Simulated and Observed Fluxes of Sensible and Latent Heat and CO_2 at the WLEF-TV Tower Using SiB2.5

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ABSTRACT

Three years of meteorological data collected at the WLEF-TV tower were used to drive a revised version of the Simple Biosphere Model (SiB 2.5). Physiological properties and vegetation phenology were specified from satellite imagery. Simulated fluxes of heat, moisture and carbon were compared to eddy covariance measurements taken onsite as a means of evaluating model performance on diurnal, synoptic, seasonal, and interannual time scales. The model was very successful in simulating variations of latent heat flux when compared to observations, slightly less so in the simulation of sensible heat flux. The model overestimated peak values of sensible heat flux on both monthly and diurnal scales. There was evidence that the differences between observed and simulated fluxes might be linked to wetlands near the WLEF tower, which were not present in the SiB simulation. The model overestimated the magnitude of the net ecosystem exchange of CO_2 in both summer and winter. Midday maximum assimilation was well represented by the model, but late afternoon simulations showed excessive carbon uptake due to misrepresentation of within-canopy shading in the model. Interannual variability was not well-simulated because only a single year of satellite imagery was used to parameterize the model.

1. Introduction

The land-surface is an important source and sink of radiation, sensible heat, water, momentum, and trace gases to the atmosphere. A parameterized representation of these exchanges is an important component in all climate and weather models (Betts et al., 1996). Land-surface parameterizations have undergone tremendous development in the past decade, and now include a much greater degree of biophysical realism and self-consistency than was being used just a few years ago (Sellers et al., 1997). Biophysicallybased land-surface parameterization has been shown to lead to better ability of numerical weather prediction (NWP) models to forecast weather under extreme climatic conditions such as droughts (Atlas et al., 1993) and floods (Beljaars et al., 1996). Land-surface parameterization is an important part of the numerical weather analysis and forecasting infrastructure at the European Center for Medium-Range Weather Forecasting (Viterbo et al., 1995). Land-surface predictions can also be used to evaluate the accuracy of and develop better parameterizations for assimilation of weather and climate data (Betts et al., 1998).

A new generation of land-surface parameterizations has emerged in recent years in which exchanges of water and heat at the vegetated land surface are linked to exchanges of CO_2 (Sellers et al., 1997). This linkage is based on the fact that physiological control of evapotranspiration by plants is an evolved optimization mechanism that seeks to maximize carbon fixed by photosynthesis (by drawing CO_2 into leaves through stomatal pores) and yet reduce water loss from the plant (by closing stomata). The representation of this linkage in land-surface parameterizations has been shown to improve the simulated diurnal cycle of temperature and humidity. It also allows key parameters controlling surface exchanges to be related to the spectral reflectance characteristics of vegetation (Sellers et al., 1996a,b). This carbon-water linkage also opens the door for the models to predict the flux of CO_2 in a self-consistent way with simulated surface energy exchanges and turbulent and convective transport in the atmosphere. By coupling photosynthesis and energy flux calculations with an atmospheric transport model Denning et al. (1996a,b) were able to achieve a greater degree of realism in simulated diurnal and seasonal variations of CO_2 than had previously been possible.

Atmospheric trace gas concentration fields contain information about the surface exchanges of these gases. This information can be interpreted using numerical transport models to deduce large-scale sources and sinks of CO_2, for example. A recent “inversion” study of this kind (Fan et al., 1998) suggests that biological processes at the land surface currently remove an enormous amount of CO_2 from the atmosphere over North America. Similar analyses by other modeling groups have found the North American sink to be much smaller (Bousquet et al., 1999a,b; Rayner et al., 1999, Gurney et al., 2001). Such analyses depend sensitively on the representation of the linkages among photosynthesis, heat fluxes, convective motions, and large-scale transport in the atmospheric models (Denning et al., 1995, 1996b, 1999). Realistic land-surface parameterizations are therefore crucial for interpreting large-scale CO_2 concentration fields in terms of the locations and processes responsible for the fluxes of greenhouse gases.

