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Sensitivity of modeled NEP to climate forcing and soil at site and regional scales: Implications for upscaling ecosystem models

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Sensitivity of modeled NEP to climate forcing and soil at site and regional scales: Implications for upscaling ecosystem models

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Highlights

- Uncertainty in modeled NEP attributed to gridded vs. site model drivers was assessed.
- NEP differences attributed to gridded vs. site inputs varied among EC sites.
- Gridded radiation, precipitation and the absence of SON affected modeled NEP.
- Shallower gridded vertical soil profiles affected modeled NEP during drought events.
- Uncertainty in gridded weather and soil would certainly affect regional carbon budget.

Abstract

The quality of gridded weather and soil datasets is one of the main sources of uncertainty in modeling regional scale land-atmosphere carbon exchange. This uncertainty may be assessed by comparing net ecosystem productivity (NEP) modeled for selected grid cells with these datasets against NEP modeled at representative sites within that grid cell for which detailed site scale measurements of weather and soil are available. In this study, a comprehensive mathematical ecosystem model, *ecosys*, was used to simulate differences in NEP at six eddy covariance (EC) flux tower sites across North America caused by using inputs for weather and soil extracted from 0.25° × 0.25° gridded datasets for the grid cells within which the towers were located vs. those measured at each tower site during years with contrasting weather (cool vs. warm and wet vs. dry). NEP differences attributed to gridded vs. measured model inputs varied among sites when tested against EC-derived values. At some sites (e.g. coastal coniferous site in British Columbia), adverse impacts of summer warming on NEP under contrasting weather in 2001 (cooler) vs. 2004 (warmer) were accurately modeled with both inputs, giving R^2 with EC NEP values >0.80. At other sites, reduced accuracy in NEP modeled with gridded vs. measured inputs was attributed to shallower soil depth in the gridded soil database. This shallower depth caused site NEP in a boreal deciduous stand in Saskatchewan not to be well simulated in 2001 and 2003, the first and third years of a major drought in central North America, due to early soil drying. At yet other sites, reduced accuracy was attributed to overestimates of soil organic nitrogen (SON) calculated from general soil organic carbon (SOC):SON relationships used in the absence of SON values in the gridded soil database. These overestimates caused excessive productivity to be modeled with gridded inputs at a boreal black spruce site in Quebec with unusually large SOC:SON. Gridded weather and soil inputs that caused such differences in NEP would certainly affect regional and global carbon budget model estimates, and so need to be improved in future large scale model input datasets.

- **Previous** article
- **Next** article

Keywords

Ecosys

Ecosystem modeling

Upscaling

Model drivers

Carbon flux

NARR

1. Introduction

Measurements of land-atmosphere carbon exchange are of vital importance in understanding the global carbon cycle (Baldocchi, 2003, Kalfas et al., 2011). Direct measurements of carbon fluxes can only be done at a site scale, for instance from eddy covariance (EC) flux towers with footprints 200 m–2 km (Houborg and Soegaard, 2004, Sasai et al., 2007). However, terrestrial biosphere models (TBMs) can be used to estimate carbon fluxes at regional and global scales (Rastetter et al., 2003, Sasai et al., 2007). Processes-based TBMs make use of biophysical and climatic relationships and processes to estimate ecosystem productivity (Beer et al., 2010, Korzukhin et al., 1996) conferring predictive capabilities that enable simulation of future impacts of ecological controls on ecosystem productivity from changes in external forcing (Huntzinger et al., 2012). Performance of these models in estimating carbon fluxes is partly determined by the accuracy, and the spatial and temporal resolution of model inputs.

Model inputs such as climate and soil exert strong controls on modeled ecosystem productivity (Pan et al., 2006) and several studies have shown their impacts on modeled carbon exchange between the terrestrial environment and the atmosphere (Delpierre et al., 2012, Jung et al., 2007a, Jung et al., 2007b, Pan et al., 2006). If these controls are to be examined at regional to continental scales, inputs in the form of gridded climate and soil datasets are needed, although these may be less accurate than site measurements (Zhao et al., 2012). One of the challenges in using these coarser resolution gridded datasets for regional model estimates is to capture the spatial heterogeneity within a pixel (Aertsen et al., 2012) needed to upscale site level processes. Ecosystems are spatially heterogeneous and temporally dynamic (Miller et al., 2004, van Nes and Scheffer, 2005) and upscaling site level ecosystem processes to a regional level should take the non-linearity of landscape level biophysical processes into account (Aertsen et al., 2012, Seidl et al., 2012). The spatial patterns of these variations can be complex and this can certainly influence the biophysical processes and hence the land-atmosphere carbon exchange (Anderson et al., 2003). Sub-pixel heterogeneity (e.g. climate, plant functional type, soil and topography variations within a pixel) increases at coarser spatial resolutions, although it may vary with model inputs. For instance, spatial variability in weather may be more homogeneous at grid scale compared to soil with more variability particularly where topography varies.

Existing North American climate and soil datasets vary in spatial and temporal resolutions and the geographic extent they cover. For instance, North American climate datasets such as Daymet (Thornton et al., 2012) and Parameter-elevation Regressions on Independent Slopes Model (PRISM) (Daly et al., 2012) have spatial resolution of 1 km. Daymet has a daily time-step whereas PRISM has a monthly time-step and both datasets only cover lower and mid latitudes of North America. The European reanalysis (ERA-1) from European Centre for Medium-Range Weather Forecasts had global spatial coverage with temporal resolution of 6-hour and spatial resolution of 0.75° × 0.75° (Berrisford et al., 2009). However, the North American Regional Reanalysis (NARR) has long-term, higher temporal resolution (3-hour) and covers the entire North America (Mesinger et al., 2004), thus providing an opportunity to model diurnal carbon exchange as affected by short-term weather events over wide ranges of climates across the continent.

Although increasing efforts are being made to improve the accuracy, spatial and temporal resolutions of these large scale datasets, the extent to which these model inputs affect regional scale carbon estimates remains uncertain. Some studies have reported deviations in carbon flux estimates associated with coarse resolution model inputs: Zhao et al. (2012) indicated biases in carbon flux estimates caused by gridded weather inputs (mainly by downward shortwave radiation) on a daily time scale. Another study (Anisimov et al., 2007) reported deviations in carbon fluxes attributed to variations in air temperature in four regional weather datasets when compared to local meteorology. Zhang et al. (2014) reported the impact of differences in spatial resolution of soil datasets (coarser [State Soil Geography-STATSGO] vs. finer [Soil Survey Geographic-SSURGO]) on model estimates of net ecosystem productivity (NEP) and had found a relatively higher loss in accuracy of modeled NEP attributed to STATSGO. Although such attempts to address the impacts of coarse resolution model inputs on NEP have been made, the combined effects of gridded soil and weather vs. measured inputs on modeled carbon exchange have not been presented. Furthermore, the extent to which model estimates of carbon exchange could be affected by these gridded model inputs should be rigorously tested. Although, direct tests of modeled NEP at grid scale are not available, site level measurements (e.g. at representative EC tower sites) could be compared to modeled NEP for the corresponding pixels where the EC towers located.

Therefore, in this study we used a comprehensive mathematical model, *ecosys*(Grant, 2001, Grant, 2014, Grant et al., 2012), to examine differences in diurnal and seasonal NEP modeled with weather and soil inputs from gridded datasets vs. those from site measurements by comparing these fluxes with those from EC measurements across different biomes. Attributes of gridded weather and soil datasets that need to be considered for future improvements were identified when gridded inputs adversely affected the accuracy of the modeled fluxes. *Ecosys* was used as the effects of weather and soil on biochemical and physical processes that control carbon fluxes in the model have been widely and rigorously tested under site level changes in weather (Grant, 2014) and soil management (Grant et al., 2001b, Grant et al., 2007a). Moreover, weather effects on seasonal and interannual variability of ecosystem productivity have also been tested in several studies using the model across different biomes: a boreal forest in a continental climate in Quebec (Wang et al., 2013), a coastal temperate forest in a maritime climate in British Columbia (Wang et al., 2011); dry grassland in a Mediterranean climate in California (Grant et al., 2012); a semi-arid grassland in a continental climate in Lethbridge, Alberta (Li et al., 2004); black spruce forests in wetlands in Saskatchewan and Manitoba (Grant et al., 2008), further summarized testing across a transcontinental transect of forest stands in the Fluxnet-Canada Research Network (Grant et al., 2009a).

2. Methods

Ecosys was run at six EC sites (Table 1) with different climates and plant functional types (cool temperate douglas-fir forest, boreal aspen forest, boreal black spruce forest, Arctic tundra, warm temperate loblolly pine forest and crop land) using weather and soil inputs from site measurements vs. inputs from gridded datasets (NARR and Unified North America Soil Map (UNASM), Liu et al., 2013) during years with contrasting weather at each site (cooler vs. warmer, wetter vs. drier). For the crop site the effect of the gridded weather input on CO_2 exchange with respect to inputs from site measurements was tested by evaluating differences in CO_2 exchange simulated during a dry year (2003) under rainfed vs. irrigated conditions. Land use/land cover dynamics, atmospheric CO_2 concentration, nitrogen deposition and disturbance were also used as model inputs for all simulations (Table 2). Biome types were the same for each site and gridded runs and model parameterization, and spin-up were kept constant for all simulations to ensure the same simulation design and model initial conditions.

Table 1. Eddy Covariance flux tower sites and years with contrasting weather used for site and gridded runs.

Site name	Ecosystem	Climate	Latitude +N/−S	Longitude +E/−W	Site climate data	Years	Contrast
CA-Ca1	Douglas-fir forest	Cool temperate with dry, warm summer	49.87	−125.33	1999–2008	2001/2004	Cool/warm
DL	Arctic tundra	Low arctic	64.87	−111.57	2004–2009	2006/2008	Warm/cool
CA-Soa	Old Aspen	Boreal	53.63	−106.20	1994–2008	2001/2003	Pre-drought vs. drought
US-Dk3	Loblolly pine forest	Subtropical	35.98	−79.10	1999–2005	2001/2002	Pre-drought vs. drought
CA-Qfo	Boreal black spruce forests	Boreal	49.69	−74.34	2004–2008	2004/2005	Cool/warm
Mead	Maize soybean rotation	Warm temperate with humid hot summer	41.18	−96.44	2001–2006	2003	Irrigated vs. rainfed

Table 2. Model inputs used in the gridded and site simulations.

Model inputs	Simulation	Temporal period	Temporal resolution	Data source
Climate	*s*	Vary with EC sites	Half-hourly	Ameriflux sites[a]
	r	1979–2010	3-Hourly	NARR[b]
Soil	*s*	One-time	One-time	Ameriflux sites
	r	One-time	One-time	UNASM[c](SSURGO (US) + SLC v3.2 (CA) + HWSD v1.21 (MX))
CO_2	*s*, *r*	1800–2010	Monthly	Enhanced GlobalView[b]
Nitrogen deposition	*s*, *r*	1800–2010	Yearly	Enhanced Dentener[b]
Land use change	*s*, *r*	1800–2010	Yearly	Hurtt's harmonized with SYNMAP[b]

* All gridded model inputs had 0.25° × 0.25° spatial resolutions.

s = simulation using measured inputs, *r* = simulation using gridded inputs.

a

http://fluxnet.ornl.gov/site_list/Network/1.

b

MsTMIP model drivers (Wei et al., 2014).

c

Unified North America Soil Map (Liu et al., 2013).

2.1. Model description

A detailed description of inputs, parameters and algorithms used in *ecosys* can be found in (Grant, 2001, Grant, 2014) and (Grant et al., 2012). However, the general descriptions of the model that are most relevant to testing the effects of temperature and water status on modeled NEP = (gross primary productivity(GPP) − autotrophic respiration (R_a) − heterotrophic respiration (R_h)) by which gridded vs. site climate and soil inputs will be compared are given below and illustrated in Fig. 1 and details of the equations used are given in Appendices A–C of the Supplement.

2.1.1. Effects of canopy water status on GPP

In *ecosys*, surface energy and water exchanges drive soil heat and water transfers, from which soil temperatures (T_s) and water contents (θ) are determined (Grant, 2004). NEP is controlled by plant water status calculated from concurrent convergence solutions for canopy temperature (T_c) from first-order closure of the canopy energy balance, and for canopy water potential (ψ_c) from equilibrating total root water uptake (U) with transpiration (T) (Grant et al., 1999). This equilibration is accomplished by finding a common ψ_c at which T driven by T_c and constrained by canopy resistance (r_c) calculated from ψ_c equals U driven by the differences between ψ_c and soil water potential (ψ_s) across soil Ω_s and root Ω_r hydraulic resistances in each rooted soil layer (Grant et al., 2007c). The rates of T and U are affected by T_c and θ that are mainly controlled by weather inputs for surface air temperature (T_a), precipitation, radiation, humidity and wind speed, and by soil hydraulic conductivity and water holding capacity (WHC) determined by soil inputs for depth, bulk density(BD), texture, saturated hydraulic conductivity (K_{sat}), field capacity (FC) and wilting point (WP) for each soil layer. CO_2 diffusion is controlled by leaf resistance (r_l) which is calculated from a minimum value ($r_{l\min}$) for each leaf surface that allows a set ratio for intercellular to canopy gaseous CO_2concentration C_i:C_b to be maintained at CO_2 fixation rate (V_c) under ambient CO_2 concentration (C_a), irradiance, T_c, leaf nutrient content and zero ψ_c (Grant et al., 2007a).

