Coupling between the University of California, Davis, Advanced Canopy–Atmosphere–Soil Algorithm (ACASA) and MM5: Preliminary Results for July 1998 for Western North America

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ABSTRACT

The University of California, Davis, Advanced Canopy–Atmosphere–Soil Algorithm (ACASA) is coupled to the fifth-generation Pennsylvania State University–National Center for Atmospheric Research (NCAR) Mesoscale Model (MM5) as a land surface scheme. Simulations for July 1998 over western North America show that this coupling, the first between a mesoscale model and a land surface model of this complexity, is successful. Comparisons among model output, National Centers for Environmental Prediction–NCAR reanalysis fields, and station data show that MM5–ACASA generally reproduces near-surface temperature in a realistic fashion, but with a stronger diurnal cycle than observations suggest. A control run using the existing Louis/European Centre for Medium-Range Weather Forecasts land surface formulation produces unrealistically low temperatures associated with high latent heating and precipitation amounts over much of the model domain. Simulations of heat and moisture fluxes using the Biosphere–Atmosphere Transfer Scheme (BATS) are generally comparable to ACASA, but near-surface air temperatures reveal excessively warm conditions. Low specific-humidity values over land in both MM5–ACASA and MM5–BATS simulations and low oceanic values in all three simulations suggest a possible dry bias in MM5. Comparison statistics between modeled near-surface climatological behavior and associated fluxes at three sites show that MM5–ACASA, out of the three simulations, agrees most with observations. Sensitivity tests show that MM5 is generally more sensitive to the choice of surface scheme than it is to soil moisture initialization. Comparisons of mean carbon dioxide fluxes reveal that ACASA can be a useful tool in examining the terrestrial carbon cycle.

1. Introduction

There is a widely recognized need to improve land surface models (LSMs) that simulate fluxes of moisture, heat, momentum, and carbon dioxide (CO_2) between the terrestrial biosphere and atmosphere. A number of long-term research objectives within the earth sciences community include the need to improve surface flux representation in weather and climate simulation. For example, Henderson-Sellers and Ciret (2000) suggest that improving the representations of physics and physiology in the soil–vegetation–atmosphere system is essential for improving numerical simulation of atmospheric processes. Steffen and de Maria (1996) list surface radiative and turbulent heat fluxes as important controlling mechanisms for the development and evolution of sea ice. Sellers et al. (1997) state that the need is ''urgent'' for more sophisticated LSMs if we are to determine the rate of future atmospheric CO_2 increases. Paw U (1997) shows that LSMs in wide use for climate investigations may be oversimplified and, as a result, may overestimate CO_2 uptake by plants under increasing atmospheric CO_2 concentration. Chen et al. (1997) implicate low vertical resolution in LSMs in wide use as a main source of discrepancy between observations and model results in the Project for Intercomparison of Land-Surface Parameterization Schemes phase 2a Cabauw, Netherlands, investigation.

This paper presents results of a preliminary coupling between a nonhydrostatic mesoscale model [the fifth-generation Pennsylvania State University–National Center for Atmospheric Research (NCAR) Mesoscale Model (MM5), version 2] and a sophisticated, multilayer LSM that incorporates higher-order closure principles for turbulent statistics [University of California, Davis, (UCD) Advanced Canopy–Atmosphere–Soil Algorithm (ACASA)]. This coupling is intended to illustrate an advanced representation of complex relations among the soil, canopy turbulent microenvironment, and plant physiological state in an atmospheric model. Simulations with MM5 and two simpler surface layer schemes, an existing LSM in the Burk–Thompson PBL scheme originally coupled to MM5 [Louis/European Centre for Medium-Range Weather Forecasts

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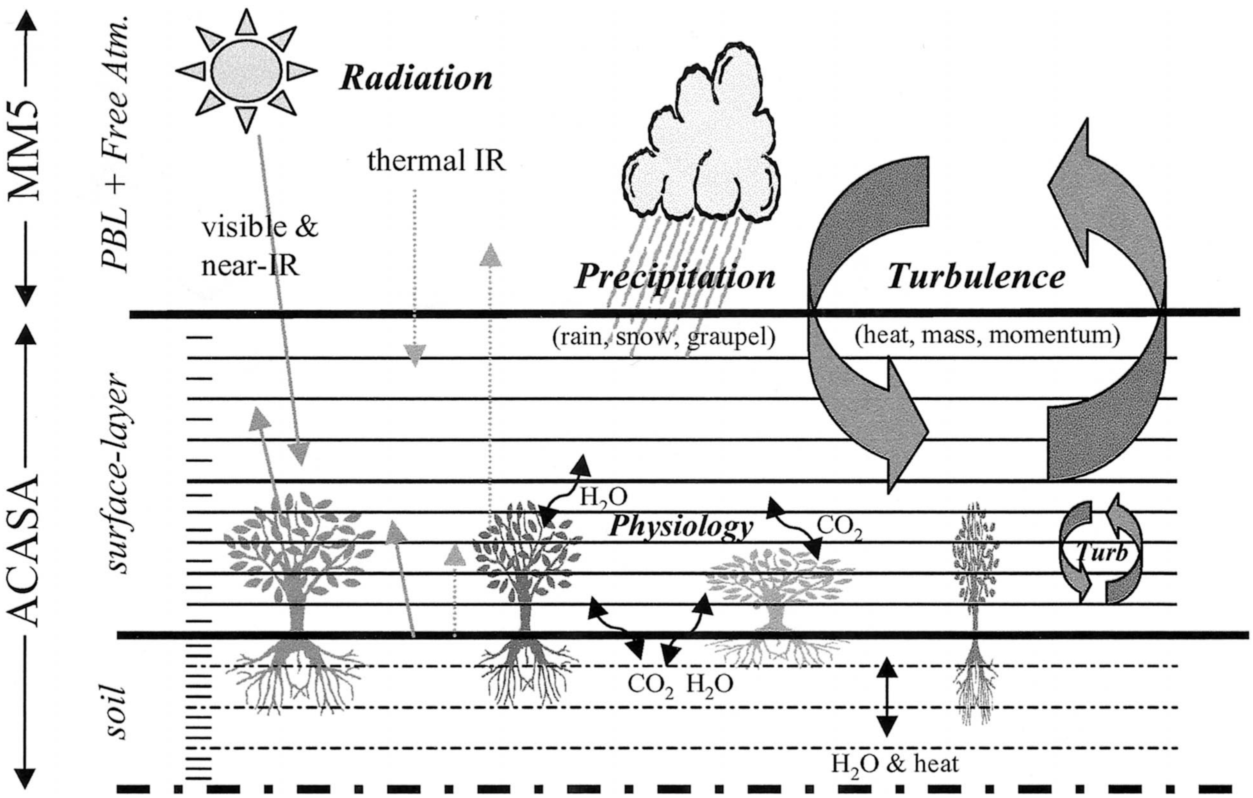

FIG. 1. Visual representation of MM5–ACASA.

(LECMWF)] and the Biosphere–Atmosphere Transfer Scheme (BATS), are used for comparison. The results presented herein are preliminary. More extensive sets of simulations designed to test further the advantages of using ACASA are under way.

