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Time series analysis of regional climate model performance

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[1] Four regional climate models (RegCM2, MM5/BATS, MM5/SHEELS, and MM5/OSU) were intercompared on a fairly small domain covering a relatively homogenous area in Kansas, United States, including the First International Satellite Land Surface Climatology Project (SLSCP) Field Experiment (FIFE) site. The models were integrated for a 2-year period covering 1987 and 1988. The model results are evaluated against data collected during this time period at the Konza Prairie Long-Term Ecological Research (LTER) site as well as over the summer observation periods of FIFE. The models all captured the proper qualitative behavior of the interannual variability, though the magnitudes varied considerably between models. They also found it particularly difficult to reproduce observed changes in the variance of surface variables. No model performed consistently better, with each model displaying particular strengths and weaknesses of its own. RegCM2 could be improved by including an ice phase in the cloud microphysics parameterization. MM5/BATS and MM5/SHEELS need revision of the formulation of stability dependence of the surface drag coefficients, including the coupling to the wind field, as well as using a total soil depth more representative of the area. MM5/OSU simulates too much resistance to evapotranspiration and fails to close the energy budget. All of the models overestimate runoff and evapotranspiration during winter, creating a dry anomaly which persists throughout the following summer. Development and verification of parameterizations involved in coupling the land surface and atmospheric components of these models together is at least as important as the development and verification of each component individually.

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1. Introduction

[2] Over the last several decades, the importance of improving land surface schemes used in climate models, both regional and global, has become apparent. Predictions of the energy and water balance at the surface, including the atmospheric feedbacks and the potential impacts of climate and/or land use change on streamflows, all need to be investigated. Very complicated Soil-Vegetation-Atmosphere Transfer (SVAT) schemes for dealing with these land surface processes [*Abramopoulos et al.*, 1988; *Dickinson et al.*, 1986; *Sellers et al.*, 1986] have been developed. The use of these complex models has brought new problems, including overparameterization and substantial computational demand when included as part of a climate model [*Pitman et al.*, 1999].

[3] Regional climate models (RCMs) share many of the same features as global climate models (GCMs) in terms of the parameterizations of their dynamics and physics, though they are generally run at much higher spatial and temporal resolution. RCMs differ, however, in their need to assimilate lateral boundary and initial conditions from global models and/or reanalysis.

[4] This paper investigates the temporal performance of selected RCMs in simulating the surface energy and water budgets over a domain that includes the First International Satellite Land Surface Climatology Project (ISLSCP) Field Experiment (FIFE) region of Kansas. This is done by examining the time series results of model runs covering two consecutive years that display significantly different climates in the study region. Emphasis is placed on the connections between the energy and hydrological budgets which occur intimately through the evaporative process as well as in the soil moisture influence over surface temperatures.

[5] The surface energy budget is given in equation (1) for non−snow-affected areas simply as

$$h_s = R_{net} - H - L_v E, \qquad (1)$$

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where R_{net} is the net incident radiation at the surface, H is the sensible heat flux, L_v is the latent heat of vaporization, and E is the rate of evapotranspiration. Evidence has shown that over the course of a year the net surface heating (or ground heat flux) h_s is negligibly small compared to the other terms in equation (1). When taking a long-term view in a stable climate the net surface heating should be essentially zero. On the other hand, in a changing climate we would expect a long-term drift of the net surface heating. Hence the net surface heating is an important indicator of long-term climate change. Unfortunately, it is difficult to measure and can be a source of considerable variation between climate models themselves.

[6] The water budget equation, which expresses the conservation of mass in a lumped or averaged hydrological system, can be written as

$$(P - E)A - Q = {}^{dS}/_{dt}. \qquad (2)$$

Here P is the mean rate of precipitation on the system, E is the rate of evapotranspiration, A is the surface area, Q is the net outflow of water (runoff), S is the water volume stored in the system, and t is time.

[7] Similarly to the ground heat flux, the change in soil moisture in a stable climate should be negligible over the long term. Unlike the ground heat flux, though, soil moisture can change considerably over the short to medium term. Even on an interannual basis the soil moisture can vary greatly from flood years to drought years.

[8] A number of previous regional climate model intercomparison studies have been conducted. The Project to Intercompare Regional Climate Simulations (PIRCS) experiment 1a involved eight RCMs (including MM5/BATS and RegCM2) run on a domain covering the continental United States for a period of 2 months covering 15 May to 15 July 1988. Some results from this experiment are reported by *Takle et al.* [1999]. They found that the RCMs were able to reproduce bulk temporal and spatial characteristics of meteorological fields; in particular, the 500-hPa-height field was well simulated by participating models. They found that large-scale precipitation was simulated well in terms of time and location though amounts often varied from observations, while convective precipitation is represented only in a stochastic sense with less agreement in temporal and spatial patterns. Simulated surface energy budget was also compared to FIFE observations. While the simulated results show broad agreement with the FIFE observations, significant scatter among results meant that no strong conclusions could be drawn. PIRCS experiment 1b was performed over a similar domain but covered the period June–July 1993 with 13 RCMs involved. This period included a flood in the central United States. The results are reported by *Anderson et al.* [2003]. They found that the models were able to reproduce recycling ratios within the range estimated from observations even though many of the RCMs demonstrated a low precipitation bias. The majority of the RCMs were able to reproduce the observed nocturnal maxima in precipitation though none of the models accurately reproduced the characteristics of the mesoscale convective system.

[9] The Project for Intercomparison of Land Surface Parameterization Schemes (PILPS) has conducted several experiments focused on assessing the performance of land surface schemes. Most of these studies have driven the various land surface models with observational data [*Henderson-Sellers et al.*, 1996; *Liang et al.*, 1998; *Lohmann et al.*, 1998; *Wood et al.*, 1998]. While studying the performance of land surface schemes in an "offline" mode may provide useful information for the development of those models, it has been shown that these results may not be directly relatable to the performance of the same models when fully coupled to an atmospheric model [*Hu and Islam*, 1996; *Kim and Entekhabi*, 1998]. *Margulis and Entekhabi* [2001] state that "offline" land surface model intercomparison sensitivity studies can lead to incomplete and misleading sensitivities of land-atmosphere interactions. Some later PILPS experiments coupled several land surface models to the same RCM [*Timbal and Henderson-Sellers*, 1998]. They found that the scatter among the schemes, while different than that observed in the offline experiments, was of the same order of magnitude. In this study the land surface models are coupled to their native atmospheric components; thus the model sensitivities are those applicable to these coupled model systems.

[10] As well as the above formal projects, there have been several other studies which have performed intercomparisons of various climate model parameterizations. *Chen et al.* [1996] compared the simulation of land surface evaporation for four land surface parameterizations over FIFE. The simplest of these models was the simple bucket model with two parameters [*Manabe et al.*, 1965], and the most complex model is the simplified Simple Biosphere (SSiB) model of *Xue et al.* [1991] with 22 parameters. They conclude that some complexity in the canopy resistance scheme is important in reducing both the overestimation of evaporation during wet periods and underestimation during dry periods with the two most complex models performing the best. They also demonstrated that simply increasing complexity of the model does not necessarily improve performance, with the most complex model (22 parameters) performing similarly to the second most complex model (15 parameters). *Leung et al.* [1999] intercompared three RCMs which were used to simulate an extreme flood event over eastern Asia. They found that each model simulated the gross flood conditions reasonably well, though significant differences were found in the simulated energy and hydrological cycles, especially over cloudy areas. The reasons for this include the simulation of the amount and vertical distribution of clouds, the treatment of cloud radiative feedbacks, and the representation of land surface processes. They also note that "One specially important criterion is the radiation balance which has serious implications for long term climate simulations."

[11] This study differs from previous intercomparison studies due to a combination of factors. Of the four RCMs used, two share the same land-surface scheme (RegCM2 and MM5/BATS), allowing their differences to be attributed largely to the atmospheric components, while three share the same atmospheric components (MM5/BATS, MM5/SHEELS and MM5/OSU), allowing their difference to be attributed largely to the land-surface schemes. All of the models use their native parameter values and initialization with no site-specific initialization performed; that is, they are applied in their default configuration just as they would be for climate change impact studies, etc. The study period

Table 1. Summary of RCM Atmospheric Parameterization Schemes

RCM	MM5	RegCM2
Longwave radiation scheme	broadband emissivity method [*Stephens*, 1984]	band-absorptance technique including contributions of CO_2, O_3, H_2O, and clouds [*Kiehl and Briegleb*, 1991]
Short-wave radiation scheme	scattering and absorption by clouds, clear air and water vapor [*Grell et al.*, 1994]	δ-Eddington approximation [*Joseph et al.*, 1976]
Stable precipitation	*Dudhia* [1989]	*Hsie et al.* [1984]
Convective precipitation	Grell scheme [*Grell*, 1993]	Grell scheme [*Grell*, 1993]
Planetary boundary layer	nonlocal-K approach [*Hong and Pan*, 1996]	nonlocal-K approach [*Holtslag et al.*, 1990]
Boundary relaxation	five-point linear	eight-point exponential

extends over the years 1987 and 1988 that are relatively wet and dry, respectively. This difference between years provides a test of the RCMs' ability to simulate not just the seasonal cycle but also their ability to capture a significant interannual difference. It also allows the physical parameterizations of each RCM to be run under essentially energy-limited conditions in 1987 and water-limited conditions in 1988. A more comprehensive evaluation of the RCM performance during summer, for which observations of many variables were collected during FIFE, is a primary focus of this study.

[12] The paper is organized as follows. Relevant components of the RCMs are described in section 2. Section 3 contains the experimental design and a description of the observations used for verification. Section 4 discusses results from the RCM simulations, and section 5 presents a discussion elaborating on the implications of the results. The conclusions are presented in section 6.

2. Model Descriptions

[13] This section presents brief descriptions of the models used. Table 1 contains a summary of the atmospheric components while Table 2 summarizes the land-surface schemes. One RCM used is the National Center for Atmospheric Research (NCAR) second-generation regional climate model, RegCM2. The three other RCMs are variations of the fifth-generation Pennsylvania State University/NCAR (PSU/NCAR) Mesoscale Model (MM5) adapted for climate studies. The land surface schemes used are the Biosphere-Atmosphere Transfer Scheme (BATS), the Simulator for Hydrology and Energy Exchange at the Land Surface (SHEELS), and the Oregon State University (OSU) schemes. It is important to note that RegCM2 and MM5/BATS share the same land-surface scheme (BATS), differing only in their atmospheric components, while each of the MM5 based models share the same atmospheric components but differ in their land-surface schemes.

2.1. RegCM2

[14] The second generation NCAR Regional climate model (RegCM2) is based on the PSU/NCAR MM4, an atmospheric circulation model. Several of the MM4's physics parameterizations were modified to adapt it to long-term climate simulations. Key modifications include detailed representations of radiative transfer [*Briegleb*, 1992], surface physics–soil hydrology processes [*Dickinson et al.*, 1993], the model planetary boundary layer [*Holtslag et al.*, 1990], and convective precipitation schemes [*Giorgi*, 1991]. Much of the development of RegCM2 is reported by *Giorgi et al.* [1993a, 1993b].