2.1.2. Effects of canopy temperature on GPP

Carboxylation is directly affected by T_c through the Arrhenius functions for light and dark reactions (Grant et al., 2007a). At leaf level, CO_2 diffusion is controlled by r_l when calculating CO_2 fixation from concurrent solutions for diffusion V_g and carboxylation V_c. The rate of CO_2 fixation is controlled by coupled schemes for gaseous diffusion and biochemical fixation as affected by plant water and nutrient status and modeled through concurrent solutions for stomatal effects (Section 2.1.1) on diffusion V_g and for non-stomatal effects $f_\psi$on CO_2 and light-limited carboxylation V_b (Grant et al., 2007a, Grant and Flanagan, 2007b).

2.1.3. Effects of nutrient status on GPP

NEP is also strongly controlled by plant N status from plant N uptake driven by net N mineralization driven in turn by decomposition of soil organic carbon(SOC) and soil organic nitrogen (SON) initialized from soil inputs (Grant, 2014). Decomposition rates of different organic matter substrates are combined functions of active biomass in heterotrophic microbial populations (M_h) and substrate concentrations, and of T_s through an Arrhenius function. These rates determine net N mineralization which controls soil mineral N contents and hence uptake through coupled algorithms for radial convection, diffusion and active uptake by root and mycorrhizal surfaces. Higher T_s driven from meteorological inputs affects NEP by hastening soil N mineralization and N uptake, and hence NEP (Grant, 2014).

2.1.4. Effects of temperature on R_a and R_h

Temperature-dependent oxidation of nonstructural pools (R_c), plus the energy costs of nutrient uptake, drive R_a by all branches, roots and mycorrhizae. The R_c by roots and mycorrhizae is constrained by O_2 uptake UO2 (Grant, 2004), and is thus affected by soil porosity. After R_c is first used to meet the $T_c$dependent maintenance respiration (R_m), the remaining is used for growth respiration (R_g) (Grant et al., 2011b). Oxidation of dissolved organic carbon(DOC) drives heterotrophic respiration (R_m + R_g) through the Arrhenius function of T_s. The R_m is driven by DOC oxidation through Q_{10} function of T_s and $R_h$remaining from R_m drives R_g (Grant, 2014). Arrhenius function used in ecosys (Eq. (A6) of the Supplement), and typical Q_{10} values used have been illustrated in Fig. 1 of Grant (2014). Soil warming hastens decomposition and mineralization (Grant, 2014).

2.2. Measured and gridded weather and soil

2.2.1. Measured weather and soil inputs

The measured weather inputs for air temperature, precipitation, downward shortwave radiation, relative humidity and wind speed were recorded at the EC flux tower sites at a half-hour time-step and averaged to hourly values in *ecosys*. Measured soil inputs for layer depth, clay/sand fraction, pH, total organic carbon and nitrogen, cation exchange capacity and bulk density were recorded from soil samples taken at specified depths at the flux tower sites (Table 2).

2.2.2. Gridded weather and soil inputs

The gridded weather inputs for air temperature, precipitation, downward shortwave radiation, relative humidity and wind speed were taken from NARR, a long-term weather dataset originally produced at the National Oceanic and Land Administration (NOAA) National Centers for Environmental Prediction (NCEP) Global Reanalysis (Kalnay et al., 1996). NARR is an extension of the NCEP reanalysis, which is a combined data and model assimilation product that made use of wide networks of observational datasets across North America (Mesinger et al., 2004). For this study, we used a NARR dataset which was resampled and re-projected to 0.25° resolution in geographic latitude/longitude projection made available through the Multi-Scale Synthesis and Terrestrial Model Inter-comparison Project (MsTMIP) (Huntzinger et al., 2013). NARR precipitation was rescaled using the Global Precipitation Climatology Project (GPCP) monthly gridded precipitation product which was derived from satellite and gauge measurements, to improve biases in magnitude and frequency of large rainfall events

(Wei et al., 2014). The NARR incoming shortwave radiation was rescaled using the weather simulation model MTCLIM version 4.3 (Wei et al., 2014). The NARR data used for this study was from 1979 to 2010 and temporal resolution of three hours, with linear interpolation to one hour in *ecosys*.

The gridded soil (UNASM) inputs with layer depths, clay/sand fraction, pH, total organic carbon, cation exchange capacity and bulk density were a reanalysis product of MsTMIP for North America that was prepared using three different soil databases (Liu et al., 2013). These included the United States General Soil Map, the State Soil Geographic (STATSGO2), the Soil Landscapes of Canada (SLC) versions 3.2 (agricultural) and 2.2 (non-agricultural) and the Harmonized World Soil Database (HWSD) version 1.21. However SON was not provided in the UNASM, and was therefore estimated for use in *ecosys* from gridded SOC in each soil layer and from a relationship between SOC and SOC:SON ratios fitted to the site measurements.

2.3. Simulation design

In the gridded simulations, weather and soil inputs were taken from NARR and UNASM for the grid cells corresponding to the locations of the EC flux towers. Model runs for each site were spun up with time-varying weather drivers for a simulation period of 1800–2010. To represent historical weather at each site, NARR data selected from 1979 to 1993 were randomly distributed to form a 100 years sequence that cycled through 1801–1978. This enabled the model to attain a steady state condition prior to 1979. Then the real time NARR data were used for the rest of the study period (1979–2010) to simulate the real time ecosystem productivity as stated in MsTMIP protocol (Huntzinger et al., 2013). The soil inputs were used to initialize the soil profiles at each site, whereas land use and land cover changes, atmospheric CO_2 concentrations, and nitrogen deposition rates varied during the runs as shown in Table 2. The model runs and inputs used for the simulations with measured inputs were the same as those with gridded inputs, except that they had measured soil attributes and measured weather substituted for the years which site level data were available (Table 1). We avoided sub-pixel heterogeneity for the runs using gridded inputs by taking the dominant land cover and plant functional type from the corresponding pixels where the EC towers were located. Four different simulations were conducted to investigate differences in NEP modeled with measured vs. gridded weather and soil (Table 3). *Simulation-s*had measured inputs for both weather and soil to model NEP under the same conditions as those of the EC measurements. *Simulation-r* had gridded inputs from NARR and UNASM to model grid cell NEP for the EC flux tower area as part of gridded simulations. Differences in NEP between *simulation-s* and EC measurements were considered to be caused by uncertainties in model parameterization and measured fluxes. Differences in NEP between *simulation-r* and EC measurements that were greater than those from *simulation-s* were considered to be a reduction in model accuracy caused by substituting gridded weather and soil inputs for those measured at the site. To attribute this reduction to weather vs. soil inputs, *simulation-n* was run with weather inputs from the NARR dataset and soil inputs measured at the sites, and *simulation-p*was run with weather inputs from the site measurements and soil inputs from UNASM. Therefore, the sensitivity of modeled NEP to weather inputs from NARR vs. measurements was evaluated by comparing NEP from *simulation-s*and *simulation-n*, and the sensitivity of modeled NEP to soil inputs from UNASM vs. measurements was evaluated by comparing NEP from *simulation-p* and *simulation-s*. These evaluations were conducted using Taylor diagrams (Taylor, 2001) of modeled vs. measured CO_2 fluxes that graphically illustrated the closeness in diurnal and seasonal patterns of the different sets of simulated NEP values to the measured benchmark NEP.

Table 3. Simulation design to partition NEP sensitivity to gridded weather and soil inputs.

Simulation name	Climate forcing	Soil	Simulation period	Output
Simulation-s	*s*	*s*	1800–2010	Site estimate
Simulation-r	*r*	*r*	1800–2010	Gridded estimate
Simulation-n	*r*	*s*	1800–2010	Model sensitivity to gridded weather
Simulation-p	*s*	*r*	1800–2010	Model sensitivity to gridded soil

s = simulation using measured inputs, *r* = simulation using gridded inputs.

3. Results

3.1. Comparison of gridded vs. measured weather and soil

The agreement of grid cell weather with measured values varied among the weather attributes for each EC site. NARR 3-hour T_a was highly correlated ($R^2 > 0.87$) with measured values at all EC sites (Fig. 2) although it was slightly higher at CA-Qfo, US-Dk3 and DL where the y-intercept of the regression of NARR on measured values exceeded 1 °C (Fig. 2). NARR and measured incoming shortwave radiation were also correlated very well ($R^2 > 0.78$ in Fig. 3for all sites except at US-Dk3 in 2001). However NARR 3-hourly shortwave radiation was slightly lower for most of the sites and years as the slope of the regression of NARR on measured values was less than 1 for all sites (Fig. 3). Total annual radiation in NARR was less than measured values particularly at

DL where the NARR values were 16 and 18% lower in 2006 and 2008 respectively and at US-Dk3 in 2001 where they were 10% lower (Table 4).

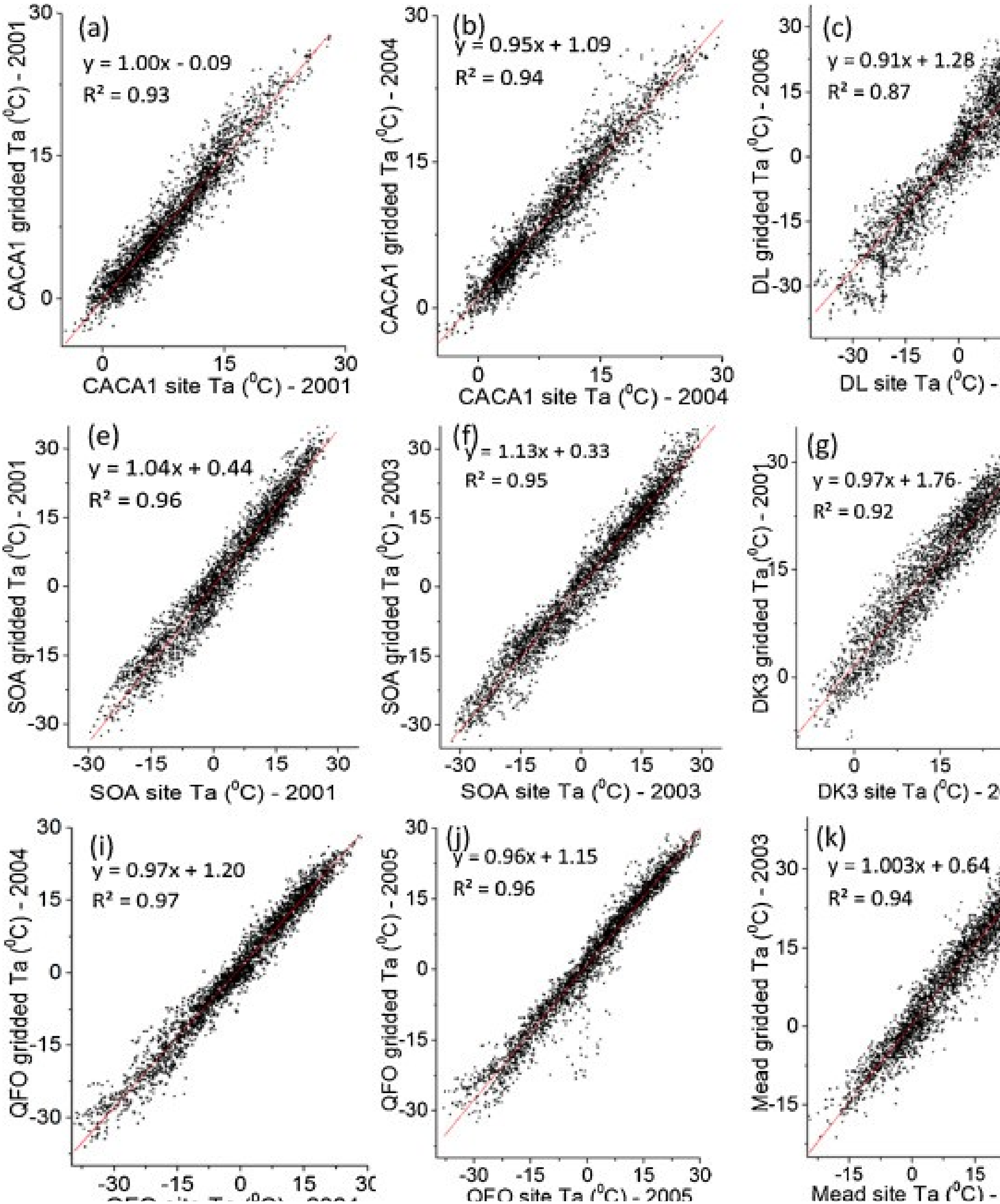
(a)
y = 1.00x - 0.09
R² = 0.93
CACA1 gridded Ta (⁰C) - 2001
CACA1 site Ta (⁰C) - 2001
(b)
y = 0.95x + 1.09
R² = 0.94
CACA1 gridded Ta (⁰C) - 2004
CACA1 site Ta (⁰C) - 2004
(c)
y = 0.91x + 1.28
R² = 0.87
DL gridded Ta (⁰C) - 2006
(e)
y = 1.04x + 0.44
R² = 0.96
SOA gridded Ta (⁰C) - 2001
SOA site Ta (⁰C) - 2001
(f)
y = 1.13x + 0.33
R² = 0.95
SOA gridded Ta (⁰C) - 2003
SOA site Ta (⁰C) - 2003
(g)
y = 0.97x + 1.76
R² = 0.92
DK3 gridded Ta (⁰C) - 2001
(i)
y = 0.97x + 1.20
R² = 0.97
QFO gridded Ta (⁰C) - 2004
(j)
y = 0.96x + 1.15
R² = 0.96
QFO gridded Ta (⁰C) - 2005
(k)
y = 1.003x + 0.64
R² = 0.94
Mead gridded Ta (⁰C) - 2003

