3.4 MODELING LONG-TERM CARBON EXCHANGE IN AN OLD-GROWTH TEMPERATE RAIN FOREST.

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1. INTRODUCTION

This paper includes results from a six-year comparison between observed and simulated $[CO_2]$ profile and flux estimates and associated meteorological quantities over an old-growth temperate rainforest in western North America using a highly sophisticated land surface process model. The Wind River Canopy Crane Research Facility (WRCCRF) is unique among AmeriFlux sites due to the height, age, and structural complexity of the canopy and provides a rare opportunity to investigate carbon cycling in such ecosystems.

2. METHODS

The Wind River Canopy Crane Research Facility (45.82 N, 121.95 W, 371 m a.s.l.) is located in a 450-500 year old temperate, coniferous forest at the T. T. Munger Research Natural Area in southern Washington. Douglas-fir (*Pseudotsuga menziesii*) and western hemlock (*Tsuga heterophylla*) dominate the site, at maximum (average) heights of 65 m (52 m) and 55 m (19m), respectively. See Paw U et al. (2004) for a complete description of the site and how measurements were gathered. Wharton, Falk, and Paw U, also presenting, provide additional information.

WRCCRF data availability percentages for each year, based on instrument failure alone, ranges from 86% (1999) to 95% (2003). Gap filling missing values involved applying the methodology described in Falge et al. (2001) for missing data. For low-wind half-hours that fall below the ustar Nocturna EC NEE (respiration) estimates are replaced with Q_{10}-derived values during low-turbulent conditions before gap filling occurs. Standard error estimates using this u_*-correction method range from ± 15 gC m^{-2} yr^{-1} (2002) to ± 27

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gC m^{-2} yr^{-1} (2003). Gap-fill errors are around ±15 gCm^{-2} yr^{-1} for this site using guidance from Falge et al. (2001). Thus total errors are between ± 30 and ± 50 gCm^{-2}yr^{-1} for the 1999-2004m period.

The University of California, Davis Advanced Canopy-Atmosphere-Soil Algorithm (ACASA) is a multi-layer regime through which exchanges of energy, mass, and momentum occur between ecosystem canopies, rock/soil/snow/ice/water, buildings, etc. and the atmosphere. Though the full set of governing equations of ACASA can be drawn from a number of sources (e.g. Meyers 1985, Paw U and Gao 1988; Su *et al.* 1996; Pyles 2000), these are listed together in Pyles *et al.* (2000). Major changes to ACASA have been added since and are summarized below.

Photosynthesis in ACASA treats plant physiological response to environmental conditions using a combination of the Ball-Berry stomatal conductance (Leuning 1990; Collatz *et al.* 1991) and the Farquhar and von Caemmerer (1982) photosynthesis equations. Moisture stress is invoked when soil moisture where most roots are present falls below a critical wilting threshold (20% water content at 0.3m depth for WRCCRF).

Respiration in ACASA is estimated by considering leaf, stem, root, and soil microbial respiration separately, each as functions of tissue/soil temperature and independently measured Q10 relationships for each (McDowell *et al.* 2006; Harmon *et al.* 2004)

Values of *k* and total surface area appearing in Table 1 are adapted from McDowell *et al.* (2006) and Harmon *et al* 2004. Here, root area index (RAI) is roughly equivalent to leaf area index (LAI), while total stem area index (SAI) is roughly 42% of LAI (Parker 1997). Both LAI and SAI change with height in the canopy, and RAI changes with depth into the soil.

Unstressed r_i values are attenuated in a parabolic fashion when the soil moisture at the depth of maximum root activity falls below a critical wilting threshold (0.22 for this site). Respiration values for each canopy layer are the weighted sums of contributions (r_i) from dry, wet, and/or ice

1

covered canopy elements at each leaf angle class, both sunlit and shaded. The same is true for stem respiration, but bark and bole temperatures are used instead. Total root respiration is the weighted sum of $r_i(T_{soil})$ values calculated for each soil layer and weighted by root amount. The same also holds for soil microbial respiration.