2. Model descriptions

MM5 is a limited-area, terrain-following sigma-coordinate model designed to simulate regional-scale atmospheric circulations (Dudhia 1993). It has been developed as a community mesoscale model and is continuously being improved by contributions from users at several universities and government laboratories. MM5 is the latest in a series, having undergone many changes designed to broaden its usage. These changes include a multiple-nest capability, nonhydrostatic dynamics that allow the model to be used for 1-km horizontal scales, multitasking capability on shared- and distributed-memory machines, a four-dimensional data-assimilation capability, and many physics options. The nonhydrostatic version of MM5 is used here.

For the current investigation, the physics options used are the NCAR Community Climate Model, version 2, (CCM2) radiation package, the National Aeronautics and Space Administration Goddard Space Flight Center cloud microphysics, and the Burk–Thompson PBL formulation (Burk and Thompson 1989). The horizontal grid spacing is 45 km, with 27 levels in the vertical direction (using sigma coordinates at varying intervals). In all simulations in this investigation, MM5 is run with no internal nesting and is driven by National Centers for Environmental Prediction (NCEP)–NCAR reanalysis meteorological fields for July of 1998 (Kalnay et al. 1996). The Burk–Thompson formulation for PBL physics above the surface layer is used instead of the other PBL options within MM5 because of its performance relative to other boundary layer schemes in MM5 (Burk and Thompson 1989) and its convenience.

The UCD ACASA, which is coupled to MM5 as a terrestrial surface-layer component embedded within the Burk–Thompson PBL scheme, is described in Pyles (2000) and Pyles et al. (2000) and is represented graphically in Fig. 1. MM5 is coupled to ACASA as follows: The layer-1 surface exchange coefficients, turbulence kinetic energy, temperature variance, and moisture–temperature covariance of the level-2.5 PBL formulation of the Burk–Thompson scheme are estimated using ACASA instead of using the preexisting LECMWF scheme. For this experiment, ACASA is called only over land, and the surface-layer exchanges are calculated using the original LECMWF formulation over open water.

ACASA incorporates higher-order representations of turbulent statistics; vertical variations of temperature, wind speed, humidity, and CO_2 concentrations; plant physiology; and surface fluxes in a multilayer context.

Surface energy fluxes are solved for wet and/or dry canopy elements for nine sunlit angle classes and one shaded class within each canopy layer. ACASA can therefore be thought of as a ''fourth-generation'' LSM, extending the naming and classification scheme for land surface parameterizations of Sellers et al. (1997). In the current MM5–ACASA coupling, ACASA is called once every 30 min for all land points, following updates of the MM5 radiative transfer calculations.

In MM5–ACASA, there are 20 atmospheric layers and 15 soil layers beneath the lowest MM5 sigma level, which is between 40 and 50 m above the ground for this experiment. There are 10 equally spaced layers within the canopy and 10 atmospheric layers above the canopy. If the canopy height is less than one-half of the height of the lowest sigma level, the ACASA vertical grid spacing of the above-canopy layers is stretched to fit the height difference between the canopy top and the lowest MM5 sigma level. The ACASA domain height should not extend beyond 150 m above the ground because the turbulence assumptions apply to the surface layer only. For canopy heights greater than one-half of the height of the lowest MM5 sigma level, the vertical grid spacing is kept constant at all above-canopy layers, but the forcing meteorological conditions from MM5 are fed into the ACASA point that is closest to the actual MM5 height.

The forcing meteorological quantities from MM5 needed to drive ACASA for this investigation are 30-min means and include pressure, air temperature, mean wind, specific humidity, downwelling shortwave and thermal infrared radiation, the cosine of the solar zenith angle, precipitation rate, the magnitude of the horizontal pressure gradient, and the height of the lowest MM5 sigma layer. To keep the PBL scheme consistent with the rest of MM5, values of downwelling shortwave and longwave radiation over land and ocean are taken directly from the CCM2 radiation scheme instead of from the more crude representation specifically designed for the MM5 PBL schemes (Grell et al. 1995). Values of albedo and radiative skin temperatures needed by MM5 proper are also updated by ACASA. Carbon dioxide concentrations above the surface layer are assumed to be 365 ppmv. ACASA internally stores the characteristics of the evolving soil and canopy biomass thermal and hydrological quantities and updates them with the passage of each time step.

Vegetation and soil characteristics are specified by arrays matched to the 13 land use categories in MM5. Land use values from the high-resolution dataset used in MM5 are aggregated to 45 km, with the values corresponding to the dominant land use type. Figure 2c and Table 1 show the land use type and associated vegetation and soil characteristics at the 45-km horizontal grid spacing considered in this investigation. The choices of the values of many of these parameters (Table 1) are designed to represent the vegetation state in as general a fashion as possible and are based on guidance from existing surface parameters in the MM5 database and Pyles et al. (2000).

3. Experimental method

a. Model simulations

This investigation involves month-long simulations (July 1998) over a region bounded by 31.23°–54.74°N and 137.95°–110.38°W. The horizontal grid spacing of 45 km × 45 km is fine enough to resolve major topographical features such as the Sierra Nevada and Rocky Mountains (Fig. 2b). Thus, the model domain contains 70 × 60 points. Initial and boundary atmospheric conditions are interpolated from NCEP–NCAR reanalysis fields (Kalnay et al. 1996). For soil conditions, each simulation's initial volumetric soil moisture values are tied to vegetation type, which range from 0.1 for desert to 0.40 for agricultural land. Initial soil temperatures are 2°C less than the initial air temperatures. The simulations contain 27 vertical MM5 layers, 6 of which lie below 2 km. The primary purpose of these simulations is to test the reliability and practicality of coupling ACASA to MM5 and to establish a preliminary comparison between ACASA and simpler schemes. Simple tests for ACASA reliability include checking for numerical stability and physically reasonable flux estimates.

Two additional MM5 simulations were performed to test the sensitivity of the simulations to the choice of surface-layer formulations. One simulation employed the existing LECMWF (see Grell et al. 1995), and the other used BATS (Dickinson et al. 1993). As in the MM5–ACASA simulation, each of these models was used in conjunction with the Burk–Thompson PBL scheme. When translation of MM5–ACASA land use parameters into those required for running MM5–BATS was not possible, the MM5–BATS simulation employed values from Dickinson et al. (1993). In the MM5–LECMWF simulation, values of the parameter related to soil moisture (soil moisture availability) were based on soil moisture values estimated from MM5–ACASA for all time steps, because this formulation only uses a prescribed, invariant soil moisture availability parameter. This method is necessary to ensure that differences in the results are not overly determined by the LECMWF scheme's reliance on prescribed soil conditions.

