simulate mesoscale variations of CO_2 concentration in the atmosphere, e.g. (van der Molen and Dolman, 2007; Sarrat et al., 2007; Ahmadov et al., 2007). In these studies the authors used mesoscale meteorological models in combination with biospheric models to perform forward simulations of CO_2 tracer. The authors compared the modeling results versus the observations for both meteorology and CO_2 fields. The CO_2 data used in these studies were from surface stations and, during some of the intensive measurement campaigns, from aircraft. The studies show how strongly mesoscale flows initiated by complex terrain and by the land-water contrast could lead to remarkable gradients in atmospheric CO_2 fields. Such model validations are also valuable since their meteorological fields can be used in regional inversions (Lauvaux et al., 2008).

As we stated, the continuous global CO_2 measurement network (mostly tall towers and mountain stations) constitute a backbone of the global CO_2 inversion system, but it is a challenge for global models to represent these sites. One of earliest comparisons of this type was done for the WLEF tall tower in USA surrounded by the boreal lowland and wetland forests. Denning et al. (2003) as well as Nicholls et al. (2004) tested the ability of the coupled high-resolution biosphere-atmosphere model SiB2-RAMS to simulate observed quantities at the WLEF site and identified some of the processes causing CO_2 variability for a few days during summer.

The above mentioned studies give us an opportunity to be aware of possible errors in future inversions. In addition the mesoscale processes have also a strong impact on CO_2 fluxes via modification of temperature and moisture fields, cloudiness and thus shortwave radiation (SWR). Those local influences on fluxes need to be taken into account in inversions, otherwise the results will be misleading. For instance, if one conducts an inversion to optimize diagnostic biospheric model parameters controlling CO_2 fluxes, one has to make sure that the shortwave radiation (SWR) fluxes used in the biospheric model are accurate enough. It is well known that the simulation of the SWR fields is sensitive to cloudiness and aerosol representation in the models which is quite challenging for the meteorological models.

Our paper discusses the advantages of using very high-resolution mesoscale simulations of CO_2 transport versus two global models for CO_2 transport in case of a coastal concentration measurement station – Biscarosse tower. The main goal of this paper is to address the deficiencies of the coarse resolution transport models in the representation of the CO_2 point measurements which we have to take into account in the inversions targeted to estimate CO_2 fluxes. In addition the paper assesses the possi-

BGD

5, 4745–4776, 2008

bility of using hourly concentration data including nighttime in inversions by involving the mesoscale model.

In Sect. 2 we describe the model setup. Section 3 introduces the observation campaign and the measurements. Section 4 presents a comparison of WRF-VPRM modeling results, global models and the observations. Finally, Sect. 5 summarizes the paper and discusses advantages and perspectives of using the WRF-VPRM modeling system for assimilating CO_2 concentration data from continental sites.

2 Configuration of the models

We set up and ran Weather Research and Forecasting (WRF) model http://wrf-model.org in high resolution on two nested grids over the CERES domain (see Fig. 1a, b). We coupled diagnostic biospheric model Vegetation Photosynthesis and Respiration Model (Mahadevan et al., 2008) to WRF as a module. The detailed description of the WRF-VPRM modeling system can be found in (Ahmadov et al., 2007), here we provide only a brief overview. The VPRM model produces biospheric CO_2 fluxes in order to perform CO_2 tracer transport by WRF. The model uses MODIS http://modis.gsfc.nasa.gov/ satellite indices – enhanced vegetation index (EVI) and land surface water index (LSWI) obtained in 500 m spatial resolution with 8 days frequency. VPRM uses eight land-use classes with different parameters constraining CO_2 uptake and respiration fluxes. Furthermore the model uses air temperature and radiation fields from the meteorological models. These parameters were optimized by using CO_2 flux measurements at few land-use classes located in the modeling domain. For the VPRM model a high-resolution land cover map – SYNMAP (Jung et al., 2006) was used. A preprocessing tool was developed in order to preprocess land-use data and MODIS indices to map on a WRF grid. The preprocessing tool and the WRF-VPRM code are available freely to users upon request.

Anthropogenic CO_2 fluxes were taken from the 10 km resolution European anthropogenic emission inventory (updated in October, 2005) developed by the Institute of Economics and the Rational Use of Energy (IER), University of Stuttgart (http://carboeurope.ier.uni-stuttgart.de/). Lateral boundary conditions (LBCs) and initial conditions (ICs) for CO_2 concentration fields are taken from the global zoomed CO_2 transport model – LMDZ (Hourdin and Armengaud, 1999; Peylin et al., 2005) with a horizontal resolution $0.83^{\circ} \times 1.25^{\circ}$ (latitude × longitude) over Europe, 28 vertical levels up to the tropopause, and half hourly time resolution (hourly for outputs) for physical processes (3 min for dynamical processes). The model is nudged to the ECMWF global model data to perform meteorological transport. The LMDZ data used here is based on forward runs using CO_2 fluxes generated by ecophysiological model – SiB2 (Sellers et al., 1996) together with fossil and ocean fluxes. There is an offset added to the LMDZ concentration fields, which was found from comparison against some European measurement sites.