2.2. MM5

[15] The PSU/NCAR Mesoscale Model 5 version 2-5 known as MM5 is described by *Dudhia* [1993] and *Grell et al.* [1994]. The original coupled model system (MM5/BATS) is described by *Lakhtakia and Warner* [1994], and a subsequent model system (MM5/SHEELS) is described in several papers [*Laymon and Crosson*, 1995; *Smith et al.*, 1993]. The MM5 allows the choice of several different physical parameterization schemes for radiation, boundary layer, and convective processes. In this study the model was implemented with the Dudhia short-wave radiation scheme described by *Grell et al.* [1994], the nonlocal-K approach given by *Hong and Pan* [1996] and the Grell scheme for convective precipitation [*Grell*, 1993]. The model has been successfully applied to study a wide range of atmospheric phenomena covering horizontal length scales

Table 2. Summary of RCM Land-Surface Schemes

Land-Surface Scheme	BATS	SHEELS	OSU
Number of layers for temperature	three	three	four
Temperature methodology	force-restore [*Deardorff*, 1978]	force-restore [*Deardorff*, 1978]	diffusion equation [*Mahrt and Ek*, 1984]
Number of layers for soil moisture	three nested	11 discrete	four discrete
Soil moisture methodology	Darcy's law	Darcy's law	Darcy's law
Canopy methodology	Penman/Monteith	Penman/Monteith	Penman/stability-dependant resistance

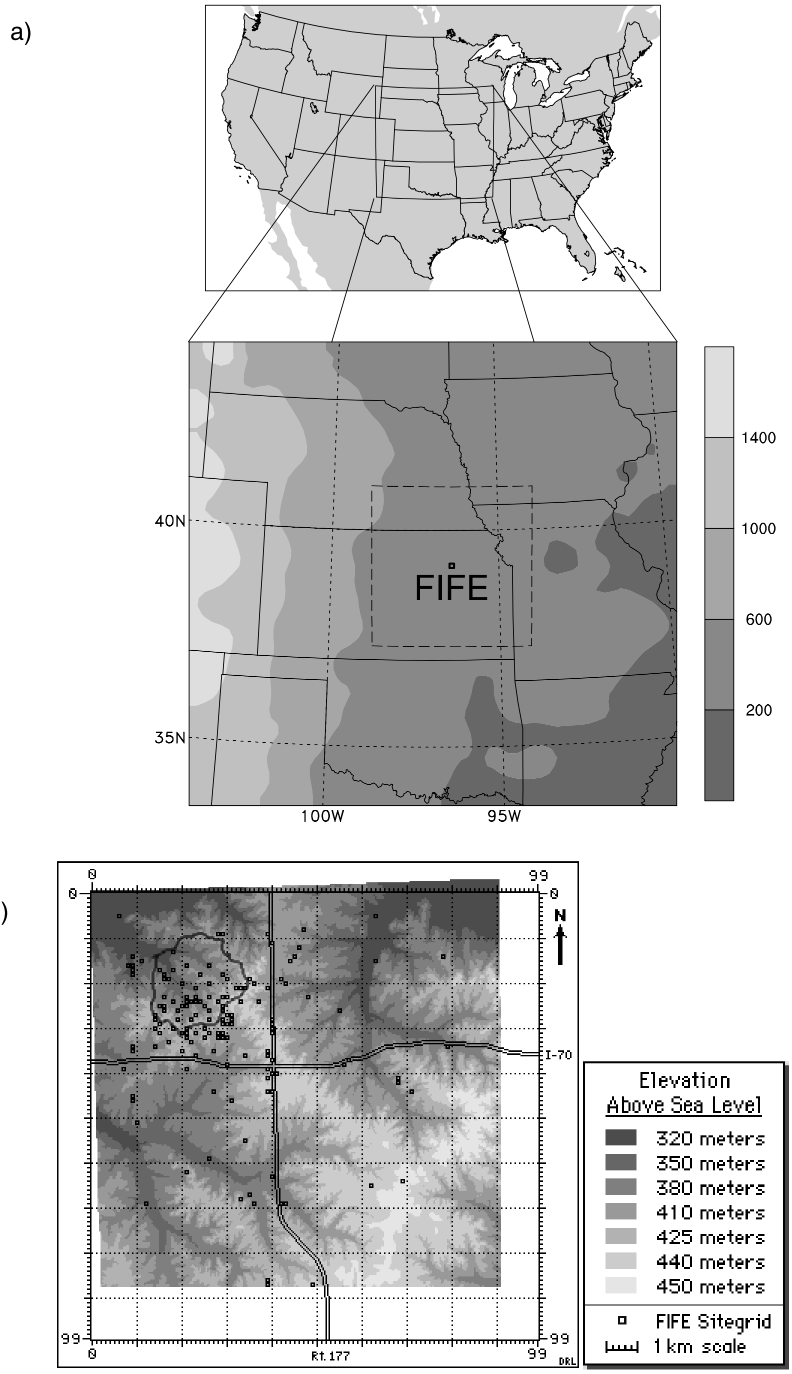

Figure 1. (a) RCM domain and topography, as well as the location of the FIFE site and neighborhood (dashed square). (b) FIFE site showing approximate location of King's Creek catchment in the northwest corner (outlined area), ground measurement stations, and the elevation.

on the order of a kilometer to several hundred kilometers [*Anthes et al.*, 1985; *Dudhia*, 1989; *Hines et al.*, 1995; *Lapenta and Seaman*, 1990] and requires lateral forcing provided either from observations or a GCM. The final RCM consists of MM5 version 3–4 [*Grell et al.*, 1994] coupled to the OSU land surface scheme [*Chen and Dudhia*, 2001]. In this study, identical physical parameterizations for atmospheric processes (i.e., PBL, convection, precipitation) were employed in all three MM5 configurations (Table 1).

2.3. BATS

[16] The BATS, described by *Dickinson et al.* [1993, 1986], incorporates a single vegetation layer, a multiple layer soil scheme, and provision for snow cover on the land surface. BATS contains 23 vegetation and soil parameters which are used to explicitly model many of the processes within the soil and vegetation canopy.

[17] When coupled to a climate model, the vegetation type, soil texture, and soil color need to be specified for each grid point, along with the initial soil moisture, and

ground and foliage temperatures. Inputs required for BATS from the atmospheric model include wind components, air density, temperature, and water vapor mixing ratio at the lowest atmospheric level, surface radiant fluxes at solar and infrared wavelengths, and precipitation. From these and other internally generated quantities, BATS calculates the temperature of the surface soil, deep soil, canopy foliage and canopy air, the soil moisture in three layers, snow cover, and surface fluxes of momentum, heat, and moisture. The surface fluxes are then fed into the momentum, thermodynamics, and water vapor equations of the climate model as lower boundary conditions

2.4. SHEELS

[18] A detailed description of SHEELS is provided by *Smith et al.* [1993] and *Laymon and Crosson* [1995]. The physics of SHEELS are based on those present in BATS. The main difference between them occurs in the representation of subsurface hydrologic processes. Instead of the nested three-layer approach of BATS, SHEELS uses a discrete layer approach with five 2-cm-thick layers in the top 10 cm of soil, a root zone containing three 30-cm-thick layers, and a lower zone extending to 10 m depth and divided into three layers. SHEELS also models surface soil water flow based on *Capehart and Carlson* [1994]. These changes were made to produce better simulations of the strong near-surface moisture and temperature gradients that are often observed, especially in areas of sparse vegetation.

2.5. OSU

[19] The OSU land surface scheme is described by *Chen et al.* [1996] and *Chen and Dudhia* [2001]. The model has one vegetation canopy layer and four discrete soil layers (0.1, 0.3, 0.6, and 1.0 m) aimed at capturing the daily, weekly, and seasonal evolution of soil moisture, with the root zone in the top 1 m, similar to BATS and SHEELS. OSU contains approximately 16 vegetation and soil parameters which are used to model water and temperature in the soil layers as well as snow cover and atmospheric feedbacks.

3. Experiment Design

[20] In this section the model domain and simulation period are discussed along with a description of the observations used for comparison.

3.1. RCM Setup

[21] The simulation domain for the experiment is centered over the FIFE region of the Konza Prairie, Kansas, and covers an area of 1200×1260 km^2 (longitude × latitude) in the central United States (Figure 1). The experiment was run for a total of 2 years beginning on 1 January 1987. The RCMs (RegCM2, MM5/BATS, MM5/SHEELS, and MM5/OSU) all used the same resolution with 17 levels in the vertical (including six layers in the lowest $\sim$1 km), horizontal grid point spacing of 20 km, and a time step of 1 min.

[22] The domain is chosen to be relatively small so that the models are well constrained at the boundary. This limits the regional models' ability to substantially change the large-scale circulation and increases the likelihood that intermodel differences are due to differences in the land surface–atmosphere interactions. The domain also excludes any major topographic feature, thus largely removing differences which may occur owing to differences in the way the models' dynamical schemes handle steep topography or sub-grid scale topographic features [e.g., *Evans et al.*, 2004].

[23] The period chosen is long enough to investigate the RCMs' representation of the seasonal cycle, and ends in 1988, which was considered an extreme drought year in the central United States [*Trenberth and Guillemot*, 1996] and provides a good test of the RCMs' ability to reproduce an extreme period. While the center of the drought-affected region lies to the east of the FIFE region, comparison of the monthly 1988 rainfall totals with their corresponding climatological values reveals that every month has below average rainfall (except April). The domain allows comparison with the intensive observations collected during FIFE as well as data collected within the Konza Long-Term Ecological Reserve (LTER) site collocated with FIFE.

[24] Atmospheric initial and boundary conditions were extracted from the analysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) (for RegCM2) and the NCEP/NCAR reanalysis (for MM5 based models). The analysis is treated as output from a "perfect" model of the atmosphere for the periods simulated and therefore assumes that differences between RCM output and observations near the center of the domain represent simulation errors due to internal shortcomings of the RCMs. This is not strictly true, and it must be remembered that some of the errors encountered will be due to errors in the analysis. It should also be noted that RegCM2 is using different boundary conditions than the MM5 based models. Each is being driven by the reanalysis used in the vast majority of publications associated with each RCM. While the ECMWF and NCEP/NCAR reanalysis are quite similar (e.g., average daily 500-hPa geopotential for the domain has a correlation coefficient of 0.824), they are not the same, and some differences associated with RegCM2 may be due to this boundary forcing.