To test model sensitivity to variations in initial soil moisture content, two additional sets of MM5–ACASA and MM5–BATS simulations were performed. These additional runs were initialized with volumetric soil moisture values of 0.10 and 0.30 everywhere, instead of the land use–dependent values shown in Table 1. These additional simulations were necessary to look at model differences dependent on the choice of land use scheme in the context of uncertainties in initial soil

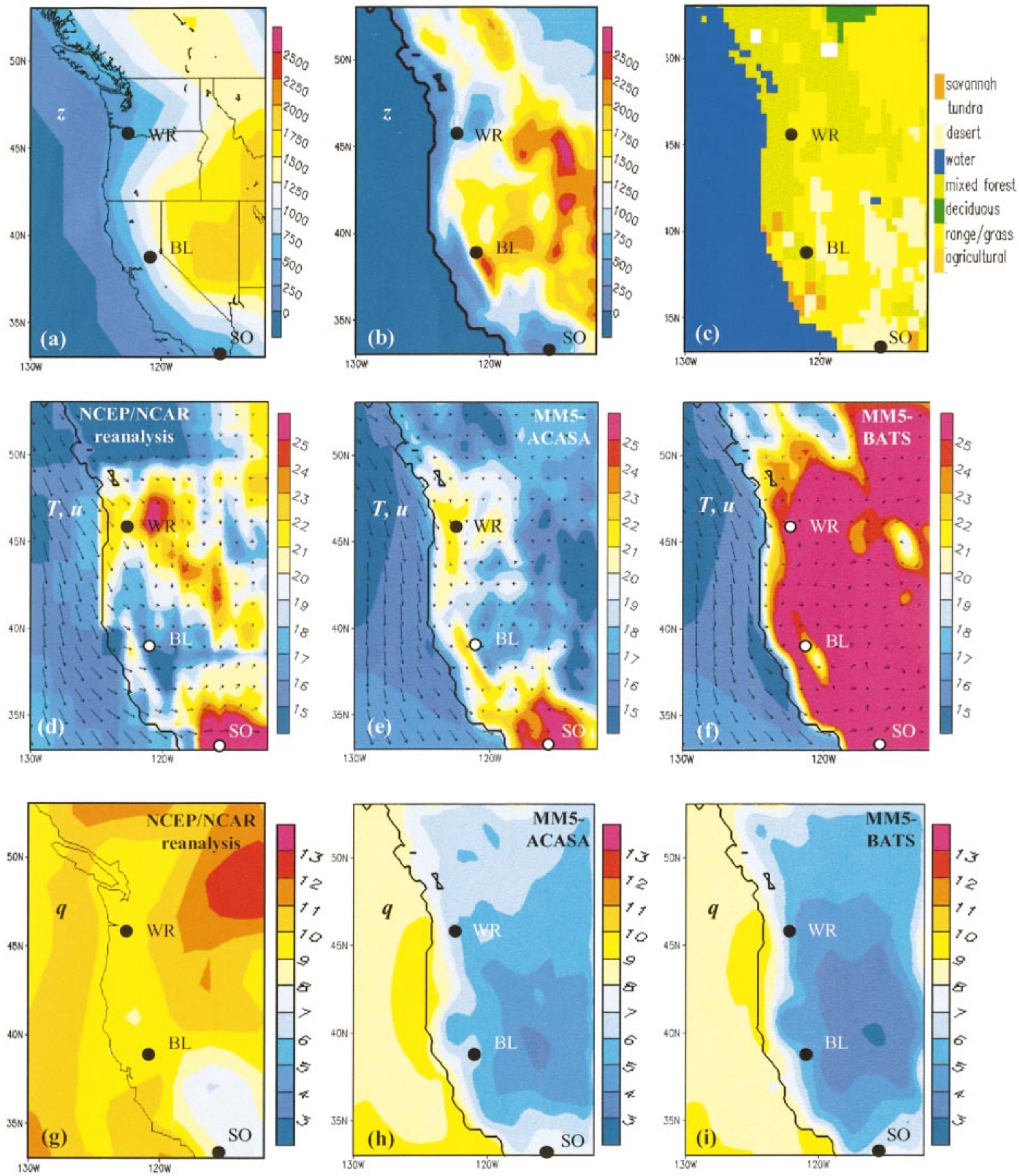

FIG. 2. (a) NCEP–NCAR reanalysis topography (m), (b) MM5 topography (m), and (c) MM5 land use categories; (d) reanalysis, (e) MM5–ACASA, and (f) MM5–BATS near-surface air temperature (°C) with wind vectors (m s^{-1}); (g) reanalysis, (h) MM5–ACASA, and (i) MM5–BATS near-surface specific humidity (g kg^{-1}). Wind vector arrows appearing in (e) and (f) are for every fourth MM5 horizontal grid point. In each of these plots, the lateral boundary condition sponge layer, consisting of five points, is not shown.

TABLE 1. Land use types and parameters used in MM5–ACASA simulations for western North America. LAI is leaf area index; STEI is stem area index.

Parameter	Land use						
	Agriculture	Range/grassland	Coniferous forest	Deciduous forest	Desert	Savannah	Tundra
Canopy height (m)	3	1	30	20	1	20	1
Tot LAI	4.4	1.0	3.0	4.0	0.5	1.0	1.0
Tot STEI	1.10	0.25	0.75	1.00	0.11	0.25	0.25
No. of LAI peaks in vertical	1	1	1	2	1	2	1
Dominant LAI peak	Main	Main	Main	Upper	Main	Upper	Main
Height of dominant LAI peak (m)	1.5	0.5	15.0	10.0	0.5	10.0	0.5
Biomass (kg m^{-2})	2	1	70	50	1	10	1
Visible leaf absorptance	0.500	0.500	0.297	0.280	0.350	0.190	0.200
Near-IR leaf absorptance	0.430	0.430	0.100	0.430	0.500	0.300	0.300
Visible leaf transmittance	0.075	0.075	0.168	0.075	0.075	0.075	0.075
Near-IR leaf transmittance	0.200	0.250	0.168	0.290	0.050	0.400	0.290
Slope of Ball–Berry stomatal response	10	20	40	10	250	30	45
Visible dry soil albedo	0.300	0.300	0.300	0.300	0.300	0.300	0.300
Near-IR dry soil albedo	0.300	0.300	0.300	0.300	0.300	0.300	0.300
Leaf drag coefficient	0.06	0.07	0.13	0.12	0.10	0.06	0.12
Mean leaf diameter (m)	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Initial soil moisture	0.40	0.15	0.20	0.35	0.10	0.20	0.3
Fractional soil moisture	0.40	0.30	0.40	0.35	0.25	0.40	0.3
Soil type (U.S. Department of Agriculture class)	Clay–loam	Loam–clay	Sandy loam	Sandy loam	Sand	Clay–loam	Clay
Fractional soil humus content	0.67	0.67	0.90	0.90	0.10	0.67	0.90
Fractional leaf litter cover	0.67	0.67	0.90	0.90	0.10	0.67	0.67
Depth of root zone (m)	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Wilting point fractional soil moisture	0.16	0.11	0.16	0.11	0.1	0.16	0.16

moisture. MM5–LECMWF was excluded from this test because soil moisture availability is prescribed.

b. Analysis of model simulations

To evaluate surface conditions and flux estimates, we have made comparisons with data at specific locations within the domain. In addition, we have compared standard meteorological variables over the whole domain with those of the NCEP–NCAR reanalysis. Site comparisons include near-surface air temperature T, mean wind speed U, specific humidity q, net radiation R_n, sensible heat flux density H, latent heat flux density LE, ground heat flux density at the soil–air interface G, friction velocity u_*, and net ecosystem exchange of CO_2 NEE. The three widely spaced sites are part of the ''Ameriflux'' observation network (see online at http://public.ornl.gov/ameriflux/Participants/Sites/Map/index.cfm as of time of writing). The Wind River Canopy Crane Research Facility (WR) lies within an old-growth coniferous forest in southern Washington State (45.49°N, 121.58°W; elevation 355 m; Paw U et al. 2002). The Blodgett Forest Research Station (BL), California, is a 1200-ha 5–7-yr-old mixed coniferous forest located in the midelevations (1300–1500 m) of the central Sierra Nevada (38.53°N, 120.57°W; elevation 1315 m; Goldstein et al. 2000). The Sky Oaks (SO) site is located in a relatively young chaparral region located in extreme southern California (33.22°N, 116.37°W; elevation 1420 m) that is recovering from a recent fire (Oechel 2000). The quantities H, LE, u_*, and NEE were all measured using eddy-covariance techniques at each site.