All necessary meteorological data for initial and lateral boundary conditions, sea surface temperature (SST) and soil initialization fields of WRF for each run were taken from the ECMWF analysis data (http://www.ecmwf.int/) with ≈35 km horizontal resolution and 6 hourly intervals.

The WRF-VPRM model was validated against a number of meteorological and tracer observations, both ground and aircraft based (Ahmadov et al., 2007; Sarrat et al., 2007; Macatangay et al., 2008). The model also participates in the TRANSCOM modeling experiment www.purdue.edu/transcom/. One of the improvements of WRF-VPRM in current study is the online coupling of VPRM to WRF, so that WRF produced air temperature at 2 m (T2) and shortwave downward radiation (SWDOWN) were used in VPRM to calculate CO_2 fluxes which were then provided to WRF at each time step. Table 1 shows the WRF model physics and grid options for these runs. Note that we ran the model on nested grids with a high vertical resolution, where first 20 layers are located below 2 km height from the ground.

In WRF-VPRM we used several concentration fields, so called “tagged” tracers, for CO_2 corresponding to the different origins: 1) total CO_2 concentration (which can be measured) that combines CO_2 fields from anthropogenic and biospheric sources and also coming from the outside of the simulation domain; 2) global CO_2 that does not include any uptake or emission fluxes, which participates only in transport; 3) anthropogenic CO_2; 4) respiration and 5) photosynthesis signals. The last three "tagged" tracers include only the corresponding surface fluxes. They use zero inflow and zero-gradient outflow lateral boundary conditions, zero fields for initial conditions. The first two types of tracers use CO_2 concentration fields from a global model in inflow and zero-gradient conditions on outflow, global fields for ICs. "Tagged" tracers allow us to separate the global CO_2 signal from the regional one, and to determine the contribution of the different processes to the total CO_2 signal.

All anthropogenic and biospheric fluxes were added at each simulation time step to CO_2 field in the lowest vertical level of the WRF grid. We ran WRF-VPRM for one month time period – from 16 May to 15 June 2005. Here only simulation results from the high-resolution (2 km) inner nest are presented.

The last model involved in this study is the TM3 model (Rödenbeck et al., 2003) with a horizontal resolution 4°×5° (latitude×longitude), 19 vertical levels up to the tropopause, and hourly time resolution (using instantaneous concentrations every 3 h for output). It uses 6-hourly NCEP data as a meteorological input. The purpose of the adding this model with a coarser resolution to the comparison presented in this paper is to get an insight how the increasing resolution improves the simulation of the CO_2 variability. Unlike the LDMZ model data the TM3 model results are based on a global inversion using atmospheric CO_2 concentration measurements. The CO_2 fields from TM3 are calculated using fluxes that were optimized in an inversion using the global CO_2 measurements. The model used biospheric model – BIOME-BGC (Trusilova and Churkina, 2008) generated CO_2 fluxes as a prior. It should be noted that the TM3 model did not use the Biscarosse site in the optimization of the surface fluxes.

3 CERES campaign

Within the CarboEurope Integrated Project http://www.carboeurope.org/, the first intensive observation campaign of CERES (the CarboEurope Regional Experiment Strategy) was performed in the Les Landes area, South-West France, during May–June 2005 (Dolman et al., 2006). The experimental domain covers an area of about 250 km×150 km in southwest France (Fig. 1b). The region consists of different land-use classes such as ocean, forest, croplands, vineyards, rivers and urban areas. The Pyrenees Mountains and the Massif Central are located in the south and in the eastern part of the domain respectively. There are two large cities located close in the south-eastern (Toulouse) and northwestern (Bordeaux) parts of the domain. According to the local climatology the dominant winds should be either from the west or the east; therefore, it was expected that the experiment design allowed to observe modification of the CO_2 concentration profiles by the land as the air mass progressed east- or westward (Dolman et al., 2006).

During the campaign CO_2 concentration measurements were carried out by several surface stations and also aircraft (Ahmadov et al., 2007). A a high-precision CO_2 instrument (CARIBOU, with an accuracy of 0.1 ppm) was installed and operated on a 40-m high tower near Biscarosse (44.38° N, 1.23° W) (Fig. 1b) (Dolman et al., 2006). The measurement site is located about 2 km from the sea shore, and about 120 m above sea level. In addition we involved data from the meteorological station BISCAROSSE/PARENTIS located in the vicinity (44.43° N, 1.25° W) of the tower to aid interpreting CO_2 measurements, given that there were no meteorological measurements made at the tower itself.

