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Modeling Regional Carbon Dioxide Flux over California using the WRF-ACASA Coupled Model

Liyi Xu*†, Rex David Pyles‡, Kyaw Tha Paw U‡, Shu-Hua Chen‡ Erwan Monier*, and Matthias Falk‡

Abstract

Many processes and interactions in the atmosphere and the biosphere influence the rate of carbon dioxide exchange between these two systems. However, it is difficult to estimate the carbon dioxide flux over regions with diverse ecosystems and complex terrains, such as California. Traditional carbon dioxide measurements are sparse and limited to specific ecosystems. Therefore, accurately estimating carbon dioxide flux on a regional scale remains a major challenge.

In this study, we couple the Weather Research and Forecasting Model (WRF) with the Advanced Canopy-Atmosphere-Soil Algorithm (ACASA), a high complexity land surface model. Although WRF is a state-of-the-art regional atmospheric model with high spatial and temporal resolutions, the land surface schemes available in WRF lack the capability to simulate carbon dioxide. ACASA is a complex multilayer land surface model with interactive canopy physiology and full surface hydrological processes. It allows microenvironmental variables such as air and surface temperatures, wind speed, humidity, and carbon dioxide concentration to vary vertically. Carbon dioxide, sensible heat, water vapor, and momentum fluxes between the atmosphere and land surface are estimated in the ACASA model through turbulence equations with a third order closure scheme. It therefore permits counter-gradient transports that low-order turbulence closure models are unable to simulate.

A new CO_2 tracer module is introduced into the model framework to allow the atmospheric carbon dioxide concentration to vary according to terrestrial responses. In addition to the carbon dioxide simulation, the coupled WRF-ACASA model is also used to investigate the interactions of neighboring ecosystems in their response to atmospheric carbon dioxide concentration. The model simulations with and without the CO_2 tracer for WRF-ACASA are compared with surface observations from the AmeriFlux network.

Contents

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1. INTRODUCTION

Carbon dioxide is widely recognized as a major contributor to the current climate change phenomenon. Its presence in the atmosphere intensifies the ability of the atmosphere to absorb and re-emit energy, resulting in increased surface temperatures. Although carbon dioxide is not the most efficient greenhouse gas on a molecule-to-molecule basis compared to other trace gases (such as methane or water vapor), its chemical stability, combined with its concentration and rate of increase make it the most important anthropogenic greenhouse gas to consider limiting both in the short and long-term.

Fortunately, not all anthropogenic carbon dioxide emissions contribute to increases in the global mean carbon dioxide concentration. The Global Carbon Project (2010) shows that only 47% of the anthropogenic carbon dioxide emissions from 2000 to 2009 remain in the atmosphere. Oceans uptakes accounts for about 26% of the emissions, and the remaining 27% is attributed to the terrestrial ecosystems, referred to as the 'missing sink' of anthropogenic carbon emissions (Wigley and Schimel, 2005). Recently compiled evidence suggests that photosynthetic bacteria in the near-surface soil horizon in recovering grasslands, bushlands, and savannah-type ecosystems account for a significant portion of the terrestrial sink (add citation 1). While this may be true, soil moisture and nutrient conditions are so widely varying that none have yet made the effort to track them with models and observations over large areas.

Though not often considered in the popular vernacular surrounding global mean concentrations, the influence of terrestrial carbon processes on seasonal timescales is visible in the atmospheric carbon dioxide concentration. The sinusoidal variation within the annual atmospheric carbon concentration is mainly due to the terrestrial growing season in the northern hemisphere, which has more land surface area than the southern hemisphere. Although it accounts for a significant of amount of carbon dioxide exchange with the atmosphere and anthropogenic carbon uptake, there are large uncertainties in estimating this terrestrial carbon flux. As a result, estimates are often implicitly calculated—for example, the terrestrial carbon sink of anthropogenic CO_2 in the Global Carbon Project is estimated as the residual of the atmospheric carbon concentration increase and the model ocean carbon uptake. Furthermore, the latest IPCC assessment report also points out that the uncertainties in climate change may be a result of uncertainties in the carbon cycle (Collins *et al.*, 2006). Hence, quantifying the carbon dioxide flux between the atmosphere and the biosphere remains a major challenge to the climate research community.

The exchange of carbon dioxide between the terrestrial system and the atmosphere is controlled by complex spatial, temporal and plant physiological variations. The eddy covariance (EC) sending method is is widely used and regarded as the most accurate method to directly measure the carbon dioxide exchange between the atmosphere and the terrestrial system at time scales that resolve turbulence-driven variations. This EC method estimates the carbon dioxide flux through high frequency measurement of vertical wind velocity and carbon dioxide density (0.1 to 0.05 Hz). However, this method is not without problems and limitations. The EC method is most appropriate over large areas of horizontally homogeneous vegetation and flat terrain. Flux is only applicable to the area of interaction under turbulent conditions, known as the "flux footprint". The expensive instrumentation, long periods of measurement, and extensive maintenance

and calibration requirements of the EC measurement system tend to limit the widespread adoption of carbon dioxide flux measurement. Therefore, it is difficult to assess the regional scale carbon dioxide flux between the terrestrial system and the atmosphere over a complex region such as California using only the EC method.

Typically, this limitation is alleviated by considering wider perspectives. Projects and analyses that combine remotely-sensed data and modeling simulations along with ground-based observations are both mutually supportive and useful in terms of advancing atmospheric sciences (and the STEM set) at large. In order to fill in the gaps where EC measurements are not available or applicable, numerical models have been developed to simulate the effects of land surface on climate and atmosphere conditions and to calculate carbon dioxide fluxes. These models are referred to as Land Surface Models (LSMs) or Surface Vegetation Atmosphere Models (SVATs). However, carbon dioxide exchange is excluded from many of the LSMs widely available in the field, such as the mesoscale Weather Research and Forecasting (WRF) model. LSMs with carbon calculations in climate studies differ greatly in complexity and atmosphere-biosphere interaction. For example, low complexity "big leaf" models oversimplify plant physiological processes and atmosphere-biosphere interactions (Paw U, 1997). The lack of multiple vegetation layers in a big leaf model renders it unable to resolve turbulence and vertical gradients that drive CO_2 fluxes (Wohlfahrt *et al.*, 2001; Baldocchi and Meyers, 1998). Thus, they tend to overestimate CO_2 uptake by plants as suggested by Paw U (1997). The development and usage of high complexity models that include representations of different vegetation covers, multiple canopy layers and interactive physiological processes are crucial in estimating carbon sequestration and and energy balances, all of which are important components of the climate system (Potter *et al.*, 1993; Sagan and Khare, 1979; Anthes, 1984; Bougeault, 1991; Mihailovic *et al.*, 1993). Furthermore, the importance of the terrestrial carbon sink is not limited to its amount of carbon uptake. Spatial and temporal distributions of the carbon sources and sinks have increasingly been the topic of discussion. Examples of this discussion include numerous studies from the AmeriFlux network using eddy covariance methods, which have shown that terrestrial carbon sinks vary in time, location, and weather conditions (Baldocchi *et al.*, 2001; Falge *et al.*, 2002; Law, 2007). Thus, estimating the distribution of carbon is crucial in understanding the mechanisms and sustainability of the current terrestrial carbon sink.

In this study, the atmosphere-biosphere carbon dioxide exchange over the complex region of California is investigated using the mesoscale Weather and Research Forecasting model (WRF) coupled with the high complexity land surface model Advanced Canopy-Atmosphere- Soil Algorithm (ACASA), which is developed in UC Davis. In addition to simulating the carbon fluxes between the two systems, the WRF-ACASA coupled model also changes the atmospheric carbon dioxide concentration according to terrestrial carbon production/sequestration and atmospheric carbon transport via spatial advection. Therefore the coupled model is capable of tracking the atmospheric carbon dioxide concentration to identify combined impact of spatial and temporal variations of carbon sources and sinks of regional scale, along with their feedbacks. With all the tools in place, the objectives of this study are to (1) quantify the biosphere-atmosphere exchange of carbon dioxide on a regional scale and (2) investigate the effect of atmospheric interactions

between the adjacent ecosystems on the plant physiological processes at local and regional scales.

2. MODELS, METHODOLOGY AND DATA

2.1 Model Description

The WRF model is a state-of-the-art mesoscale weather model developed for both operational forecasting and atmospheric research. The model physics and dynamic features include an Eulerian solver for the fully compressible non-hydrostatic equations with mass vertical coordinates, third-order Runge-Kutta time-integration, and fully conservative flux divergence integration. The high spatial and temporal resolution is ideal for studying the complex region of California. However, because its default land surface models are relatively simplistic and none of them simulate carbon dioxide, the microscale land surface model ACASA is introduced as a submodel of WRF.

ACASA represents the interaction between vegetation, soil, and the atmosphere based on physical and biological processes described at the leaf or field scale (microscale). It is a complex multilayer analytical land surface model that simulates both the microenvironment profiles and turbulent exchanges of energy, mass and momentum within the surface-layer. The surface layer is represented as multiple vertical layers within and immediately above the canopy into the lowest planetary boundary layer, the "surface sub-layer" or "constant flux layer". The model also incorporates the higher third order turbulent closure scheme based on Meyers and Paw U (1986) and Meyers and Paw U (1987) to allow turbulent kinetic and thermodynamic processes to transport energy, mass, and carbon fluxes in both down-gradient and counter-gradient directions, which many lower-order models are unable to directly simulate. Surface processes such as moisture, heat, momentum, and carbon dioxide fluxes are calculated for each of the interactive layers and integrated to represent the canopy level. In addition to the turbulent processes, the fourth-order technique from Paw U and Gao (1988) is used in the model to calculate the non-linear energy budget and surface energy temperature.