[25] The aim of the current study is not to optimize the RCM parameterizations for a particular location, but rather to compare the performance of the schemes through time at the site of best observations (FIFE). As such, the RCM parameters have the values that are used as the default for this location, that is, the parameter values have been predefined using global scale data sets. For land use the simple 13-category (PSU/NCAR) data set was used, resulting in all models having a land use of agriculture at the FIFE site. Initial values for various fields are also taken as the model defaults (often depending on model parameters); this includes soil moisture and thermal properties. These values have been chosen by the developers of each coupled modeling system and hence are considered a good starting point for each RCM rather than imposing some other arbitrary value. That is, the models are run just as they would be when applied to the vast majority of the Earth's surface where lack of data precludes the possibility of special initialization. This is important because physically based models such as these have a plethora of parameters whose values are only weakly constrained and for any particular location may be tweaked to improve the models performance. To do so removes any pretence of general

Table 3. Root Zone Soil Moisture (RZSM) Values

RZSM	RegCM2	MM5/BATS	MM5/SHEELS	MM5/OSU	Observations
Initial (1 January 1987)	261	344	352	315	N/A
At initial observation (28 May 1987)	262	316	332	356	319
1 August 1987	230	179	202	261	240

applicability of the model, which is a primary interest of this study.

[26] The soil fields (particularly soil moisture) are thought to require "spin-up" time on the order of weeks to possibly months, this means that any impact of this spin-up is limited to the earliest part of the simulations and certainly does not influence the summer periods over which FIFE observations were collected and on which the majority of this paper focuses. During the first 5 months, many wetting and drying periods occur in every model and the initial soil moisture number occurs several times for each model. This implies that soil moisture would have been the same if initialized at the time of any one of these occurrences of the initial soil moisture value; i.e., the soil moisture has lost its memory of what occurred previously, and the actual initial value is significantly less relevant. This spin-up is considered to be different from any longer-term trend which may be present in the soil moisture field. The effect of the initial soil moisture is further elucidated by Table 3. At the time of RCM initialization, no observations exist and each coupled model begins with its default value. Almost 5 months later, at the time of the first observation, all of the models simulate root zone soil moisture within 18% of that observed, which indicates that the choice of default value for each coupled model allowed the models to perform quite well. Subsequent evolution of the soil moisture is much more influenced by modeled processes (precipitation, runoff, etc.) than by the initial values with MM5/BATS being initialized second wettest, beginning the observation period with almost exactly the correct value but just over 2 months later being the driest model, substantially drier than the observations. Each of the models' evolution of soil moisture in the observation period, as shown by the values in Table 3, shows no clear dependence on initial value but rather each responds differently owing to differences in internal modeled processes.

3.2. Observations

[27] The FIFE experimental domain consists of 15 × 15 km tall grass prairie on an undulating topography. The experiment itself is described in detail by *Sellers et al.* [1992]. The FIFE data set consists of nearly continuous observations of surface parameters from the Portable Automated Mesonet stations (PAM) and summer surface flux measurements. The PAM data (10 stations) consist of wind at 5.4 m and temperature and humidity at 2 m, together with radiometric measure of the ground surface temperature, downward short-wave radiation, net radiation, downward longwave radiation, and rainfall.

[28] Soil moisture measurements were made using two methods. The gravimetric method was used to measure the near-surface layer (0–10 cm), and the neutron probe method was used for data for depths of up to 2 m. In 1987, there were 20 gravimetric sites and 31 neutron probe sites. Measurements were made almost daily during the intensive field campaigns and less frequently between them. In 1988, 21 sites took gravimetric measurements and 11 took neutron probe measurements, approximately every 5–7 days.

[29] The summer surface flux measurements for 1987 include four intensive field campaigns (IFCs) (from 26 May to 7 June, from 25 June to 11 July, from 6 to 21 August, and from 5 to 16 October) with measurements made at 22 sites; during 1988, measurements were made at 10 sites. These surface flux measurements were collected by many individual principal investigators [*Fritschen et al.*, 1992; *Kanemasu et al.*, 1992; *Nie et al.*, 1992; *Smith et al.*, 1992a, 1992b]. During 1987, six sites measured fluxes by the eddy correlation method and 16 by the Bowen ratio method, while during 1988, all 10 sites used the Bowen ratio method.

[30] The FIFE data have been quality controlled, edited, and averaged by *Betts and Ball* [1998], resulting in a single time series that represents the mean over an area of 15 × 15 km square. Betts and Ball also estimate the standard deviation associated with these means. Meteorologically, the most significant difference between 1987 and 1988 was the slightly extended wet/green phase through summer 1987 compared to the spring and early summer of 1988 which was a period of drought over the central United States.

[31] The RCM results used in this study were given by the grid point centered within the FIFE site. Each grid point is representative of an area 20 × 20 km square, which is somewhat larger than the FIFE site itself. There are several reasons why the comparison is meaningful. Conditions over the FIFE grassland site were relatively homogenous, so that simple averaging of the data gave a representative mean. The Konza prairie itself covers over 50,000 km^2, and the diurnal cycle over land integrates over considerable advection distances (up to 100–200 km) [*Betts et al.*, 1998]. The areal water and energy budgets were calculated for the FIFE neighborhood (shown as a dashed square in Figure 1) and were found to be very similar to that simulated by the FIFE grid point.

4. Results

[32] An analysis and comparison of the simulated seasonal cycles for the energy and water budgets are presented in this section. The basic meteorological quantities of surface temperature and precipitation are shown first, in this case for the full annual cycle (as observations exist for this full period). Most remaining model quantities are shown only for those periods for which FIFE observations exist, starting with surface radiation, then soil moisture and runoff, and finally, the sensible and latent heat fluxes.

4.1. Surface Meteorology

4.1.1. Temperature

[33] Figure 2 presents the monthly mean near surface air temperature for the four RCMs and the observations. Despite 1988 being considerably drier than 1987, the observations indicate similar mean daily temperatures dur-

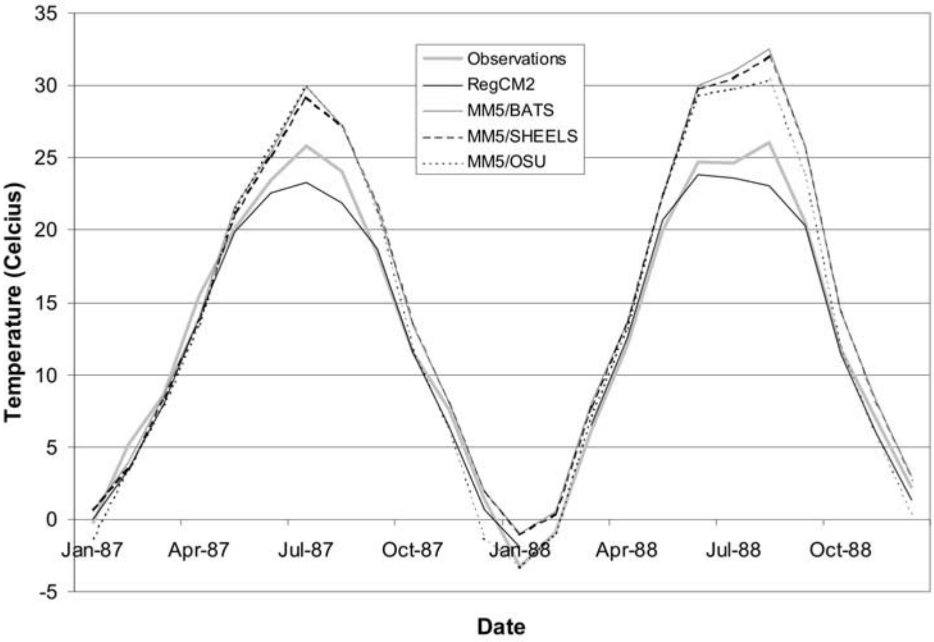

Figure 2. Monthly mean temperature simulated by the four models and observations.

ing the summers. The RCMs perform well at reproducing these observations, with disagreement occurring during summer in both years. The MM5 based RCMs tend to overestimate the temperature during summer while RegCM2 tends to underestimate it. The summer overestimation by the MM5 based RCMs increases from a maximum of ~3°C in 1987 to ~6°C in 1988, this can be largely attributed to the low level of soil moisture in the models inhibiting evapotranspiration and increasing the sensible heat and near-surface temperatures. This low level of soil moisture entering the observation period in 1988 highlights one of the most significant differences between the model and observations due to feedbacks on other aspects of the climate system. The soil moisture continues to decrease throughout the summer with the MM5 based models eventually reaching wilting point in August, creating the temperature maximum then. Unlike the MM5 based models and the observations RegCM2 does not quite reach wilting point and hence does not reproduce this August maximum. MM5/BATS and MM5/SHEELS overestimate the temperature in winter (early 1988) while MM5/OSU is better able to reproduce the observations.

4.1.2. Precipitation

[34] In 1987, 782 mm of precipitation is observed, while in 1988 only 503 mm is measured, a decrease of almost 36%. Each of the RCMs simulate a significant decrease in precipitation as well, with RegCM2 decreasing by ~36% while the MM5 based models decrease by over 50%. RegCM2 overestimates the precipitation by just over 10% in each year. MM5/BATS and MM5/SHEELS overestimate substantially in 1987 (by ~33%) while they underestimate in 1988. MM5/OSU underestimates in both years, being within 5% in 1987, but with the 1988 underestimation being ~25%.

[35] When looking at the seasonal split between summer (May–October, the FIFE intensive observation period) and winter (November–April), shown in Figure 3, we note several things. Around twice as much rain falls in summer as winter. In winter, very little of the precipitation falls as convective while in summer this accounts for at least half the total precipitation. No one model appears to perform the best compared to observations.

[36] The model split between stable and convective precipitation is most varied during summer when the MM5 based models all simulate a 50–50 split while RegCM2 simulates ~30% of the precipitation to be stable. In general, RegCM2 tends to produce more precipitation in winter (both stable and convective). MM5/OSU simulates the least precipitation in summer, especially convective. In the wet year RegCM2, MM5/BATS, and MM5/SHEELS all produce similar summer convective amounts, but these MM5 models produce significantly more stable precipitation. In the dry year, RegCM2 produces significantly more convective precipitation than the MM5 models.