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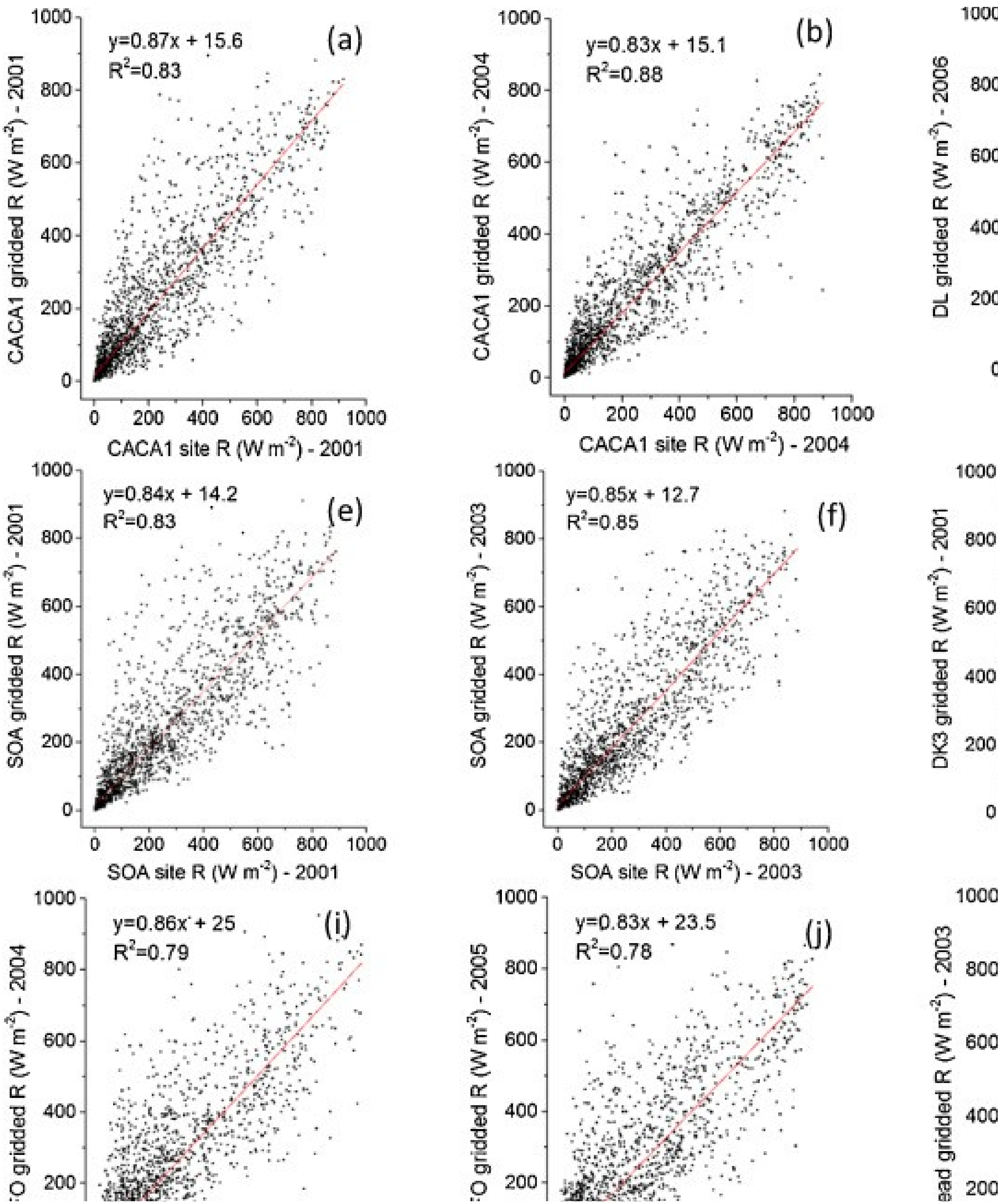
Fig. 2. Correlation between 3-hour air temperature of site and gridded climate datasets for six EC flux tower sites, each with two years of contrasting weather.



y=0.87x + 15.6
R2=0.83
(a)
CACA1 gridded R (W m-2) - 2001
CACA1 site R (W m-2) - 2001
y=0.83x + 15.1
R2=0.88
(b)
CACA1 gridded R (W m-2) - 2004
CACA1 site R (W m-2) - 2004
DL gridded R (W m-2) - 2006
y=0.84x + 14.2
R2=0.83
(e)
SOA gridded R (W m-2) - 2001
SOA site R (W m-2) - 2001
y=0.85x + 12.7
R2=0.85
(f)
SOA gridded R (W m-2) - 2003
SOA site R (W m-2) - 2003
DK3 gridded R (W m-2) - 2001
y=0.86x + 25
R2=0.79
(i)
gridded R (W m-2) - 2004
y=0.83x + 23.5
R2=0.78
(j)
gridded R (W m-2) - 2005
gridded R (W m-2) - 2003

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Fig. 3. Correlation between 3-hour incoming short wave radiation of site and gridded climate datasets for six EC flux tower sites, each with two years of contrasting weather except Mead.

Table 4. Measured and gridded mean annual T_a, annual total precipitation and radiation for contrasting years.

EC-site	Year	Model inputs	Surface air temperature		Precipitation		Incoming shortwave radiation	
			Mean annual (°C)	Standard deviation (°C)	Annual total (mm)	Standard deviation (mm month^{-1})	Annual total (MJ m^{-2})	Standard deviation (W m^{-2} day^{-1})
CA-Ca1	2001	*s*	8.1	5.8	1115	222	3935	196
		r	8.0	5.9	1575	297	3943	189
	2004	*s*	8.8	6.7	1232	152	4109	212
		r	9.4	6.6	2319	270	3919	188
DL	2006	*s*	−7.3	15.7	288	40	3608	177
		r	−5.4	15.4	311	16	2968	148
	2008	*s*	−10	17.3	277	29	3569	181
		r	−6.8	17.8	304	22	3003	151
CA-Soa	2001	*s*	3.0	12.2	235	18	4574	213
		r	3.7	14.2	313	20	4293	197
	2003	*s*	1.9	14.5	261	15	4412	206
		r	2.4	15.4	385	23	4185	192
US-Dk3	2001	*s*	14.5	8.9	947	48	5241	229
		r	15.8	9.1	1106	30	4662	206
	2002	*s*	15.0	9.8	1092	59	4896	221
		r	16.4	10.2	1118	47	5237	219
CA-Qfo	2004	*s*	−0.3	13.8	1016	29	3931	196
		r	0.8	13.6	941	30	4166	190
	2005	*s*	1.6	14.3	943	50	4144	204
		r	2.7	14	933	35	4170	191
Mead	2003	*s*	10.3	12.3	570	35	5616	253
		r	10.9	12.7	631	36	5248	221

s = measured at EC sites, *r* = extracted from gridded dataset.

NARR 3-hourly precipitation agreed less with measurements than did T_a and incoming shortwave radiation. However, monthly average NARR aggregated from 3-hourly precipitation was fairly well correlated with measured values (Fig. 4) with R^2 ranging from 0.5 to 0.9 except at DL in 2006 where NARR missed a particularly heavy rainfall event in June and at CA-Soa in 2003 where NARR had excessive precipitation in June and July during the 2001–2003 drought (Fig. 4). Total annual precipitation was generally higher in the NARR dataset at all sites, except for CA-Qfo (Table 4).

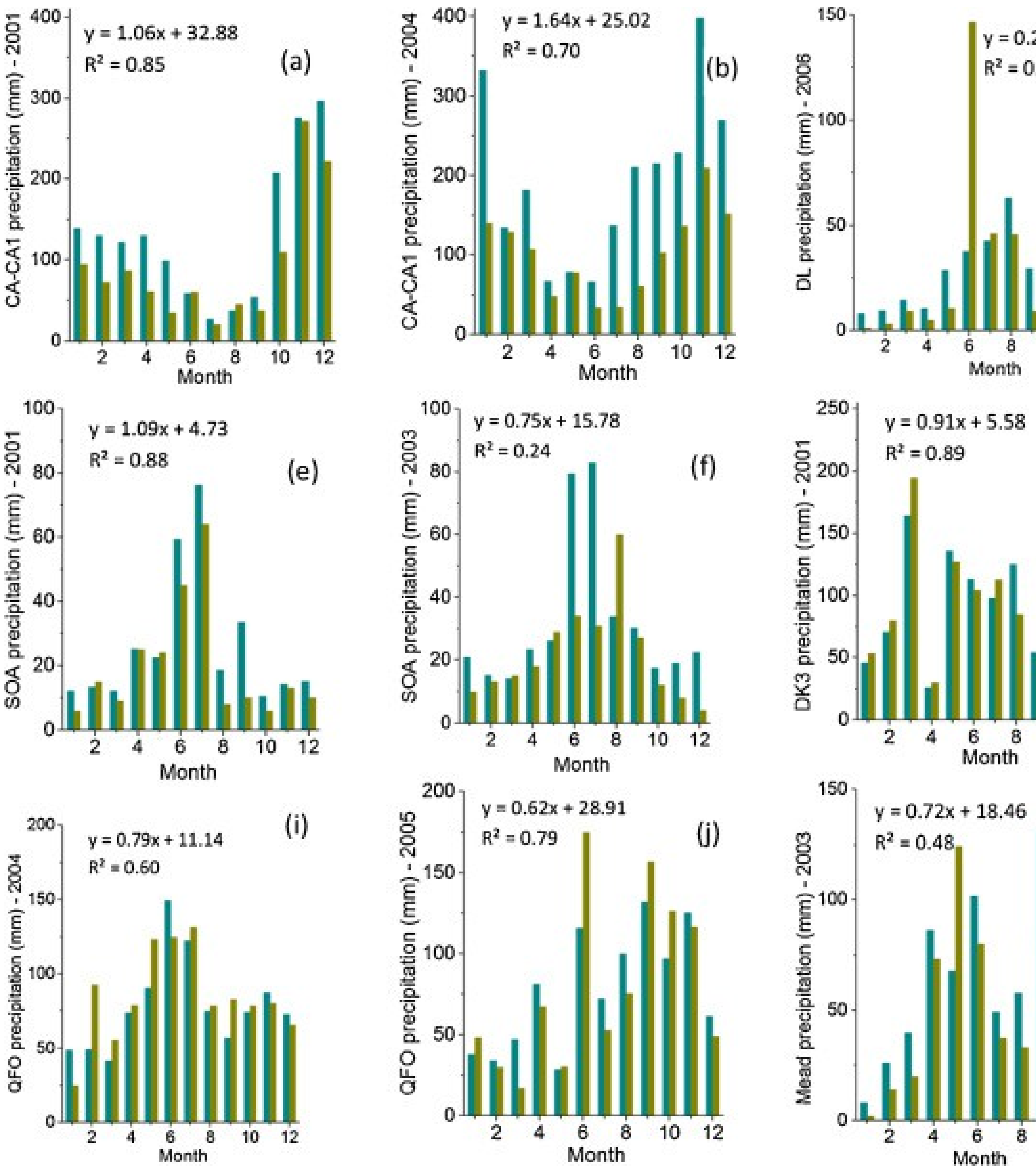

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Fig. 4. Correlation between monthly aggregated precipitation of site and gridded climate datasets for six EC flux tower sites, each with two years of contrasting weather.

Measured and UNASM soil inputs differed for most of the EC sites (Table 5). UNASM soil depths were smaller than measured values for all sites (particularly at CA-Soa and US-Dk3) except CA-Qfo. Although there were differences in measured vs. UNASM SOC and measured vs. estimated SON, no systematic bias was observed as half of the sites (CA-Ca1, CA-Soa and DL) were shown to have smaller UNASM values than measured whereas they had larger UNASM values in the rest of the sites (CA-Qfo, US-Dk3 and Mead) (Table 5). There was anomalously higher UNASM SON estimated in *ecosys*from SOC inputs at CA-Qfo compared to measured values.

Table 5. List of soil variables (maximum depth, initial available soil water and organic carbon) for measured and gridded soil inputs of the six EC flux tower sites.