Carbon dioxide flux within the model is calculated from a combination of the Ball-Berry stomatal conductance (Leuning, 1990; Collatz *et al.*, 1991) and the Farquhar *et al.* (1982) photosynthesis equation:

$$g_{s,w} = m\frac{A_n}{c_s}rh_s + b \tag{1}$$

$$rh_s = \frac{g_b q_A + g_{s,w} q_s(T_L)}{g_b + g_{s,w} q_s(T_L)} \tag{2}$$

$$c_s = c_A - \frac{A_n}{g_b} \tag{3}$$

$$A_n = V_c - 0.5V_0 - R_d = min(A_R, A_E) - R_d \tag{4}$$

$$V_c - 0.5V_0 = min(W_c, W_j)(1 - \frac{\Gamma}{C_i}) \quad (5)$$

where $g_{s,w}$ is the leaf stomatal conductance to water vapor, A_n is the net CO_2 uptake rate at the leaf surface, c_s and rh_s are the CO_2 concentration and the fractional relative humidity at the leaf surface, m and b are empirical regression coefficients; c_A is the CO_2 concentration in air, $q_s(T_L)$ is saturated mixing ratio of water vapor at leaf temperature T_L, g_b is the leaf boundary layer conductance, q_A is the mixing ratio of water vapor tin the air, V_c, V_0 and R_d are the carboxylation, oxygenation (photorespiration) and dark respiration rates of CO_2 exchange between the leaf and the atmosphere (in $\mu mol\, m^{-2}\, s^{-1}$), A_R is the Rubisco activity limit of CO_2 assimilation rate at lower intercellular CO_2 concentration when ribulose bisphosphate (RuBP) is saturated, A_E is the CO_2 assimilation rate when the whole chain electron transport limits RuBP regeneration; W_c and W_j are the rates of carboxylation when RuBP is, respectively, saturated and limited by election transport (in $\mu mol\, m^{-2}\, s^{-1}$), Γ is the CO_2 compensation point in the absence of dark respiration and C_i is the intercellular CO_2 concentration ((in $\mu mol\, m^{-3}$).

Because carbon fixation and respiration vary significantly across vegetation types, the ACASA model requires meteorological inputs and additional species-specific physiological parameters (e.g. leaf area index; maximum rates of carboxylation; biochemical photosynthetic coefficients). As long as these physiological parameters can be provided or estimated, this requirement allows ACASA to couple with WRF and calculate carbon flux to and from any vegetation cover. More details on the stand-alone ACASA model can be found in Pyles (2000) and Pyles *et al.* (2000). The ACASA model has been successfully applied to the Wind River Canopy Crane site, an AmeriFlux site near Skamania, Washington, with a full set of eddy-covariance measurements that includes CO_2 flux (see Paw U *et al.*, 2004, for a site description). The ACASA model has been also applied and tested in a spruce forest site in Germany (Staudt *et al.*, 2010) and a Mediterranean maquis ecosystem in Italy (Marras *et al.*, 2011). All three studies have shown that the ACASA model agrees well with surface observations of energy, moisture, and carbon dioxide fluxes.

2.2 Carbon Dioxide Tracer

In addition to examining the atmosphere-biosphere carbon dioxide exchange, the WRF-ACASA model is also used to investigate the interaction of carbon dioxide between neighboring regions in California. Because physiological processes vary across different land cover types and growing seasons, the carbon uptake or emissions of one land cover should impact other regions. However, these interactions are difficult to determine since traditional in-situ carbon studies are limited to small areas with homogeneous land cover types. A carbon dioxide tracer is introduced to the WRF model. The new CO_2 tracer transports carbon dioxide (simulated through the surface plant physiological process) in the atmosphere, and modifies the atmospheric CO_2 concentration. Consequently, variations in CO_2 concentration driven by ecosystem exchanges in one region can induce interactions down-wind and between neighboring regions and biomes.

The carbon dioxide tracer uses the same physics as those used for moisture in the MRF boundary layer model, but without chemical reactions and phase changes (Hong and Pan, 1996). This moisture transport scheme has been well used and tested within the WRF model. The model is initialized with a background atmospheric carbon dioxide concentration of 385 ppm. It is then changed through biosphere-atmosphere exchange of carbon dioxide from plant physiological processes in time and space. Like other atmospheric variables WRF represents, the atmospheric CO_2 concentration is calculated using a terrain-following hydrostatic pressure vertical coordinate. These vertical sigma coordinates are normalized hydrostatic pressure levels derived between surface pressure and a constant upper atmosphere pressure (Laprise, 1992; Klemp *et al.*, 2003).

2.3 Data

The WRF-ACASA coupled model simulation produced carbon dioxide concentration and exchange estimates for all of California's geographic regions with various complex ecosystems and climate variations. Many characteristic ecosystems in California (chaparral, agricultural crops, Central Valley grassland, woodland, conifer forest, and steppe) are included. The extensive topographic and vegetation variability in California provides a great opportunity to study the interactions of neighboring land cover types and their effects on carbon flux. The climate in the region is mostly Mediterranean—summer is warm and dry, while winter is cool and moist.

There are six Ameriflux Network Eddy Covariance stations in California that are available to evaluate the WRF-ACASA coupled model over the simulation period of 2005 and 2006 (see Fig. 1). Due to the model's horizontal resolution, the Vaira Ranch and the Tonzi Ranch stations share the same model grid cell; however, the surface characteristics differ considerably. he model also assumes that each grid cell is horizontally homogeneous, and so the Vaira Ranch vegetation growing season of Oct-May is not accurately represented. The three Sky Oak sites are all located in a single grid cell over Southern California. Consequently, carbon dioxide flux simulations from the WRF-ACASA model are compared to the carbon flux measurements from these sites over different vegetation covers.

Comparing model simulations and surface observations is challenging due to the differences in heights and land covers between the observational stations and model grid points. As a result of this land-type registration issue, the Plant Functional Types (PFTs) used in the WRF-ACASA simulations can sometimes match poorly with the observed PFT at the sites (Table 1). Previous chapters show that the land cover type is an important component of the surface representation in land surface models, especially high complexity land surface models such as ACASA. Therefore, the mismatch of PFT in the WRF-ACASA coupled model is an initial condition error that negatively impacts the plant physiological simulations. When the PFTs in the WRF-ACASA coupled model agree with the observed PFT, the simulated carbon dioxide exchange improved, as will be shown in this paper. Within the framework of numerical modeling experience, though desired, this type of result is not assured in advance.

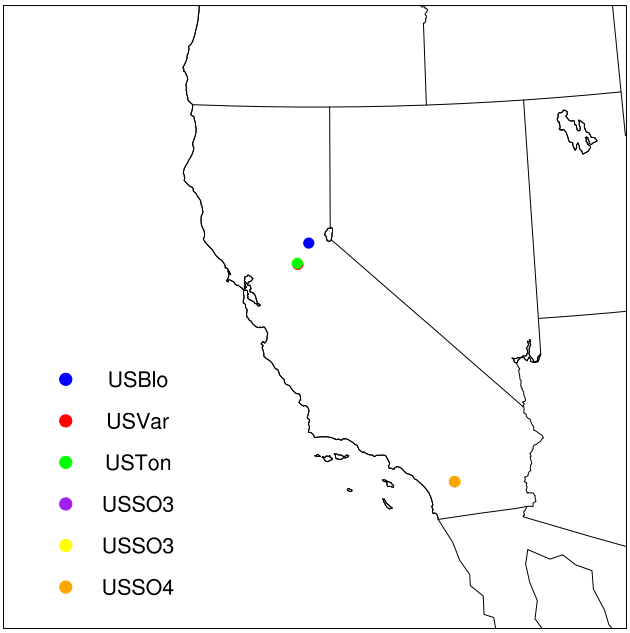

Figure 1. Locations of the six AmeriFlux sites used in this study. In Northern California, Blodgett Forest site is northeast of the Tonsi and Vaira sites (shown as one point). The three Sky Oak sites are closely located within the same WRF grid cell, therefore only one site is visible on the map.

2.4 Model Setup

Two WRF-ACASA simulations are compared: (1) WRF-ACASA with constant atmosphere carbon dioxide concentration at 385 ppm, and (2) WRF-ACASA with CO_2 transport in the atmosphere using the new CO_2 tracer. Simulations are forced by the Moderate Resolution Imaging Spectroradiometer (MODIS) LAI dataset and the Northern America Regional Reanalysis (NARR) dataset for surface and meteorological conditions to drive the initialization and boundary conditions of the WRF models (Mesinger *et al.*, 2006). Year 2005 and 2006 are simulated over California at an 8 km x 8 km horizontal resolution. Each run contains 13 months of simulations with the first month being discarded as spin-up. For example, year 2006 is simulated from December 2005 through December 2006. Atmospheric physics schemes used in this study are the Purdue Lin et al. scheme for microphysics (Chen and Sun, 2002), the Rapid Radiative Transfer Model for long wave radiation (Mlawer *et al.*, 1997), the Dudhia scheme for shortwave radiation (Dudhia, 1989), the Monin-Obukhov Similarity scheme for surface layer physics of non-vegetated surfaces and the ocean (Monin and Obukhov, 1954), and the MRF scheme for the planetary boundary layer (Hong and Pan, 1996). Results presented here are mostly from year 2006 because of the large amount of missing observational data in 2005.

3. RESULTS AND DISCUSSION

The diurnal patterns of carbon dioxide flux simulated by the WRF-ACASA model with or without varying atmospheric CO_2 concentration are shown in Fig. 2 and 3. Both WRF-ACASA simulations have good agreements with the surface observations when plant functional types (PFT) match between the surface observation and model. Observed diurnal patterns are created

Table 1. Information on AmeriFlux Stations are compared between the observation sites and the model assumptions.