[37] It has been recognized that accurately simulating the timing and magnitude of a precipitation event is a very difficult task. While reproducing the observed magnitude of any particular event is generally beyond the RCMs' capabilities, they should be able to reproduce the observed temporal distribution of precipitation. Figure 4 presents the precipitation distribution simulated by each of the models as well as the observed. Only events with at least 0.5 mm of precipitation are considered. As expected, all of the MM5 based models simulate similar distributions. The major difference between their distributions and the observed is an underestimation of the number of small (<2 mm) events. RegCM2, on the other hand, overestimates the number of events compared to the observed for events

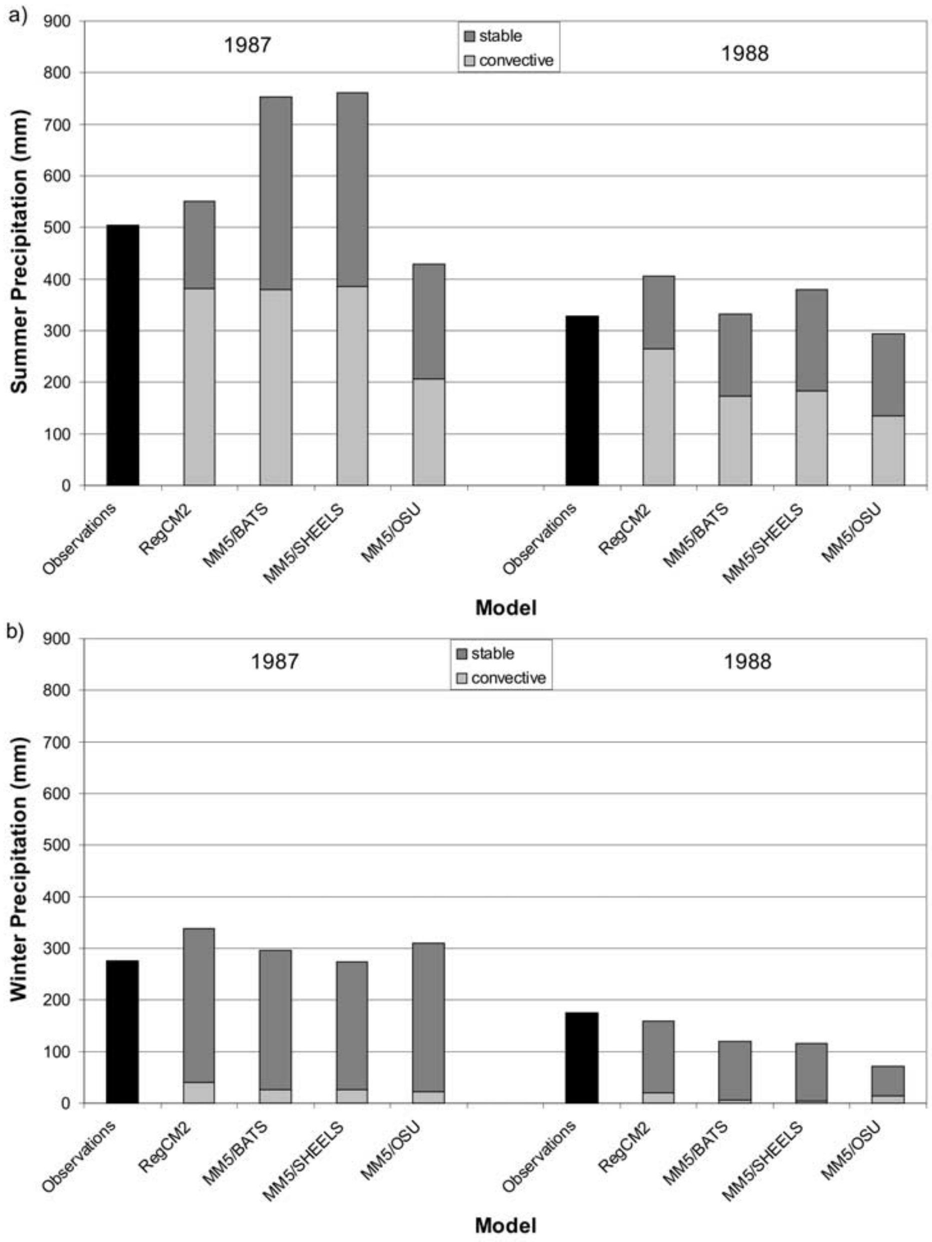

Figure 3. Seasonal precipitation simulated by the RCMs and observations. (a) Summer (May–October, FIFE observation period) precipitation. (b) Winter (November–April) precipitation.

up to 10 mm in size. It also significantly underestimates the number of large events (>20 mm). The MM5 based models were better able to simulate these extreme events.

[38] Further analysis (not shown) indicates that the stable precipitation parameterization in the RCMs is almost exclusively responsible for producing the observed large events. RegCM2 simulates many more small (<4 mm) stable precipitation events, and significantly less large (>20 mm) events compared to the MM5 based models. On the other hand, RegCM2 simulates the most convective events of all the RCMs, particularly the small events (<2 mm). MM5/OSU simulates the fewest events of all the RCMs; in particular, it produces only one convective event with greater than 12 mm of precipitation.

4.2. Soil Moisture

[39] A series of soil moisture measurements were taken in the FIFE site in both 1987 and 1988, in this section, RCM simulated soil moisture is evaluated against those measurements. Two layers in the soil profile are considered: the surface layer which is considered to be the top 10 cm, and the root zone taken to be the top 1 m of soil. Observations of soil moisture in the surface layer were taken using a gravimetric water content method (weight of water in the sample/weight of dried sample), while deeper observations of soil moisture were taken using a neutron probe, down to a depth of 2 m. Here only the top meter is considered. Measurements were made at as many as 30 sites, and then an areal average for each soil layer was compiled by *Betts*

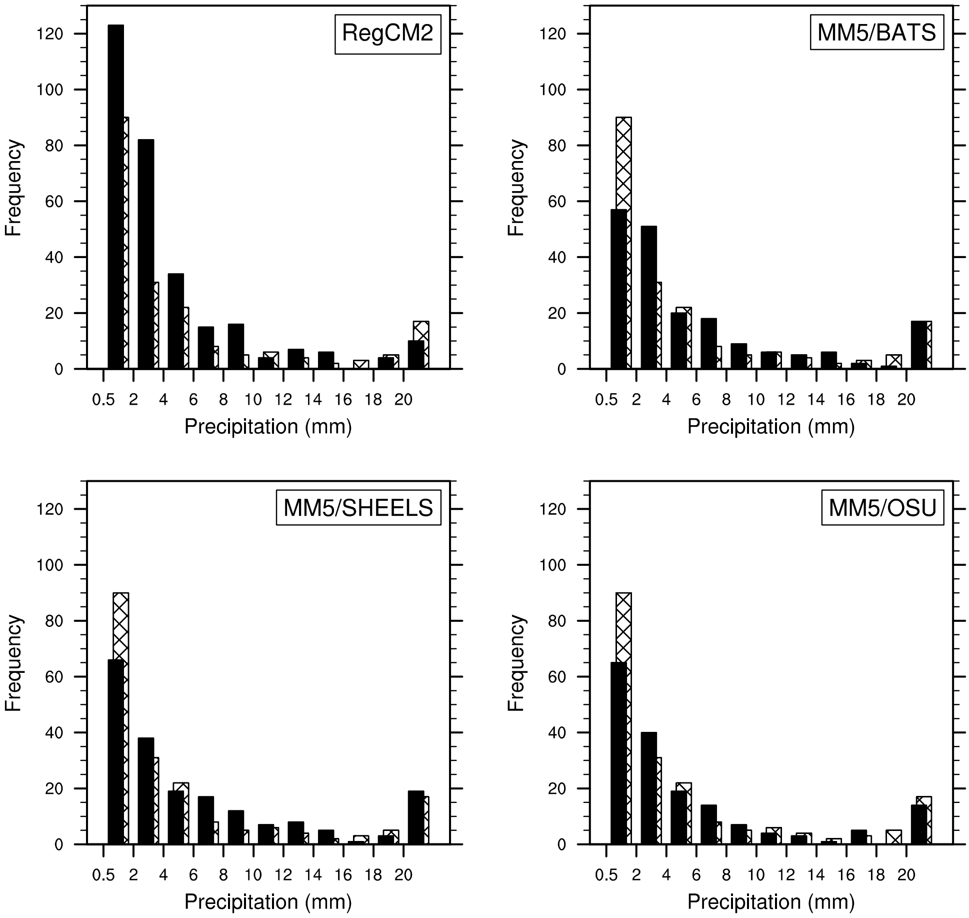

Figure 4. Daily precipitation distributions, during both 1987 and 1988, simulated by the models (black bars) and observations (hashed bars).

and Ball [1998]. In 1987 the observations began on 29 May and continued until 6 November, while in 1988 the observations began on 11 of April and finished on 29 September. Measurements were not made every day, so for the following comparison only RCM simulated soil moisture on those days that measurements were also taken is considered. The overall similarity between the RCMs in terms of soil moisture trends (Figures 5 and 6) is an indication that the lateral boundary conditions provide similar forcing.

[40] A complicating factor is that the dynamic soil moisture range in the root zone differs substantially between models with MM5/SHEELS using the largest range (~230 mm) and RegCM2 using the smallest range (~100 mm). The magnitude of the initial soil moisture also differs considerably between models with MM5/SHEELS starting with almost 130 mm more soil moisture in the root zone than RegCM2. All of the MM5 based RCMs simulate significant decreases in soil moisture in both years while RegCM2 simulates only a minor decrease in soil moisture in 1987 but a significant decrease in 1988. Also note that in 1988 the MM5 based models soil moisture approaches wilting point in late summer.

[41] The observed soil moisture in the surface layer, shown in Figure 5a, displays a much smoother response than is simulated by any of the RCMs. The MM5 based RCMs perform best at reproducing the observed surface layer soil moisture. The range of soil moisture values observed in the surface layer is reproduced by the RCMs reasonably well. The observed soil moisture in the root zone can be seen in Figure 5b. Again, the observations produce a smoother time series than is simulated by the MM5 based RCMs; however, this is not the case for RegCM2. RegCM2 generally simulates less root zone soil moisture than any of the other RCMs or the observations, throughout the period under consideration.

[42] Similar graphs for the 1988 observation period can be seen in Figure 6. During this period, there is less scatter in the RCM simulated soil moisture. In the surface layer, all of the RCMs begin the period with surface moisture estimated to be around half of that observed. By the end of the period, though, this massive underestimation has been reduced considerably since the observations display a decrease through the period, while the RCMs simulate the surface moisture to remain fairly constant (MM5 based RCMs) or even increase (RegCM2). The RCMs begin the 1988 observation period with only ~60% of the root zone soil moisture that is measured. This separation between the RCMs and the observations began as far back as August 1987 and continued to increase during the winter when no observations were taken. During the summer the observations show a considerable drying out of the root zone with an overall decrease of ~120 mm, which would be expected