The Biscarosse site is located very close to the coast, thus the small area of the land biosphere between the tower and the ocean is not expected to change the marine air masses' CO_2 content significantly while the air is transported to the site by westerlies. Thus the tower detects marine air masses, with measurement periods that have large scale representativeness, but also air masses coming from inland with influences from the terrestrial biosphere and the anthropogenic emissions. This feature makes a coastal CO_2 station an interesting and information-rich site for atmospheric inversions. We chose this site for the current study assuming that the Biscarosse data could be used widely in inversion studies in future.

4 Results and discussion

Here we present the results for WRF-VPRM simulations for the Biscarosse site and the nearby weather station. Figure 2 exhibits the comparison of air temperature (T2) simulated by WRF and observed from the meteorological station. This plot gives insight into the weather evolution over the period as well as the model performance for the important meteorological variable, which also drives biospheric CO_2 fluxes. The comparison reveals that the high-resolution model is able to accurately predict temperature variations with only a slight cold bias.

As we stated above the Biscarosse tower is located very close to the ocean coast (see Fig. 1b) and it is exposed to air flows of both, oceanic and continental origin. It is obvious that changes of air flow direction results in a noticeable change in CO_2 fields due to completely different CO_2 fluxes in land and ocean, with ocean fluxes that are much weaker compared to the terrestrial fluxes (also they show weaker variability). Due to changes in the wind flows from night to daytime caused by the sea-land breeze, the recirculation of nighttime respired CO_2 back to the land may occur, such as airborne measurements and model studies indicated for the CERES campaign in 2005 (Ahmadov et al., 2007). Even if there is a synoptic flow, the sea-land breeze may modify the wind field during sunny days.

Figure 3a, b and c shows hourly CO_2 concentration measurements at the Biscarosse tower during one month together with simulated CO_2 from the global models TM3 and LMDZ, and from the mesoscale model WRF-VPRM. The figures show that all the models perform reasonably well in capturing day to day variability of the concentration. Figure 3c shows that WRF-VPRM model can capture much more variability in the ob-

BGD
5, 4745–4776, 2008

served time series than two global models. Also the amplitude of the signal is captured reasonably well for both daytime minimum and nighttime maximum by WRF-VPRM in many cases. Unlike the global models, WRF-VPRM is able to simulate the second maximum of CO_2 concentration in the afternoon which appeared due to the front passage or sea breeze in some days, e.g. during the 20, 27 and 28 May.

The TM3 model shows some bias and less correlation with the observed data compared to LMDZ, due to its coarser resolution. For example, due to the size of the grid-cells of several hundred kilometers within TM3 it is impossible to represent a coastal station correctly by the model. The grid box comprising the Biscarosse tower is fully located over land in TM3, therefore land influence is significantly overestimated, leading to much stronger uptake as compared to the observation. It is worthy to note that TM3 and LMDZ have comparable performances when used with comparable resolution (Law et al., 2008). Mismatches can also arise from the fine-structure of the biospheric fluxes used as input for the models.

LMDZ captures the observed daytime minimum and nighttime maximum in CO_2 concentrations with some discrepancy, while the average signal is captured quite well. Since the LMDZ model still has a relatively coarse horizontal resolution, it cannot accurately resolve subdiurnal variability in CO_2 concentration associated with atmospheric transport and mixing processes near the coastline.

The relevant statistics for the model-data comparisons can be found in Table 2, where also the mean standard deviation within the measurement periods of one hour is presented. The high root mean square error (RMSE) in the model-measurement comparison is partially caused by averaging the measurements over each hour, while using instantaneous values in the models. Averaging in the observation data is necessary to minimize the effects of eddies and other small scale effects that are not resolved by any of the models. Interestingly, the variability of CO_2 within an hour (last column of Table 2) is a factor of three smaller during the day than during the night, most probably due to stronger and deeper vertical mixing.

The numbers in Table 2 show that WRF-VPRM exhibits much more correlation com-

BGD
5, 4745–4776, 2008
WRF-VPRM simulations of CO_2
R. Ahmadov et al.

pared to the coarse models. The main reason for such agreement is a better representation of the transport, especially mesoscale flows and vertical mixing in the 2 km resolution WRF-VPRM runs. In addition, the more accurate representation of the fine-scale variability in the surface CO_2 fluxes by VPRM, especially in the near-field of the site, improves the CO_2 simulation as compared to the coarser global models. Although the average bias in LMDZ against hourly observation data is smaller, its deviation from the measurements (RMSE) is greater than in WRF. The existing discrepancy between WRF-VPRM model and the measurement is caused by several reasons – uncertainties in CO_2 fluxes simulated by VPRM, initial and boundary conditions of CO_2 from LMDZ model, also uncertainties in transport and mixing within WRF. It should be noted that VPRM fluxes are based on a simple diagnostic model (Mahadevan et al., 2008). The model were validated against flux data and demonstrated its strong predictive ability for Net Ecosystem Exchange from hourly to monthly timescales (Mahadevan et al., 2008). However, the quality of VPRM fluxes would undoubtedly benefit from an optimization against atmospheric concentration measurements, while we only optimized the VPRM parameters against flux data from a few sites operated during the campaign (Ahmadov et al., 2007). VPRM is able to mimic the spatial and temporal distribution of surface fluxes because of using high resolution satellite indices, land-use map and high spatiotemporal resolution meteorological fields from WRF. This is sufficient to determine the influence of the main transport and mixing capabilities of the model on the CO_2 tracer distribution.