Measurements at the WR, BL, and SO sites were compared with the simulated values from the nearest MM5 points that have the appropriate land surface designation. For the BL site, which has the ''coniferous-forest'' designation, and SO, which is ''range/grassland'' (Table 1), these points are the actual nearest grid points. However, for the WR site, which is coniferous forest, the closest MM5 point that has that designation lies 45 km to the west. Values from this farther point, therefore, were used in the comparisons. The MM5 comparison locations corresponding to the WR, BL, and SO sites are located at 45.42°N, 122.44°W; 38.12°N, 120.51°W; and 33.61°N, 116.46°W; respectively.

Several factors limited the number of available times for the comparisons. Based on how long it takes for MM5–ACASA soil to arrive at a quasi equilibrium (~18 days), only days 21–31 of the simulation were used. This approach was used to help to reduce the dependence of model simulations on the arbitrariness of soil initialization, because of a lack of observed values (Fast et al. 1995). In addition, hourly observations of H and LE for these sites were often missing. In addition, some of these data were not consistent with a reasonable closure of the energy budget. Such energy budget closure errors, which are often on the order of 25% for forest ecosystems, have a variety of possible sources (Wilson et al. 2002). Thus, only those values of H, LE, u_*, and NEE at times for which $|R_n - H - \mathrm{LE} - G|$ is less than 75% of $|R_n|$ were considered. Such a screen is loose enough to exclude suspicious outliers and to allow consideration of points exhibiting ''normal'' levels of observed closure error. This energy budget closure selection criterion was not applied to values of R_n, G, T, and q because of greater observational confidence in these measurements.

Errors in cloud conditions during this summer month with little frontal activity can bias any comparisons. Though all models may simulate cloudiness near the time and place where such phenomena actually happened, small shifts may heavily influence the statistical comparisons. Therefore, to provide as fair a comparison as possible, daytime values of all flux quantities (R_n, H, LE, u_*, and NEE) were considered only when modeled and observed downward solar fluxes differ by less than 100 W m^{-2} (i.e., ''clear-sky conditions''). Only results from MM5–ACASA and MM5–BATS were used in this selection process. The MM5–LECMWF simulation possessed so much daytime cloudiness that using these results would have eliminated most of the data points from the analyses.

All quantities are compared using statistical methods that incorporate observational uncertainties similar to those used for offline ACASA validation in Pyles et al. (2000). Analyses used in this investigation include mean differences between modeled and observed estimates, linear regression coefficients of determination (r^2) for composite mean hourly values, and differences between the mean maximum and mean minimum values. This comparison method is designed to evaluate model performance using three climatological criteria: mean bias, phase of the diurnal cycle, and amplitude of the diurnal cycle. Comparisons of modeled versus observed station reports of near-surface air temperatures were adjusted for differences in topographical heights between the model point and observation site. For WR, BL, and SO, model points depart from observed elevations by ~850, ~1000, and ~100 m, respectively. Model temperature values have been adjusted for these topographical differences by assuming an environmental lapse rate of −4.0 K km^{-1}.

In addition to the site comparisons, mean 21–31 July 1998 values of modeled near-surface mean wind, temperature, and humidity estimates over the model domain are compared with corresponding NCEP–NCAR reanalysis mean estimates for the domain. The reanalysis fields used in these comparisons are the 2-m values of air temperature interpolated to the MM5 grid and adjusted for topography (−4.0 K km^{-1}), 2-m specific-humidity estimates, and 10-m values of wind speed and direction. As is the case for initial and boundary conditions used to drive MM5, reanalysis fields are on a $2.5° \times 2.5°$ horizontal grid with 6-h temporal resolution. These comparisons are designed primarily to establish whether the broad features of the simulations with MM5–ACASA are realistic. In addition, these full-field

TABLE 2. Comparison statistics for 21–31 Jul modeled and observed surface conditions at three Ameriflux sites within the model domain. Boldface, italic mean difference values for individual sites in mean diff columns are not significant at the 95% confidence level. Boldface (nonitalic) values of r^2 show statistically significant highest values of the three simulations (including ties). For ratios of modeled to observed magnitudes of diurnal cycles, boldface, italic values indicate statistical equivalence to unity with 95% confidence. The total number of points considered (n) at WR, BL, and SO for T and q is 232, 232, and 232, respectively; for R_n, H, LE, G, and NEE, n is 232, 160, and 232, respectively; model temperature values are adjusted to remove effects of model and actual topographical heights by assuming a −4.0 K km^{-1} lapse rate.

		Mean diff (model minus observed)			r^2 for composite diurnal cycle (a value of 1.0 indicates model and obs phases perfectly match)			Ratio of modeled to obs amplitude of composite diurnal cycle ($\lvert max - min\rvert_{model} \div \lvert max - min\rvert_{obs}$)		
Variable	LSM	WR	BL	SO	WR	BL	SO	WR	BL	SO
T (K)	ACASA	***0.10***	***−0.35***	***−1.79***	**0.78**	**0.82**	**0.68**	1.47	1.54	2.17
	BATS	9.30	4.97	10.76	0.74	0.59	0.01	0.67	0.72	0.65
	LECMWF	−9.90	***−0.18***	−3.04	0.09	0.01	0.37	0.45	0.62	0.49
q (g kg^{-1})	ACASA	−4.91	−9.27	−2.54	**0.96**	**0.95**	**0.42**	0.38	0.26	0.24
	BATS	−5.33	−10.12	−4.16	0.88	**0.94**	0.10	0.70	0.13	0.15
	LECMWF	−3.84	−4.17	5.99	**0.95**	0.85	0.14	1.48	1.15	***1.23***
H (W m^{-2})	ACASA	***5.26***	41.82	***−5.41***	**0.88**	0.76	**0.90**	***0.80***	2.20	1.72
	BATS	52.40	137.12	34.01	**0.86**	0.81	**0.90**	1.35	1.55	2.01
	LECMWF	−114.01	−42.47	−70.44	**0.87**	**0.87**	0.56	0.34	0.44	0.36
LE (W m^{-2}	ACASA	85.10	***−24.42***	***−29.82***	**0.93**	**0.94**	**0.95**	3.21	***1.12***	0.28
	BATS	12.41	−147.62	−51.23	0.51	0.79	0.35	1.31	0.11	0.03
	LECMWF	33.06	102.29	***12.98***	**0.94**	0.82	0.86	2.81	1.67	1.25
R_n (W m^{-2})	ACASA	***−25.37***	***11.49***	−86.44	**0.96**	**0.99**	**0.99**	0.69	***1.27***	0.60
	BATS	***−42.02***	***5.35***	***−60.14***	**0.97**	0.91	0.95	0.79	0.64	0.79
	LECMWF	−170.60	60.24	−107.70	0.91	0.93	0.89	0.40	1.27	0.53
G (W m^{-2})	ACASA	−3.30	−5.63	−14.88	**0.74**	**0.49**	0.05	0.15	0.04	0.17
	BATS	12.45	15.09	***−0.21***	0.02	0.01	**0.35**	12.51	7.33	1.64
	LECMWF	—	—	—	—	—	—	—	—	—
NEE (μmol m^{-2} s^{-1})	ACASA	−13.09	***−1.94***	***1.01***	**0.35**	0.01	0.26	1.18	1.25	0.52

comparisons of temperature, humidity, and winds, along with mean sensible and latent heat fluxes, provide insight into how MM5–ACASA performs relative to MM5 simulations using the BATS and the LECMWF land surface schemes.