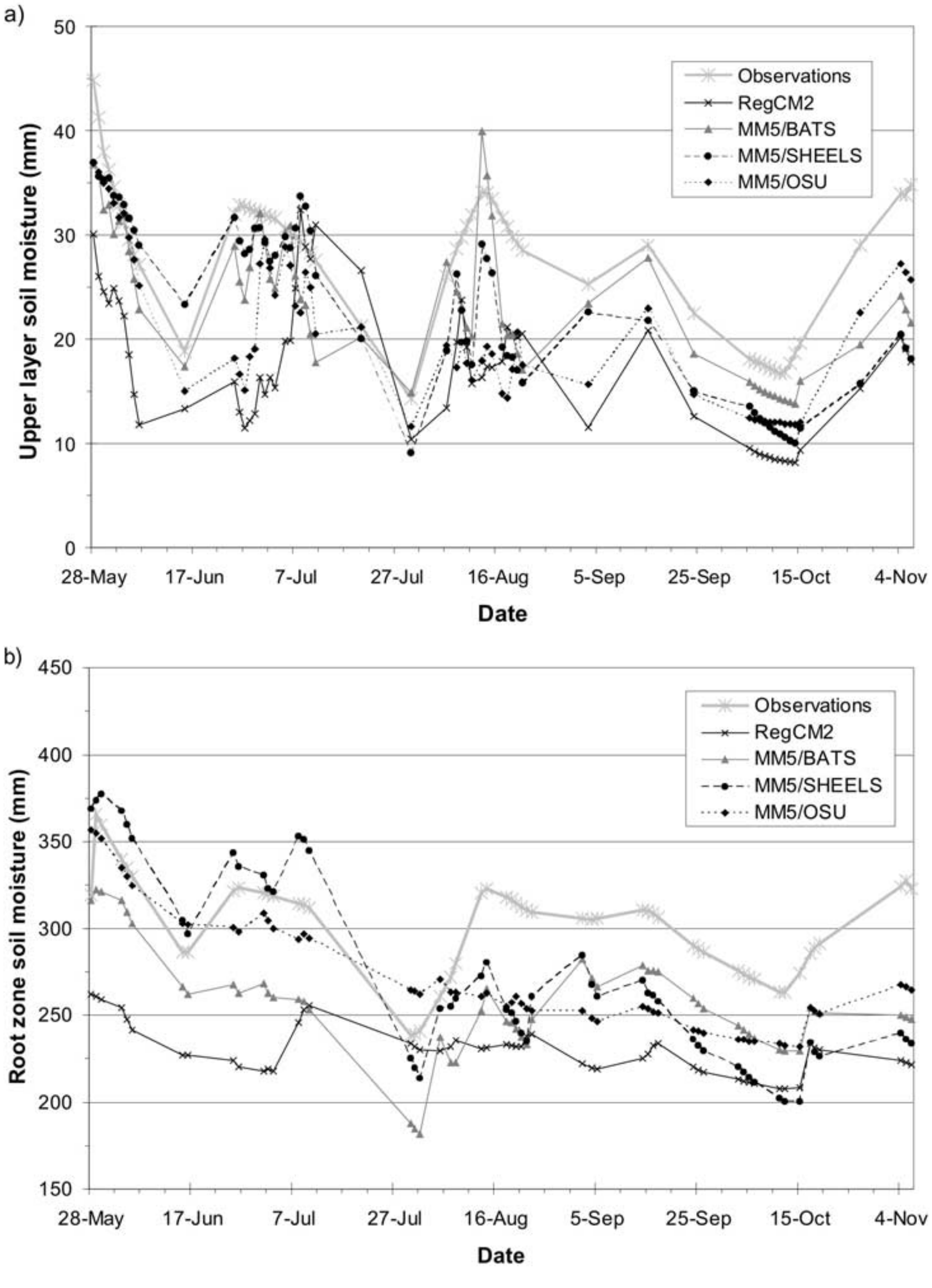

Figure 5. Soil moisture simulated by the RCMs and observations in the wet year (1987) for the (a) upper layer and (b) root zone.

during a year that is considered a drought year. While all of the RCMs simulate a decrease in the root zone soil moisture during this period, the decrease simulated is generally less than that observed.

[43] Previous intercomparison studies (most notably PILPS) have shown that it is somewhat problematic to attempt to compare modeled soil moisture values directly with observations owing to model defined terms like wilting point soil moisture and saturation soil moisture which determine the dynamic range over which the soil moisture may vary and which may not reflect the actual observation site accurately. Thus they concentrated on looking at changes in the soil moisture.

[44] In order to obtain a statistical measure of which model best captures the observed change in soil moisture (ΔSM), we calculated the root mean square error (RMSE) as

$$\mathrm{RMSE} = \sqrt{\overline{\Sigma}(\Delta \mathrm{SM}_m - \Delta \mathrm{SM}_o)^2}, \quad (3)$$

where $\overline{\Sigma}$ represents the sum divided by the number of occurrences, subscripts m and o stand for modeled and observed, respectively, and the change occurs from one observation time to the next. Here the change is calculated from one observation time to the next.

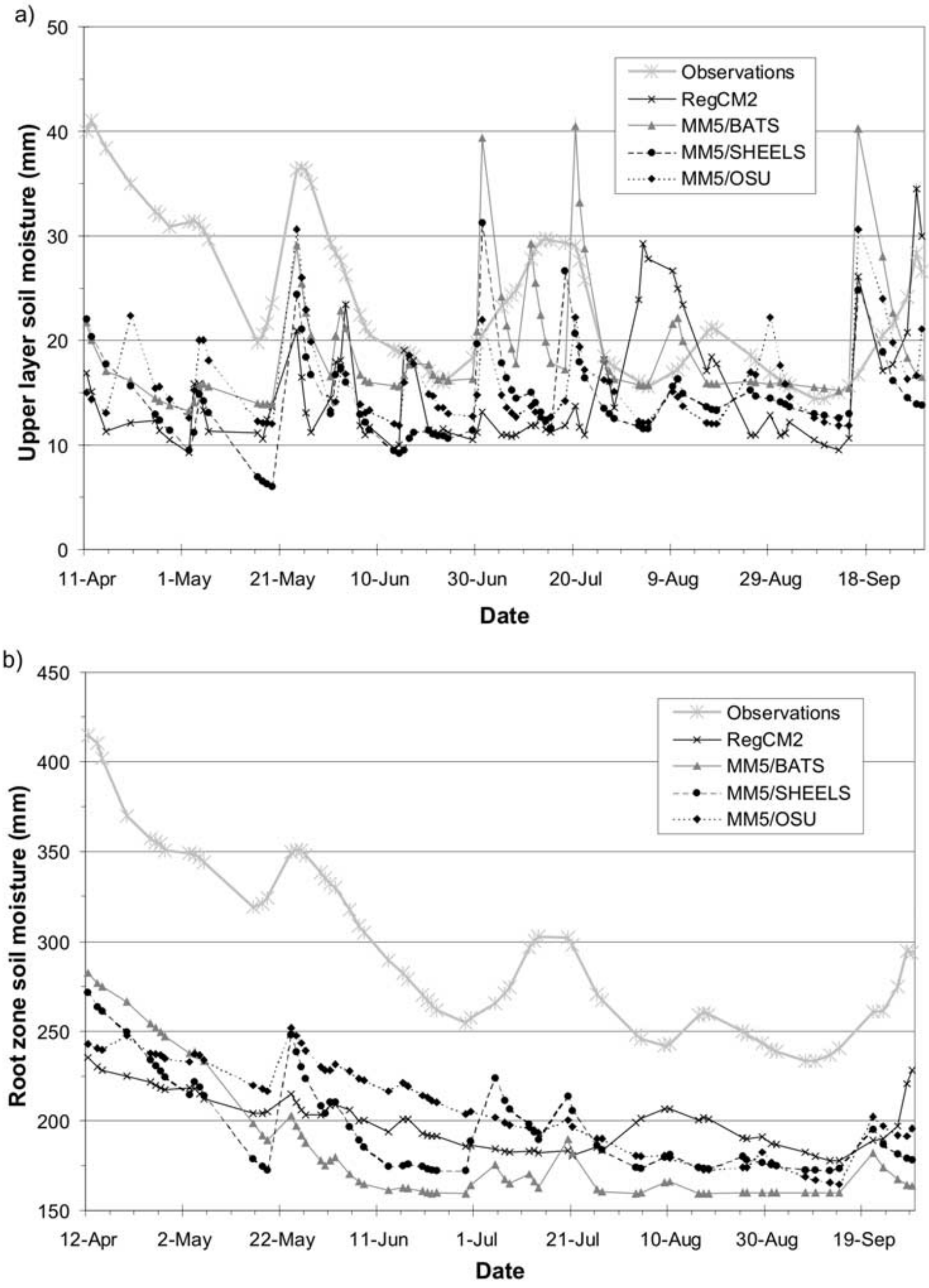

Figure 6. Soil moisture simulated by the RCMs and observations in the dry year (1988) for the (a) upper layer and (b) root zone.

[45] The observed daily area averaged values were constructed using all of the measurements taken each day. Hence each daily value represents very different numbers of measurements, ranging from 1 to over 100 measurements. Clearly, less confidence can be placed in an areally averaged value when it was based on one measurement rather than many, so the RMSE is calculated based on the number of measurements taken. The resulting RMSE for all of the RCMs are shown in Table 4.

[46] Generally, MM5/SHEELS performs best in terms of ULSM, with MM5/BATS performing the worst. Meanwhile, RegCM2 performs the worst overall in terms of root zone soil moisture, with the MM5 based models all performing similarly. Hence it seems that the many small soil moisture layer approach in the top 10 cm does

Table 4. RMSE in Soil Moisture Changes Based on the Occurrence of Measurements

Model	ULSM 87	ULSM 88	RZSM 87	RZSM 88
RegCM2	3.52	4.91	17.39	11.51
MM5/BATS	3.72	6.33	13.30	10.11
MM5/SHEELS	2.89	3.62	13.78	12.93
MM5/OSU	2.81	4.33	14.79	10.02

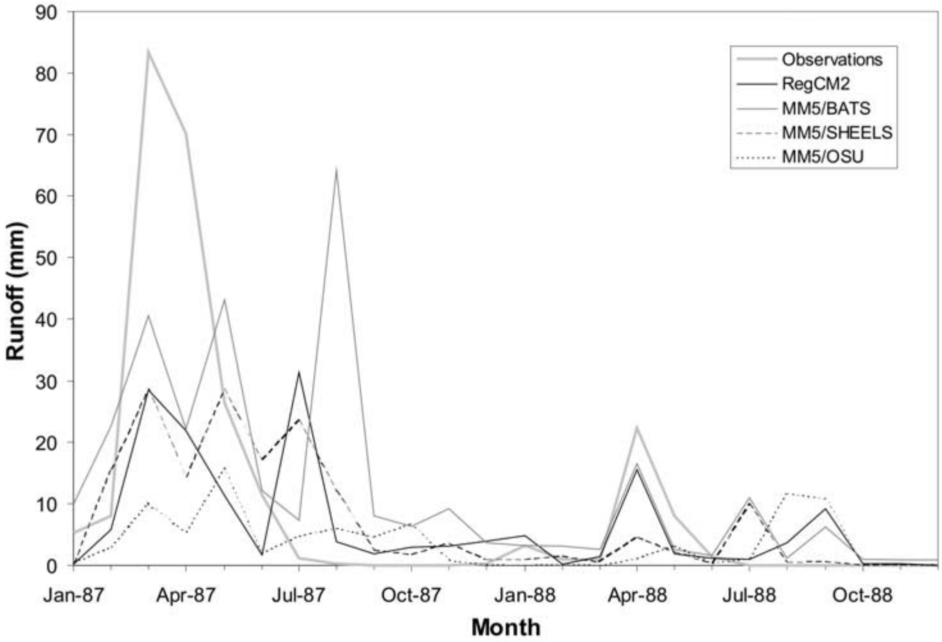

Figure 7. Monthly runoff totals for the four RCMs and observations for Kings Creek catchment.

provide some advantage for MM5/SHEELS in dealing with the upper layer soil moisture. However, this advantage is no longer clear once you reach the root zone depth (1 m).