In order to make clearer the contribution of different sources to the CO_2 concentration at the measurement location, we present hourly time series of the different "tagged" tracers from the WRF-VPRM model (Fig. 4). There is a release of CO_2 by biosphere and accumulation of anthropogenic CO_2 in the shallow nighttime boundary layer in the night. During some nights, for instance on 20 May there is an evident correlation between biospheric and anthropogenic CO_2 tracers since the tower detects the inland respired CO_2 and also emission from power plants and other anthropogenic sources, but respired CO_2 largely dominates in amplitude. The analyzed time series reveal that in the CERES region during the summer season the biospheric CO_2 fluxes are dominant compared to the anthropogenic emissions, therefore we may neglect the anthropogenic component in further interpretations of the observations. The global CO_2 tracer, i.e. the advected lateral boundary condition, shows (Fig. 4) some subdiurnal variability in contrast to LMDZ CO_2 concentration given in Fig. 3b. This is because LMDZ CO_2 field is distributed by the high-resolution WRF transport with mesoscale features.

During cold and cloudy days when strong synoptic westerly winds occur (e.g. 21–23 May 2005) both the biospheric and the anthropogenic CO_2 concentration at the site become negligible. In such cases the global CO_2 tracer plays the main role in contributing to the measured signal. During June the overall CO_2 uptake signals are stronger than during May, the first part of the simulation period. This is caused by the phenological changes associated with the intensifying growing season. Some of the large cropland areas in the region become strong CO_2 sinks in June as shown by Ahmadov et al. (2007).

The recirculation of the respired nighttime CO_2 fields, for which the term "3-D rectifier effect" was established (Riley et al., 2005; Pérez-Landa et al., 2007; Ahmadov et al., 2007) is demonstrated for the case 20 May 2005. During this day a south-westerly flow brought warm air masses over France. The weather was warm and sunny, with only some high clouds, temperatures ranging from 8°C in the morning to 32°C in the afternoon in interior regions (Fig. 2), and weak westerly winds observed near the surface. It is obvious that this condition favors the formation of sea-land breeze, which enhances the westerly wind component of the surface wind towards the afternoon. Figure 5a shows the diurnal cycle of CO_2 for this day. It is noteworthy that during this night the highest CO_2 signal of the May–June period at the Biscarosse tower was registered, with an enhancement of about 30 ppm compared to the afternoon values (Fig. 3a). As Fig. 5a shows, WRF-VPRM underestimates this signal by about 10 ppm during the early morning when the nocturnal boundary layer is enriched with the respired CO_2 advected from the inland by weak easterly winds (Fig. 5b). The underestimation might be related to an overestimation of the easterly wind in WRF during the night when comparing to the measurements at the nearby weather station (Fig. 5c). There was stagnation in the air in early morning, which is seen as a measured low wind speed in Fig. 5c. During this time the tower detects only respired CO_2 from the ground beneath. Since WRF could not well capture this case occurring around 05:00 UTC (07:00 Local Time), it failed also to resolve huge respired CO_2 at this time. After 06:00 UTC with sunrise photosynthesis begins, and simultaneously the convective turbulence initiates mixing over the growing boundary layer depth. It is interesting to see that WRF-VPRM captures the minimum in CO_2 concentration at around 08:00 UTC (although 2 h earlier), associated with the change in wind through southerly at the onset of the sea breeze (Fig 5b). This reduction in CO_2 is most probably related to local influence from photosynthesis. Close to 10:00 UTC the strengthening and reversing the wind flow becoming more westerly advects a large plume of CO_2 respired during the previous night. Therefore we see a second strong maximum near 10:00 UTC in the measurement, but again a bit earlier in the models (Fig. 5a), since the wind rotation is faster in the model. The magnitude of this second maximum is also underestimated by WRF-VPRM, similar to the first maximum. After a few hours the westerly winds start bringing marine air masses with lower constant CO_2 concentration until the next day. The model captured this very well, indicating that the lateral boundary condition from the LMDZ model is appropriate. TM3 and LMDZ both show a smoothed diurnal cycle of CO_2 without a second maximum during that day. TM3 underestimates the nocturnal and daytime signals, while LMDZ captures the afternoon signal well. It is clear that due to coarse resolution these models cannot capture the mesoscale flows around the tower. Thus they give a smoothed diurnal cycle.