4. Results and discussion

a. *Surface conditions—Temperature, winds, specific humidity, and precipitation*

The MM5–ACASA simulation of near-surface air temperature is in very good agreement with observed estimates of this quantity (Table 2 and Figs. 2d,e). Topographical dependencies are represented well, including warmth in the desert regions south of 37°N and east of 120°W and cooler conditions north of 50°N and along the Rocky Mountains. Although similar topographical dependencies are present in the MM5–BATS temperature field (Fig. 2f), values are excessively high. Mean differences in T (Table 2) corroborate an MM5–BATS warm bias at all three sites. MM5–LECMWF estimates of mean temperatures are 3°–8°C lower than interpolated reanalysis estimates throughout most of the domain (not shown). This result is also corroborated by the means in Table 2 for the three sites. The MM5–ACASA r^2 values of temperature are the highest of the three simulations at all sites with 95% confidence, indicating an improvement in simulating the phase of the diurnal cycle. MM5–ACASA versus observed diurnal temperature ratios (Table 2) are significantly greater than unity at the 95% significance level at all three sites, indicating a more rigorous diurnal cycle than observations suggest. In converse, MM5–BATS and MM5–LECMWF underestimate the strength of the diurnal cycle at each site. The more vigorous day–night swings in temperature in MM5–ACASA are related to low biases in overall atmospheric humidity and ground heat storage (discussed later).

Most specific-humidity results show that MM5 has a general dry bias near the surface independent of the land surface scheme (Figs. 2g–i and Table 2). This dry bias is most evident over land, with differences exceeding 3 g kg^{-1} in many areas. There is also a consistent dry bias over the ocean, where MM5 values are 1–2 g kg^{-1} less than reanalysis values, despite the use of the LECMWF surface scheme over ocean points. Aside from this bias, both reanalysis and MM5–ACASA and MM5–BATS q fields show the appropriate spatial patterns, with minima over the desert and mountain regions and relatively higher values toward the coast and northern interior lowlands. Reanalysis values of near-surface specific humidity are largely based on the surface model used to drive the reanalysis (Kalnay et al. 1996), so some of the discrepancy in Figs. 2a–c could be independent of MM5. Mo and Higgins (1996) suggest that evaporation in the NCEP–NCAR reanalysis over the oceans may have been overestimated, which could be part of the reason for the MM5-versus-reanalysis differences in q offshore. Large dry biases in q at WR and BL (Table 2) are largely responsible for the excess cooling at night discussed earlier.

All model simulations capture the main observed features of the 21–31 July 1998 mean near-surface wind field, including relatively slight winds over land surfaces as compared with most values over the ocean (Figs. 2d,e). Comparison statistics for each of the three sites (not shown) demonstrate that MM5–ACASA generally simulates 21–31 July average wind speed values with the greatest statistical agreement with observations of all the simulations. Results also show that MM5–LECMWF, in contrast to both MM5–ACASA and MM5–BATS, produces much higher wind speeds, with values more than 2 m s^{-1} higher than observed estimates at all three sites.

MM5–ACASA (Fig. 3h) and MM5–BATS (not shown) 21–31 July 1998 accumulated precipitation estimates are less than 0.35 cm throughout most of the land portion of the domain, with 0 values at each of the three sites. In contrast, MM5–LECMWF precipitation totals for this period are unrealistically large and widespread (Fig. 3i). As will be discussed in the next section, the heavier MM5–LECMWF precipitation is likely associated with large latent heating rates and higher specific-humidity values (not shown) over much of the interior domain. MM5–ACASA and station reports (not shown) show no measurable precipitation at WR and BL during 21–31 July 1998. Observed values at SO are missing, but high daytime net radiation values suggest little, if any, precipitation at that site as well for the same period.

b. *Simulations of surface fluxes*

MM5–ACASA-simulated values of H and LE are realistic, with spatial patterns showing sensitivity to land use type. Greater amounts of simulated H and LE are evident over forested regions than over desert (Figs. 2c and 3a,d), which is due mainly to increased radiative absorption and soil insulation in the presence of heavy vegetation. MM5–ACASA values of mean LE are least, with H greatest, over desert and range/grassland areas. These spatially coherent patterns reflect what one might expect for summertime conditions in western North America. A similar spatial distribution of mean 21–31 July H and LE is evident in the MM5–BATS simulation, but with even less LE and more H (Figs. 3b,e). Though all simulations employed the same physics over ocean points, the lower humidity values in the MM5–BATS simulation allowed for somewhat higher LE rates over the ocean. In sharp contrast to the MM5–ACASA and MM5–BATS simulations, MM5–LECMWF simulates unrealistically high values of LE and low values of H over much of the terrestrial domain (Figs. 3c,f). That MM5–LECMWF H and LE estimates show little relation to land use type is to be expected given the LECMWF scheme's simplicity relative to BATS and ACASA.

Results in Table 2 also suggest that MM5–ACASA simulated H and LE in the most realistic fashion of the three simulations at the three sites, with comparatively low mean biases and high hour-to-hour composite correlations with observations, especially for LE. MM5–ACASA versus observed mean differences in H and LE are statistically insignificant at the 95% confidence level in four out of six cases, as compared with zero out of six for MM5–BATS and one out of six for MM5–LECMWF. MM5–ACASA hourly LE values are the most highly correlated with observations at BL and SO (and are tied with MM5–LECMWF at WR), indicating greater diurnal phase accuracy for MM5–ACASA as compared with the other simulations. Despite these general results, MM5–ACASA average LE values at WR are 85 $\pm$ 25 W m^{-2} higher than observed estimates with 95% confidence. However, Paw U et al. (2002) report that observed daytime LE estimates at the site may be underestimated by as much as 50 W m^{-2}. Another exception is at BL, where high values of H and low (but statistically insignificant at the 95% confidence level) LE values indicate that MM5–ACASA may have underestimated evapotranspiration there. This result is most likely due to the youth of the stand at that site, whereas the MM5 land use designation applies to mature trees.