In this paper, we evaluate the performance of a land-surface parameterization (SiB2.5) that has been used in an atmospheric GCM and in a mesoscale atmospheric model. Unlike some previous studies comparing SiB performance to observations (Sellers and Dorman, 1987; Sellers et al., 1989; Colello and Grivet et al., 1998; Sen et al., 2000), we made no effort to “tune” model parameters to improve the agreement with the observations. Parameters were specified using the methods of Los et al. (2000) with the following adjustments: When using 1km AVHRR data, a representative footprint is extracted from each of the twelve months and the time varying calculations as well as the respiration calculation are performed on the average NDVI for that footprint. This footprint is meant to incorporate the primary source region of the measured fluxes, and is based on Large Eddy Simulations conducted by Marek Uliasz (Colorado State University, personal communication) and the prevailing wind direction at the site. For the 122m footprint a 24 km^2 region was extracted from the 1km NDVI data. The state of the canopy in the model therefore represents our best ability to represent the actual canopy as derived from remote satellite observations and soil/vegetation maps, and is analogous to the use of the model to simulate regional fluxes when coupled to a mesoscale model (see Denning et al., this issue) or a global model (see Denning et al., 1996b).

2. **Methods**

Model Description

The Simple Biosphere (SiB) Model, originally developed by Sellers et al. (1986), was substantially modified (Sellers et al., 1996*a*), and has since been referred to as SiB2. The number of biome-specific parameters was reduced, and most are now derived directly from processed satellite data (Sellers et al., 1996*b,c)* rather than prescribed from the literature. Another major change is in the parameterization of stomatal and canopy conductance used in the calculation of the surface energy budget over land. This parameterization involves the direct calculation of the rate of carbon assimilation by photosynthesis (Farquhar et al., 1980), making possible the calculation of CO_2 exchange between the global atmosphere and the terrestrial biota on a time step of several minutes (Denning et al., 1996*a*,*b*; Zhang et al., 1996). Photosynthetic carbon assimilation is linked to stomatal conductance and thence to the surface energy budget and atmospheric climate by the Ball-Berry equation (Collatz et al., 1991, 1992), which is the basis for the ability of the model to calculate the climatic effects of physiological responses to elevated CO_2 (Sellers et al., 1996*c*). Soil respiration is calculated from the temperature and moisture of each layer of soil, and is scaled to achieve carbon balance over an annual cycle (Denning et al., 1996a). Recent improvements include the introduction of a 6-layer soil temperature submodel based on the work of Bonan (1996, 1998), and a revised surface energy budget that includes prognostic temperature and moisture in the canopy air space reservoir. We refer to the revised model as SiB2.5.

Modeled fluxes of heat, water vapor, and carbon are derived not only from meteorological drivers (temperature, humidity, wind and precipitation) but are also highly dependent on the characteristics of the canopy vegetation and soil type. In midlatitudes especially, leaf area index is highly correlated with carbon flux, and soil type has a strong impact on heat and water fluxes. A major difference between SiB2.5 and many other land surface schemes is in the specification of vegetation and soil parameters. These parameters are commonly specified as monthly values tied to vegetation type through a "look-up table," (e.g., Bonan, 1998) whereas SiB specifies leaf area index (LAI), absorbed fraction of photosynthetically active radiation (FPAR) and greenness fraction from normalized difference vegetation index (NDVI) derived from satellite imagery. The result is that although SiB defines a small number of biome types within its parameter set, use of the observed NDVI values creates spatial heterogeneity in canopy properties even over large areas of vegetation classified as a single type.

Vegetation and soil physical parameters were specified as described earlier, using a combination of land cover type (Hansen et al., 2000), monthly maximum Normalized

Difference Vegetation Index (NDVI) derived from Advanced Very High Resolution Radiometer (AVHRR) data (Teillet, et al., 2000) and soil properties (STATSGO, 1994). Time invariant vegetation biophysical parameters such as canopy height, leaf angle distribution, leaf transmittance and parameters related to photosynthesis, are based on values recorded in the literature and assigned via look-up tables. Time varying vegetation biophysical parameters such as leaf area index and fractional absorbed photosynthetically active radiation are calculated from one year of NDVI monthly maximum value composites for the site. The time varying parameters are based on equations in Sellers *et al*. (1996b) and Los *et al*. (2000). Soil hydraulic and thermal parameters are calculated from the percent of sand and clay in the soil using the equations from Clapp and Hornberger (1978).

The choice of observation height was an important consideration for preparation of the boundary conditions. NDVI data was available as monthly images with 1-kilometer resolution, but the "footprint" or area of canopy seen by the tower instrumentation was dependent on instrument height as well as wind speed and direction. For each month and measurement height, an average wind speed and direction was determined, and influence functions taken from mesoscale modeling studies were used to determine which pixels from the NDVI image should be used. Both the areal coverage and orientation around the tower site were taken into consideration. The chosen NDVI image pixels were then averaged together to obtain a mean NDVI value, which was passed into the code that produced the boundary condition data.