4.3. Runoff

[47] The runoff simulated by each of the RCMs is compared with observations taken from Kings Creek Catchment in the northwest quadrant of the FIFE site. The runoff simulated by the RCMs is representative of runoff from a 20 km × 20 km grid square. This runoff is then scaled down to be representative of an area of approximately 11 km^2 (the area covered by Kings Creek catchment) using an area proportionality approach. This can be justified since the RCMs represent the grid square using a single land cover type, assuming homogeneity within the grid square for the land-surface parameters. Runoff provides one of the only spatially integrating observational data sets, making it more appropriate for comparison with RCM simulations than point observations.

[48] The monthly runoff totals are presented in Figure 7; note that entire annual cycles are present. During the wet year (1987), MM5/BATS simulates significant runoff to occur from March through August with August producing the largest peak. MM5/SHEELS simulates consistent runoff from March through July. RegCM2 simulates a runoff peak in March, in agreement with observations, but it also simulates another runoff peak in July, which is not observed at all. MM5/OSU simulates far less runoff than is observed, though the majority of it is placed at the correct time of year, March through May. All of the RCMs fail to capture the very dry, no-flow period at the end of 1987. This failure is responsible, in part, for the increase in the underestimation of soil moisture by the models between the two summer observation periods. During 1988, runoff is observed to occur in April and May with almost no runoff occurring in any other month. All four RCMs simulate runoff from April until much later in the year than is observed. RegCM2 and MM5/BATS capture the runoff peak in April, while MM5/SHEELS simulates some runoff in April though its main runoff peak occurs in July. MM5/OSU barely captures any runoff in the April/May period and instead produces significant runoff in August and September.

4.4. Radiation Budget

[49] The largest difference in the net surface radiation balance occurs between RegCM2 and the MM5 based models, with RegCM2 simulating ~18% less over an annual cycle. While there are some differences in the downward shortwave radiation, these are small enough that the models simulate similar net shortwave radiation. The major differences between them occur in the longwave radiation. All of the models simulate less downward longwave radiation reaching the surface in 1988 compared to 1987. In terms of the upward longwave radiation, RegCM2 simulates a decrease in 1988 compared to 1987, while the MM5 based models simulate an increase. This is explained largely by RegCM2 having a lower summertime surface temperature during 1988 while the MM5 based models all simulate higher summertime surface temperatures. In terms of the net radiation the difference between RegCM2 and the MM5 based models is in the magnitude of the downward longwave radiation. RegCM2 simulates significantly less downward longwave radiation reaching the surface in both years.

[50] In Figure 8 the simulated downward longwave radiation is compared to the area averaged radiation measured during FIFE. Observations were taken over slightly different dates in 1987 (Figure 8a) and 1988 (Figure 8b). During the 1987 (wet) observation period, RegCM2 does a particularly good job at reproducing the observed downward longwave flux, while during 1988 (dry) it tends to

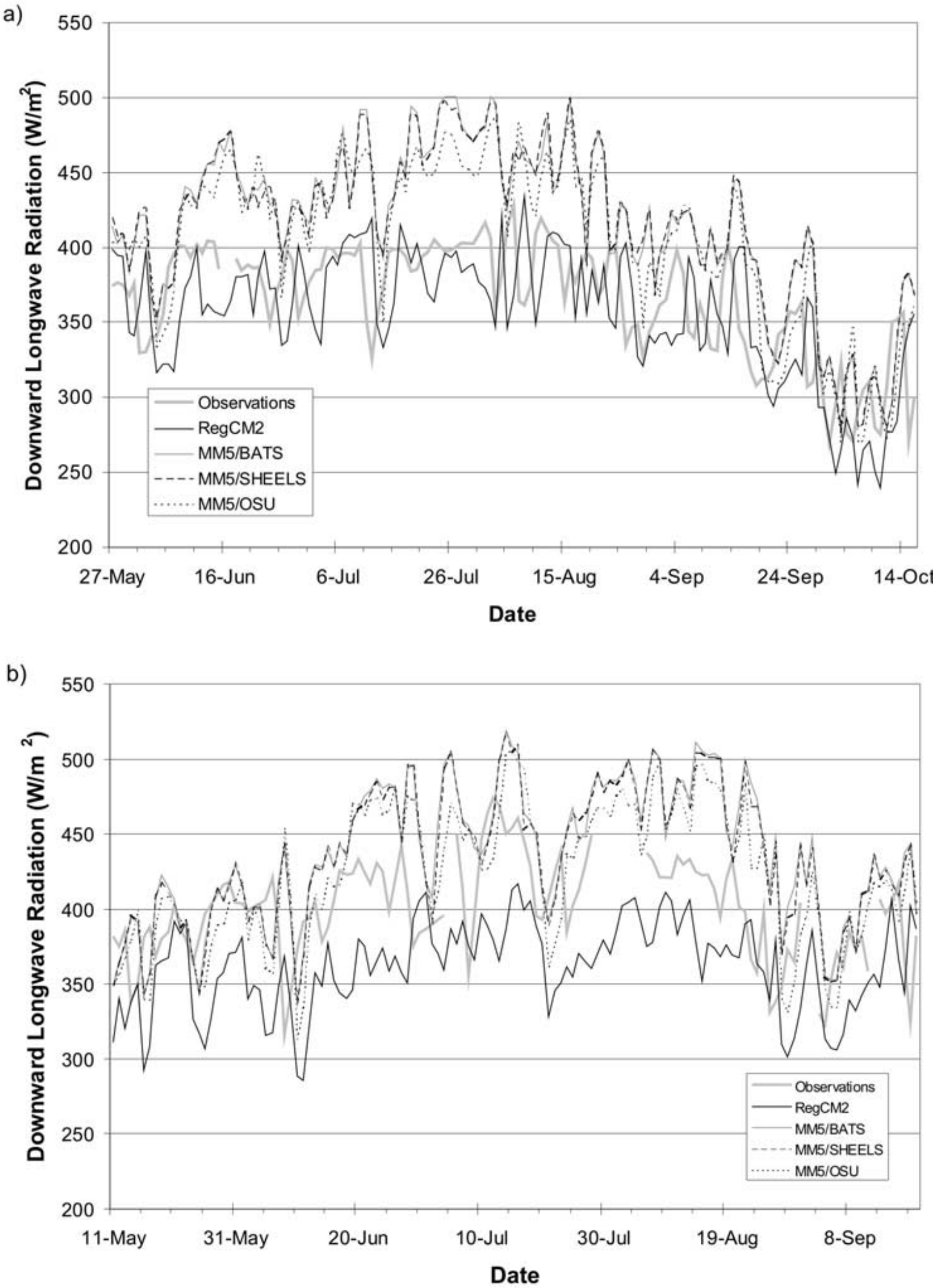

Figure 8. Downward longwave radiation simulated by the RCMs and observations during (a) 1987 and (b) 1988.

underestimate the flux. For the MM5 based models we see that in 1988 there is a small overestimate of the downward longwave radiation; in 1987 this error is considerably worse.

4.5. Sensible and Latent Heat Fluxes

[51] The latent and sensible heat fluxes are related to each other through the Bowen ratio, and reflect partitioning of the components of the surface energy balance. These quantities are difficult to measure and are usually only done so indirectly; hence significant uncertainty is associated with model structure for calculating these variables. Several model intercomparison studies have previously noted considerable scatter among models for these variables [*Liang et al.*, 1998; *Qu and Henderson-Sellers*, 1998; *Shao et al.*, 1994].

4.5.1. Evapotranspiration (Latent Heat)

[52] Figure 9 presents the daily evapotranspiration simulated by the RCMs, as well as observations taken in both years. The first thing to note from Figure 9 is that no RCM performs particularly well at simulating the daily evapotranspiration (ET) totals. The daily variation simulated by the MM5 based RCMs is significantly greater than that simulated by RegCM2 and is present in the observations

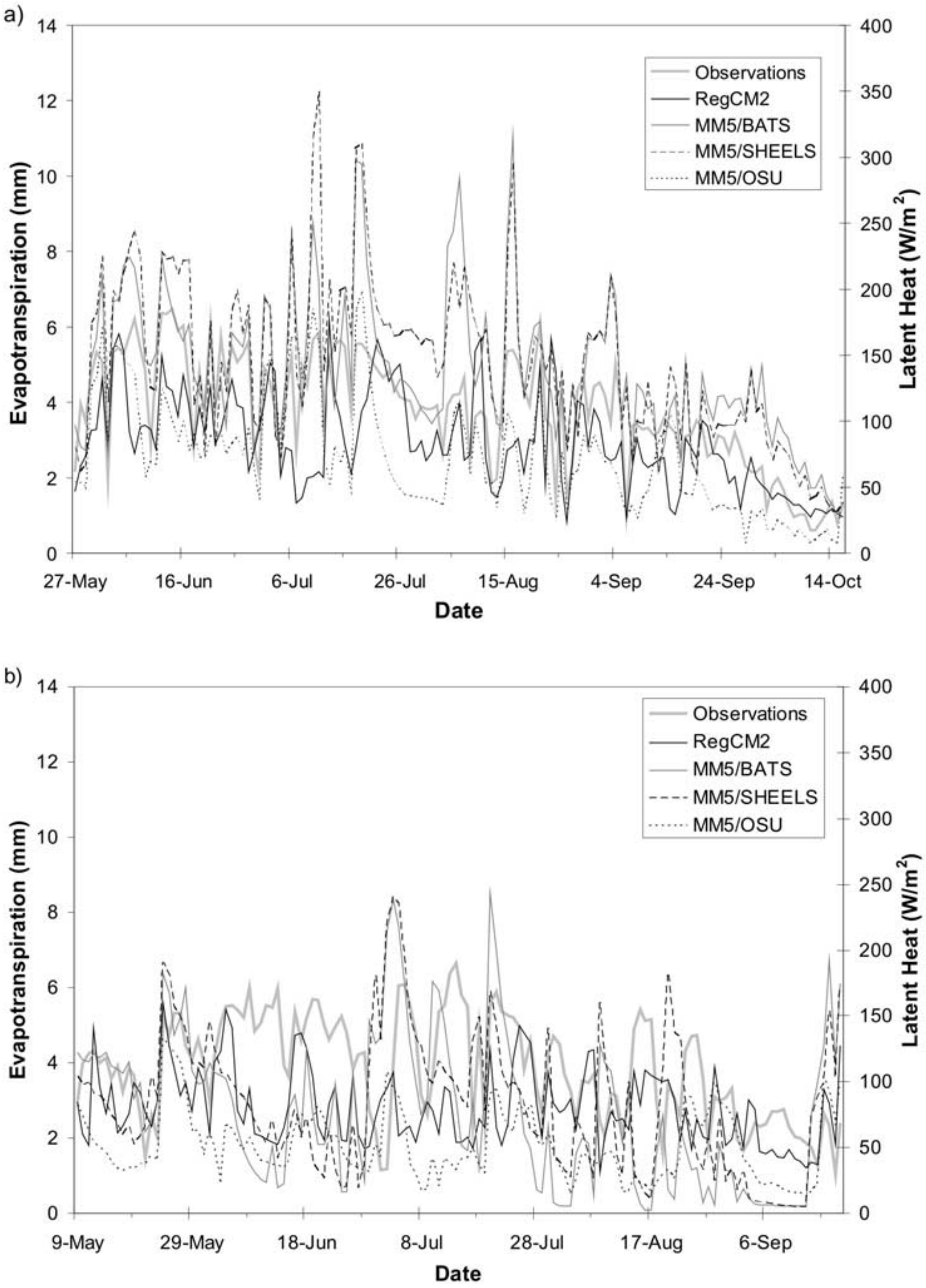

Figure 9. Daily accumulated evapotranspiration (latent heat) simulated by the RCMs with observations during the observation periods in (a) 1987 and (b) 1988.

during 1987 (Figure 9a). RegCM2 also appears to best estimate the ET on average in 1987. In 1988 (Figure 9b) all of the RCMs appear to underestimate the ET on average, while the variance appears much closer to the observed variance than for 1987. This underestimate in summer 1988 can be directly related to the previously mentioned underestimate of soil moisture. The mean and standard deviation statistics for the common observation period in each year can be found in Table 5.