3. RESULTS AND DISCUSSION

Overall, ACASA appears to estimate NEE in a manner that is consistent with observations, despite there being high interannual variability in forcing conditions. Figure 1 contains scatter diagrams for both daily and monthly accumulated NEE for 1/1/1999-12/31/2004. As one would expect, the scatter in the daily values is greater than for the monthly counterpart. There appears to be a tendency for observed daily totals that are extreme to show more variation than their ACASA counterparts, but the total number of these points falling outside of the uncertainty locus (shaded grey region) is less than 15% of the total (Fig 1b). The monthly plot looks more consistent by comparison, owing to the tendency for daily observed-model discrepancies to cancel in the monthly sums. In both instances, however, the linear regression slopes are close to unity.
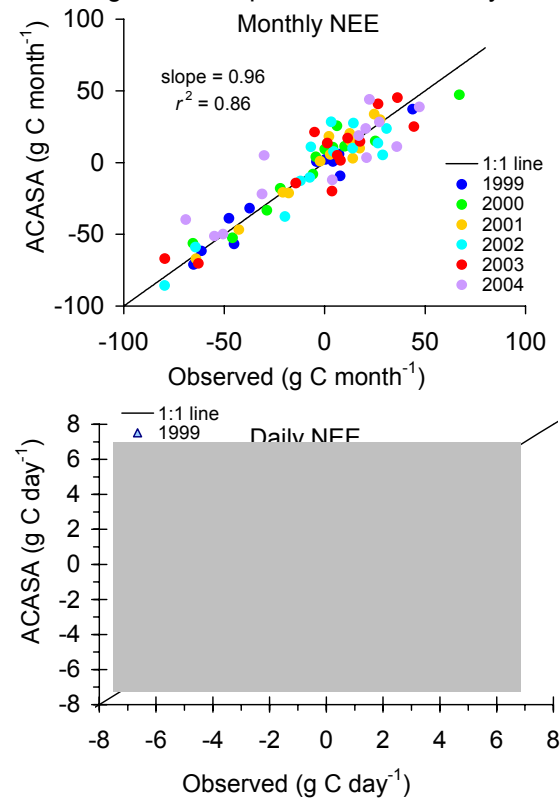
Fig. 1: Monthly (top) and daily (bottom) Cumulative NEE for 1/1/1999-12/31/2004.

Figure 2 shows modeled and observed results of cumulative NEE vs time for each year 1999-2004. In each year, annual differences were within observational uncertainties calculated for this site. There are some model-observation disagreements, seen as skewing ACASA-observed lines in the cumulative NEE plots (Figure 2), that seem to last on the order of weeks, namely during times of late summer or fall when the system is undergoing phenological transitions punctuated by sporadic rain events. The forest ecosystem at WRCCRF is likely to be complex and varied enough in species diversity, such that to model it effectively requires much more information that we have currently.

Periods of significant drought and excessive heat are frequent after 2000 (Fig. 3). Both ACASA and observations suggest that during 2003 (and possibly 2004), the ecosystem released more carbon than it absorbed. Values for 2003 suggest that biological productivity was moderate-at best. Though moisture was somewhat normally abundant, abnormally high temperatures in 2003-4 increased the overall metabolic rates of plants and microbes enough to spend down most of the sugar produced both years (Fig. 4).

values exhibit a nontrivial pulse in $[CO_2]$ that switches in sign with height. This can be seen also in the composite profiles taken from early evening hours when these differences are apparent as a marked burp after 6pm in the composite time series (Figure 3).
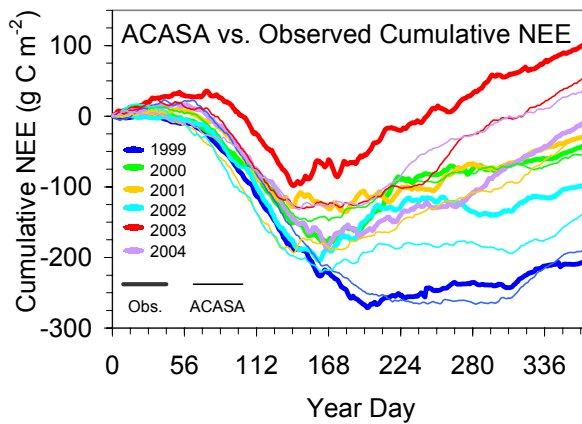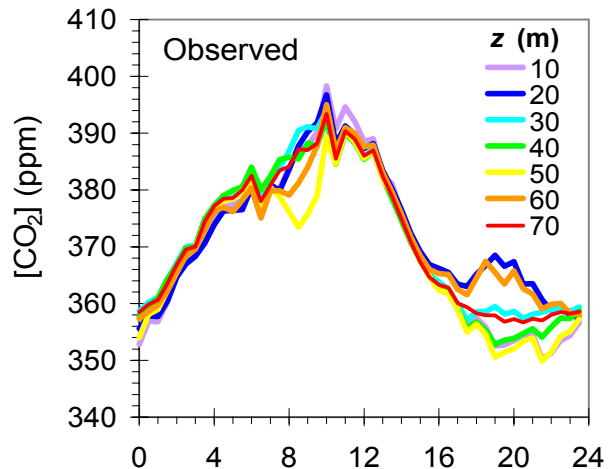

Fig. 2: Observed and modeled cumulative NEE for each year 1999-2004.