Station	Site Name	WRF PFT	WRF-ACASA Canopy height (meter)	Observed height (meter)	Observed PFT
USBLO	Blodgett Forest	Evergreen Needleleaf Forest	17	12.5	Evergreen Needleleaf Forest
USVAR	Vaira Ranch	Savanna	10	1	Grassland
USTON	Tonzi Ranch	Savanna	10	23	Woody Savannas
USSO2	Sky Oak Old	Evergreen Needleleaf Forest	17	4.2	Woody Savannas
USSO3	Sky Oak Young	Evergreen Needleleaf Forest	17	1	Closed Shrublands
USSO4	Sky Oak New	Evergreen Needleleaf Forest	17	1.5	Closed Shrublands

only from days with complete 24-hour data. As pointed out in previous chapters, accurate surface representation is important for a land surface model, especially with the high complexity models such as WRF-ACASA. Both simulations perform well over the Blodgett Forest and the Tonzi Ranch, where PFTs match between observation and model. The simulated diurnal patterns of CO_2 flux over the Blodgett Forest and Tonzi Ranch sites are well within the one standard deviation of the surface measurements. This shows that the complex plant physiological processes in the WRF-ACASA model are robust and able to simulate the CO_2 fluxes correctly across the region. Although the WRF-ACASA model overestimates the CO_2 exchange at the three Sky Oak sites and Vaira Ranch, these flux problems are due to the input biases of PFT mismatch and lack of heterogeneous surface representation. Improvement of these surface representations will improve the WRF-ACASA simulations.

The scatter plots of hourly CO_2 flux (FCO2) are shown in Fig. 4 for the WRF-ACASA simulations without and with CO_2 tracer over the AmeriFlux sites for 2006. Both WRF-ACASA simulations compared well with the surface observations, except for the Vaira Ranch during warm months of summer and autumn, when the site vegetation is dormant due to summer drought. There are no significant differences between the two simulations from the scatter plots. The statistical analysis, however, shows that the WRF-ACASA simulation with CO_2 tracer reduces the Root Mean Square Error (RMSE) values for almost all stations and all seasons (Table 2).

Figures 2, 3 and 4, along with Table 2, illustrate a positive impact of varying atmospheric CO_2 concentration on plant physiological processes. This positive impact mainly occurs during the daytime when plants are most active. Photosynthesis by plants reduces the ambient CO_2 concentrations, and new CO_2 is transported to the site through the atmosphere. When less CO_2 is available in the atmosphere, photosynthetic uptake of carbon by plants is reduced. As a result, when no tracer is used and the ambient CO_2 concentration is held constant at 385 ppm, we can reduce the overestimation of photosynthesis and RMSE values (Table 2). For example, the diurnal CO_2 flux for the Blodgett forest improves during the spring, summer, autumn of 2005 and spring and

autumn of 2006 with a CO_2 tracer (Fig. 2 and Fig. 3).

The time series of net ecosystem CO_2 exchange (NEE) for each of the AmeriFlux sites during the years 2005 and 2006 display the overall ecosystem physiological activities (Fig. 5 and Fig. 6). NEE is the cumulative net primary production of carbon minus respiration, and it is calculated as the cumulative sum of carbon flux throughout the year. When NEE at the site is positive at the end of the year, the site is a carbon source, i.e. more carbon is released into the atmosphere than is absorbed; a negative annual NEE indicates an annual carbon sink.

As expected for the Blodgett Forest in 2006, the usage of a CO_2 tracer generally reduces the overestimation and improves the simulation of annual NEE. For example, the WRF-ACASA model with CO_2 tracer simulation of NEE (-930 $gC\,m^{-2}\,yr^{-1}$) closely followed the observed NEE

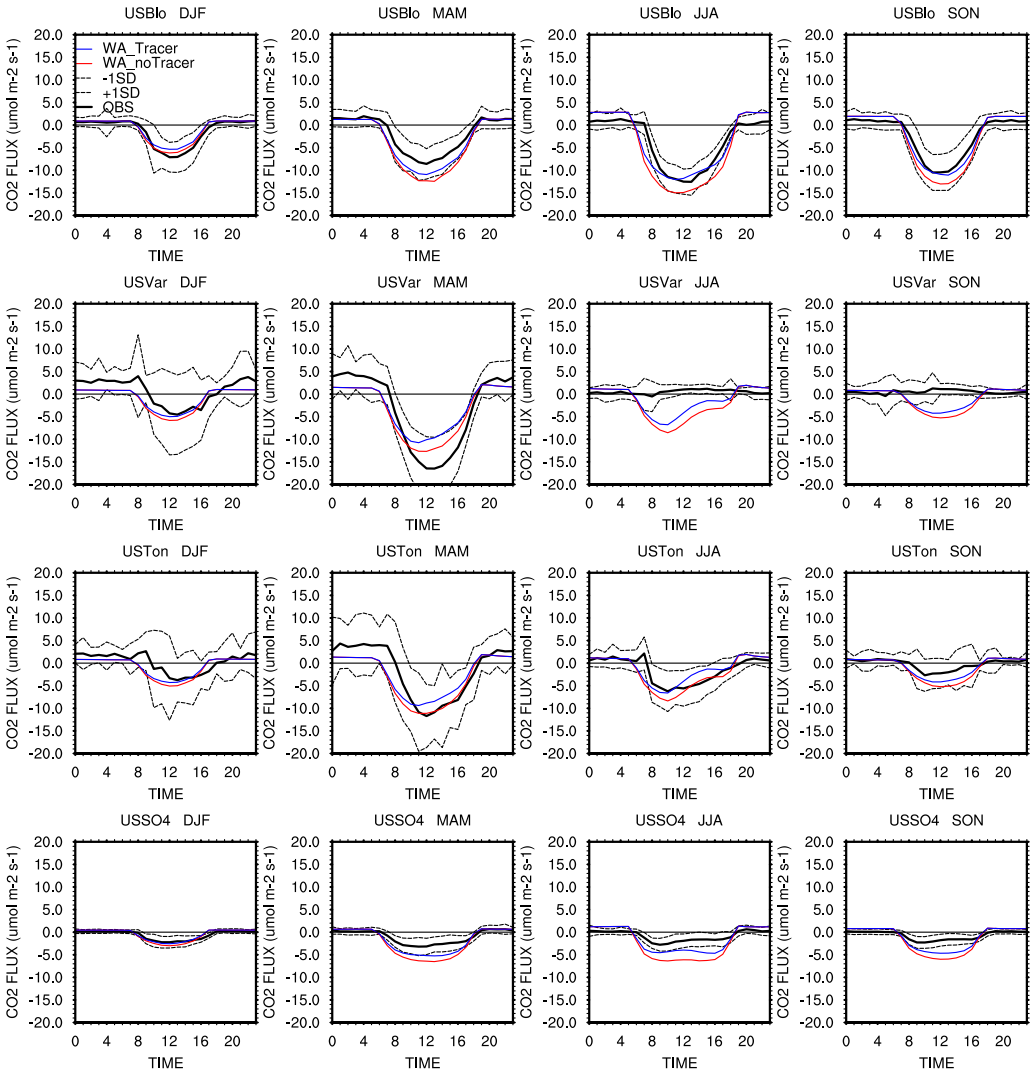

Figure 2. Diurnal patterns of carbon dioxide flux for the AmeriFlux sites for year 2005 by seasons. The solid black line is observation, with the dash lines representing 1 standard deviation. Blue line is WRF-ACASA with CO_2 tracer module, and the red line is WRF-ACASA without CO_2 tracer. Winter is December, January, February (DJF). Spring is March, April, May (MAM). Summer is June, July, August (JJA). And fall is September, October, November (SON).