EC-site	Simulation	Maximum depth (m)	Available water content (mm)	Total organic carbon (g C m^{-2})		Total nitrogen* (g N m^{-2})	
				0–30 cm	Below 30 cm	0–30 cm	Below 30 cm
CA-Ca1	*s*[1]	1.63	279	24,062	12,395	1197	1913
	r[3]	1	281	5984	14,650	624	1606
DL	*s*[2]	2.3	576	23,215	8327	1032	580
	r[3]	1.8	494	4080	12,239	448	1344
CA-Soa	*s*[1]	3	323	19,176	4794	1259	355
	r[3]	1	100	7600	4463	660	388
US-Dk3	*s*[1]	3.75	378	7270	3116	586	316
	r[3]	1.65	170	2928	11,716	345	1383
CA-Qfo	*s*[1]	1	140	10,077	1115	328	165
	r[3]	1	178	10,047	6698	820	546
Mead	*s*[1]	2	366	7377	6542	561	608
	r[3]	1.5	308	12,769	27,135	1012	2150

s = measured at EC sites, *r* = extracted from gridded dataset.

* Gridded total soil nitrogen was estimated from gridded total organic carbon.

1. Data source: http://ameriflux.ornl.gov/;http://fluxnet.ornl.gov/.

2. Data source: Lafleur and Humphreys (2008).

3. Data source: The Unified North American Soil Map: Liu et al. (2013).

3.2. Sensitivity of NEP to gridded climate and soil

The Taylor diagrams in Fig. 5 considered closeness of modeled vs. EC-derived NEP based on correlation, central root mean square difference (RMSD) and standard deviations (SD) between modeled and measured fluxes. Simulated values nearest to the EC values on the *x*-axis were considered to be the closest to observations, with highest correlation, lowest RMSD and a SD closest to the observed SD. The daily NEP in *simulation-s* had lower RMSD, higher correlation coefficients and SD closer to the measured values compared to *simulation-r* for most of the sites (Fig. 5). Therefore, CO_2 fluxes modeled using inputs from NARR and UNASM had less accurate diurnal and season patterns than did those using measured weather and soil, when tested against NEP measured at EC flux towers. However, the loss in accuracy with gridded data varied among sites with little loss at some (e.g. CA-Ca1) and more at others (e.g. CA-Soa, CA-Qfo). The lower accuracy with inputs from the NARR and UNASM databases are explained as follows.

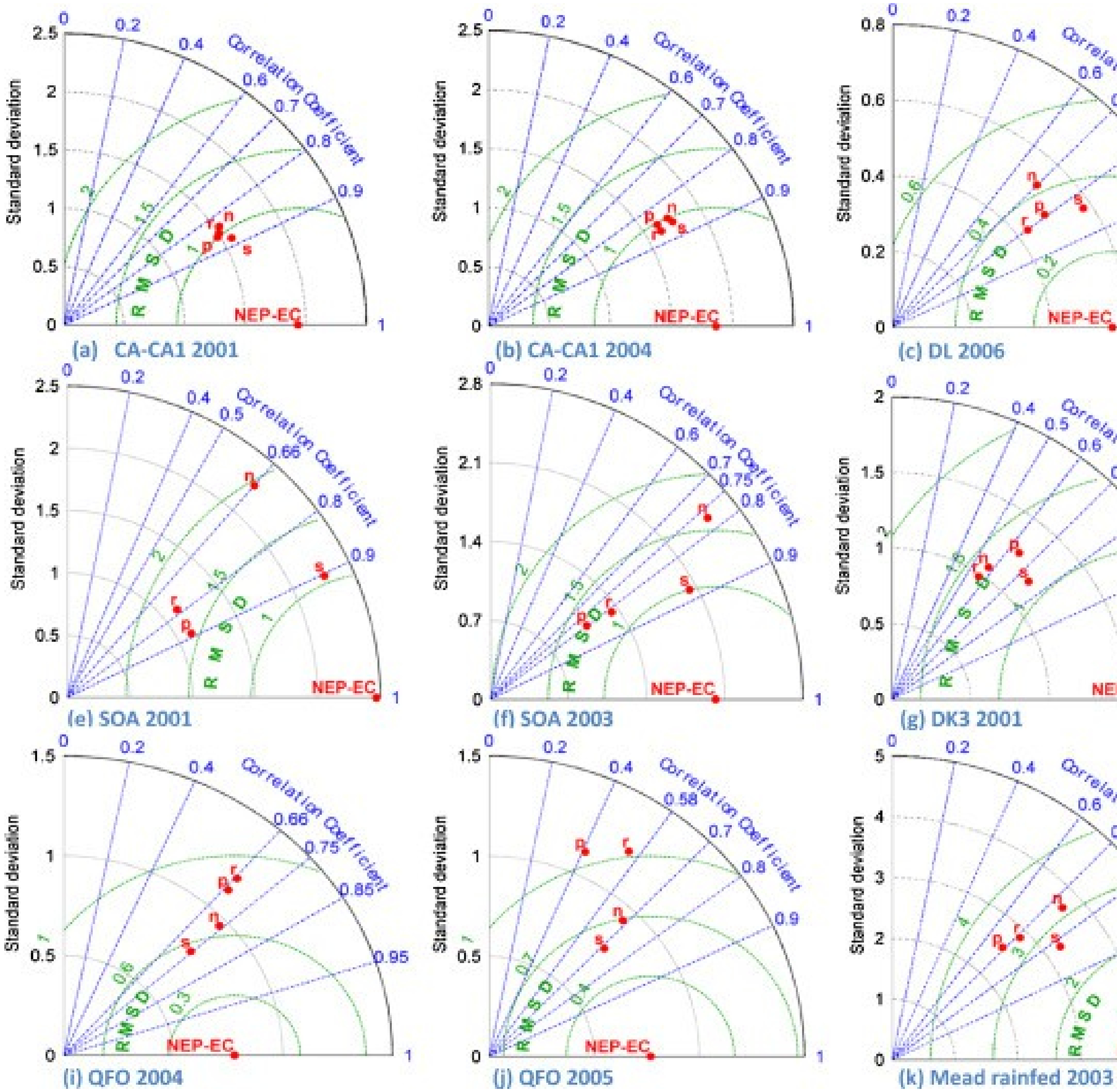

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Fig. 5. Taylor diagrams showing a comparison of four sets of simulated NEPs (g C day^{-1}) (*s*: site weather and soil, *n*: NARR weather and site soil, *p*: site weather and UNASM soil, *r*: NARR weather and UNASM soil) with observed NEP (NEP-EC) of six EC flux tower sites under a contrasting weather (Table 1). The RMSD (g C day^{-1}) between the

simulated and observed NEP is the distance between a simulated values along the green line to the *x*-axis at NEP–EC, standard deviation (g C day^{-1}) is the distance from a point to the origin and correlation coefficient of each simulated values is shown in the blue line.

3.2.1. Campbell river: Douglas-fir forest (CA-Ca1)

The Campbell river Douglas-fir forest EC site has a cool temperate climate with a dry summer. Taylor diagrams (Fig. 5(a and b)) showed close clustering of the four simulations indicating only small differences among them. Daily NEP from all simulations for this site closely agreed with measured values (correlation coefficient >0.8) during both cooler (2001) and warmer (2004) years (Fig. 5). Therefore, key modeled responses of net CO_2 exchange to changes in weather were maintained when inputs from site weather and soil were replaced by those from NARR and UNASM for the grid cell in which CA-Ca1 is located. The good agreement in seasonal patterns of modeled vs. measured NEP during the cooler and warmer year allowed adverse effects of summer warming events on NEP to be simulated with both NARR and measured weather data. For instance, days 168–173 for 2004 in Fig. 6(b1 and b2) had particularly higher T_a(>20 °C) that reduced NEP (Fig. 6b3) through the coupled hydraulic scheme for soil-root-canopy-atmosphere water transfer that lowered g_c (Fig. 7), hence reduced CO_2 influxes (Fig. 7) as well as temperature sensitivity of respiration processes that increased CO_2 effluxes (Fig. 7) as described in Sections 2.2.1 Measured weather and soil inputs, 2.1.4 Effects of temperature on. R_a and $R_h$increased in the warmer year (2004) above those in the cooler year (2001) in both site and gridded simulations (Table 6), thereby reducing the annual NEP by 192 and 133 g C m^{-2} yr^{-1} for runs with measured and gridded inputs respectively. This modeled decline in NEP was corroborated by a similar decline of 214 g C m^{-2} yr^{-1} in EC-measured NEP in 2004 vs. 2001 (Table 6).

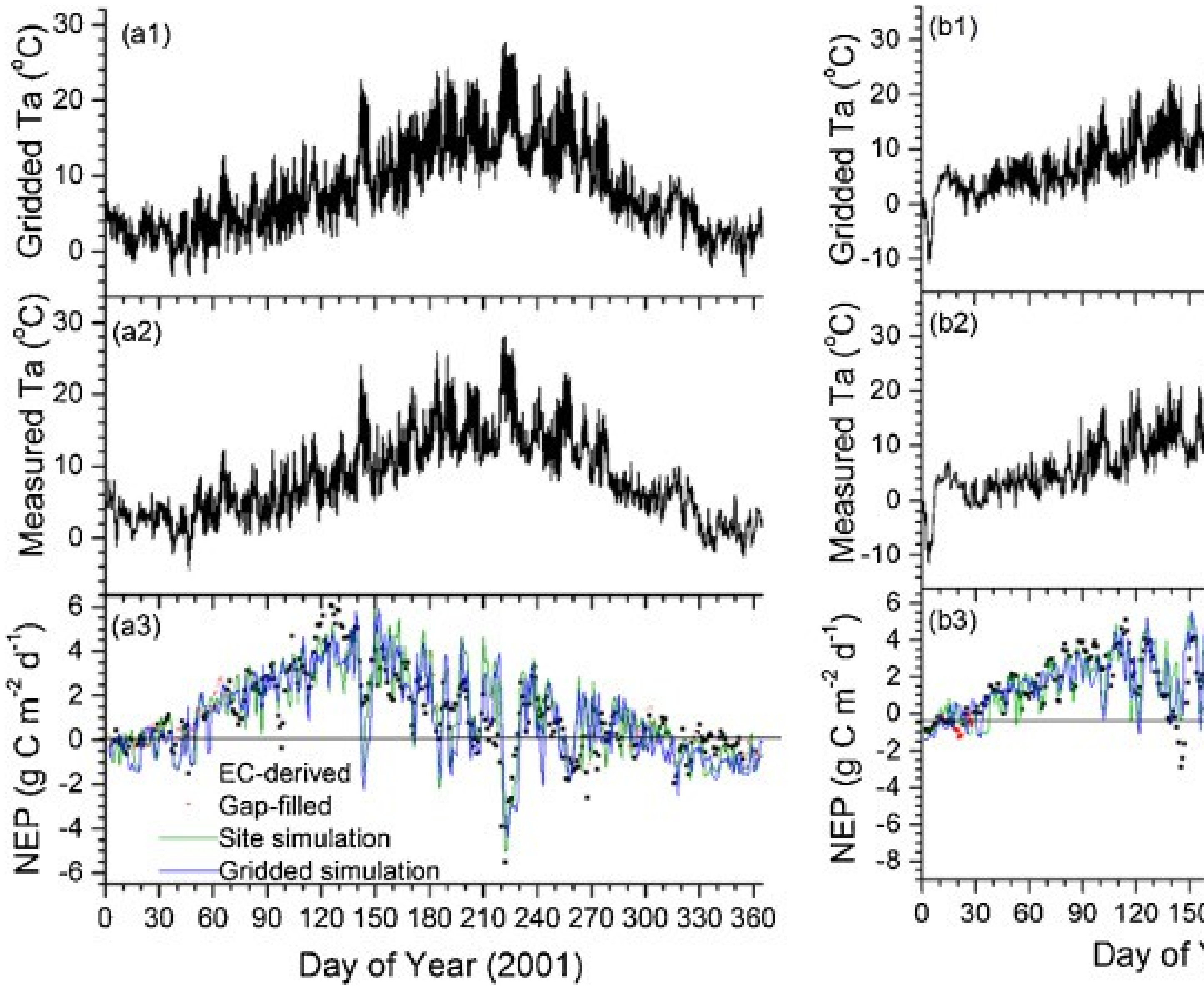

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Fig. 6. Campbell river Douglas-fir forest (CA-Ca1): (a1, a2, b1, b2) 3-hourly air temperature, (a3, b3) daily NEP measured at EC (black closed symbols), gap-filled from EC measurements (red closed symbols), modeled NEP using site climate and soil (green lines) and regional climate and soil (blue lines) for a cooler year 2001 and a warmer year 2004. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