Mean difference and composite r^2 values in clear-sky R_n (Table 2) suggest that both MM5–ACASA and MM5–BATS simulate net radiation in a reasonable fashion. Both MM5–ACASA and MM5–BATS estimate R_n within statistical uncertainty at WR and BL. However, mean difference values suggest that all models simulate less R_n at SO, with all but the MM5–BATS values significantly different at the 95% confidence level. The MM5–ACASA underestimation could in part be due to differences in modeled versus observed albedo. For dry soil with no vegetation (desert), the ACASA surface albedo is 0.35, which is probably too high. Observed maximum daytime values of 750 W m^{-2} are common at SO, implying a possible observed albedo of 0.25 or less. That MM5–LECMWF underestimates mean net radiation at WR and SO by over 50 W m^{-2} with 95% confidence is largely due to persistent cloudiness that is not present in the observations or the other two simulations.

Results indicate that MM5–ACASA simulates G with good correlation with composite hourly observations but with a slight negative bias and suppressed diurnal cycle at all three sites, with 95% confidence (Table 2). Negative mean difference values indicate that MM5–ACASA simulates too little thermal energy penetrating into the ground at all three sites over the long term. This long-term bias may be related to the initial soil temperature values being too low. Low ratio values in Table 2, indicating underestimated diurnal cycle am-

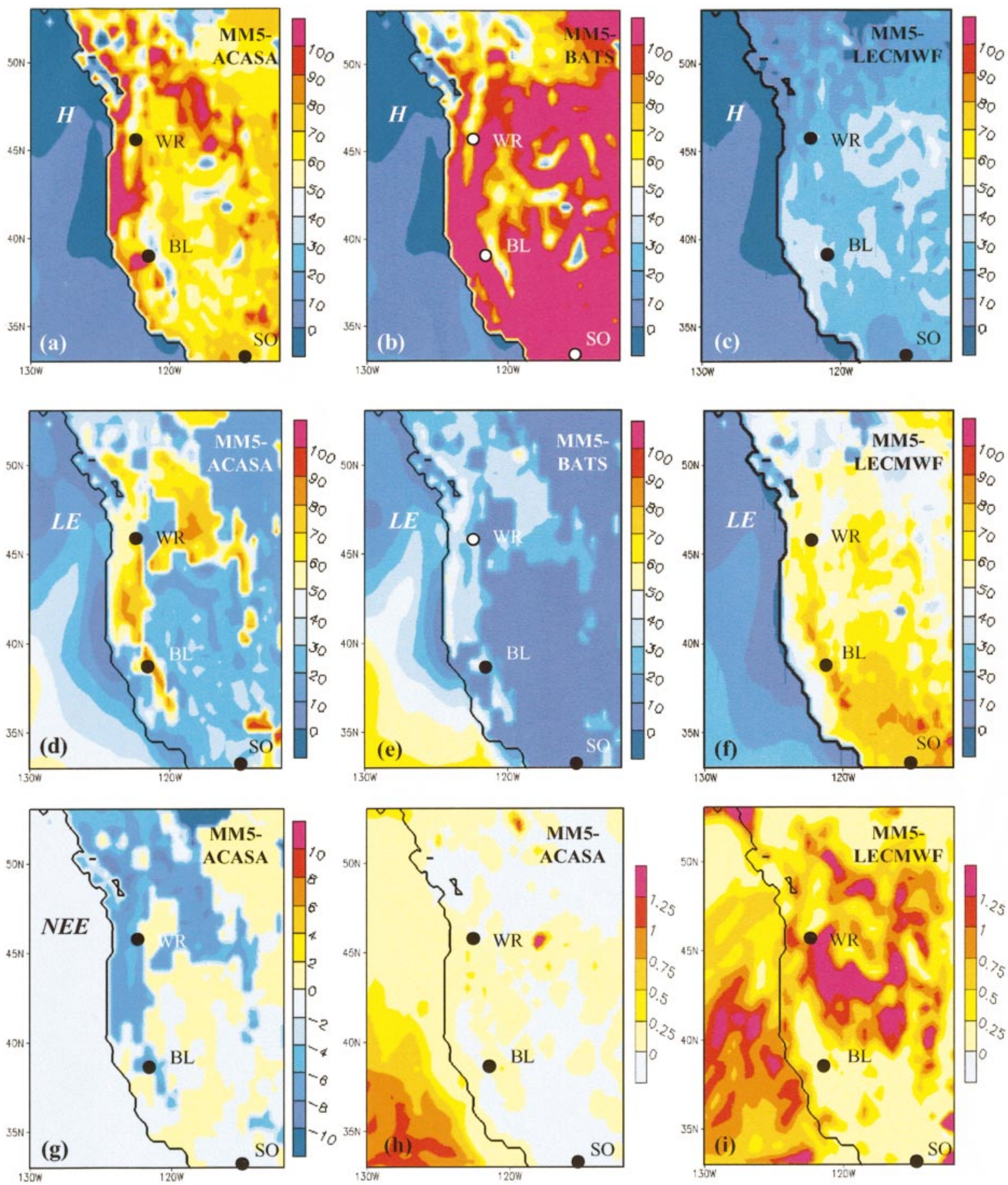

FIG. 3. Average 21–31 Jul 1998 fluxes and precipitation for western North America: (a) MM5–ACASA, (b) MM5–BATS, and (c) MM5–LECMWF *H* (W m^{-2}) values, respectively; (d)–(f) Same as (a)–(c), respectively, but for LE (W m^{-2}); (g) mean MM5–ACASA NEE, or CO_2 flux density (μmol m^{-2} s^{-1}); (h) MM5–ACASA and (i) MM5–LECMWF 21–31 Jul accumulated precipitation (cm), respectively. In each of these plots, the lateral boundary condition sponge layer, consisting of five points, is not shown.

plitude at all sites, suggest that the settings of insulating leaf litter cover for these types of vegetation may be unrealistically high, because *G* is sensitive to this parameter. For MM5–BATS, ratio and mean difference results in Table 2 suggest an opposite pattern than that of MM5–ACASA: the diurnal cycle is too vigorous, and long-term storage of thermal energy in the soil is overestimated. MM5–LECMWF does not estimate soil thermal exchanges.

Preliminary comparisons between MM5–ACASA and observed estimates of net ecosystem carbon dioxide show promise in simulating an important aspect of the regional carbon cycle. Mean 21–31 July 1998 NEE values are in statistical agreement at BL and SO with 95% confidence (Table 2). Correlations between modeled and observed estimates are highest at WR and SO, but overall the values are small relative to other quantities. The relatively low r^2 value at WR is due mainly to abrupt shifts between negative and positive values in the observations occurring during hours of full sunlight, shifts that are absent in the MM5–ACASA simulated values. These observed oscillations could be indicative of complex surface-layer interactions that are not understood well, such as mean subgrid-scale horizontal transport due to vegetative and terrain heterogeneities. Ratios in Table 2 indicate a slight overestimation of diurnal cycle amplitude at WR and BL and an underestimation at SO. Mean difference at WR shows that MM5–ACASA simulates too much daytime photosynthetic sequestration of carbon, which is partly due to the extreme moisture stress observed at that site—the observed value (+0.58 mol m^{-2} s^{-1}) shows a net *production* of CO_2 for this period (Paw U et al. 2002). Offline tests using ACASA for the WR site were run for longer periods and showed that allowing soil moisture to evolve more realistically yields less photosynthetic uptake for this period. Therefore, part of the MM5–ACASA bias may be due to the choice of soil moisture initialization values.