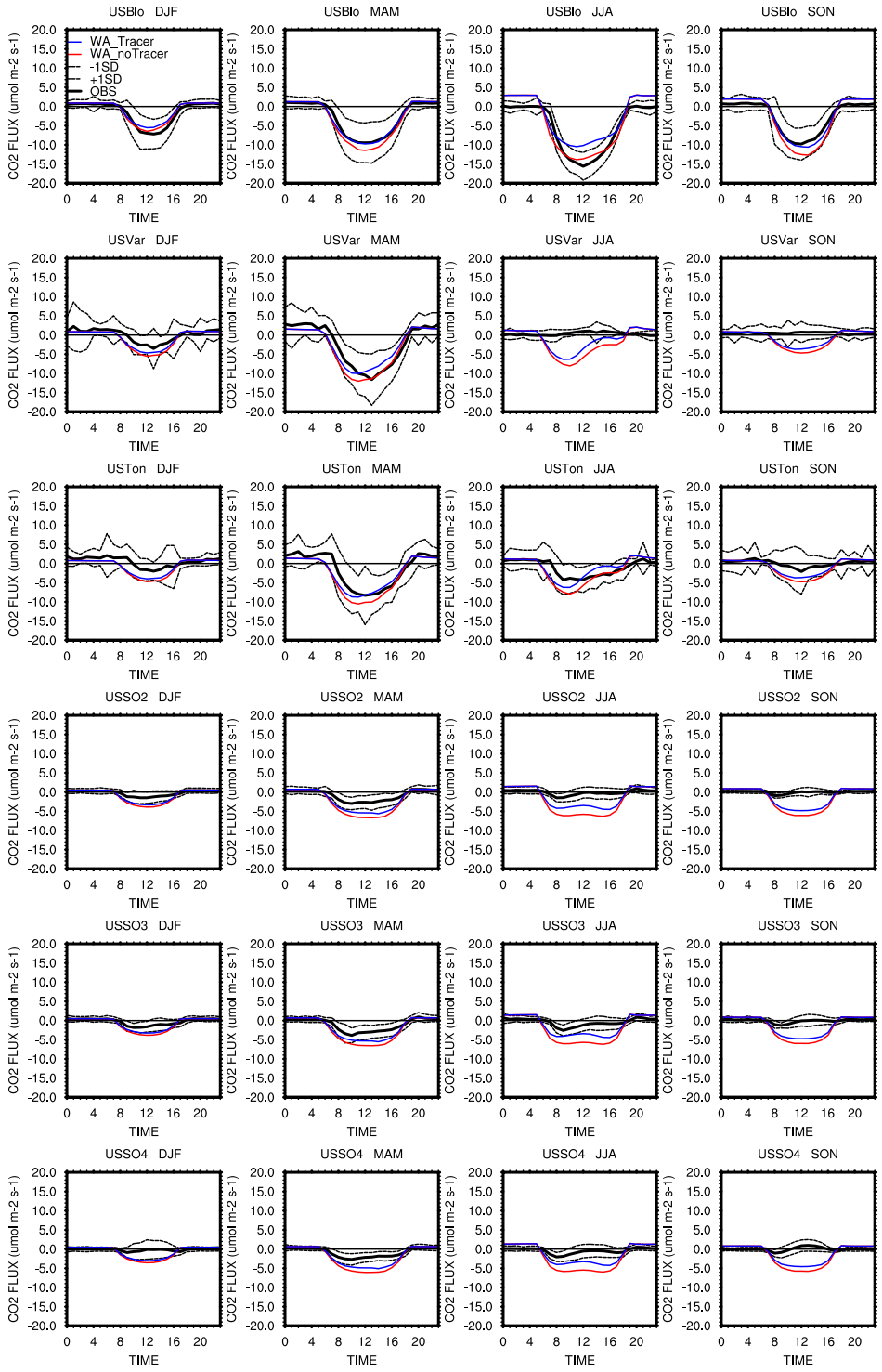

Figure 3. Diurnal patterns of carbon dioxide flux for the AmeriFlux sites for year 2006 by seasons. The solid black line is observation, with the dash lines representing 1 standard deviation. Blue line is WRF-ACASA with CO_2 tracer module, and the red line is WRF-ACASA without CO_2 tracer. Winter is DJF. Spring is MAM. Summer is JJA. And fall is SON.

(-908 gC m^{-2} yr^{-1}) for the Blodgett forest throughout year 2005 (Fig. 5, Fig. 6 and Table 3). And the CO_2 tracer simulated NEE for Tonzi Ranch site was -529gC m-2 yr-1 , comparing well with

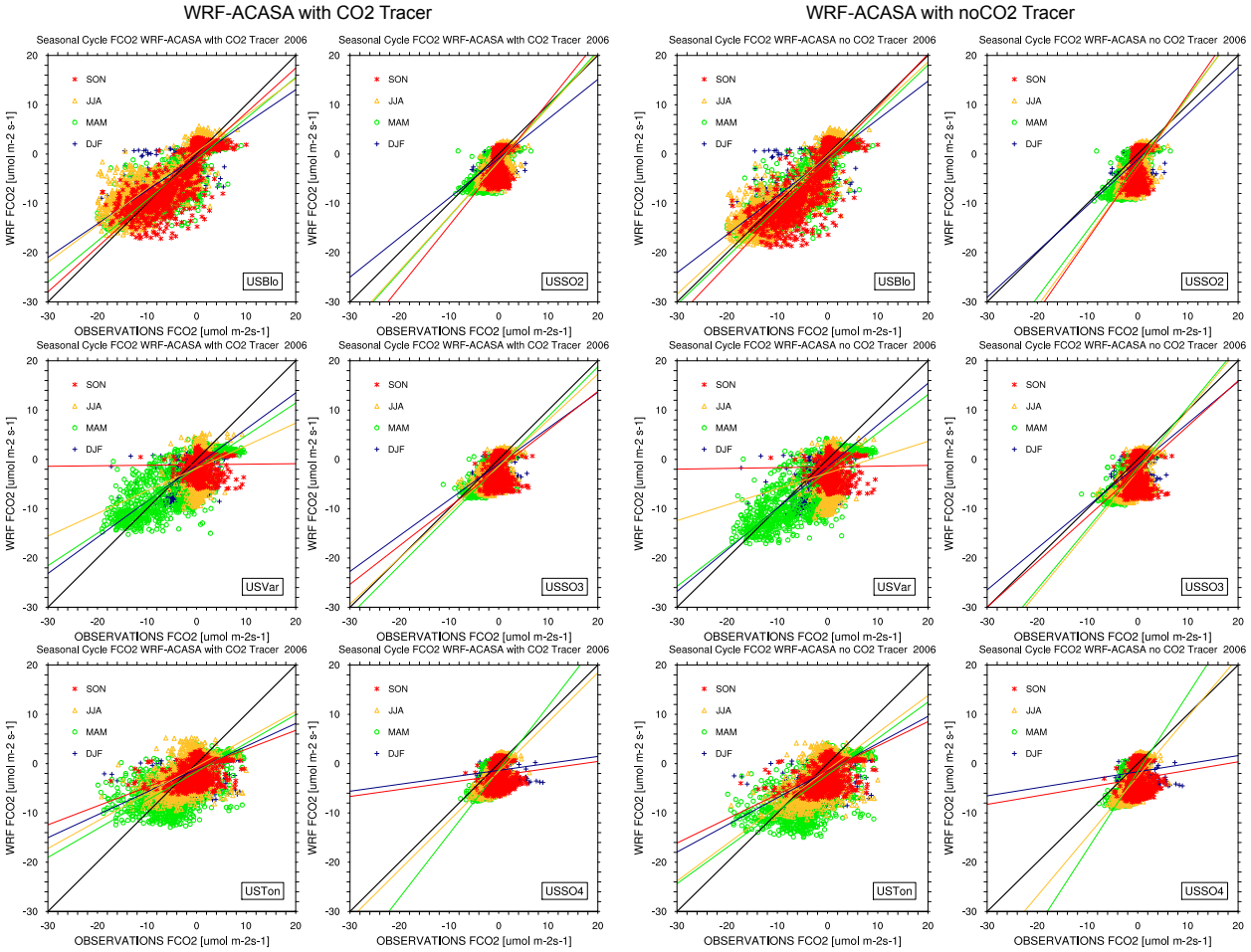

Figure 4. Scatter plots of CO_2 flux (FCO2) by season for both WRF-ACASA with CO2 tracer and WRF-ACASA without CO2 tracer. Each dot represent one daily value, and each line represent the regression of the season. Winter is in blue (DJF), Spring is green (MAM). Summer is orange (JJA). And fall is red (SON).

the observed annual NEE 0f -505 $gC\,m^{-2}\,yr^{-1}$.

There is, however, a large interannual variability between 2005 and 2006. Carbon sinks were larger for most sites in 2005, except the Blodgett Forest. The WRF-ACASA with CO_2 tracer underestimated the annual NEE magnitude in 2006 for the Blodgett Forest mainly due to the underestimation of photosynthesis during the summer months as indicated in Fig. 2 and Fig. 3. Meanwhile, the model overestimated the carbon uptake for the Tonzi Ranch during the autumn season for 2006. The carbon sinks for Vaira Ranch, Tonzi Ranch and the three Sky Oaks sites are also smaller in 2006 than 2005. Although the WRF-ACASA model overestimated the NEE for the Sky Oak sites due to the initial mismatch of PFT, improvement in PFT will improve the WRF-ACASA model by using more appropriate parameters such as maximum carboxylation velocity for physiological processes.

The spatial distributions of NEE for the four seasons using the WRF-ACASA model with and without CO_2 tracer are shown in Fig. 7. The inclusion of CO_2 tracer in the model reduced the

Table 2. Statistical Analysis for WRF-ACASA with no CO_2 tracer and with CO_2 tracer.

	DJF		MAM		JJA		SON	
Station	**RMSE**	**R^2**	**RMSE**	**R^2**	**RMSE**	**R^2**	**RMSE**	**R^2**
WRF-ACASA no CO_2 Tracer								
USBlo	2.79	0.89	3.44	0.95	3.58	0.99	3.66	0.96
USVar	3.00	0.76	4.51	0.82	5.14	0.16	3.84	0.06
USTon	3.61	0.37	4.98	0.69	3.67	0.62	3.35	0.30
USSO2	1.93	0.79	3.25	0.77	4.04	0.72	4.11	0.71
USSO3	1.89	0.76	3.01	0.80	3.71	0.76	3.89	0.71
USSO4	2.78	0.26	3.21	0.75	3.84	0.73	4.52	0.28
WRF-ACASA with CO_2 Trace								
USBlo	2.67	0.80	3.08	0.94	4.32	0.82	3.16	0.97
USVar	2.71	0.68	4.28	0.71	3.99	0.23	3.30	0.05
USTon	3.26	0.31	4.83	0.48	3.45	0.35	3.02	0.19
USSO2	1.65	0.77	2.54	0.82	2.75	0.81	3.29	0.74
USSO3	1.63	0.72	2.35	0.84	2.51	0.83	3.14	0.69
USSO4	2.49	0.24	2.42	0.80	2.54	0.79	3.70	0.25

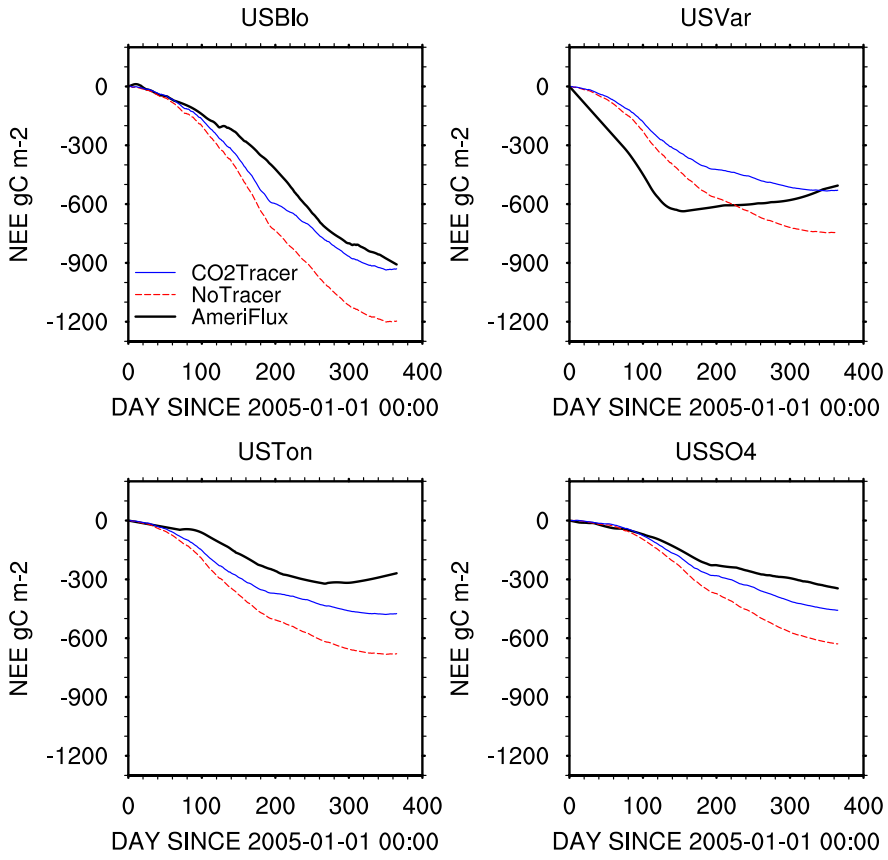

Figure 5. Time series of annual NEE for model simulations and surface observations for year 2005. The black line is observation, the red line is WRF-ACASA result without CO_2 tracer, and the blue line is WRF-ACASA result with CO_2 tracer.