In case of strong synoptic disturbance the diurnal CO_2 signal at the site looks much different. For instance, on the 18 May 2005 after the crossing of a cold front during the previous day, the wind shifted to north-west over the western part of France, colder and drier air moved into the country. The weather was changing, and the sky was mostly cloudy. The temperatures were varying from 10°C in the morning up to 20°C in the afternoon (Fig. 2). During this day diurnal CO_2 concentration variation measured at the Biscarosse tower was less than 5 ppm (Fig. 3a). These are ocean air masses which are not affected by diurnal CO_2 fluxes as on the continent. A weak temperature variation during this day was observed (Fig. 2). In this case strong westerly flow brought large scale CO_2 signal to the measurement area during the whole day since there was no nighttime transport of CO_2 from the land. This case was well simulated by all the models.

Since in the global inversions usually afternoon CO_2 concentration data is used it is important to check how realistically the models used here simulate this kind of data. We analyzed CO_2 concentration time series averaged for daytime between 12:00 UTC to 17:00 UTC, which characterize the well-mixed hours for the region. Figure 6a demonstrates the comparison between all the models and the observation for the averaged concentration time during the well-mixed hours within one month period. The related statistics for the comparison is given in Table 2, indicating increasing correlation with increasing horizontal resolution. According to the Table 2, the LMDZ model generally represents day-to-day variability of the afternoon averaged concentrations, while TM3 shows lower performance, especially in magnitude due to the above mentioned negative bias. The mean bias in LMDZ is larger than in WRF-VPRM. Only the root mean square errors are high in both models and even slightly bigger in WRF-VPRM. This can be explained by the larger variability in the high-resolution model which leads to more scattering of the model predicted CO_2 fields (Fig. 3c). All models show quite good agreement against the observation until 27 May. Later we see a remarkable mismatch especially in the global models. On 30 May the observation showed the highest CO_2 signal during this period. Both LMDZ and TM3 underestimate this signal. However WRF-VPRM captures this highest signal with some overestimation.

Focusing on night-time concentration (05:00–07:00 UTC, representing the later part of the night), WRF-VPRM agrees much better with the observations as compared to global models (Fig. 6b). From Fig. 6b and Table 2 it can be seen that generally the correlation between the models and the observation is slightly higher during night than during day; usually all models predict an early morning maximum in CO_2 concentrations due to the release of CO_2 into nocturnal boundary layers. But the global models show significant deviation from the observation for the nighttime data. This is caused by a poor simulation of nighttime vertical mixing. The correlation coefficients for both daytime and nighttime averaged CO_2 concentrations are significantly better in the high-resolution model. It is worth to note that WRF-VPRM can capture the phasing of the observed signal quite good, while there is some bias in amplitude, but much smaller than in the global models. This indicates that also for a mesoscale model such as WRF it is difficult to parameterize the nocturnal stable boundary layer, which is an active area of research in meteorology (Steeneveld, 2007).

5 Conclusions

We have used the high-resolution coupled atmosphere-biosphere model WRF-VPRM in order to interpret a CO_2 concentration time series observed from a tower at the coastal station near Biscarosse during the CERES campaign 2005. The station is strongly influenced by mesoscale flows. Sea-land breeze and its combination with local CO_2 fluxes can lead to a significant "contamination" of the observation signal, such that the time series is problematic to use quantitatively in coarse models. These errors come also from the poor simulation of vertical mixing during the night and day over the land. Similarly these kinds of errors are typical for the stations located on complex terrain such as mountains.

Simulated CO_2 from two global models used in CO_2 inversions, TM3 and LMDZ, with different spatial resolutions, were confronted with the tower observations as well as with the high-resolution simulation from coupled atmosphere-biosphere model WRF-VPRM. The results have shown that only WRF-VPRM is able to simulate the observed diurnal variability. The simulations also confirmed that the recirculation of the nighttime respired CO_2 requires modeling the covariance of mesoscale circulation and biospheric fluxes. Thus when our models are not able to simulate nighttime CO_2, this may imply

BGD

5, 4745–4776, 2008

WRF-VPRM simulations of CO_2

R. Ahmadov et al.

the "repeated bias" in the daytime simulation due to recirculation with sea-breeze effect or in some cases frontal passage. The case of 20 May 2005 showed a strong night-time buildup that persisted throughout the late morning, interrupted only by a short but remarkable drop in CO_2 due to local influence at the onset of the sea breeze. One may conclude from such situations that even averaging CO_2 measurements over periods with a well-mixed boundary layer cannot prevent a contamination from recirculated continental respiration signals; consequently large representation errors in inversions when using such data are expected.

The work clearly demonstrates that an appropriate representation of synoptic variations and mesoscale effects can substantially improve the representation of hourly CO_2. Although we used fluxes from the simple diagnostic VPRM model that were not optimized against concentration measurements, the WRF-VPRM model is able to capture much more variability in the tower measured CO_2 time series. This indicates the importance of capturing the transport and mixing processes at high resolution and the spatiotemporal variability of biospheric fluxes. The high-resolution representation of the spatial heterogeneity in CO_2 fluxes especially in the near field is very important for proper simulation CO_2 distribution (Gerbig et al., 2008a). In addition, flux covariance with meteorology is necessary to capture rectifier effects and thus to avoid bias errors (Ahmadov et al., 2007).