The 21–31 July mean NEE field (Fig. 3g) shows that net CO_2 uptake (negative values) is greatest over the unstressed deciduous forests of the northern Rocky Mountains (north of 50°N and between 120° and 115°W), with more moderate uptake over areas of coniferous forest along the Pacific Northwest coast (35°–50°N, 120°–125°W). Many of these forestlands were experiencing drought stress associated with a strong ENSO warm-phase event (e.g., Paw U et al. 2002). Values in Fig. 3g are negligible over the more sparsely vegetated desert and rangeland areas (see Fig. 2c). In general, the pattern in mean NEE is realistic, despite WR site results that suggest an overestimation of photosynthetic uptake in that region for the period in question.

In summary, climatological results for the three site comparisons indicate that MM5–ACASA simulations agree with observed estimates much more frequently than do those from MM5–BATS and MM5–LECMWF. The number of instances in which mean differences of T, q, R_n, H, and LE are statistically negligible for MM5–ACASA, MM5–BATS, and MM5–LECMWF are nine, three, and three, respectively. MM5–ACASA, MM5–BATS, and MM5–LECMWF values of r^2 are highest in a statistically significant manner on nine, zero, and one occasions, respectively (there are four instances of statistical ties between MM5–ACASA and MM5–BATS for highest r^2 values and three such instances for MM5–LECMWF). Occurrences in which ratios of modeled to observed mean diurnal cycle amplitudes are statistically indistinguishable from unity with 95% confidence for MM5–ACASA, MM5–BATS, and MM5–LECMWF number three, zero, and one, respectively. This summary excludes results for *G* and NEE because not all models could be tested against each other for these quantities.

c. Sensitivity to soil moisture initialization and vegetation specification

Because initial soil moisture values are uncertain in any modeling effort of this kind, sensitivity tests involving initializing the MM5–ACASA and MM5–BATS simulations with uniformly wet and dry soil conditions were performed. In general, MM5–ACASA values exhibited moderate sensitivity to initialization with uniformly moist and uniformly dry soil relative to the standard land use–dependent soil moisture simulation. In the dry case, higher temperatures (from +1° to +3°C), lower humidity (from −1 to −4 g kg^{-1}), and corresponding shifts in sensible (from +20 to +50 W m^{-2}) and latent heat fluxes (from −10 to −50 W m^{-2}) predominate over much of the land area south of 45°N. These differences are largely the result of the MM5–ACASA dry simulation effectively having little or no transpiration because the soil moisture values in the entire domain remained below the critical wilting threshold. Despite this, situation, the differences in temperature (1°–3°C over land south of 45°N) are small in comparison with the differences between the MM5–ACASA and MM5–BATS temperature values and cover a smaller region (see Figs. 2a–b) despite lower LE values in the MM5–ACASA dry simulation than in the MM5–BATS simulation. For the wet case, differences from the standard simulation were generally opposite in sign to those of the dry simulation, were less than one-half as large, and were confined to land areas south of 40°N. Results are similar for the MM5–BATS simulations, but overall the sensitivity of MM5–BATS to varying the initial soil moisture was weaker than for MM5–ACASA. This is largely due to it taking longer for soil moisture values to change in MM5–BATS than in MM5–ACASA.

Table 3 provides a representation of the relative sensitivities of soil moisture initialization versus choice of LSM for each of the three sites. The values that appear in Table 3 are from the following formulation:

TABLE 3. Sensitivity of MM5–ACASA to initial soil moisture for the WR, BL, and SO sites. Values are the ratios of absolute values of differences between mean MM5–ACASA wet and MM5–ACASA dry to the absolute value of the difference between MM5–ACASA and MM5–LSM, where LSM in this case refers to either BATS or LECMWF.

	LSM = BATS			LSM = LECMWF		
Variable	WR	BL	SO	WR	BL	SO
T	0.67	<0.01	0.54	0.27	<0.01	0.29
q	0.12	0.08	0.14	0.11	2.33	1.38
H	0.61	1.33	0.57	0.07	1.30	0.71
LE	0.83	0.17	0.37	0.33	0.19	0.22
R_n	0.34	0.42	0.05	0.48	0.41	0.03
G	0.07	0.03	0.12	—	—	—

$$\frac{|\overline{X}_{\mathrm{WET}} - \overline{X}_{\mathrm{DRY}}|}{|\overline{X}_{\mathrm{ACASA}} - \overline{X}_{\mathrm{LSM}}|} \qquad (1)$$

where $\overline{X}$ is the 21–31 July mean for a particular quantity, and subscripts WET and DRY refer to MM5–ACASA simulations initialized with 0.30 and 0.10 volumetric soil moisture, respectively. Subscripts ACASA and LSM refer to MM5–ACASA and either MM5–BATS or MM5–LECMWF simulations initialized with the soil moisture values that appear in Table 1. Results in Table 3 show some sensitivity to initial soil moisture, but that these impacts in most cases are smaller than time-averaged differences between MM5–ACASA values and those from MM5–BATS or MM5–LECMWF (Table 2). The percentage of instances (18 total for MM5–BATS and 15 total for MM5–LECMWF) in which MM5–ACASA versus MM5–BATS (MM5–LECMWF) sensitivity is more than 2 times that of MM5–ACASA soil moisture sensitivity is 67% (73%). In contrast, the corresponding percentage of instances in which soil moisture sensitivity is more than 2 times that of MM5–ACASA versus MM5–BATS (MM5–LECMWF) sensitivity is 0% (7%). This simple test does not consider the impact of statistical uncertainties.

The relative sensitivity of soil moisture initialization to choice of LSM in these simulations was also tested by considering statistically significant differences between modeled and observed mean 21–31 July values of T, q, R_n, H, and LE (15 total cases). Results from these tests also show that MM5 is more sensitive to choice of LSM type than it is to choice of initial soil moisture when comparing mean statistics at the WR, BL, and SO sites. To be specific, the occurrence of MM5–ACASA surface meteorological conditions and associated fluxes matching observed estimates with 95% confidence for the three sites taken together is 60%, 66%, and 73% for the standard, dry, and wet cases, respectively, while the corresponding occurrence for MM5–BATS is 20%, 20%, and 27% for the standard, dry, and wet cases, respectively. MM5–LECMWF mean values agree with observed values within 95% confidence in 13% of the cases.

It is unlikely that the comparative sensitivities to initial soil moisture and LSM type are related to LSM-related differences in model spinup time for soil moisture for the domain and time in question. Both MM5–ACASA and MM5–BATS soil moisture show a smooth relaxation to a quasi equilibrium by 20 July under generally persistent meteorological conditions. For the simulations beginning with initial soil moisture values shown in Table 1, mean soil moisture values for the land portion of the domain declined from 0.26 to 0.12 from day 1 to day 20 and from 0.12 to 0.11 from day 21 to day 31. MM5–BATS mean near-surface soil moisture declined from 0.26 to 0.18 between day 1 and day 20 and from 0.18 to 0.17 between day 21 and day 31. In cases in which the meteorological situation is more complicated and soil moisture varies more vigorously in time or cases in which there is no constraint on the lateral boundaries (i.e., GCM simulations), model sensitivity to choice of soil moisture initialization might become more comparable relative to model sensitivity to the choice of LSM.