seasonal NEE in several regions in California. The differences between the two simulations are small during the winter and autumn seasons, which are similar to the results shown in Figure 2;

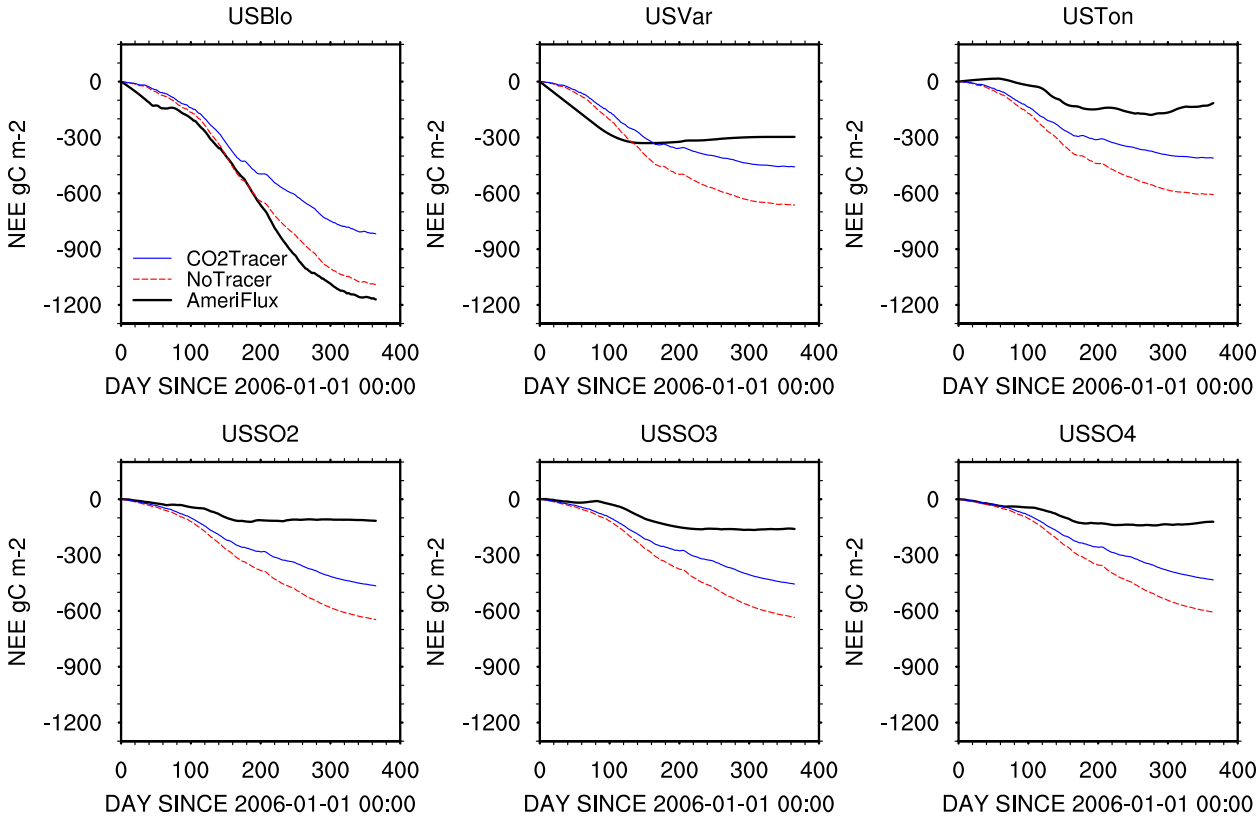

Figure 6. Time series of annual NEE for model simulations and surface observations for year 2006. The black line is observation, the red line is WRF-ACASA result without CO_2 tracer, and the blue line is WRF-ACASA result with CO_2 tracer.

not surprisingly since the NEE magnitudes are smaller, and therefore the effects of advected CO_2 are reduced. During spring and summer, when plants are more active, the seasonal carbon sink or negative NEE values over the Sierra Nevada mountain region is smaller when CO_2 tracer is used. Furthermore, the Central Valley changed from a carbon sink when no CO_2 tracer is used to a carbon source with CO_2 tracer during the summer months. This is due to the reduction in photosynthesis in response to the lower ambient CO_2 concentration when carbon (or in this case, depleted carbon concentrations) is transported in the atmosphere. This switch of carbon sink to carbon source demonstrates the importance of a fully coupled biosphere-atmosphere interaction. Feedbacks between the two systems through exchange and transport of carbon reflect a more realistic representation of the natural processes of interaction between ecosystems and the atmosphere, and with advection of carbon dioxide concentrations, between the atmosphere and ecosystems downwind.

Overall, the annual NEE for 2006 show that plants in the Northern California regions actively uptake more carbon dioxide from the atmosphere than carbon emissions through respiration, creating net carbon sinks (Fig. 8). The Southern California regions, which include the Mojave Desert and other low-vegetation regions, are carbon sources, where more carbon is released into the atmosphere than is absorbed. The coupled CO_2 tracer reduced the annual NEE over the northern California and the Sierra Nevada mountain regions. The regions with large carbon sources as

Table 3. Annual NEE ($gC\,m^{-2}\,yr^{-1}$) of the six AmeriFlux sites for years 2005 and 2006. Due to large amount of missing data in 2005, no data is displayed for Sky Oak sites: USSO2 and USSO3.

Year	Site	OBS	WRF-ACASA without CO_2 tracer	WRF-ACASA with CO_2 tracer
2005	USBlo	-908	-1197	-930
	USVar	-506	-744	-529
	USTon	-269	-679	-475
	USS02	No Data	-670	-491
	USS03	No Data	-658	-481
	USS04	-346	-629	-458
2006	USBlo	-1171	-1091	-818
	USVar	-297	-664	-458
	USTon	-116	-608	-411
	USS02	-116	-647	-465
	USS03	-160	-635	-456
	USS04	-121	-607	-433

indicated in red are generally urban areas where more carbon dioxide is released into the atmosphere than carbon uptake by vegetation. Default urban carbon emission from traffic is based on urban land use area. Future improvement on urban emission will link the model to observed urban population and traffic data. Even though, the WRF-ACASA model overestimated carbon uptakes for the AmeriFlux sites due to various reasons mentioned previously, the CO_2 concentration and transport in the atmosphere have an important role in modeling plant physiological processes.

Diurnal patterns of ambient CO_2 concentration are compared for each AmeriFlux site between observed values and the simulated values by the WRF-ACASA model, in which CO_2 tracer is used to transport carbon dioxide in the atmosphere (Fig. 9 and Fig. 10). They show that the CO_2 tracer in the WRF-ACASA model is able to mimic the natural evolution of atmospheric CO_2 concentration (ACO2) due to changes in surface plant physiological processes and atmospheric transport. Photosynthesis from the vegetation actively removes carbon dioxide from the atmosphere and thus lowers the ambient CO_2 concentration during the daytime, whereas respiration increases the ambient CO_2 concentration.

When PFTs match between site observations and model assumptions, the simulated concentrations over the Blodgett Forest and the Tonzi Ranch have good agreements with the surface observation. The reduction of ambient CO_2 concentration is more pronounced over sites with higher plant physiological activities such as the Blodgett Forest, the Vaira and Tonzi ranches. For both years, the Blodgett Forest reduced the ambient CO_2 concentration by an average of 6 to 7 ppm during the daytime. The lower ambient CO_2 concentration persisted into the evening, when respiration slowly increased the CO_2 concentration toward and excessed the initial 385 ppm. The time lags in the diurnal patterns of atmospheric CO_2 concentration compared to the diurnal patterns of CO_2 flux reflect the cumulative effect of daytime and nighttime carbon dioxide exchanges between the biosphere and atmosphere. Meanwhile, the atmospheric CO_2 concentration over the Sky Oaks sites exceeded the initial concentration during the winter season when plants released more CO_2 into the atmosphere than uptake by photosynthesis.