This paper shows the potential of using WRF-VPRM in the context of inverse modeling in order to utilize high-frequency CO_2 concentration data, which can substantially improve the inversion accuracy. The modeling system also could be applied for the "difficult sites" not used in current inversions. Running WRF-VPRM in very high resolution in the global scale is computationally expensive, and needs to be used efficiently together with global inversion models. It is feasible to setup small domains around some measurement stations and to run WRF-VPRM model for these domains in high spatial resolution. Regional scale inversions can be done using the STILT-VPRM modeling framework (Matross et al., 2006), which can be driven by WRF generated transport fields. Roedenbeck et al. (2008) showed that such nested inversions within global

BGD
5, 4745–4776, 2008
WRF-VPRM simulations of CO_2
R. Ahmadov et al.

models are feasible, even with completely different transport representations for global and regional scales. Moreover forward modeling of CO_2 transport by WRF-VPRM for some sites is essential validation of the model, and to better understand the near-field influence on measurements at continental sites and consequently on regional flux estimates (Lauvaux et al., 2008). Using such flexible modeling tools as WRF would allow us to test different physics and dynamics options in order to improve the modeling capabilities for a given region.

The agreement of nighttime simulated CO_2 with observations suggests that it should be feasible to also use the nighttime observations in the inversions, providing important information on the partitioning of biosphere-atmosphere exchange between respiration and photosynthesis. Although the proper simulation of the stable boundary layers remains difficult even in advanced mesoscale models such as WRF, there is hope that within the large community involved in WRF model development http://wrf-model.org there will be substantially improvements in its capabilities to simulate mixing in nighttime cases. The inversion studies would be able to constrain respiration fluxes at regional scales using the numerous continuous CO_2 monitoring sites by involving nighttime data from continental sites in addition to the daytime data.

Because of its great flexibility, WRF-VPRM can serve to bridge the gap between the measurements and inversion models in almost all the regions of the globe including complex terrain areas. The fast growing global greenhouse gas monitoring network makes this tool very attractive.

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Table 1. Parameters and physics options used in WRF model.

Vertical coordinates	Terrain-following hydrostatic pressure vertical coordinate
Basic equations	Non-hydrostatic, compressible
Grid type	Arakawa-C grid
Time integration	3rd order Runge-Kutta split-explicit
Spatial integration	3rd and 5th order differencing for vertical and horizontal advection respectively; both for momentum and scalars
Domain configuration	2 domains with resolution – 10 and 2 km for outer and inner domains respectively; size 690×690 km and 320×280 km; 51 vertical levels for both domains up to 150 mb
Time step	60 and 12 s for outer and inner domains respectively
Physics schemes	Radiation – Rapid Radiative Transfer Model (RRTM) Longwave and Dudhia Microphysics – WSM 3-class simple ice scheme Cumulus – Kain-Fritsch (new Eta) scheme (only for the coarse domain!) PBL – YSU; Surface layer – Monin-Obukhov Land-surface – NOAH LSM

BGD
5, 4745–4776, 2008

Table 2. Statistics of the comparison between measured and simulated CO_2 for the different models. RMSE-root mean square error is the standard deviation of the differences between the models and the observations.

Time	Model	R^2	Bias, ppm	RMSE, ppm	Mean(std_{obs}), ppm
Hourly	TM3	0.16	–3.87	5.09	0.58
	LMDZ	0.29	0.11	4.66	
	WRF-VPRM	0.59	0.67	4.26	
Afternoon Averaged	TM3	0.06	–2.49	3.67	0.35
	LMDZ	0.18	0.95	3.28	
	WRF-VPRM	0.52	–0.27	3.42	
Nighttime Averaged	TM3	0.02	–6.76	6.68	1.05
	LMDZ	0.22	–1.91	6.1	
	WRF-VPRM	0.58	0.95	4.95	