Observational dataset

The WLEF-TV tower is located in north-central Wisconsin, USA, near the town of Park Falls. The tower is a 447-meter tall television transmitter (WLEF TV 45^{o}55'N, 90^{o}10'W) located in the Chequamegon National Forest, 14km east of Park Falls. The region is in a heavily forested zone of low relief. The region immediately surrounding the tower is dominated by boreal lowland and wetland forests typical of the region. Much of the area was logged, mainly for pine, during 1860-1920, and has since regrown. The concentration of CO_2 has been measured continuously at 6 heights (11, 30, 76, 122, 244, and 396 m above the ground) since October 1994, and CO_2 flux has been measured since May 1995, and at three heights (30, 122, and 396 m) since early 1996 (Berger *et al*., 2001). Micrometeorology and soil temperature and moisture data are collected at the site or at the nearby USDA Forest Sciences Laboratory. These measurements have been reported by Bakwin *et al*. (1998) and in many of the companion papers in this special issue.

The meteorological measurements required to drive SiB2.5 include near-surface temperature, humidity, incoming solar and long-wave radiation, wind speed and precipitation. For this study these data were defined directly using measurements averaged at 30-minute intervals at the tall tower site. Incoming long-wave radiation was not measured, so the method of Idso *et al*. (1981) was used to estimate long-wave radiation from air temperature and humidity. The driver data were incomplete because of intermittent instrument or data-logger failures. Since the model requires unbroken series of driver data, data gaps were filled using a hierarchical set of methods that included interpolation within the data set and use of alternative measurements made at the WLEF site and at a nearby meteorological station (Willow Springs).

The gap-filling sequence included, in order of preference: (1) temporal interpolation within the data stream for gaps of less than 2 hours, (2) use of data from an alternative height on the WLEF tower, with adjustment for systematic differences caused by height, (3) use of data from Willow Springs, with adjustment for systematic differences caused by location, (4) use of an average for the time of day of missing measurements, using data from the previous and following 15 day period, and (5) use of an average for the time and date of missing measurements, using data from the previous and following 15 day period, in the same year and any other available year. In methods (2)-(5) the mean adjustment and averages were calculated, with standard deviations, using measurements at that time of day during the 15-day period before and after the time and date of the missing measurement. To increase confidence in the filled data, methods (2)-(5) were not used if the variability of the adjustment or average was more than a threshold value (defined as standard deviation/mean = 2.0). In the case of solar radiation and precipitation, where multiple measurements were not available on the tall tower, method (2) was not available. In the particular case of precipitation, the spatial and temporal variability of the process is such that no adjustment for location was attempted and measurements at Willow Springs were used directly during data gaps at WLEF. During the wintertime, the WLEF and Willow Springs gauges had problems recording snowfall events. To produce more accurate snowfall driver data, snowfall observations from Rhinelander WI (40 miles southeast of the WLEF tower) were used to determine wintertime precipitation driver data. The daily observation of Rhinelander precipitation provided no information as to the intensity breakdown during the previous 24 hours, and so was divided into equal hourly increments with the assumption that winter precipitation would be generally stratiform in nature.

For the present study, SiB was run in offline mode to compare model fluxes with WLEF observations taken between 1997 and 1999. 122 meters was used as the “above-canopy” height, and data recorded at that level as the driver data for SiB. The WLEF dataset provided a large number of observations of sensible (H) and latent heat (LE), as well as net ecosystem exchange (NEE) of carbon between the canopy and the boundary layer. Net Ecosystem Exchange (NEE) and latent and sensible heat fluxes were calculated for 3 levels (30m, 122m, and 396m) on the tower, with a correction term added for heating/moistening of each layer. Because of the multiple-level and high-altitude flux and mixing ratio data, as well as clearing around the base of the tower, an algorithm was developed that selected one or more of the multiple measurements for each hourly flux value. Data were taken from 122 and 396 meters under strongly unstable conditions (surface sensible heat flux greater than 100 W/m^{-2}), and from 30 meters under stable to slightly unstable conditions. If the preferred levels were missing, data was taken from any existing turbulent flux level. One and two missing holes were interpolated. Observations were taken hourly, while SiB output was averaged from the 10-minute model time step to hourly output, to correspond with the observational time step.