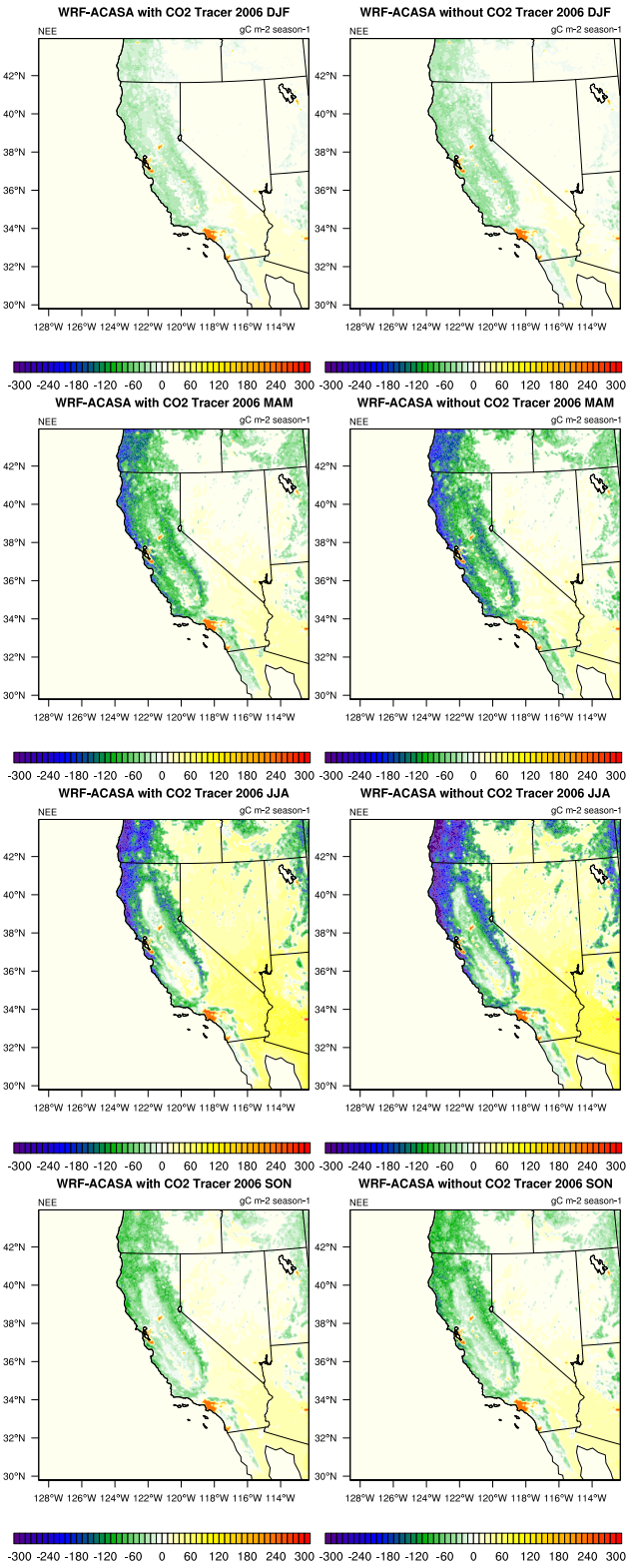

Figure 7. WRF-ACASA simulations of seasonal NEE with and without CO_2 Tracer for 2006. Winter is DJF. Spring is MAM. Summer is JJA. And fall is SON. Results for 2005 (not shown) is similar to 2006.

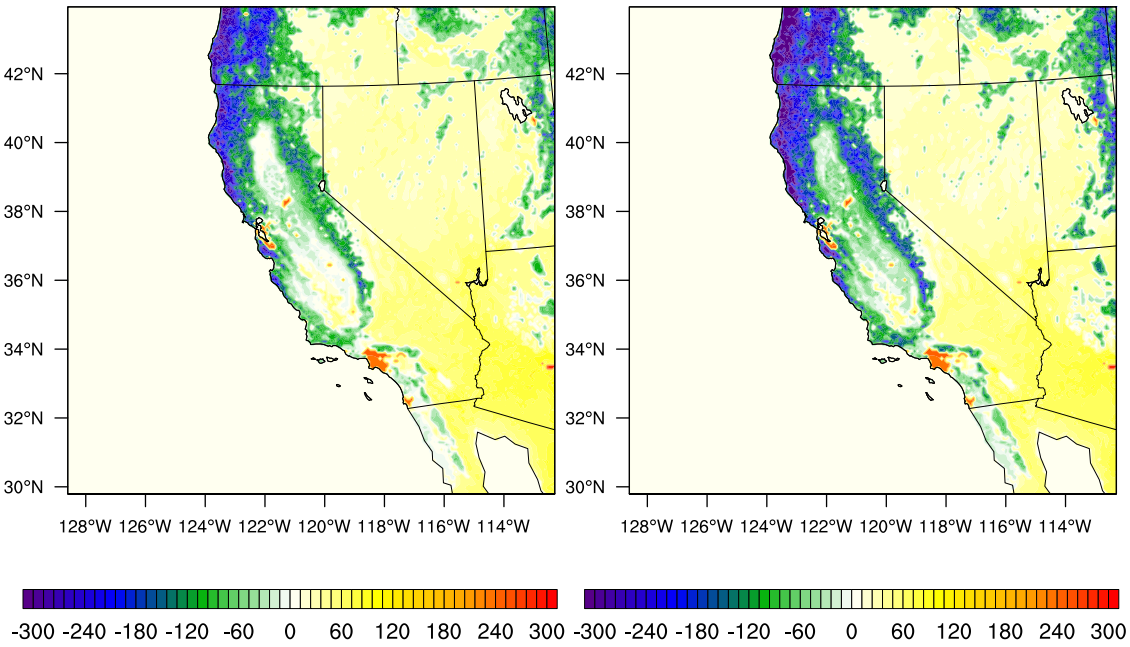

Figure 8. Annual NEE of carbon dioxide for year 2006 for WRF-ACASA simulations with CO_2 tracer (Left) and without CO_2 tracer (Right).

Over the Sky Oak sites where mismatch of PFT occurs, there are large differences between the simulated and observed diurnal pattern of ACO2. The poor performance over the Sky Oak sites could be the result of initial conditions at the sites, where the constant field of 385 ppm applied over the domain is much higher than the observed ACO2 (around 365 to 370 ppm). Despite the bias from initial conditions, the changes in time and magnitude from the simulated ACO2 match well with the observed ACO2 seasonal and diurnal patterns for both year 2005 and 2006. While there are no data to evaluate the model performance in atmospheric carbon dioxide concentration over the entire region, the evaluations from the AmeriFlux sites shows that the CO_2 tracer in the WRF-ACASA model is robust and physically sound.

The WRF-ACASA model with CO_2 tracer simulates the seasonal averages of ACO2 at different vertical levels. The spatial distribution of ACO2 anomalies from the initial field of 385 ppm is shown in Fig. 11 for the year 2006, because the CO_2 is transported both horizontally and vertically. Surface CO_2 concentration (sigma level 1) closely follows the plant physiological processes as shown in Fig. 7 and Fig. 8. The spatial distributions of ACO2 at higher vertical levels, however, show that the CO_2 concentration above the surface is also modified by transport of CO_2 through wind and diffusion. For example, during the summer of 2006 the large reduction of ACO2 at the surface (sigma level 1) from photosynthesis propagated into the upper levels (sigma levels 3, 7 and 10) and spread to the surrounding areas. At sigma level 13, the surface effect on ACO2 became negligible compared to the lower levels. As the vertical level increases, the effects on surface CO_2 flux decrease, and the CO_2 transport increases spatially to reach farther regions. Therefore, surface plant activities from one location would have an impact on the neighboring

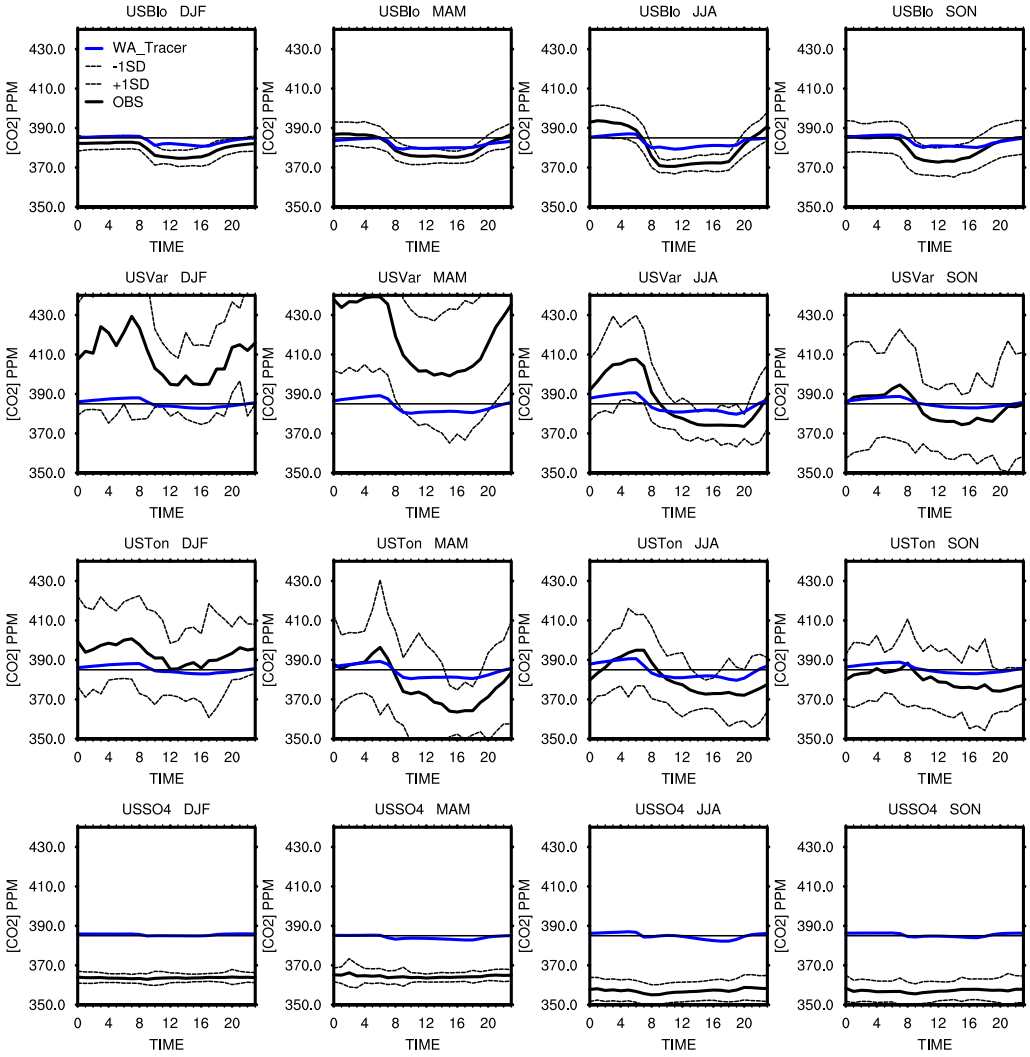

Figure 9. Seasonal diurnal patterns of atmosphere carbon dioxide concentration for the six AmeriFlux sites for year 2005. Black solid lines represent observation from AmeriFlux sites, and black dash lines represent one standard deviation below and above the diurnal means. Blue lines are WRF-ACASA simulations with CO_2 tracer. Winter is DJF. Spring is MAM. Summer is JJA. And fall is SON.

ecosystems as CO_2 concentration is transported in the atmosphere both spatially and temporally.