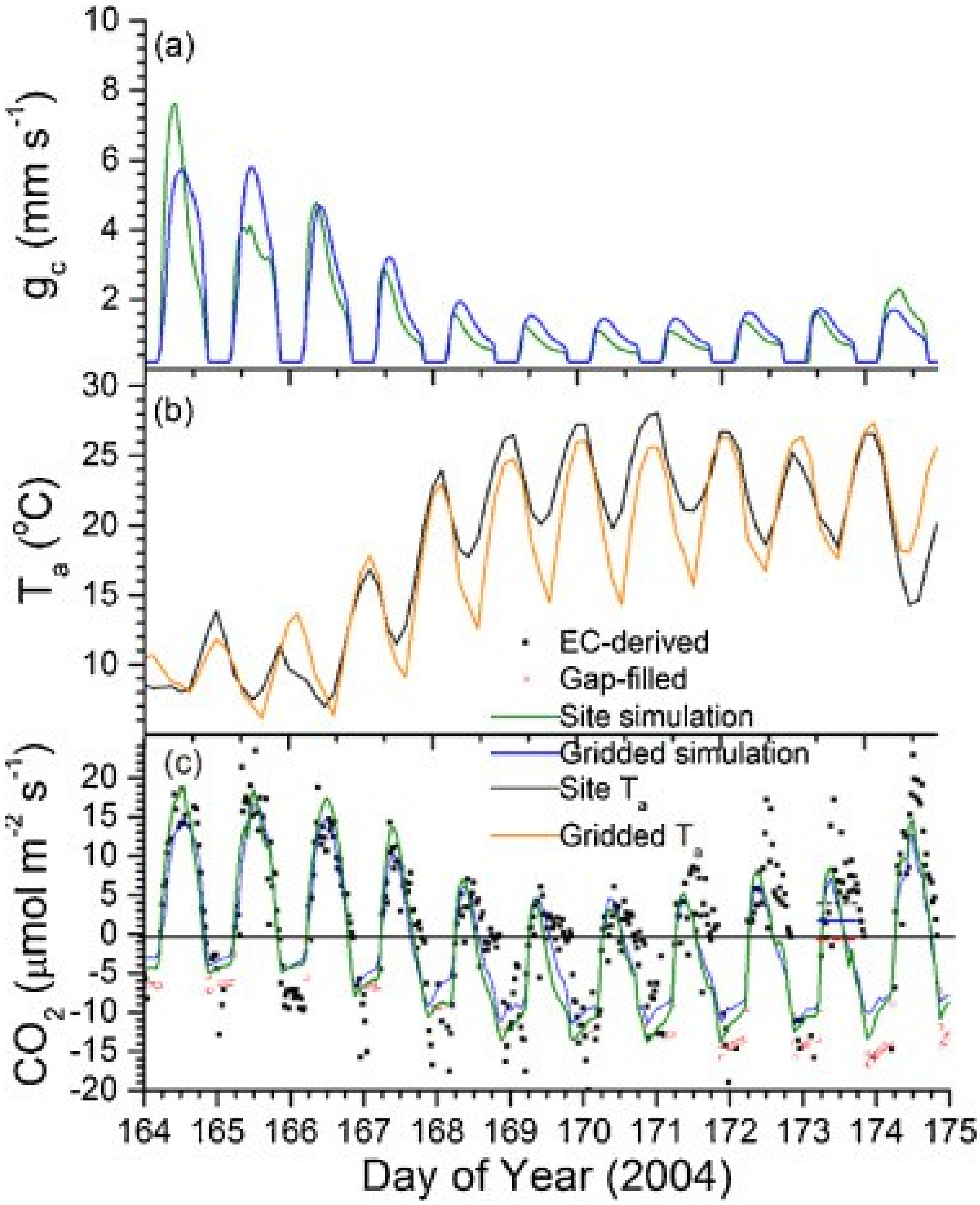

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Fig. 7. Campbell river Douglas-fir forest (CA-Ca1), (a) hourly modeled canopy stomatal conductance (g_c), modeled with site climate and soil (green lines) and regional climateand soil (blue lines) (b) hourly site (black line) and gridded (orange line) air temperature (T_a), (c) hourly modeled CO_2 flux, modeled with site climate and soil (green lines) and regional climate and soil (blue lines) at EC (black closed symbols), gap-filled from EC measurements (red closed symbols), for DOY 164–174 of a warmer year (2004). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 6. Annual carbon budget of measured vs. gridded simulations and EC measurements for contrasting years for six EC flux tower sites.

EC-site	Year	Model inputs	C balance[a] – modeled						C balance – derived from EC measurements			
			GPP	Ra	NPP	Rh	Re	NEP	GPP	Re	NEP	Source
CA-Ca1	2001	*s*	1969	1163	806	386	1549	420	2077	1668	409	Krishnan et al. (2009)
		r	1923	1211	711	362	1573	349				
	2004	*s*	1872	1195	677	440	1635	228	2338	2143	195	
		r	2015	1330	685	469	1799	216				
DL[b]	2006	*s*	308	137	170	103	238	68	–	–	61[b]	Lafleur and Humphreys (2008)
		r	245	106	139	98	204	41				
	2008	*s*	261	120	141	78	198	63	–	–	73[b]	
		r	252	111	141	83	194	58				
CA-Soa	2001	*s*	1457	779	678	449	1228	229	1217	892	325	Krishnan et al. (2006)
		r	730	392	337	249	641	88				
	2003	*s*	1190	680	509	444	1124	65	917	823	91	
		r	789	413	376	272	685	104				
US-Dk3	2001	*s*	2640	1219	1421	712	1931	709	–	–	607	Oren et al. (2006)
		r	1669	927	745	437	1364	304				
	2002	*s*	2316	1228	1088	639	1867	449	2346	2076	270	
		r	1519	943	575	423	1366	153				
CA-Qfo	2004	*s*	692	378	314	304	682	10	600	590	9.8	Bergeron et al. (2008)
		r	997	569	428	322	891	106				
	2005	*s*	790	452	338	305	757	34	699	656	42	
		r	1034	650	384	346	996	39				
Mead	2003	*si*	1895	792	1103	278	1070	825	1793	1221	600	Verma et al. (2005)
		ri	138	539	845	158	697	687				

EC-site	Year	Model inputs	C balance[a] – modeled						C balance – derived from EC measurements			
			GPP	Ra	NPP	Rh	Re	NEP	GPP	Re	NEP	Source
			4									
		sr	1593	657	936	296	953	640	1337	940	410	
		rr	1167	457	710	153	610	557				

s = measured at EC sites, *r* = gridded dataset, *si* = measured and irrigated, *sr* = measured and rainfed, *ri* = gridded and irrigated, *rr* = gridded and rainfed.

a

C balance in g C m^{-2} yr^{-1} except for.

b

DL in g C m^{-2} growing $season^{-1}$ measured during day of the year (DOY): 137–240 for 2006 and 121–246 for 2008.

3.2.2. Daring lake: Arctic tundra (DL)

The Daring lake site is a tundra ecosystem located in the lower central Arctic at which we compared NEP during 2006, a warmer year, with that in 2008, a cooler year (Fig. 8). NEP from *simulation-p* was closer to the measured NEP than was NEP from *simulation-n* (Fig. 5(c and d)), indicating that the NARR inputs, particularly the overestimation of T_a (Table 4) and underestimation of shortwave radiation (Table 4) caused the deviations in seasonal patterns of modeled NEP from *simulation-n* and -*r* (Fig. 5(c and d); Fig. 8(a3 and b3)) by reducing T_c and T_s, hence lower soil heat and water transfers that reduce the rate of CO_2 fixation. The NARR seasonal precipitation pattern also differed from measured values in 2006 when the NARR missed a particularly large precipitation event measured in June (Fig. 4c). However, spring T_a in 2006 was higher than in 2008 (Fig. 8(a1, a2, b1, b2)) resulting in earlier net C uptake, thus key modeled responses of net CO_2 exchange to changes in spring warming, apparent in the EC-measured NEP, were captured in both measured and gridded simulations (Fig. 8(a3 and b3)). Moreover, for those summer days with T_a exceeding 20 °C (e.g. days 200 and 220 for 2006 in Fig. 8(a1 and a2)) and around day 200 for 2008 in Fig. 8(b1 and b2), NEP declined (Fig. 8(a3 and b3)) due to a decrease in CO_2 fixation and an increase in R_a and R_h, as noted earlier for Campbell river site (Fig. 6b3), and these responses were captured in both site and gridded simulations (Fig. 8(a3 and b3)).

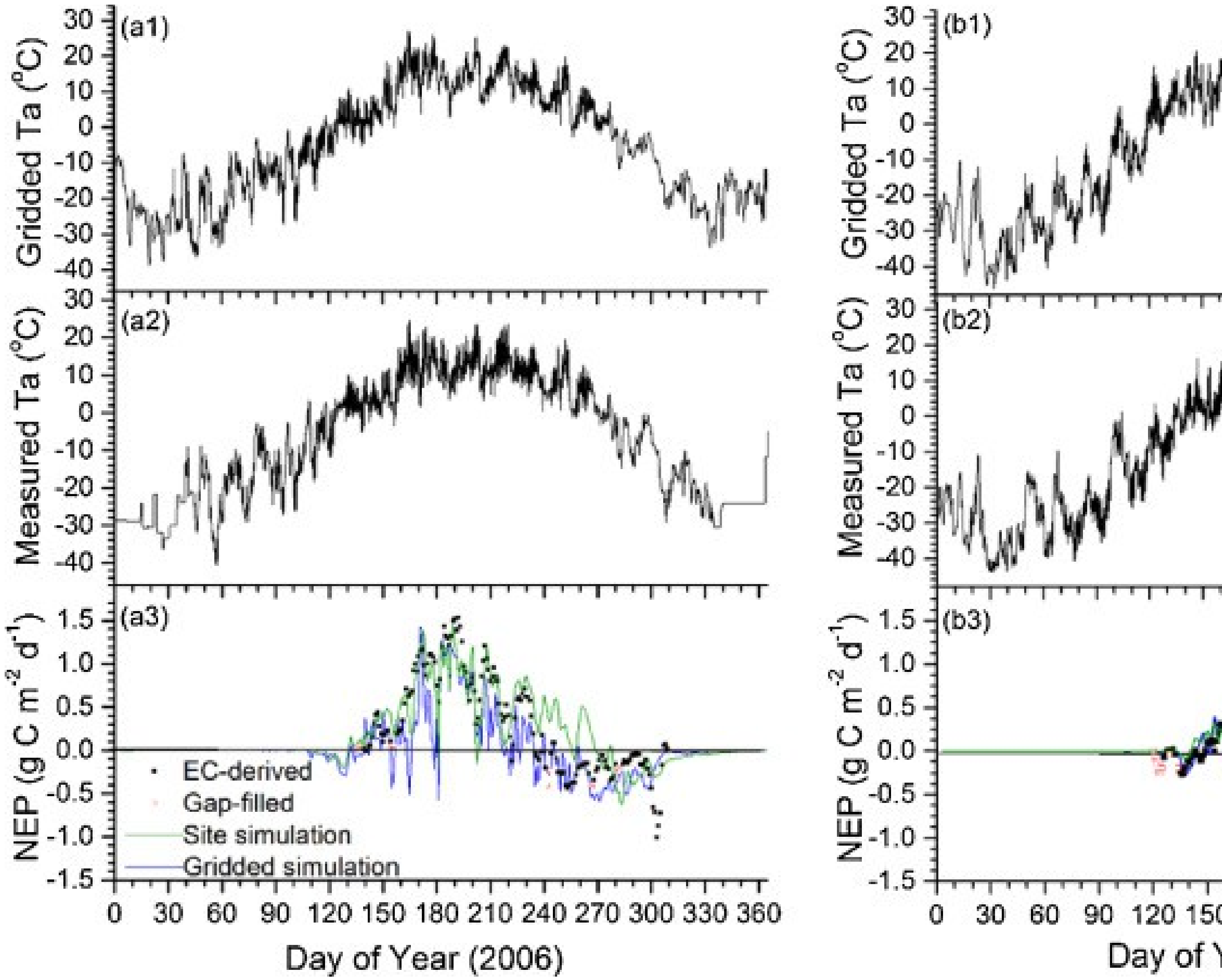

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Fig. 8. Daring lake Arctic tundra (DL): (a1, a2, b1, b2) hourly air temperature, (a3, b3) daily NEP measured at EC (black closed symbols), gap-filled from EC measurements (red closed symbols), modeled NEP using site climate and soil (green lines) and regional climate and soil (blue lines) for the years of 2004 and 2005. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.2.3. Old Aspen forest (CA-Soa)

This site is an old Aspen forest in the boreal climate zone in which we compared NEP during 2001 and 2003, the first and third years of a major drought in central North

America (Fig. 9). The Taylor diagrams (Fig. 5(e and f)) showed that NEP modeled from both NARR and UNASM inputs differed from EC-derived values more than did NEP modeled from measured inputs. Regression of modeled on EC-derived CO_2 fluxes in *simulation-s* had larger correlation coefficient, lower RMSD, and SD closer to SD from EC-derived values, compared to *simulation-n* and *simulation-p* for both 2001 and 2003. Variations in seasonal amplitude of NEP (Fig. 9) apparent as smaller SD (Table 4) in simulations with UNASM vs. measured soil inputs (*p* vs. *s* and *r* vs. *n* in Fig. 5(e and f)) were attributed to shallower UNASM vs. measured soil depth (1 vs. 3 m in Table 5) which reduced water holding capacity and consequently hastened soil drying. Annual NEP of *simulation-r* was therefore lower than that of *simulation-s* (Table 6) due to inadequate soil water in the shallow UNASM to sustain productivity during the first drought year in 2001 (Fig. 9a1). NEP measured and modeled with site inputs in 2001 was sustained by water deeper in the measured soil profile carried forward from previous wetter years. This deeper water was depleted by 2003, reducing NEP (Fig. 9b2 vs. 9a2; Table 5). However this deeper water was absent in the UNASM soil profile in 2001, resulting in faster soil drying, lower g_c and hence CO_2 uptake rates to values much lower than EC measurements (Fig. 9a2) while net C uptake modeled with measured soil remained close to EC values. Excess summer NARR precipitation in 2003 (Fig. 4f), however resulted in higher soil water content (Fig. 9b1), hence better CO_2 uptake rates, although subsequent rapid soil drying as a result of the shallow soil depth.