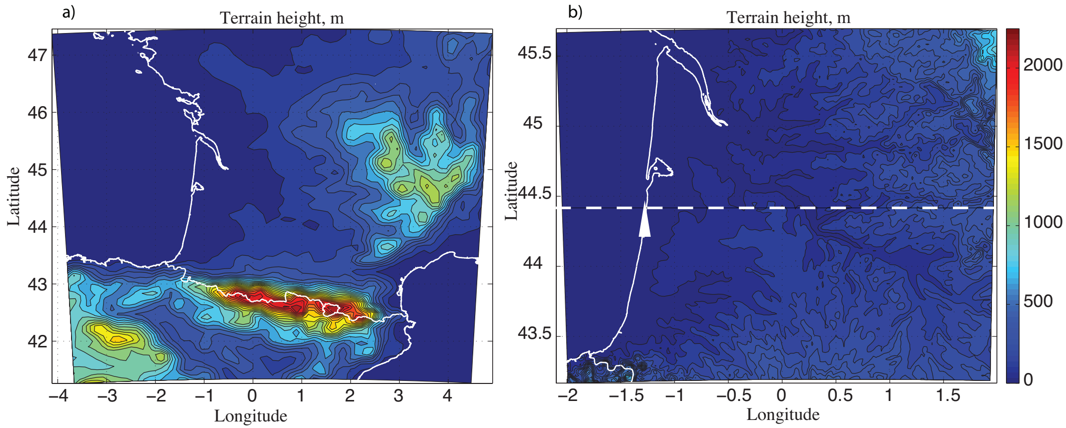

Fig. 1. Topography of the WRF domains – **(a)** the outer and **(b)** the inner grids with 10 and 2 km resolutions respectively; The white triangle indicates the Biscarosse tower location.

BGD
5, 4745–4776, 2008

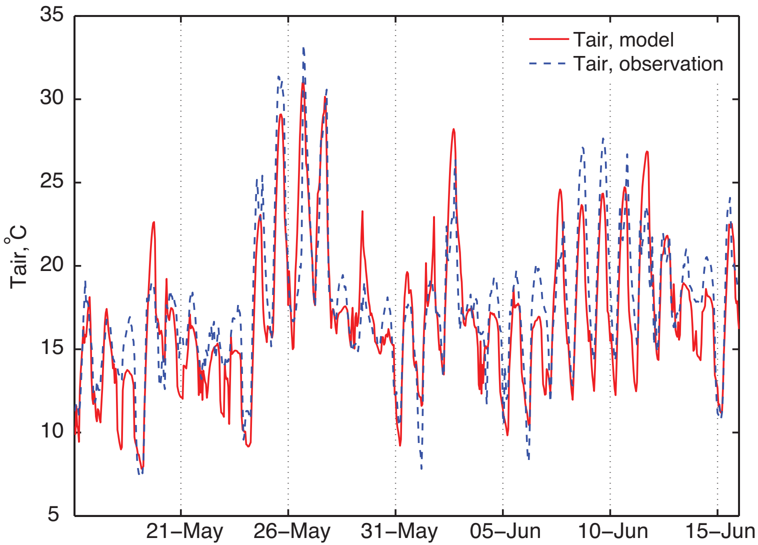

Fig. 2. Comparison of measured air temperature at 2 m with WRF simulated temperature at the meteorological station Biscarrosse Parentis. The statistics: r2=0.77, average bias is −0.74°C, RMSE=2.14°C.

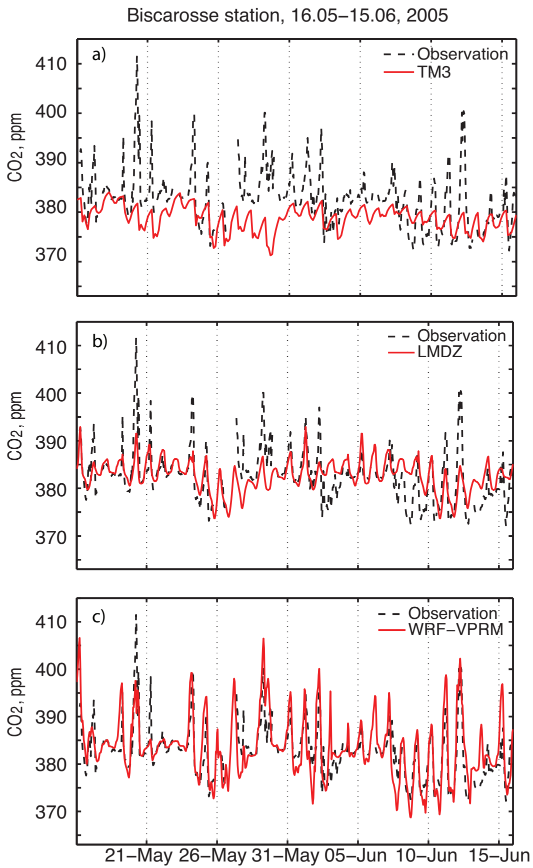

Fig. 3. CO_2 concentration time series from the Biscarosse tower and the models **(a)** TM3, **(b)** LMDZ, **(c)** WRF-VPRM.