4.5.2. Sensible Heat

[53] The daily sensible heat flux simulated by the RCMs can be found in Figure 10. The mean and standard deviation statistics for the common observation period in each year can be found in Table 6. It is clear from both the figure and the table that MM5/OSU massively overestimates both the mean value (by 3 times) and the standard deviation (by 2 times) in both years. RegCM2 to a lesser extent also overestimates the mean value while doing a good job of reproducing the observed standard deviation. MM5/BATS and MM5/SHEELS are able to reasonably reproduce the mean sensible heat in 1987 but then massively overestimate the mean in 1988, with the standard deviation massively overestimated in both years.

Table 5. Means and Standard Deviations of Daily Latent Heat Over the Common Observation Period, 27 May to 19 September

	1987		1988	
	Mean, mm	Standard Deviation, mm	Mean, mm	Standard Deviation, mm
Observations	4.23	1.19	3.89	1.41
RegCM2	3.23	1.20	2.76	0.98
MM5/BATS	5.23	1.87	2.52	2.07
MM5/SHEELS	5.59	2.03	2.78	1.88
MM5/OSU	2.96	1.39	1.74	0.88

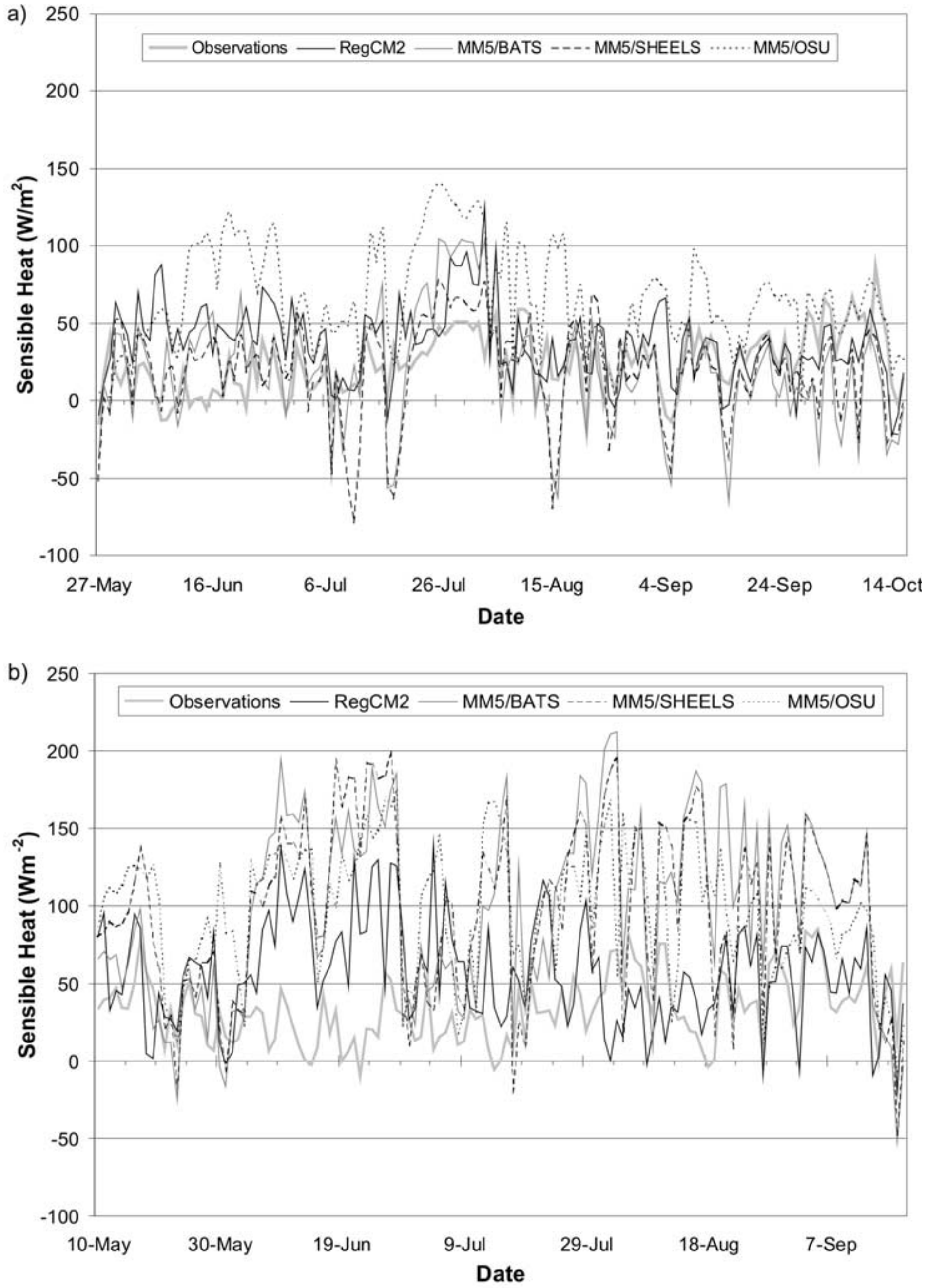

Figure 10. Daily Sensible heat flux simulated by the RCMs with observations taken during the observation periods in (a) 1987 and (b) 1988.

Table 6. Means and Standard Deviations of Daily Sensible Heat Over the Common Observation Period, 27 May to 19 September

	1987, W m^{-2}		1988, W m^{-2}	
	Mean	Standard Deviation	Mean	Standard Deviation
Observations	20.95	18.29	32.23	22.00
RegCM2	39.92	24.95	57.68	21.12
MM5/BATS	22.69	37.22	104.90	57.87
MM5/SHEELS	18.36	33.37	102.37	56.01
MM5/OSU	66.85	36.47	99.26	42.39

4.5.3. Evaporative Fraction

[54] The evaporative fraction (EF) which represents the proportion of available energy used for ET is defined as

$$\mathrm{EF} = \frac{L_v E}{L_v E + H}. \quad (4)$$

For most of the observation period in 1987, RegCM2, MM5/BATS, and MM5/SHEELS do reasonably good jobs at reproducing the evaporative fraction. MM5/BATS and MM5/SHEELS do, however, significantly overestimate the evaporative fraction several times late in the period. In the dry year (1988) all of the RCMs underestimate the observed evaporative fraction. In this year, RegCM2 comes closest to the observed, though no model does particularly well. MM5/OSU is the only model to consistently underestimate the observations in both years.

5. Discussion

[55] The interannual change in the summer mean daily temperature, with the maximum occurring in July 1987 and August 1988, can be related to soil moisture in spring. The observations show relatively high soil moisture at the beginning of summer 1988 (see Figure 6), this indicating that through the winter months, when measurements were not taken, root zone soil moisture must have increased by ~90 mm. This change in soil moisture is partially explained by the below average runoff throughout winter and the fact that April has above average precipitation in 1988. Water balance arguments would imply that the cumulative winter ET was lower than that simulated by the models; however, since no observations were taken, this remains speculation. The high soil moisture at the beginning of the 1988 observation period allows ET to remain relatively high for most of the summer, keeping sensible heat and near-surface temperatures lower than would otherwise have been the case. The maximum mean daily temperature occurs in July in 1987, the month with the highest net radiation; however it occurs in August in 1988. This occurs as the soil continues to dry throughout the summer with some vegetation eventually reaching wilting point, decreasing ET and increasing the surface temperature.

[56] The models all begin summer 1988 with only ~60% of the observed root zone soil moisture. This is largely due to the underestimation of precipitation over the winter for MM5/OSU; however, the other RCMs are within ~10% of the observed winter precipitation. Overestimation of runoff in RegCM2 and MM5/BATS accounts for 17% and 37%, respectively, of the underestimation of soil moisture change during winter. MM5/SHEELS does a good job of reproducing cumulative runoff through the winter. This implies that the SHEELS infiltration approach to runoff parameterization performs better in winter than the approach used in BATS. The remainder of the difference in the root zone soil moisture must be due to overestimation of ET. Since no observations of ET were taken through winter, this assertion cannot be verified. That these relatively small winter errors can accumulate, such as in the soil moisture, and then propagate throughout the following summer emphasizes the importance of understanding RCM performance over entire annual cycles rather than for isolated seasons as has been commonly done in previous intercomparison studies. The fact that all of the models simulate a larger and more consistent drying of soil moisture over the 2-year period compared to the observations may also be indicative of a long-term drift in the models. Such a long-term drift would need to be confirmed in model runs many annual cycles longer than the current study.

[57] Intermodel differences in precipitation are largely due to differences in stable precipitation during the wet year (1987) and due to differences in convective precipitation during the dry year (1988). This difference in stable precipitation may be explained by RegCM2 containing a different stable precipitation parameterization than the MM5 based models; however, all of the models contain the same convective parameterization, suggesting that differences in convective precipitation should be related to differences in the amount of moist static energy present in the atmosphere.

[58] In terms of stable precipitation (cloud microphysics) parameterizations, the difference between RegCM2 and the MM5 based models is the lack or presence of an ice phase. The fact that RegCM2 simulates only "warm" rain (i.e., no ice phase) leads to this model simulating many more small magnitude (drizzle) events while it is unable to simulate the large events which are observed. In the convective case all of the models share the same parameterization so that differences between them must be explained by differences in the forces driving the parameterization, in this case the moist static energy of the atmosphere as well as the clouds' available buoyant energy.