Furthermore, Fig. 12 shows the effect of plant physiological processes from one location on the neighboring ecosystems. The time series graphs of ACO2 show that the CO_2 tracer transports the enhanced atmospheric CO_2 concentration from Los Angeles due to morning traffic eastward to the neighboring ecosystems. This CO_2 enrichment therefore influences the plant physiological processes in nearby regions. Active photosynthesis in the Northern California, on the other hand, creates lower ACO2 air parcels that move southward to offset the urban carbon emission from San Francisco Bay and Sacramento regions.

The illustration of the vertical and horizontal transport of ACO2 is also displayed in the vertical cross-section of a ACO2 transect that stretches from the central coast across the Central Valley and to the Sierra Nevada Mountains (Fig. 13). The impact of surface plant physiological

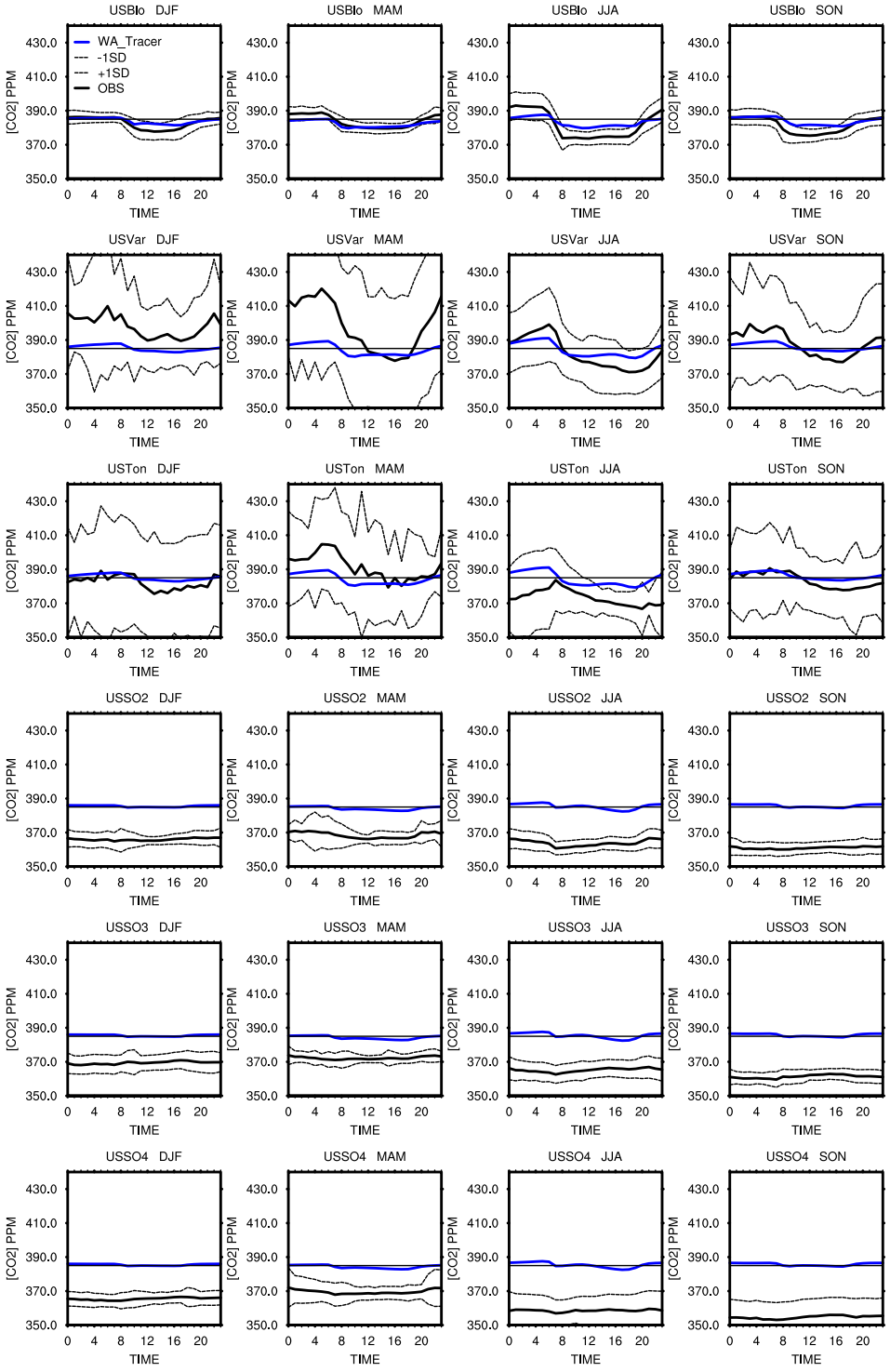

Figure 10. Seasonal diurnal patterns of atmosphere carbon dioxide concentration for the six AmeriFlux sites for year 2006. Black solid lines represent observation from AmeriFlux sites, and black dash lines represent one standard deviation below and above the diurnal means. Blue lines are WRF-ACASA simulations with CO_2 tracer.

processes that change the atmospheric CO_2 concentration propagates high into the atmosphere and spreads throughout the region. During the nighttime, respiration increases the ACO2 near the

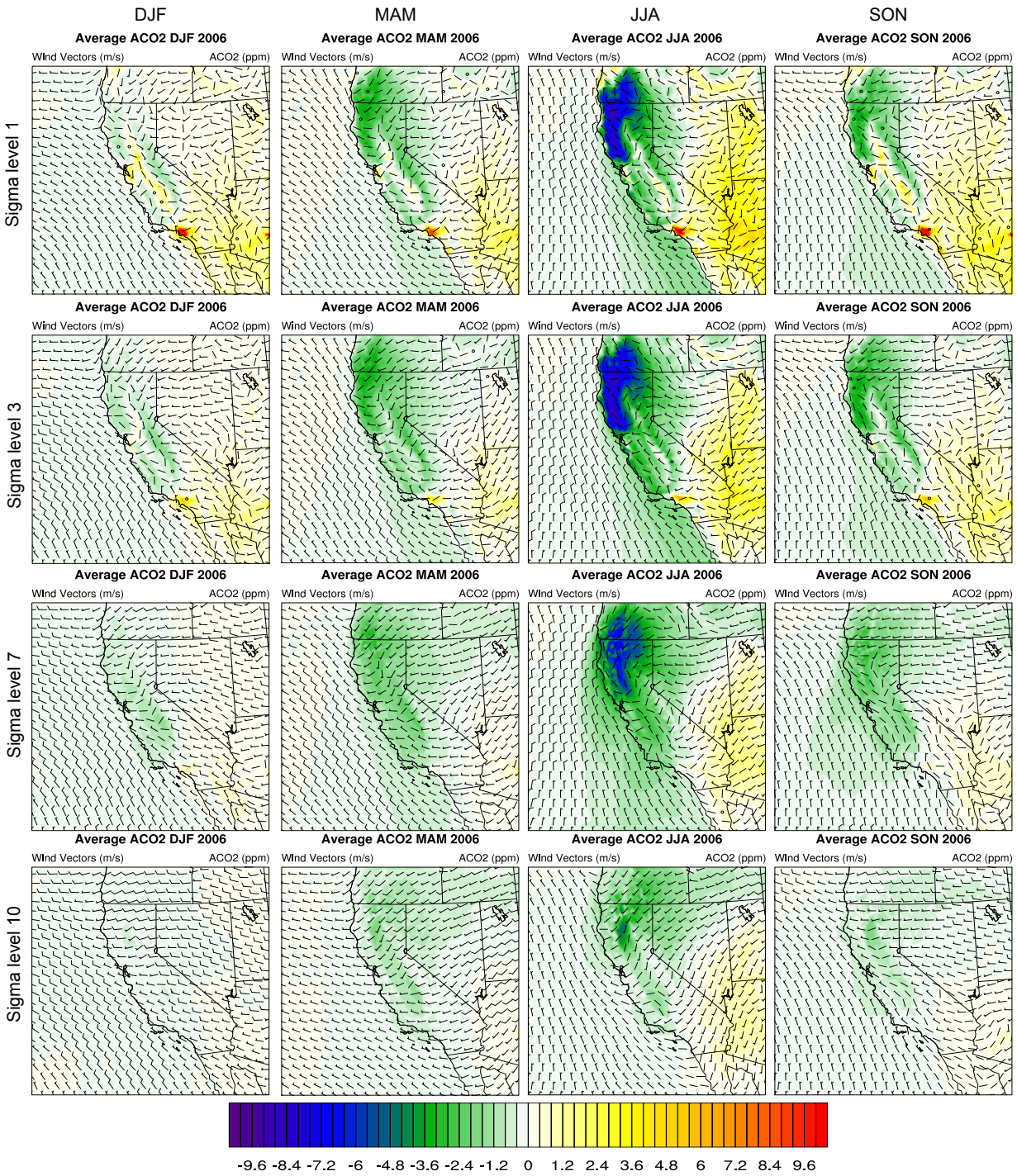

Figure 11. Map of atmospheric CO_2 concentrations and wind patterns using the CO_2 tracer by seasons and sigma levels for year 2006.

surface and increases ACO2 over the Central Valley. The marine layer wind patterns carry these higher atmospheric CO_2 concentrations eastward toward the foothills and up the Sierra Nevada Mountains. Photosynthesis during the daytime reduces the surface ACO2. Stable atmospheric conditions allow the lower ACO2 parcels to extend upward as shown during midday of Fig. 13.