3. Results and Discussion

The model results presented here are ‘untuned’, in that no directly observed canopy information is used. All vegetation and soil parameters were obtained from satellite information and previously published maps. Model output was analyzed as is, we did not iterate through runs and modify model parameters until the best match to the observations was found. We looked at model output across temporal scales from time series of individual days to monthly diurnal composites and monthly means.

a. *Synoptic and Diurnal Scales*

During the summer months, both respiration and assimilation fluxes reached their largest values of the year. Warm, moist soil provided optimum conditions for respiration, and by June (all years) the canopy was in full leaf and the greatest leaf area index (LAI) values of the year were seen. SiB performance during the summer months (June, July and August) was quite reasonable with regards to LE and NEE, but model H exceeded observed values by a considerable margin. Figure 1 shows diurnal composites of monthly LE for the three years simulated. Simulated fluxes capture the observed variation with no obvious bias. The exception to this is 1998, when the model was transpiring normally while the actual forest was drying out. In that year the forest around WLEF came into full leaf early in the season, and dried out during the summer-by late June the forest floor was ‘crunchy’ when walked upon (Davis, personal communication). In the model simulations there was no water stress on the vegetation during this time, suggesting that the model was transpiring normally while the ‘real world’ was drying out.

The simulated sensible heat flux (Figure 2) did not compare well with observations in the summer months. The best comparison between modeled and observed H was in 1998, when the forest was dry. Observed sensible heat flux peaks in July were almost double the values seen during 1997 or 1999, and August 1998 H flux was high as well. In other years the simulated daily peak values exceed observed, sometimes by a factor of 2 or more.

Hourly composites of summertime daylight Bowen ratio are shown in Figure 3. In 1997 and 1999 SiB values are approximately twice observed, while in 1998 simulated and observed Bowen ratios are similar. Some explanations for the Bowen ratio discrepancy, when taken with the data from Figures 1 and 2, are (a) systematic overestimation of net radiation in SiB, possibly resulting from underestimation of the broadband solar albedo; (b) underestimation of heat flux into the soil by SiB; (c) underestimation of observed sensible heat fluxes by the eddy covariance system; or (d) some combination of these explanations.

Several authors (Davis *et al*., this issue; Twine *et al*., 2000; Desjardins *et al*., 1997; Mahrt, 1998) have noted that observed latent and sensible fluxes are generally under-measured by 10-30% by eddy covariance instruments at flux towers, and that observed energy budgets often fail to achieve closure. However, across-the-board increases of H and LE will not result in more a favorable comparison between model and observations, which is easily seen in Figures 1 and 2. That the observed and simulated Bowen ratios often differ by a factor of 2 (Figure 3) suggests that there are fundamental differences between the energy partition in the model and that observed at the tall tower.

By design, the energy budget within the model is perfectly balanced (R_n – H – LE – G = 0). Simulated LE was generally in good agreement with the observations, yet simulated H was often much greater than observed. This implies that either R_n was overestimated in the model, or G was underestimated, or both. Net radiation measurements made at the base of the tall tower don't represent the forested ecosystem that defines the flux footprint, since they are made less than 2 m above the mowed grass clearing in which the TV tower is anchored. Radiative forcing was applied to SiB using measurements of downward solar and estimated longwave radiation at the tower. Solar radiation was parsed into visible and near-IR components, and radiative transfer within the model was computed using a two-stream approximation (Sellers, 1985). For several months in 1998, data from a four-component radiometer were available for a forested site close to the WLEF tower (Willow Creek).

The model underestimates reflected July solar radiation by about 60 W m^{-2} at mid-day in the monthly mean (not shown). This error was due to underestimation of albedo (9.3% at mid-day in SiB vs. 16.5% at Willow Creek), which is not too surprising given the heterogeneous vegetation cover in the area-the mowed grass where the observations were taken would have considerably less albedo than the forest. Downward longwave radiation exhibits more diurnal variation in the observations than in the prescribed meteorological driver data (derived from air temperature and humidity), and upward longwave in the model was greater than the observations during the day. These errors largely cancel the error in reflected solar radiation, with the result that the model captures the average diurnal variations in the net radiation components very well (top panel, figure 4).

The energy balance can be evaluated using the four-component radiometer, the latent and sensible heat flux data (all from figure 4), and the energy closure assumption

$$G_{implied} = R_n - H - LE$$

to calculate an implied ground heat flux for the observations. The net radiation (R_n) and latent, sensible and ground fluxes are shown in figure 4. The ground heat flux is explicitly calculated in SiB, while energy budget closure is assumed to obtain the observed $G_{implied}$. In July 1998, the diurnal composite of model G peaks at around 60 W m^{-2} shortly after sunrise, then slowly drops to near zero by sunset. Observed $G_{implied}$ remains at zero until two hours after sunrise, then rises to near 200 W m^{-2}at midday, which is quite high, even with the assumed under-estimation of H and LE factored in.