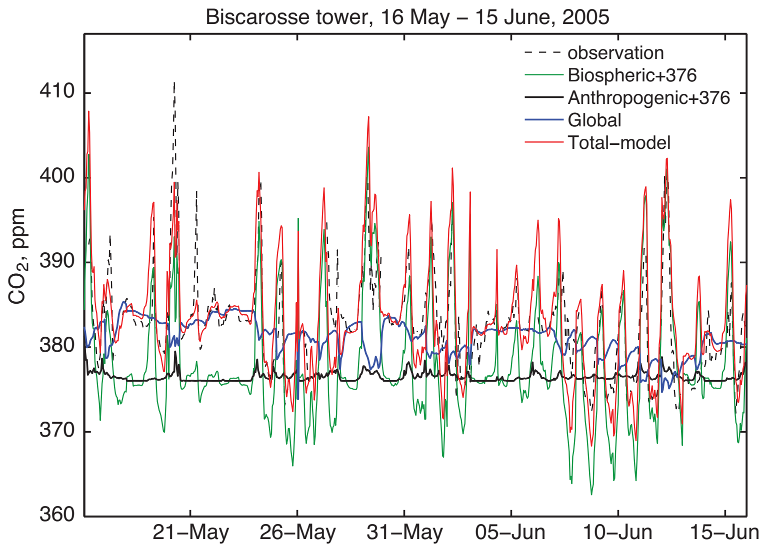

Fig. 4. Time series of the different tagged tracers at the tower site from the WRF-VPRM.

BGD

5, 4745–4776, 2008

WRF-VPRM simulations of CO_2

R. Ahmadov et al.

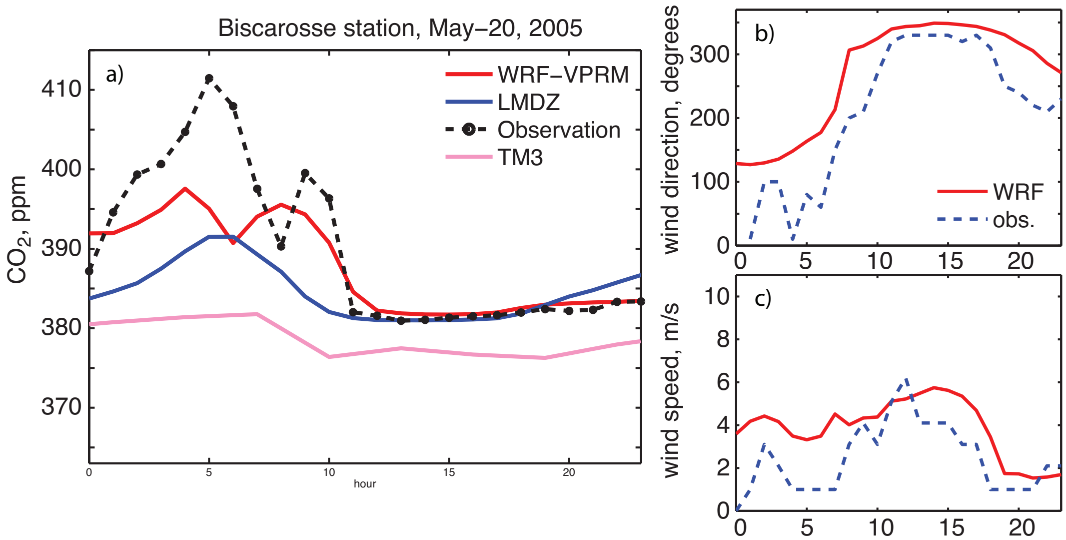

Fig. 5. (a) CO_2 concentration comparison for the 20 May; **(b)** wind direction and **(c)** wind speed comparison on that day at the meteorological station.

BGD

5, 4745–4776, 2008

WRF-VPRM simulations of CO_2

R. Ahmadov et al.

BGD

5, 4745–4776, 2008

WRF-VPRM simulations of CO_2

R. Ahmadov et al.

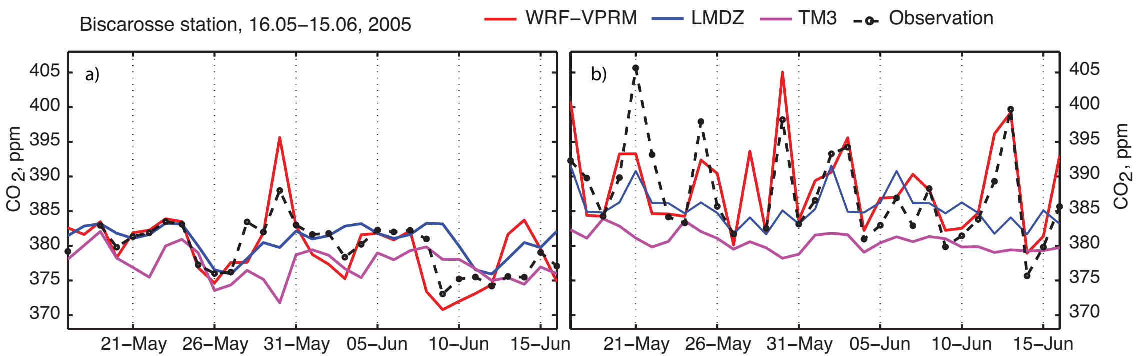

Fig. 6. Comparison of measured CO_2 concentration against WRF-VPRM for **(a)** daytime and **(b)** nighttime averaged cases.