Land and sea breezes transport plumes of higher or lower CO_2 concentration air parcels across the region and influence the local ecosystems. Figure 13 demonstrates the interactions of neighboring ecosystems through atmospheric CO_2 transport at a regional scale. Plant physiological processes from one location would have an impact on the neighboring ecosystems.

4. SUMMARY AND CONCLUSION

In this study, a coupled WRF-ACASA model was used with a new CO_2 tracer routine to simulate CO_2 exchange between the atmosphere and the biosphere as well as the effect of CO_2 transport on surface plant physiology. Two simulations of CO_2 fluxes and ACO2 using the WRF-ACASA model with and without CO_2 tracers were performed over California for the years 2005 and 2006. The ACASA surface scheme calculated physiological processes of photosynthesis and respiration at the local surface level and carbon fluxes were fed back into the WRF atmosphere layers above. The CO_2 tracer modified the atmospheric CO_2 concentration according to the surface carbon fluxes and transported carbon dioxide both spatially and temporally through wind and diffusion. This two-way feedback between the biosphere and atmosphere reflected a more realistic representation of the natural system. Communications through carbon dioxide exchange between the various ecosystems allow us to examine the interactions across different geographical regions and identify the possible sources and sinks of carbon. Seasonal and annual distribution of carbon sinks and sources were determined.

When the model PFTs match the observed PFTs, carbon dioxide fluxes from the WRF-ACASA simulations agree well with the surface observations. For example, the simulated diurnal patterns of CO_2 flux for the Blodgett Forest match well with the surface observations. Although the WRF-ACASA model overestimates the three Sky Oak sites and Vaira Ranch, the biases are due to initial PFT mismatch and lack of homogeneous land cover type in the grid cell rather than the model physics. As pointed out in the previous chapters, surface representation is crucial to the

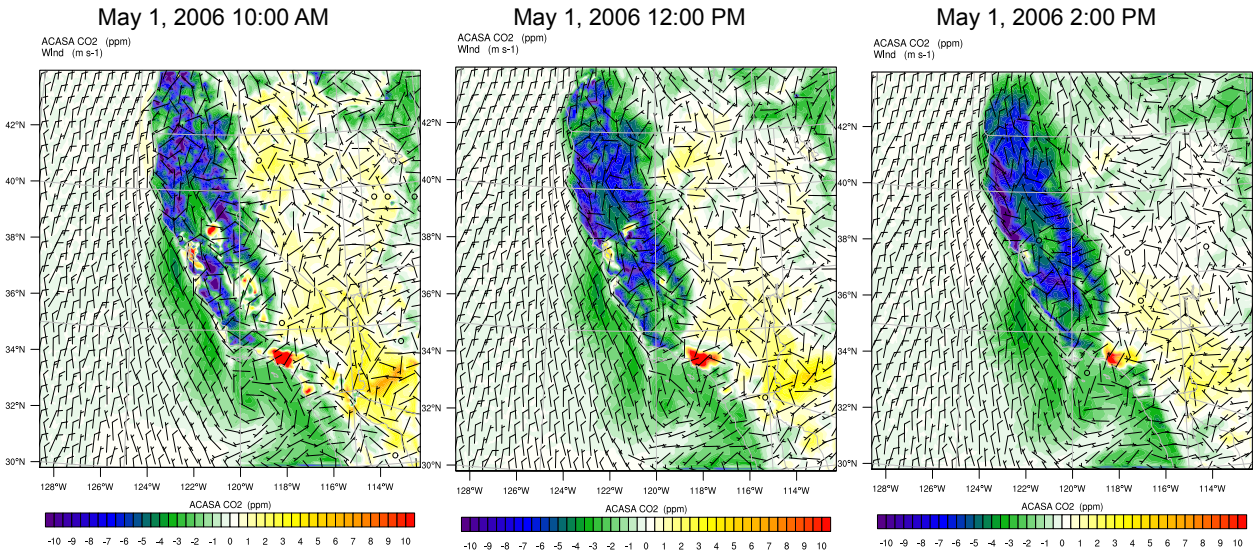

Figure 12. Atmospheric CO2 concentration of May 1 2006 for 10 AM, 12 PM, and 2 PM.

high complexity WRF-ACASA model. Improvement of PFT as well as inclusion of more than one vegetation type in each of the grid cell will improve the WRF-ACASA model performance for CO_2 flux.

There is a positive impact on simulating plant physiological processes from varying atmospheric CO_2 concentrations. The inclusion of the CO_2 tracer in the WRF-ACASA model reduces the overestimate of photosynthesis for most of the AmeriFlux sites. Active CO_2 uptake by plants reduces the ambient CO_2 concentration and thus lowers available CO_2 for plant physiological ac-

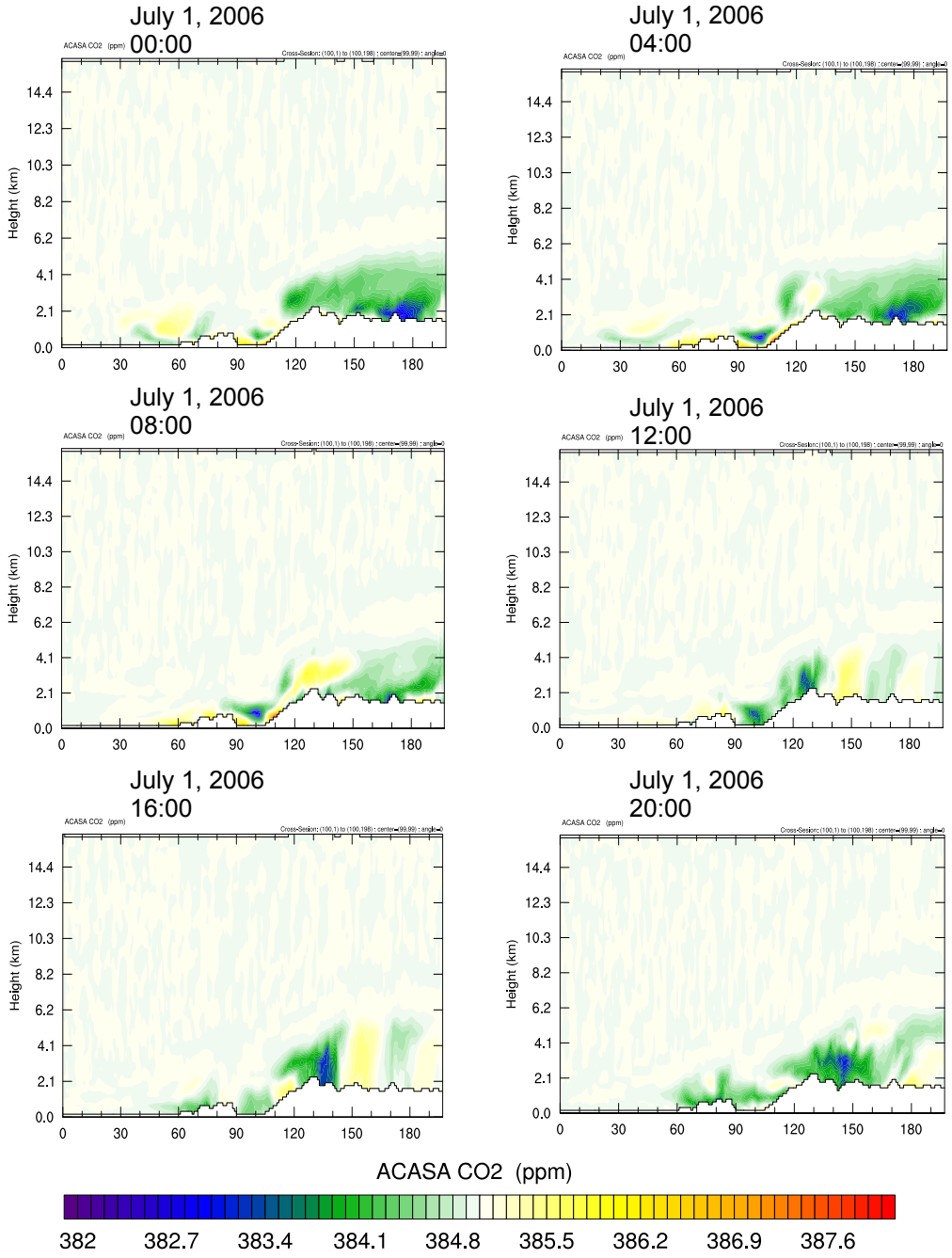

Figure 13. Vertical Cross-section of atmospheric CO_2 concentration.

tivities during the daytime. The CO_2 tracer therefore helps reduce the RMSE values for hourly CO_2 fluxes as well as improve the annual NEE. In addition, the effect of CO_2 transport in the atmosphere is not limited to the local areas as CO_2 is transported both horizontally and vertically throughout the region. Atmospheric transport of CO_2 concentration allows surface activities from one region to influence the neighboring ecosystems.

Overall, this study shows that the WRF-ACASA model is robust and able to simulate the CO_2 fluxes well across the region if given correct surface representations. The comparison between the two model simulations with and without the CO_2 tracer shows that the impact of atmospheric CO_2 transport is important and it should not be neglected when simulating CO_2 flux at a regional scale. The interactions between atmosphere and biosphere as well as between neighboring ecosystems influence the plant physiological processes at both local and regional levels.

It must be noted that the atmospheric CO_2 concentration in this study is initialized with a constant field of 385 ppm, and it changes through time and space from surface processes. This initial condition, however, might not reflect the actual atmospheric concentrations since there are no available observations. Therefore, spatially distributed measurements of atmospheric CO_2 concentration could be a valuable input for the WRF-ACASA model in the future.

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