Simulated values of *G* may also be too weak. Observations of soil temperature were taken at the surface as well as 5, 10, 20 and 50cm depths. Figure 5 shows the temperature profiles for the observational and SiB data, as well as the difference between the surface and 50 cm depth. SiB soil temperature data was interpolated to match observation depths. A notable difference between the simulated soil temperature and observations is the timing of extrema: monthly mean observed soil temperatures attain their highest (and lowest) yearly values in the same month for all levels. The SiB data revealed an offset of one to two months between extreme values at the surface and at depth. Also, the strength of the temperature gradient in the observed soil is much smaller than simulated. A 10-15 C difference between the surface and 50cm is common in the model in both summer and winter, while the observed gradient rarely exceeds 5 degrees. The strong thermal gradient in the model suggests that heat flux within the soil is unrealistically weak.

When under-estimation of observed fluxes is taken into account, then the SiB-tower comparison emerges as follows: Model LE is close to or even slightly smaller than observed, model H is much larger than observed, and observed G is much larger than simulated. A potential explanation from these differences may lie in the wetlands in the region of the WLEF tower. In a comparison of aircraft with tower data at BOREAS (Desjardins *et al*., 1997), it was noted that the aircraft fluxes were generally smaller than those observed at a tower due to the fact that the tower was located in a dry area, while the aircraft flew over both dry and wetland areas. The tower in the BOREAS study was only 20m tall, and the suggestion was that the tower footprint encompassed mostly dry upland areas, while the aircraft flew over wetlands more representative of the region. In the BOREAS study the wetlands LE sampled by the aircraft was similar to or larger than the LE observed at the 'dry' tower, while wetlands H was much smaller. At WLEF, the tower is tall enough (fluxes sampled at 30, 122 and 396 meters) that the footprint is on the order of 24 km^2 (Uliasz, personal communication), and therefore contains some of the considerable wetlands that surround the tower. In SiB, however, wetlands are not simulated. Model phenology is determined by vegetation maps, which do not currently contain wetlands as a vegetation type.

Figure 6 shows a time series of 3 days in July 1997 (Julian days 184-186). On the first day (184) conditions were cool and rainy. Model and observed H and LE compare quite closely with each other, likely because all surfaces were wet and differences between the observed canopy/wetlands and model canopy would be minimized. Rainfall ended on the morning of day 185, and while large latent heat fluxes were observed, the model partitioned more of its energy into sensible heat. This is likely due to the fact that runoff that would form pools and puddles (in addition to any wetland within the flux footprint) in the observed forest is removed immediately from the model once it exceeds storage capacity limits. As the area dries out by day 186, the flux comparison more closely resembles monthly mean values, where model LE is similar to observed and model H is much larger.

The mean diurnal cycles of simulated CO_2 flux compared favorably with observations during the summer months (Figure 7). In general SiB captured the behavior of the initial drawdown of carbon following sunrise, although it showed a slight tendency to overestimate morning carbon flux into the canopy. Daily peak assimilation rates were simulated quite well. In many months SiB exhibited excessive respiration at night (June 1997 being the exception), and SiB had a tendency to maintain vigorous photosynthesis and assimilation of carbon well into late afternoon, at times when the observed canopy carbon flux was near zero or even positive.

During the growing season, the model consistently simulated excessive photosynthesis and transpiration in the late afternoon, after the observations showed decreased canopy activity. SiB treats canopy radiative transfer using a two-stream approximation for the calculation of heating rates (Sellers *et al.*, 1985). The leaf-to-canopy scaling of photosynthesis and stomatal function assumes diffusive extinction, however (Sellers *et al.*-, 1992, 1996). Yet direct beam illumination should be attenuated more immediately in the upper canopy. Directly illuminated leaves are likely light-saturated, and thus have much lower light-use efficiency than shaded leaves receiving lower levels of diffuse radiation. Adopting such a revised canopy radiation model would likely result in somewhat reduced photosynthesis and latent heat fluxes at mid-day, and a gradual reduction of canopy activity in late afternoon and evening as light levels fall.