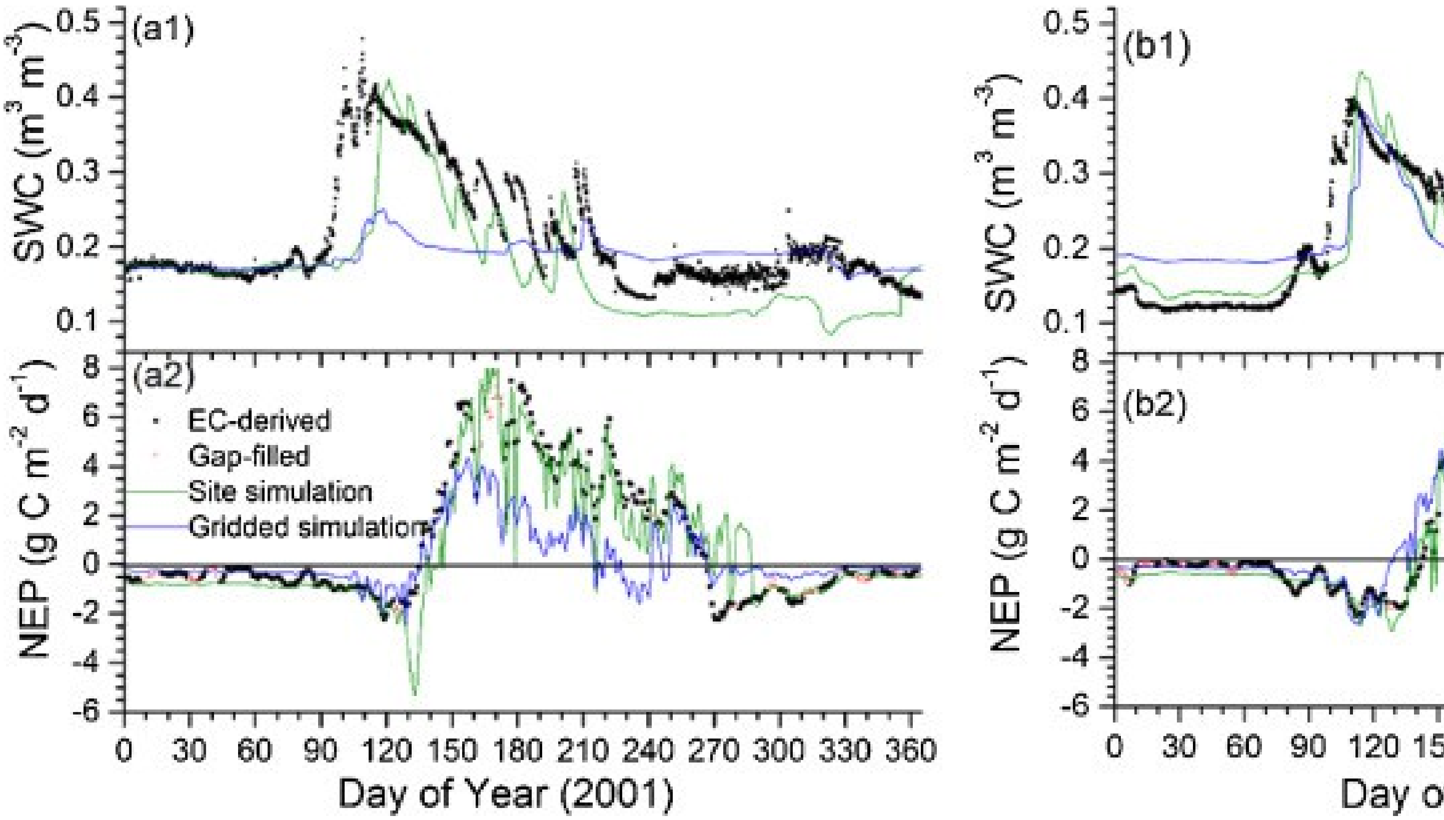

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Fig. 9. Old Aspen forest (CA-Soa): (a1, b1) daily volumetric soil water content at 15 cm soil depth, (a2, b2) daily NEP measured at EC (black closed symbols), gap-filled from EC measurements (red closed symbols), modeled NEP using site climate and soil (green lines) and gridded climate and soil (blue lines) for the first (2001) and third (2003) years of a drought. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.2.4. Duke loblolly pine forest (US-Dk3)

Duke forest is a loblolly pine in a subtropical climate where NEP was compared during the first and second years of the 2001–2002 drought (Fig. 10). Lower correlation and greater RMSD of *simulation-n* vs. *s* than of *simulation-p* vs. *s*(Fig. 5(g and h)) indicated that the simulation of NEP was more adversely affected by inputs from NARR vs. measured weather than from UNASM vs. measured soil. Although a good correlation (R^2 = 0.86) of NARR vs. measured incoming shortwave radiation was observed in 2002 (Fig. 3h), a 10% decline in NARR annual incoming shortwave radiation was observed in 2001 (Table 4) with R^2 = 0.68 (Fig. 3g). Also, NARR T_a was higher than measured values, especially in 2001 where the *y*-intercept of the regression lines was 1.76 °C

([Fig. 2]g), resulting in rapid soil drying, lowering g_c hence NEP. The slight deviation of *simulation-p* vs. *-s* observed in 2001/2002 could mainly be attributed to shallower UNASM soil depth that reduced soil water holding capacity ([Table 5]), hence contributed to the lower net CO_2 fixation. Decline of NEP in summer 2002 was greater than that in 2001 for both site and gridded runs ([Fig. 10]b3 vs. 10a3) due to lower summer precipitation ([Fig. 4](g and h)). The seasonal NARR precipitation pattern allowed this decline to be modeled in the gridded simulation similarly to that in the site simulation.

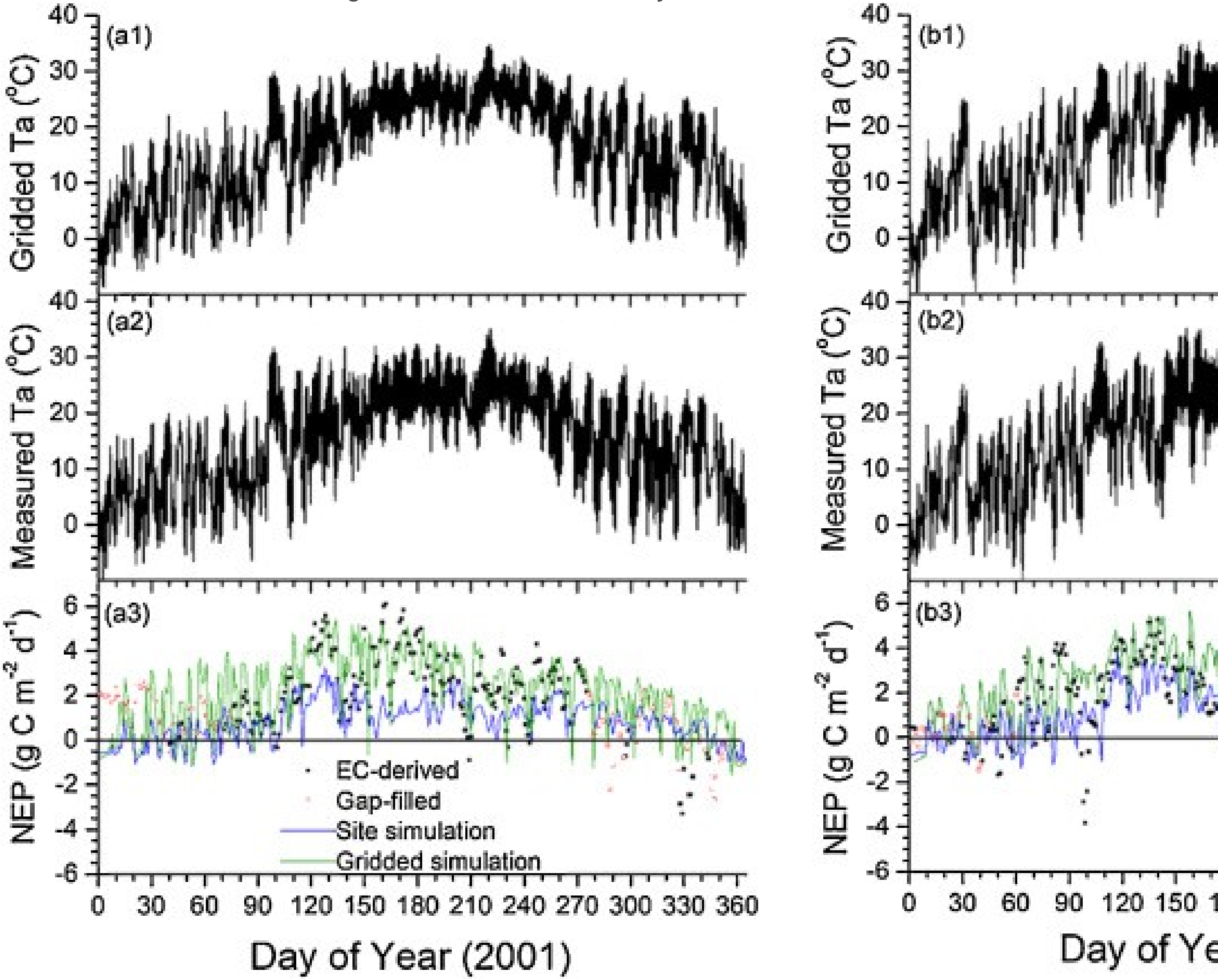

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Fig. 10. Duke forest (US-Dk3): (a1, a2, b1, b2) hourly air temperature, (a3, b3) daily NEP measured at EC (black closed symbols), gap-filled from EC measurements (red

closed symbols), modeled NEP using site climate and soil (green lines) and regional climate and soil (blue lines) for a pre-drought year 2001 and a drought year 2002. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.2.5. Quebec mature boreal black spruce forest (CA-Qfo)

CA-Qfo is a boreal black spruce forest site at which we compared 2004, a cooler year, with 2005, a warmer year. *Simulations-s* and *-n* were closer to measured NEP than were *simulations-p* and *-r* (Fig. 5(i and j)) for both years, indicating that the UNASM soil input was mainly responsible for the differences in NEP. These differences were attributed to anomalously low SON measured at the CA-Qfo site (Table 5) which was less than that estimated from general SOC:SON relationships used with the UNASM inputs. This lower SON resulted in smaller uptake hence lower NEP with measured soil inputs (Table 6) which was more consistent with EC values (Fig. 11). However, key seasonal variations in NEP were simulated with both NARR and measured weather. Earlier spring warming in 2005 vs. 2004 caused 10 days earlier increase in net CO_2 uptake (Fig. 11b3 vs. a3) which was captured in both site and gridded simulations. Despite increased earlier carbon uptake, more frequent summer warming events during 2005 (e.g. DOY 180, 240) vs. 2004 (e.g. DOY 185) caused declines in NEP when T_a was higher than 20 °C through processes described in Sections 2.1.1 Effects of canopy water status on GPP, 2.1.4 Effects of temperature on. Diurnal variations in NARR T_a allowed the effects of these events on NEP to be represented similarly to those with measured inputs (Fig. 11).