Observed carbon dioxide concentrations measured at 10 m intervals within the canopy are compared with ACASA values interpolated to corresponding heights (as each ACASA layer is 6.7 m). Values are shown in Figure 3. The time series used here runs run from June 19-June 26, 2002 in 30-minute intervals. Overall, the two sets of estimates compare well, with a linear regression coefficient of determination exceeding 0.90 at most levels. Variations are subtle, often less than 5 ppm between 20 and 70 m values. Such a result is noteworthy as there are both active sources and sinks of CO_2 throughout the forest. It implies that the system is close to equilibrium despite the vertical stratification of metabolic activity common in late-succession forests.

Throughout most of the day, both observed and modeled $[CO_2]$ values show modest variations in the vertical, except for a small number of noteworthy instances. Several marked departures can be seen in Fig. 3, especially during midmorning and evening hours, when observed
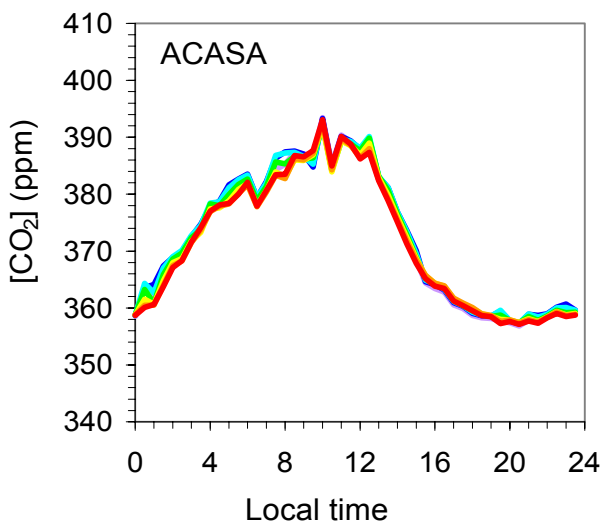
nocturnal regime to an unstable daytime pattern in surface-layer turbulence is an unlikely source of this pattern, since a similar trend in 70 m values does not appear as one would expect if this were the case.

ACASA values show none of these patterns, which is the main contributor to observed –ACASA differences (Fig. 3). As a single point model that does not handle advection, it stands to reason that ACASA would not reflect such trends. Comparing ACASA and observed values for times other than late morning/early evening shows remarkable agreement, with differences at all layers statistically negligible at the 95% confidence level.

4. CONCLUSIONS

NEE for an old-growth temperate rainforest has been measured and simulated for 6 continuous years. Broad agreement between model and observed estimates occurs throughout the period, with annual totals comparable within observational uncertainty ($\pm$ 30 gC m^{-2} yr^{-1}). There is considerable year-to-year variation in NEE in both the model and observed results, which appear to be related mostly to temperature variations and the timing of precipitation events.

Positive 2003 NEE values, both observed and modeled, appear to be the result of both excessive heat and drought, with a rapid shift to respiration-dominance appearing by early June. This result suggests that the net ecosystem sourcing of carbon from the European continent that occurred in 2003 (Ciais *et a*l 2005) may have been more widespread than continental Europe.

Comparisons of carbon dioxide concentrations within the canopy for June 19-26, 2002 show that ACASA and observations agree within 95% confidence except for brief periods in the mid-morning and evening at some levels. These evening differences may be related to advective or other nonturbulent processes that occur as thermal inversions and unstable layers develop within the canopy.

That 2003 was a net source year is in sharp contrast to 1999 and 2002, where abundant moisture allowed for photosynthesis to dominate well into July. These latter results have ominous implications for ecosystem health if such anomalous trends in heat and precipitation persist or worsen in the future. Areas which we have assumed to be (and rely upon) being either neutral or net sinks of carbon may become net sources instead, setting up a dangerous positive feedback cycle between climate instability, deteriorating

Figure 3: Composite-averaged diurnal plots of observed (top), and ACASA (bottom) [CO$_2$] for the 7 tower levels over the period June 19-26, 2002).

This reversal in sign in the vertical could represent multidirectional, laminar flows as the canopy environment becomes layered with both stable and unstable layers in the evening (Pyles *et al.* 2000, 2004). One physical explanation for this could be CO$_2$-poor air flowing downhill from elevated areas that are cooler (less respiration), sliding along into the midcanopy at lower elevations as compressional heating raises the isentropic glide somewhat off the ground.

Another observed blip in observed [CO$_2$] occurs in mid-late morning, this time a drawdown of CO$_2$ at 50 m and 60 m relative to layers above and beneath. This observed pattern also seems robust and unrelated to instrument error, and may be linked to trees photosynthesizing as if they had been refreshed from a night of sugar and nutrient re-allocations. Entrainment from switching from a

ecosystem health, and rising carbon dioxide concentrations.

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