Model performance during spring months was highly variable, and the degree of agreement with observations varied as well. Simulations for the spring months showed a tendency to over-estimate springtime assimilation, both in magnitude of diurnal cycles and in the "bud-burst" or activation of the canopy. In May 1998, the simulations matched the observations well; May 1997 and 1999 the model signal was over-estimated. In all three years the April assimilation signal was quite obvious in the simulations, while only very weak in the observations, and weak daytime assimilation was even simulated in March 1998 and 1999.

For the present study, all three years used vegetation parameters based upon 1995 1-km AVHRR data. Our preference would be to use satellite data from the appropriate years, but unfortunately these data were not available for 1997-1999. Specifying canopy phenology from NDVI data is intended to allow the model to capture spatial and interannual variations, but the simulated canopy was obviously much more active in early spring than was the case in the observations. The AVHRR data used for canopy phenology for all three years of the simulation was 1995, during which leaf-out was relatively late. Some of this discrepancy may be the result of the very different spatial scale of the NDVI imagery and the radiation measurements under the canopy at the Willow Springs site. At the 1-km scale of the NDVI data, the site is quite heterogeneous and includes evergreen trees that would account for a higher LAI in early spring. To minimize artifacts from cloud contamination and other atmospheric interference, the NDVI data were treated as monthly maximum-value composites assigned to the middle of each month. Thus May NDVI is likely to reflect conditions at the end of the month, and our procedure for linear interpolation to daily values begins introducing the influence of this May value on April 16. Finally, simulated springtime soil temperatures showed a strong cold bias relative to the observations (figure 5). Since soil respiration is exponential with soil temperature, this deficiency nearly eliminated CO_2 efflux from the soil and amplified the error in the simulated springtime NEE.

The dependence of SiB on prescribed phenology is readily apparent in figures 8 and 9. The bottom panels of figures 8 and 9 show the NEE for several days in 1997 and 1998. The canopy specification in the model was identical for the two years, and maximum assimilation for May in either 1997 or 1998 was around –10 to –12 micromoles m^{-2} sec^{-1}. In 1997 (figure 8) the observed assimilation peaks around –5 micromoles m^{-2} sec^{-1}, and was closer to –10 in 1998 (much closer to modeled values), indicating that there were significant differences in canopy phenology between the two years. The 1998 values of water vapor flux in figure 9 show a better comparison to observations than the corresponding fluxes from 1997, highlighting the link between carbon and water vapor fluxes. The PAR ratio between wooded and clearcut areas in late May 1997 (not shown) were still quite high (0.6), suggesting that leaf-out had not occurred yet. The PAR ratio for 06-07 May 1998 was near 0.05-0.1; more leaves on trees would shade the PAR sensor, resulting in a lower ratio. These LAI differences were probably sufficient to explain the differences in the observed NEE values shown in figures 8 and 9. However, model-observation comparison was much worse for 22-23 May 1997 than for 06-07 May 1998, which would not be explained wholly by differences in LAI between the model and the actual forest. In late May 1997 the model retained a small amount of snow on the ground, which resulted in decreased soil temperatures when compared to 1998 (not shown). The reduced model soil temperature in 1997 retarded soil respiration. In 1998 all snow was gone from the ground by the 3rd of May, resulting in higher soil temperatures through the column, so soil respiration values increased with the result that peak NEE values would be less negative, and closer in line to observed values.

a. Seasonal and Interannual Variability

Figure 10 shows monthly averages for latent heat (LE), sensible heat (H) and net ecosystem exchange of CO_2 (NEE). Missing data was an issue: some months (January-March1997) had no observations of LE present, while other months (October 1997, February 1999) had so little H and/or LE data available that the value of comparison was insignificant. NEE was a more complete record, and as no individual month contained less than 25% of possible records, all months are shown. It was assumed that the missing observations were randomly spaced throughout the month, and that the monthly mean was not biased by the missing periods. Data filling of the meteorological driver data had only been performed through mid-August 1999, so the model output fluxes for the last quarter of 1999 were not plotted, as they represent fluxes from an averaged or composite climatology as outlined in the data-filling procedures.

The model closely simulated the monthly average of observed latent heat, except in summer 1998. The SiB simulation captured the annual cycle, as well as interannual variation, with respect to timing/season of maximum and minimum values. Model LE showed greatest deviation from observations during 1998.

The observed annual cycle of sensible heat flux peaked in spring and decreased rapidly until early summer. This decrease coincides with leaf-out, and represents a shift in the Bowen ratio toward increasing transpiration associated with increasing leaf area. Sensible heat flux stabilized from early summer until fall, when the flux dropped to near zero or slightly negative values by midwinter. Although the simulated H peaks coincided with observations in the spring, the late spring/summer drop in sensible heat flux was much smaller than observed. The simulation produced a secondary peak in July or August that was not seen in the observations save for July 1998. By late summer to early fall, the model H flux came back into line with observations, and fall and winter simulations were closely matched with the observations.