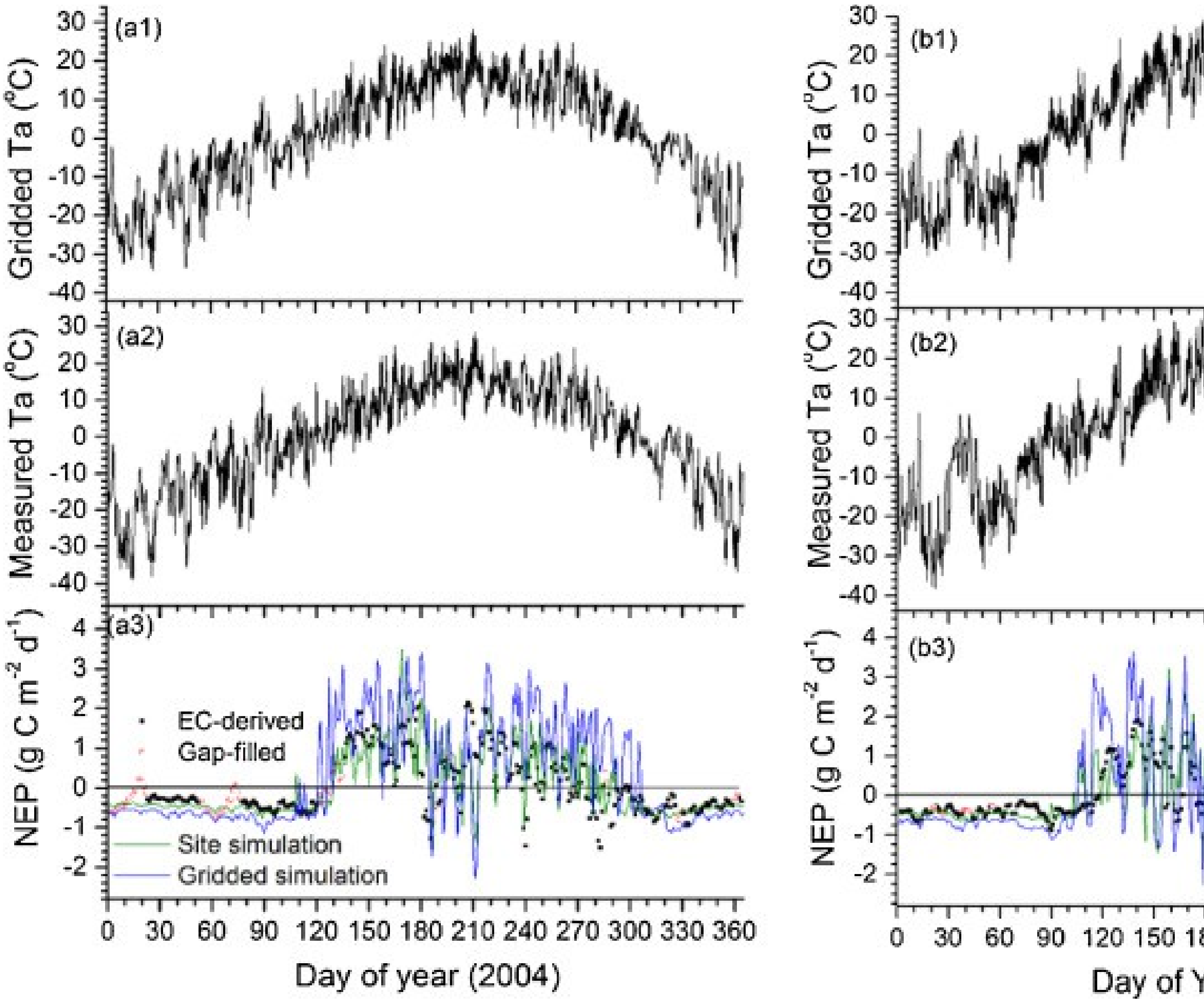

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Fig. 11. Quebec mature boreal black spruce forest (CA-Qfo): (a1, a2, b1, b2) 3-hourly air temperature, (a3, b3) daily NEP measured at EC (black closed symbols), gap-filled from EC measurements (red closed symbols), modeled NEP using site climate and soil (green lines) and regional climate and soil (blue lines) for a cooler year 2004 and a warmer year 2005. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Mead crop site (Mead)

This site had an irrigated vs. rainfed maize soybean rotation where in 2003 maize was simulated with and without irrigation. The Taylor diagrams (Fig. 5(k and l)) showed that NEP from *simulation-n* were closer to the EC values than were those of *simulation-p*, indicating that the slight differences were mainly attributed to the UNASM soil inputs (UNASM soil depth (1.5 m) compared to site soil depth (2 m)). However, key responses of earlier decline in modeled NEP to water stress effects during soil drying in the rainfed vs. irrigated runs were captured in both *simulation-s* and *-r* (Fig. 12). The rainfed simulations were shown to have faster soil drying, causing more rapid declines in ψ_s, ψ_c, and g_c, hence lower CO_2 influxes (Fig. 13; Table 6) than the irrigated simulations for both runs with site and gridded inputs. These declines were apparent in declines of latent heat (LH) and CO_2 fluxes with in the rainfed vs. irrigated simulations. These declines reduced productivity for the rainfed simulations, in both the site and gridded simulations (Fig. 12), allowing water stress in the rainfed run to be simulated consistent with fluxes from EC measurements (Fig. 13).

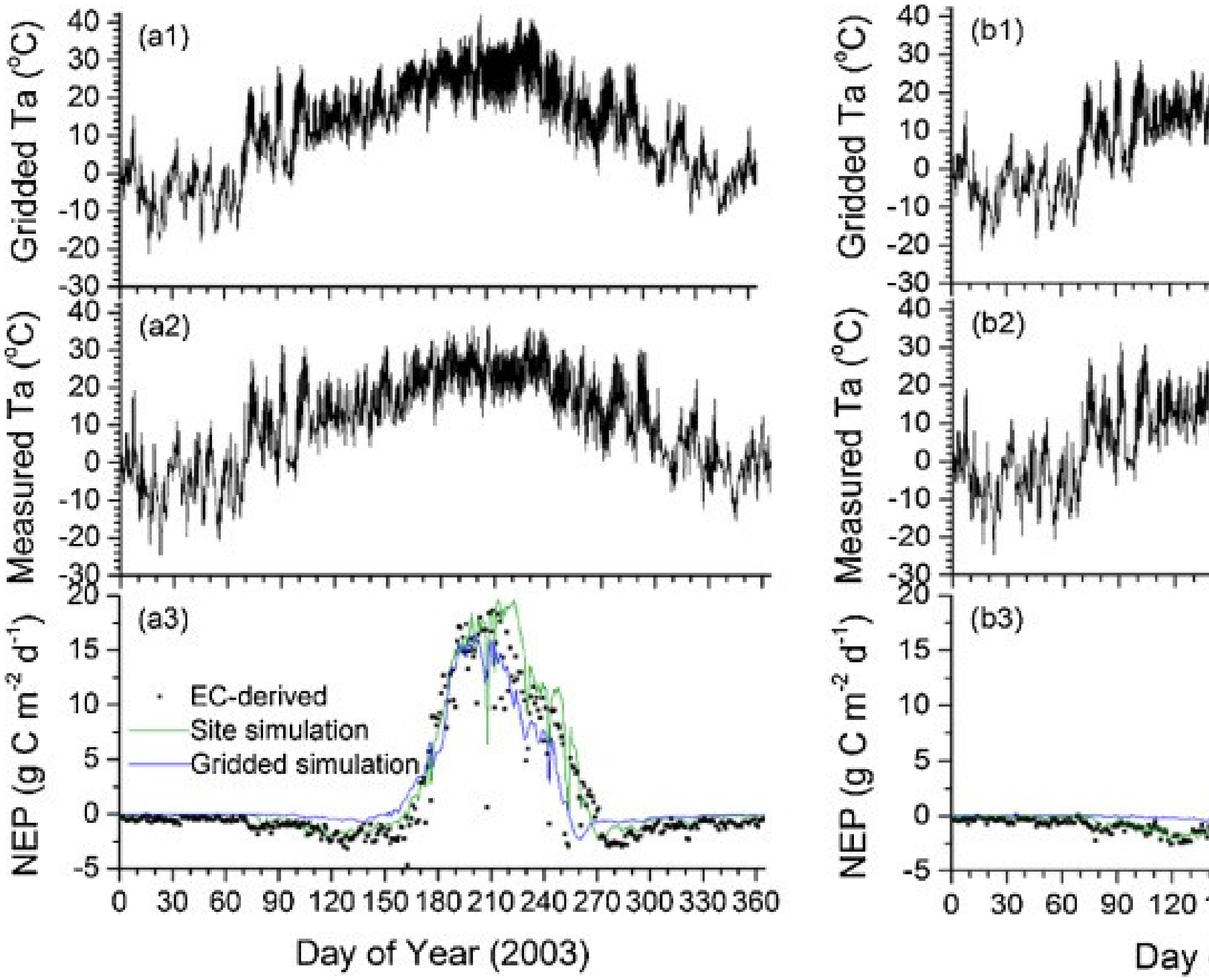

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Fig. 12. Mead crop land site (Mead): (a1, a2, b1, b2) 3-hourly air temperature, daily NEP measured at EC (black closed symbols), modeled NEP using site climate and soil (green lines) and regional climate and soil (blue lines) for (a3) irrigated vs. (b3) rainfed for maize in 2003. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

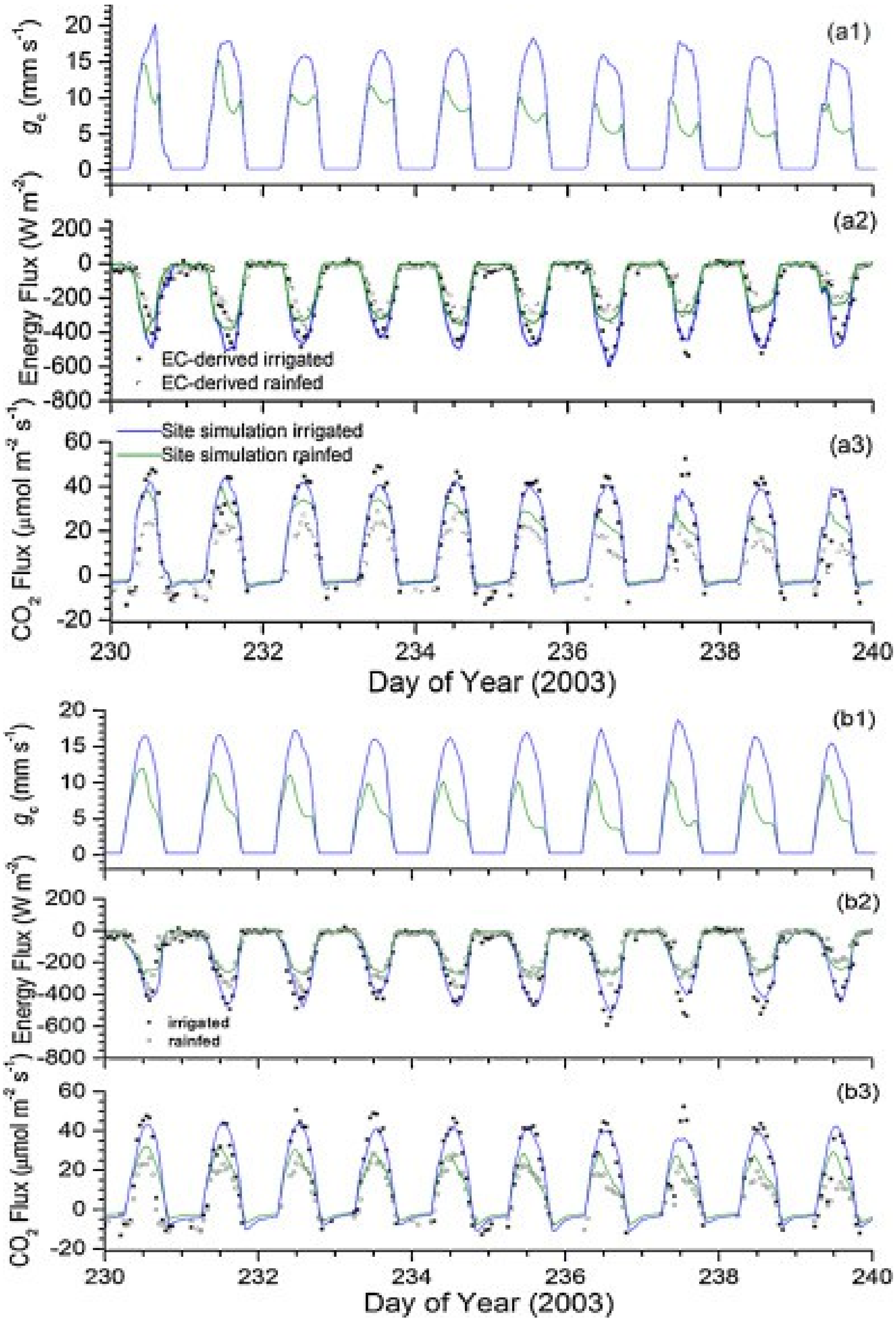

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Fig. 13. Mead crop land site (Mead): comparison of CO_2 fluxes, energy fluxes (latent heat fluxes) and canopy conductance for irrigated vs. rainfed for maize in 2003 modeled for runs with site (a1, a2, a3) and gridded (b1, b2, b) inputs for soil and weather.

4. Discussion

4.1. Uncertainties in gridded weather and soil

Differences in modeled NEP using gridded vs. measured inputs at site scale (Fig. 5) could be an important indicator in quantifying sources of uncertainty in NEP when such gridded model inputs are used to estimate continental carbon balance. In aggregating carbon exchange from site to regional scales uncertainties could originate from inaccuracies in (1) the model, (2) the model inputs (Moorcroft, 2006), (3) the measured fluxes at EC towers used to test model values and (4) spatial representativeness mismatches. Uncertainty in modeled NEP attributed to model structure and parameterization were shown by testing NEP simulated with measured inputs against EC values, with which the model results had generally a good agreement (Fig. 5; Table 6). This agreement demonstrated the ability of the model to simulate land-atmosphere carbon exchange across different climatic zones with varied plant functional types, under contrasting weather. In earlier studies *ecosys* has been tested rigorously under a wide range of climates and biomes as described in the introduction. Moreover, the model performed very well in the North American Carbon Program site synthesis model intercomparison study (Schaefer et al., 2012, Schwalm et al., 2010) where the skill of the model to simulate carbon exchange over several EC sites across North America was compared with more than 22 participating models.