There are two main sources of uncertainty that arise from the method of specifying vegetation type in MM5. The MM5 version used in the current investigation (version 2) possesses 13 land use categories. One source of uncertainty is related to the fact that the dominant species type is used for each MM5 point, so coniferous forest, for instance, refers to grid points at which there can actually be a mix of deciduous and coniferous species. Another source of uncertainty is finding a representative set of characteristics that can generally describe the vegetation, such as 35-m canopy heights for coniferous forests, which can range from less than 1 (young) to over 60 (old growth) m in reality. Several offline tests were run to determine ACASA sensitivity to these kinds of uncertainties. These tests were conducted for 21–31 July for the WR site, whereby certain vegetation parameters were altered within reasonable uncertainties given these crude land use representations.

Results from these offline tests at the WR site (not shown) show that ACASA estimates of H and LE are most sensitive to uncertainties in the specification of stomatal response slope. Offline sensitivity analyses suggest that changing the slope of stomatal response (see Table 1) to correspond with broadleaf instead of coniferous species increases (decreases) mean latent (sensible) heating rates by 48 W m^{-2}. As well, results for the WR site indicate that ACASA is also somewhat sensitive to the total leaf area index (LAI) with mean daytime latent (sensible) heating rates increasing (decreasing) by 6 W m^{-2} when LAI is set to an observed estimate near 5 (Paw U et al. 2002) instead of the MM5-prescribed value of 3 (Table 1). This sensitivity to LAI is about 3 times as great for deciduous species. Using a canopy height of 67 m (Paw U et al. 2002) instead of 35 m (Table 1) for the WR site increased (decreased) LE (H) by 5 W m^{-2}. Changing the leaf optical properties to correspond to deciduous vegetation instead of coniferous vegetation decreased net radiation by 10 W m^{-2}.

Complicated surface–atmosphere feedbacks in the MM5–ACASA simulations compound the effects of these vegetation specification factors, leading to more disagreement with observations than would occur in offline tests using ACASA or any other physiologically based surface layer scheme. Radiation, humidity, and temperature are the most crucial in the current simulations. Though cloudy instances were screened in the site comparisons for this investigation, errors in MM5 cloud amount can bias flux estimates by several hundred watts per square meter during daytime conditions. The apparent specific-humidity bias in the MM5 simulations is large and can affect transpiration of dry leaves by shutting down photosynthesis in the physiological calculations under arid conditions. These effects vary depending upon land use, but offline tests show that decreasing specific humidity by 5 g kg^{-1} decreases mean LE by 20 W m^{-2} for coniferous forest, by less for desert scrub, and by more for broadleaf vegetation. Tests also show that coniferous forest is more sensitive to variations in specific humidity than are areas with minimal vegetation, and less so for broadleaf species. Temperature variations are also important in estimating evapotranspiration, with a 2°C increase in temperature giving rise to a 10–30 W m^{-2} increase in LE during summertime daylight hours for most vegetation regimes. Variations in near-surface wind speeds of 1 m s^{-1} or less have little impact ($<$10 W m^{-2}) on MM5–ACASA flux estimates.

d. Computational costs of using ACASA versus BATS and LECMWF in MM5

When deciding on an appropriate LSM to use in numerical simulations, it is important to consider the computational cost of different schemes. In the MM5 simulations performed for this experiment, it was found that MM5–ACASA is about 20% more computationally expensive in terms of processing time than is MM5–LECMWF on a single Digital Equipment Corporation DEC-Alpha processor running at ~400 MHz. This added expense is small in comparison with the cost of doubling the horizontal or vertical resolution in MM5. BATS added relatively little computational expense to MM5 as compared with MM5 using LECMWF ($<$5%). The additional RAM needed to run MM5–ACASA and MM5–BATS instead of MM5–LECMWF is negligible ($<$1 MB).

5. Concluding remarks

Results show that the coupling between MM5 and ACASA is successful and that the MM5–ACASA estimates of near-surface air temperatures, winds, precipitation, and surface fluxes are realistic. Comparisons between simulated and observed NCEP–NCAR reanalysis and station reports also show that MM5–ACASA has a greater tendency to simulate near-surface meteorological conditions and associated fluxes more accurately than each of the simulations employing simpler land surface parameterizations. This tendency is most apparent in estimates of latent heat flux, friction velocity, air temperature, and wind fields. This hierarchy of occurrences of model–observation agreement matches what one might expect, with the most sophisticated land surface model generally enhancing simulation accuracy. Near-surface specific humidity and precipitation over the ocean are sensitive to *terrestrial* LSM choice, despite the use of the same surface-layer physics over water. This finding highlights the importance of terrestrial surface processes (and modeling) on adjacent atmosphere–ocean interactions. Specific-humidity values from individual sites and the reanalysis fields suggest that MM5 may underestimate near-surface specific humidity when coupled to sophisticated land surface schemes such as ACASA or BATS. Using the simple LECMWF scheme offsets this bias but severely compromises overall model accuracy. More investigation is needed to determine which model and/or reanalysis assumptions are responsible for this apparent dry bias and how to correct it. Preliminary results for biogenic CO_2 fluxes reveal that ACASA can be a useful tool in addressing issues related to future atmospheric CO_2 concentration.

The sensitivity of MM5–ACASA and MM5–BATS results to changing the initial soil moisture content is small in comparison with the sensitivity of MM5 results to the use of ACASA, BATS, and LECMWF. The relatively dry and uneventful conditions that dominated the region in question during July of 1998 probably contributed to the mild sensitivity to soil moisture initialization.

The differences between MM5–ACASA and observations from particular sites are likely associated with a multitude of factors, including vegetation specification and MM5-based meteorological uncertainties. Indeed, 1D offline tests show far greater agreement between ACASA and observed fluxes when driven with observed meteorological conditions, initial soil moisture content, and vegetation characteristics than with the prescribed values used in the coupled comparisons (Pyles et al. 2000). Although ACASA possesses a number of physically based vegetation parameters tied to land use for areas in which few in situ measurements are available, this issue is common to all sophisticated physiologically based land surface schemes. Results from simple offline tests show that the combination of model sensitivities to vegetation and initial soil specification is large enough to explain the discrepancies between the MM5–ACASA and observed surface energy flux estimates in the site comparisons.

More extensive validation work is needed to establish whether ACASA can improve model simulations, which should include a broader array of observed data than that used in this investigation. It would be particularly interesting to evaluate MM5–ACASA performance over longer timescales that include full seasonal cycles and/or heavy convective precipitation events. Simulations over regions and times possessing more observations of surface fluxes, precipitation, and boundary layer behavior in both tropical and extratropical regions are therefore being planned.

Future MM5–ACASA simulations could be improved through several ways. First, it would be very useful to use the 24 summer and 24 winter land use classifications available in MM5, version 3. It would particularly be helpful to use remotely sensed vegetation parameters (Buermann et al. 2001). Using U.S. Geological Survey soil types as provided in MM5, version 3, (independent of land use) would also benefit model accuracy. In addition, using remotely sensed or existing model values for soil moisture initialization would potentially improve simulations.

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