The magnitude of the simulated NEE was too high in both summer and winter. Observed NEE may have been under-estimated during times when the atmosphere was stable (night, winter) due to possible advective carbon losses. The model also mis-timed the springtime shift from net carbon efflux to net uptake, although the timing of the October peak in respiration was correctly simulated.

When available observations were summed over the entire 36 month period, the observed Bowen ratio was 0.53, while the modeled Bowen ratio was much higher, 0.65. This is consistent with the theory of wetlands within the observed flux footprint. The differences between observation-simulation are smallest in the winter when almost all fluxes are from snowcovered surfaces, largest in the spring and summer months.

The model was reasonably successful in capturing variations of fluxes on diurnal, synoptic, and seasonal time scales, but failed to properly simulate differences in the seasonal variations from one year to another. This is likely the result of the use of a single year (1995) of NDVI data to derive phenological variations in physiological parameters such as leaf-area index. The meteorological driver data record, however, was reasonably complete, so we expect to be able to simulate responses to climate anomalies that are present in the data used to force the model.

Vegetation in north-central Wisconsin was in full leaf quite early in the spring in 1998, and by midsummer the canopy was noticeably dry and brown (Ken Davis, personal communication). Precipitation was at near-normal levels in the early part of the year, but little or no rain fell in June and July, providing a probable reason for canopy desiccation. However, the observed record of these “drought” conditions of 1998 is not reflected in the flux and NEE observations. Net ecosystem exchange of carbon peaked earlier in 1998 than 1997 (June vs. July), but 1999 exhibited a June peak in NEE as well. The monthly mean NEE values (Fig.10) do not show a significant difference in the magnitude of assimilation between the years, but the monthly diurnal composite data indicated that in 1998 canopy assimilation started slightly later and tended to shut down earlier than in either 1997 or 1999.

Incorrect specification of canopy phenology (arising from the use of a single year’s NDVI data) is most likely to create a mismatch between the model and the observations during the “shoulder” seasons (spring and autumn). For the period under investigation (1997-1999) interannual variability in the observed fluxes during fall and winter was small. Springtime variability can have a large effect on NEE, as shown in Fig. 11 and in Fig. 10. May monthly mean NEE varied from positive or near zero in value (1997 and 1999) to assimilation values near the maximum seen for the year (1998). These variations were not simulated by the model, and highlight the need to match the period of the satellite imagery to the period being simulated. Furthermore, the use of monthly maximum NDVI values to specify LAI and fraction of absorbed PAR in the model likely produce excessive assimilation values in early spring.

The interannual variability in the measured surface fluxes was not well captured by the model, especially in the spring. Changes in canopy phenology, in particular, could not be replicated because of the unavailability of NDVI data for the actual years of the study. This can certainly be remedied as the newer data become available. The most salient feature of the observed interannual variations was the early leaf-out in 1998, which was associated with above-average temperatures during the early spring of that year. The use of monthly maximum NDVI would likely obscure vegetation transformations taking place on temporal scales of days to weeks, with the result that unless time of leaf-out changed by several weeks from one year to the next, the changes may be unnoticed by the model. By late spring/early summer, when the canopy had come into full leaf, the year-to-year differences were due more to atmospheric conditions (atmospheric driver data) than to the phenology prescribed to the model. The senescence of the Wisconsin forest displayed less interannual variation for the three years simulated, as comparison of fluxes in the fall of the year did not show the variation seen in the spring. Although the model canopy parameters were identical for 1998 to those of the other two years, simulated soil temperatures were higher earlier and simulated soil moisture (not shown) was lower in May and June of 1998 than in 1997 or 1999. These changes were also present in the observations, though in neither the data nor the simulation were these anomalies sufficiently strong to induce much physiological stress: carbon uptake and transpiration were nearly as strong in 1998 as in the other years, though the growing season began earlier.

5. Conclusions

The offline simulations of 3 years (1997-1999) of surface fluxes at the WLEF-TV tower by SiB provided an opportunity to closely assess model performance. The intention here was not to produce the most accurate simulation possible: model parameters were not "tuned" to obtain a better match to observations. Rather, the simulation was treated as an opportunity to test model performance for a location in which meteorology and fluxes are well-observed, but which is otherwise like any other model grid cell. Parameters were estimated from 1-km NDVI data, as has been done for a large domain surrounding the tower site. A fully coupled simulation (Denning et al., this issue) uses exactly the same approach, except that the weather is interactive with the simulated biophysics and biogeochemistry, being simulated in a mesoscale model.