Uncertainties in the quality of gridded model inputs were assessed in the Taylor diagrams (Fig. 5) that illustrated differences in NEP modeled with inputs from gridded vs. measured weather and soil when compared to EC-derived NEP. These differences were larger for NEP modeled with gridded inputs than with measured inputs at most of the sites (Fig. 5) indicating that agreement of NEP modeled in those grid cells with EC-derived values was adversely affected by gridded inputs, particularly during years with extreme climate events such as drought, as in CA-Soa site in 2001/2003 (Fig. 9). However, the magnitude of these differences in NEP varied among sites (Fig. 5) with relatively little differences at some sites (e.g. Fig. 5(a and b)) and greater differences at others (e.g. Fig. 5(e and f)). Overall, NEP from the gridded simulations tended to exceed or fall below EC-NEP more than did those from the site simulations (Table 6).

These uncertainties associated with the quality of NARR and UNASM could be attributed to different causes, and improvements of these gridded datasets could increase the accuracy of model estimates, hence our understanding of the continental and global scale carbon cycle. These can be realized by ensuring better representations of the soil and weather attributes at a pixel level. Uncertainties from NARR could be attributed to variations in the density of the networks of observational datasets that were used to construct the gridded dataset (Mesinger et al., 2004). For instance, sparse distribution of weather stations, especially in higher latitudes of NA, due to less accessibility and higher operational costs to maintain stations in remote areas, could affect the accuracy of the gridded product. Therefore, increasing the number of observation stations to better represent the spatial heterogeneity is crucial to improve the accuracy and spatial representativeness of the weather datasets, thus minimize the uncertainties of model estimates associated with weather inputs. Uncertainties from UNASM could be attributed to spatial heterogeneity within a 0.25° × 0.25° pixel, as soil properties vary at much smaller spatial scales which makes it difficult to assess how well the measured or gridded soil represents the diverse soils of a grid cell. Uncertainties associated with sub-pixel heterogeneity could partly be improved by increasing the spatial and temporal resolutions of model inputs. In this regard, there is always a trade-off between higher computational resource requirements for simulations vs. better spatial representation of weather and soil characteristics. Furthermore, UNASM was a product from the fusion of three different soil datasets (STATSGO2, SLC version 2.2 and HWSD version 1.21) that were constructed using different inputs and methods of upscaling across different regions of North America. These products had different spatial resolutions and a certain loss of accuracy can be expected while harmonizing these products thereby affecting the skill of the model in simulating land-atmosphere carbon exchange.

It should also be noted that estimating uncertainties from inherent model structure, by comparing NEP from site and gridded simulations with EC-derived values, should also consider some uncertainties that might be associated with the measured benchmark data itself (e.g. EC data processing methods and gap-filling,) which we have not accounted for in this study. Uncertainties associated with mismatches in spatial representativeness of EC-derived fluxes and modeled fluxes from site and gridded simulations should also be considered. The gridded simulations were compared with EC-derived fluxes based on the idea that the dominant land cover of a pixel where the EC tower was located is a representative of the larger ecosystem. However, observed flux from EC towers may not fully represent the fluxes within areas of the flux footprint and the gridded pixel, due to spatial heterogeneities in land cover. Chen et al. (2012) evaluated the spatial representativeness of 12 EC sites of the Canadian Carbon

Program across different plant function types using and Normalized difference Vegetation Index (INDVI), land cover map and a footprint model. They reported that at most of the sites the dominant land cover observed from the footprints of the towers were higher than 60%. They suggested the use of footprint models that estimate the probability of flux sources within the EC footprint. Such approach can be used to directly compare modeled fluxes against EC-derived fluxes and may reduce the effects of spatial scale mismatch, providing a better model testing. Available remote sensing products also provide an opportunity to understand sub-pixel heterogeneity, flux footprints and up-scaling ecosystem processes (Masek et al., 2015).

Although, the degree of EC flux footprint area heterogeneity vary among EC sites (Chen et al., 2012), most flux towers are located in a fairly homogenous environment (Barcza et al., 2009), thus provide the opportunity to compare EC-derived fluxes with modeled fluxes from the dominant plant functional type. However, higher uncertainty due to spatial scale mismatch is apparent in modeled fluxes from gridded pixels with coarser spatial resolution than those from the EC tower footprints. Spatial representativeness of flux footprint in gridded pixels can be improved by implementing cohorts of multiple plant functional types at a grid cell level and it is important for TBMs to integrate multiple cohorts to better represent sub-pixel heterogeneity, hence improve regional estimates of carbon fluxes.

4.2. Gridded weather attributes that caused differences in modeled NEP

NARR 3-hourly T_a had generally better fits with measurements than did NARR incoming shortwave radiation and precipitation (Fig. 2; Table 4). However, the accuracy of gridded T_a was spatially and temporally variable, being slightly overestimated for some sites compared to measured values (Fig. 2), resulting in more adverse impacts of warming with NARR weather in some sites (e.g. US-Dk3 2001) by hastening rapid soil drying, lowering g_c hence NEP (Table 6). Nevertheless, for most of the sites NARR T_a was accurate enough that the effects of diurnal and seasonal changes in T_a under contrasting weather (cool vs. warm years) on NEP, shown in the site simulations, were mostly captured in the gridded simulations (e.g. Fig. 6). NARR enabled simulation of key model responses to changes in seasonal weather, such as earlier spring warming that caused earlier increases in net CO_2 uptake as shown in DL 2006 (Fig. 8) and CA-Qfo 2005 (Fig. 11) and the impacts of intense warming events that reduced CO_2 uptake and increased respiration as shown in CA-Ca1 (Fig. 6).

The NARR incoming shortwave radiation and precipitation that we used in this study were rescaled from the original NARR datasets (Mesinger et al., 2004) to improve their quality (Wei et al., 2014). Comparison of original NARR incoming shortwave radiation with measurements from 23 EC sites has shown that NARR values were overestimated (Wei et al., 2014). A comparison of the original NARR precipitation with measurements has shown that the amount and frequency of large rainfall events in NARR precipitation were underestimated (Sun and Barros, 2010). Although the rescaled NARR incoming shortwave radiation and precipitation were shown to improve the original NARR, in this study we identified biases at some of the sites as described earlier in Section 3.1 that affected modeled NEP to sufficient extents that further improvements are needed (e.g. Fig. 5(c, d and h)).

Although NARR incoming shortwave radiation was well correlated with measurements, underestimation of more than 10% in some sites, (e.g. DL, Table 4) could reduce soil heat and water transfers and hence reduce the rate of CO_2 fixation by lowering T_c and T_s. Seasonal patterns of modeled NEP could also be controlled by variations shown in NARR vs. measured precipitation, apparent in variations in total annual precipitation and SD (Table 4). These variations control NEP by directly controlling the amount of soil moisture available for plant uptake and indirectly affecting the availability of nutrients. For instance, CA-Soa 2001/2003 NARR precipitation had higher summer values than measured (Fig. 4(e and f)) which caused higher SD of NEP from EC values (Table 4) than did site precipitation (Fig. 8). Similar to the NARR $T_a$and incoming shortwave radiation, the relative differences of NARR vs. measured precipitation and their effects on modeled NEP varied among sites (Fig. 4).

4.3. Gridded soil attributes that control NEP deviations

UNASM soil attributes such as maximum soil depth and SOC, as well as SON which was estimated independently from UNASM SOC, were shown to affect NEP for most of the sites as demonstrated from the deviations of *simulation-p*compared to *simulation-s* shown in the Taylor diagrams (Fig. 5). McKenney and Pedlar (2003) reported a decline in modeled productivity of jack pine and black spruce when replacing measured soil properties with coarser scale soil properties and this was particularly attributed to shallower soil depth of the coarser dataset across much of the northern forests of Canada. This result corroborated our findings at CA-Soa, DL, US-Dk3 and Mead in which UNASM had shallower soil depth compared to measured soil (Table 5). These effects of shallower soil depth were shown to reduce productivity in some of the sites (e.g. CA-Soa) by reducing soil water storage, hastening soil drying (Fig. 9(a1 and b1)), lowering ψ_s and water uptake, hence lowering NEP (Fig. 9(a2 and b2); Table 6). Soil databases that were used to make UNASM in the higher latitudes such as SLC version

3.2 and Harmonized World Soil Database (HWSD) version 1.21 had much smaller maximum soil depth values than measured. There were also significant differences in total SOC between UNASM and measured soil inputs (Table 5) and between estimated and measured SON that directly affected the amount of available nutrients hence ecosystem productivity (e.g. Fig. 11(a3 and b3)).

4.4. Implications of biases in gridded datasets to modeled NEP

Although effects of NARR and UNASM on NEP were shown at a pixel scale of the gridded datasets, it is apparent that the effects could be reflected in model estimates when scaled-up and that would certainly affect the regional and continental carbon budget estimates. These impacts at regional scales could have direct implications when modeling the impacts of climate change on ecosystem productivity. Studying the impacts of climate change on ecosystem productivity at regional scale under future climate requires a well-tested TBMs. Thus, examining gridded model drivers as one of the main sources of uncertainties in modeling regional scale land-atmosphere carbon exchange has a direct implication in evaluating model performance, hence the ability to study climate change impacts. While improving of model structure and parameterization of TBMs is crucial, evaluating model performance need to consider uncertainties associated with the model drivers itself. Ecosystem modelers need to test gridded model inputs against measured values at selected pixels before implementing regional runs to isolate systematic biases in the gridded model inputs which may be rescaled and calibrated to reduce inaccuracies.

Biases in UNASM and NARR can have important implications when applied at regional scale. For instance, although the effect of gridded SON (e.g. CA-Qfo in Fig. 11(a3 and b3)) was modeled to overestimate NEP at the site scale, it has important implications, as the site represents an ecosystem (boreal black forest) widely distributed across boreal NA. Lack of detailed information on soil physical and hydraulic properties and vertical multi-layer profiles in UNASM affected simulation of sub-surface movement of water and of available soil water for plant uptake, hence CO_2 fixation. For instance, at CA-Soa 2001 (Fig. 7(a2)), NEP was underestimated as a result of shallower soil depth in the gridded simulation. UNASM maximum soil depth were less than what was measured at CA-Oas site hence key responses of the model to extreme climate events such as drought was not well captured (Fig. 7(a2)), hence NEP was underestimated. Lack of deeper soil vertical profile in UNASM could limit responses of modeled rooting depth to climate change, particularly at higher latitudes where rooting depth is determined by deepening permafrost which is explicitly modeled in *ecosys*. Deepening of the active layer depth as a result of warming is a key climate change feedback in permafrost regions that can release large volume of stored carbon to the atmosphere as a result of increasing ecosystem respiration. Better representation of SOC through soil profiles is also crucial to better simulate climate change feedbacks in higher latitudes. Although these biases could be localized, it can certainty have important implications in our ability to model and understand regional and global carbon cycle and climate change impacts, thus need to be carefully examined. There was no systematic bias in over/underestimations of fluxes from site vs. gridded simulations. Thus, under/overestimation of fluxes among pixels would possibly compensate each other, thereby smoothing out and reducing the overall impacts of the gridded model inputs on carbon estimates at regional and continental scales. Nevertheless, these differences in modeled NEP associated with the quality of gridded model drivers that we tested for the selected EC sites at grid cell level would certainly be reflected at regional scale and could affect continental carbon budget estimates and need to be carefully examined.

Testing uncertainties in modeled NEP related to gridded weather and soil provided valuable information on limitations on continental scale carbon budget estimates. This rigorous testing has provided a basis to examine the extent to which accuracies in the continental scale simulations of land-atmosphere carbon exchange were subject to the combined effects of gridded weather and soil, besides the uncertainties in the inherent model characteristics. Such testing has a direct implications in simulating the impact of climate change on NEP over a wide range of biomes and have allowed us to see the limitations in NARR and UNASM. Moreover, it also provided confidence that key responses of the modeled NEP to changes in climate were reasonably maintained.

5. Conclusion

NEP differences attributed to gridded vs. measured model inputs varied among sites when tested against EC-derived values (Fig. 5). The degree of agreements between the NARR and site T_a were shown to be generally high enough (Fig. 2) that the NEP modeled under contrasting weather could be reproduced with NARR with an accuracy similar to that with measured weather for most of the sites (e.g. Fig. 6). Incoming shortwave radiation was slightly underestimated for most of the sites, hence needing further improvements (Fig. 3). Deviations in precipitation intensity should also be improved (Fig. 4), as accurate temporal distribution of precipitation determines water availability for plant growth. Possible inaccuracies in wind speed and relative humidity should also be carefully examined in gridded datasets.

Lack of detailed and deeper UNASM soil vertical profiles affected modeled NEP at most of the sites, especially by reducing WHC and hence θ during extreme weather events such as drought as demonstrated at CA-Soa 2001 (Fig. 7(a2)). Total SOC content of UNASM was also varied from what was measured at the sites (Table 5). Besides, UNASM did not include SON and therefore, incorporating this attribute in the database is important to better estimate available soil nitrogen, hence NEP.

These differences in modeled NEP associated with the quality of gridded model inputs that we tested for the selected EC sites at grid cell scale would certainly be reflected at regional scale. Therefore, further refinement of these gridded datasets to improve their accuracy, spatial and temporal resolutions and better representation of sub-pixel spatial heterogeneity is essential for improving estimates of carbon fluxes, hence our understanding of the carbon cycle at regional and global scales.

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Appendix A. Supplementary data

The following are the supplementary data to this article:

Download Word document (231KB)Help with docx files

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