Overall, the model was reasonably successful in capturing variations in fluxes of latent and sensible heat and CO_2 at the WLEF-TV site over diurnal, synoptic, and seasonal time scales. The agreement between the model and the observations was particularly good for latent heat flux, but less good for sensible heat flux and net carbon exchange. Simulated sensible heat flux was generally greater than observed. Analysis of surface energy budget components suggests that this disagreement may reflect a combination of errors in model albedo and soil thermal conductivity, and underestimation by the eddy flux system. Furthermore, the presence of wetlands within the flux footprint, and absence of wetlands in the SiB simulation provide a possible explanation for some of the differences in the model-observations comparison. As described by Desjardins *et al.* 1997, wetlands would result in larger ground heat flux and smaller sensible heat flux; if these mechanisms were included in the simulation, the Bowen ratio would shift towards values closer to those observed.

Interannual variability was less well simulated, especially in springtime, due to the unavailability of NDVI data for parameterization of canopy properties during the actual years of the study. Interannual variability during summertime, when the canopy was in full leaf, were more successfully simulated given changes in climatic drivers.

The model consistently overestimated late-day photosynthesis and transpiration relative to the observations, typically producing "U-shaped" diurnal cycles whereas the observed diurnal cycle was more typically "V-shaped." This was likely due to the model's treatment of within-canopy light extinction, which was appropriate for diffuse light but failed to correctly represent shading and extinction of direct-beam radiation. The radiative transfer submodel essentially treats all light within the canopy as diffuse, resulting in an unrealistically high canopy-average light-use efficiency.

The highest priority for model improvement is placed on canopy radiative transfer, soil thermodynamics, and obtaining better NDVI data sets for this period. In a companion paper (Denning et al., this issue), we proceed to test the current model in fully coupled mode in a set of mesoscale simulations.

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Figure 1. Monthly mean values of observed and model latent heat flux, sensible heat flux, and net ecosystem exchange of carbon for the years 1997-1999, inclusive.

Figure 2. Diurnal composites of model and observed latent heat fluxes for summer months during the years 1997-1999. In all plots model data is the dashed line, observed the solid line. Shaded area indicates +/- 1 standard deviation of the mean of the observations.

Figure 3. Diurnal composites of model and observed sensible heat fluxes for summer months during the years 1997-1999. In all plots model data is the dashed line, observed the solid line. Shaded area indicates +/- 1 standard deviation of the mean of the observations.

Figure 4. Diurnal composites of model and observed net ecosystem exchange of carbon for summer months during the years 1997-1999. In all plots model data is the dashed line, observed the solid line. Shaded area indicates +/- 1 standard deviation of the available observations.

Figure 5. Time series of 3 days of modeled and observed fluxes in July 1997.

Figure 6. Diurnal composites of model and observed net ecosystem exchange of carbon for spring months during the years 1997-1999. In all plots model data is the dashed line, observed the solid line. Shaded area indicates +/- 1 standard deviation of the available observations.

Figure 7. Comparison of time of leaf-out for six years (1995-1999) at the Willow Springs site, 20km SE of WLEF. Leaf-out was measured by comparing ratio of PAR between an instrument in the forest, and an instrument in a clearcut.

Figure 8. Monthly averages of soil temperature at surface and layers 5, 10, 20 and 50cm deep (top 2 panels), as well as temperature difference between surface and 50cm depth (bottom panel).

Figure 9. Diurnal composites of model and observed latent heat fluxes for spring months during the years 1997-1999. In all plots model data is the dashed line, observed the solid line. Shaded area indicates +/- 1 standard deviation of the mean of the observations.

Figure 10. Time series of latent heat, sensible heat, and carbon flux 22-23 May 1997.

Figure 11. Time series of latent heat, sensible heat and carbon flux 06-07 May 1998.

Figure 12. Diurnal composites of model and observed net ecosystem exchange of carbon for fall months during the years 1997-1999. In all plots model data is the dashed line, observed the solid line. Shaded area indicates +/- 1 standard deviation of the available observations.

Figure 13. Diurnal composite of comparison of model/observed net radiation, sensible heat flux, latent heat flux and model ground heat flux vs ‘implied’ ground heat flux from observations for July, 1998.