[59] Since the MM5 based models receive the same forcing at the boundary, differences between these models are due to local effects. The fact that MM5/OSU simulates significantly less convective precipitation than the other MM5 based models can be related to differences in the moist static energy produced through differences in the water vapor mixing ratio. Since the boundary forcing is identical for all MM5 runs, this comes about largely through the significant difference in summer ET simulated by the models, and implies significant local recycling of precipitation.

[60] It is clear that the way the models determine the allocation of available energy between sensible and latent heat is a source of significant differences between the models over the seasonal cycle. This confirms results from various PILPS studies [*Liang et al.*, 1998; *Pitman*, 1993] which demonstrated a large degree of disagreement among the land surface models when used ‘‘offline,’’ about the partitioning of energy between sensible and latent heat. Intercomparison studies of coupled models [*Qu and Henderson-Sellers*, 1998; *Takle et al.*, 1999] show that significant disagreement also exists for coupled models and, if anything, the scatter among coupled models is even larger than that for the land surface schemes alone. Determining the causes for intermodel differences in these surface fluxes is complicated by the presence of multiple feedback mechanisms; however, they can be roughly broken down into two categories: differences in the surface flux parameterizations themselves and differences in the driving variables. These driving variables include those that provide the energy, radiation and wind, and those that control the moisture availability, precipitation and runoff, through the soil moisture.

[61] The difference in the simulated net incident radiation is related to the longwave radiation parameterization in each model. Figure 8 shows the MM5 based models having downward longwave radiation peak at ~500 W m^{-2} in both years while RegCM2 peaks at ~415 W m^{-2} in both years. In contrast, the observations show a significant increase in downward longwave radiation between the years with 1987 peaking at ~415 W m^{-2}, in agreement with RegCM2, and 1988 peaking at ~470 W m^{-2}, closer to the MM5 based models. This interannual consistency in the MM5 based models occurs despite the models simulating significant decreases in the number of rain (and presumably cloudy) days. Thus it seems that the gray body approach of *Stephens* [1984] as implemented in the MM5 models is inadequate for dealing with the cloud–longwave radiation interaction. In this method the cloud water path is determined by the models' cloud water field, but the upward and downward cloud absorption coefficients are set to constant values. It should also be noted that the ice cloud absorption coefficient is defined as being around half that of cloud water. Here it appears that the downward absorption coefficient may be generally too low and should depend on cloud properties rather than being held constant. These longwave radiation model biases tend to accumulate through seasonal cycles.

[62] RegCM2 simulates a similar number of rain days in each year, and hence one would expect similar radiation-cloud interactions to be present. However, RegCM2 overestimates the number of rain days in both years (especially 1987), and if the radiation parameterization were correct, then the results should not reproduce the observations as well as they do. The first step in addressing this radiation parameterization issue requires addressing the models' drizzle tendency. Once the model is better able to reproduce the number of rain days, any shortcomings of the radiation-cloud interaction should become more apparent.

[63] The higher incident longwave radiation of the MM5 based models results in higher near surface air temperature (Figure 2), especially during summer. This effect is largest during the dry year (1988). Significant differences can also be seen in the near-surface wind speeds simulated by the RCMs during summer, with MM5/BATS and MM5/SHEELS overestimating the wind speed. The combination of higher net longwave radiation and wind speed combine such that the MM5 based RCMs simulate higher total surface fluxes than RegCM2. How this energy is split between sensible and latent heat fluxes depends largely on the moisture availability and demonstrates significant interannual variability in the simulations.

[64] Precipitation and runoff effects feed through to the latent heat via the soil moisture. Studies such as that of *Oglesby* [1991] emphasize the impact of the soil moisture on the subsequent evolution of the climate. *Pal and Eltahir* [2001] suggest that the soil moisture–rainfall feedback is an important mechanism for hydrologic persistence during the late spring and summer over the midwestern United States. This effect is clearly seen in 1988 when the RCMs enter late spring with substantially lower soil moisture than the observations and remain that way throughout the summer. The relatively high initial soil moisture in MM5/SHEELS and MM5/BATS helps to explain the high latent heat fluxes that these models simulate in 1987. The fact that MM5/OSU begins with similar soil moisture to the other MM5 based RCMs but simulates a low latent heat may be related to both the lower model wind speed and the resistance formulation associated with the vegetation.

[65] None of the models is able to simulate the observed daily mean ET with any accuracy. RegCM2 performs the best of all of the models, though it significantly underestimates the mean ET in both years and the standard deviation in 1988 (see Table 5). MM5/BATS and MM5/SHEELS both significantly overestimate both the mean and the variance in 1987, while MM5/OSU significantly underestimates the mean but does a reasonable job simulating the variance. During 1988, though, all of the RCMs significantly underestimate the mean daily ET. MM5/BATS and MM5/SHEELS continue overestimating the variance, while RegCM2 and MM5/OSU underestimate. It is worth noting that moving from a wet to a dry year, a decrease in the mean daily ET accompanied by an increase in the variance can be observed, while only MM5/BATS is able to reproduce this trend.

[66] Since RegCM2 and MM5/BATS share the same land surface scheme, the differences between their simulated ET must be explained by differences in their atmospheric forcing. In this case it seems likely that the stronger wind regime and greater incident radiation simulated by MM5/BATS is largely responsible for the significant difference between it and RegCM2. Correspondingly, since MM5/BATS, MM5/SHEELS, and MM5/OSU share the same atmospheric component, differences in their simulated ET must be explained by differences in their land surface parameterization. In this case, OSU simulates more resistance to ET then either BATS or SHEELS.

[67] Sensible heat is also a source of considerable disagreement among the models. The mean and standard deviation statistics for the common observation period in each year can be found in Table 6. Clearly, MM5/OSU massively overpredicts the sensible heat in both years. Like the observations, both RegCM2 and MM5/OSU simulate a 50% increase in the mean sensible heat flux going from 1987 to 1988. MM5/BATS and MM5/SHEELS, on the

other hand, simulate around a 500% increase in the mean. At least part of the reason for this massive interannual variation is the existence of several large negative sensible heat events present in 1987 but not in 1988. The observations do not contain any events comparable to these large negative anomalies.

[68] In MM5/BATS and MM5/SHEELS the sensible heat fluxes are obtained using the formulation given by *Zhang and Anthes* [1982].

$$H = K_s C_g \left(T_{g1} - T_a \right), \tag{5}$$

where C_g is the thermal capacity, K_s is a function of the friction velocity such that $K_s = \omega + K_s' u^*$, and ω and K_s' are constants. T_{g1} is the temperature of the ground surface, and T_a is the temperature of the air.

[69] The surface bulk Richardson number is given by

$$Ri_B = \frac{g z_1 \left(\theta_a - \theta_{g1} \right)}{\theta_a U^2}, \tag{6}$$

where g is gravity, z_1 is the height of the lowest model level, and θ is the potential temperature. Subscript a represents the surface layer air.

[70] There are four different turbulent mixing states which may be encountered. One such state occurs when the condition $0.2 > Ri_B > 0$ prevails; the surface layer is assumed to be in a state of damped mechanical turbulence. In this case the nondimensional stability parameters for heat and momentum are given by

$$\psi_h = \psi_m = \frac{-5 Ri_B}{1 - 5 Ri_B} \ln \frac{z_a}{z_0}, \tag{7}$$

where z_0 is the surface roughness length. The friction velocity is then calculated as

$$u^* = \frac{kU}{\ln(z_a / z_0) - \psi_m}. \tag{8}$$

Here k is the von Karman constant.

[71] For these MM5 models we can see that the large negative peaks in sensible heat occur when strong winds and a negative temperature difference (in equation (5)) coincide. For such a situation the system is in a state of damped mechanical turbulence given by equations (6) to (8) above. While strong winds exist, this leads to a Richardson number close to zero and through the stability parameters and friction velocity to a large negative sensible heat flux.

[72] The generally high sensible heat simulated by MM5/OSU, particularly in the wetter year, is related to its underestimation of ET. While the choice of formulation for the surface drag coefficient [*Chen et al.*, 1997] differs from that used in MM5/BATS and MM5/SHEELS, any effect this difference has is overwhelmed by the difference in ET. In MM5/OSU, for each time step, the latent heat flux is first calculated by reducing the potential evaporation using canopy resistance. Using this updated latent heat flux, equation (9) is then solved to update the soil temperature profile and the surface skin temperature, T_g. Knowing the surface drag coefficient for heat (and moisture), C_h, the air temperature, T_a, air heat capacity C_p, and air density, ρ, the sensible heat flux, H, can then be determined using equation (10).

$$C(\Theta) \frac{\partial T}{\partial t} = \frac{\partial}{\partial z} \left[K_t(\Theta) \frac{\partial T}{\partial z} \right], \tag{9}$$

where the volumetric heat capacity, C, and the thermal conductivity, K, are formulated as functions of volumetric soil water content, Θ.

$$H = \rho C_p C_h \left(T_g - T_a \right). \tag{10}$$

[73] Hence, if the canopy resistance is generally too high, causing the ET to be consistently underestimated, this is translated through T_g to a consistent overestimation of the sensible heat. This tendency to underestimate ET, not surprisingly, causes the largest discrepancies when moisture is more freely available.

[74] MM5/BATS and MM5/SHEELS significantly overestimate the evaporative fraction several times late in 1987; in particular, they estimate peak evaporative fractions of 24 and 4.5, respectively. These overestimations are caused by the simulation of negative sensible heat that is large enough to almost cancel the simulated latent heat. The high EF values simulated by these RCMs are significantly larger than the highest observed values. This suggests that these RCMs convert energy from sensible to latent heat flux much more readily than is observed in the field. In the dry year (1988) all of the RCMs underestimate the observed evaporative fraction. This is largely the result of lower ET due to the underestimation of soil moisture during the summer. MM5/OSU is the only model to consistently underestimate the observations in both years.

[75] Figures 11a–11e shows the daily net incident radiation and latent and sensible heats as well as the cumulative ground heat flux of the observations and models in 1987. The observations clearly show that the net incident radiation provides a strong control over the latent heat flux, constraining the latent heat to be almost always less than the net incident radiation. Only a few minor transgressions occur on days with unusually low incident radiation. RegCM2 does a reasonable job at reproducing this behavior, while MM5/OSU generally simulates a too low latent heat flux and hence rarely breaks the incident radiation constraint. MM5/BATS and MM5/SHEELS, however, regularly break this constraint and allow the simulation of more latent heat than there is net incident radiation.

[76] Note also that the simulation of the cumulative ground heat flux by RegCM2, MM5/BATS, and MM5/SHEELS contains a maximum in July followed by a significant decrease. Both the observations and MM5/OSU show a consistent increase, perhaps leveling off toward the end of the observation period. These observations were collected using heat flux panels inserted below the surface of the Earth. The amount of energy accumulated in the ground according to the observations would be approximately equivalent to increasing the soil temperature of the root zone by 20°C. Of course, the temperature

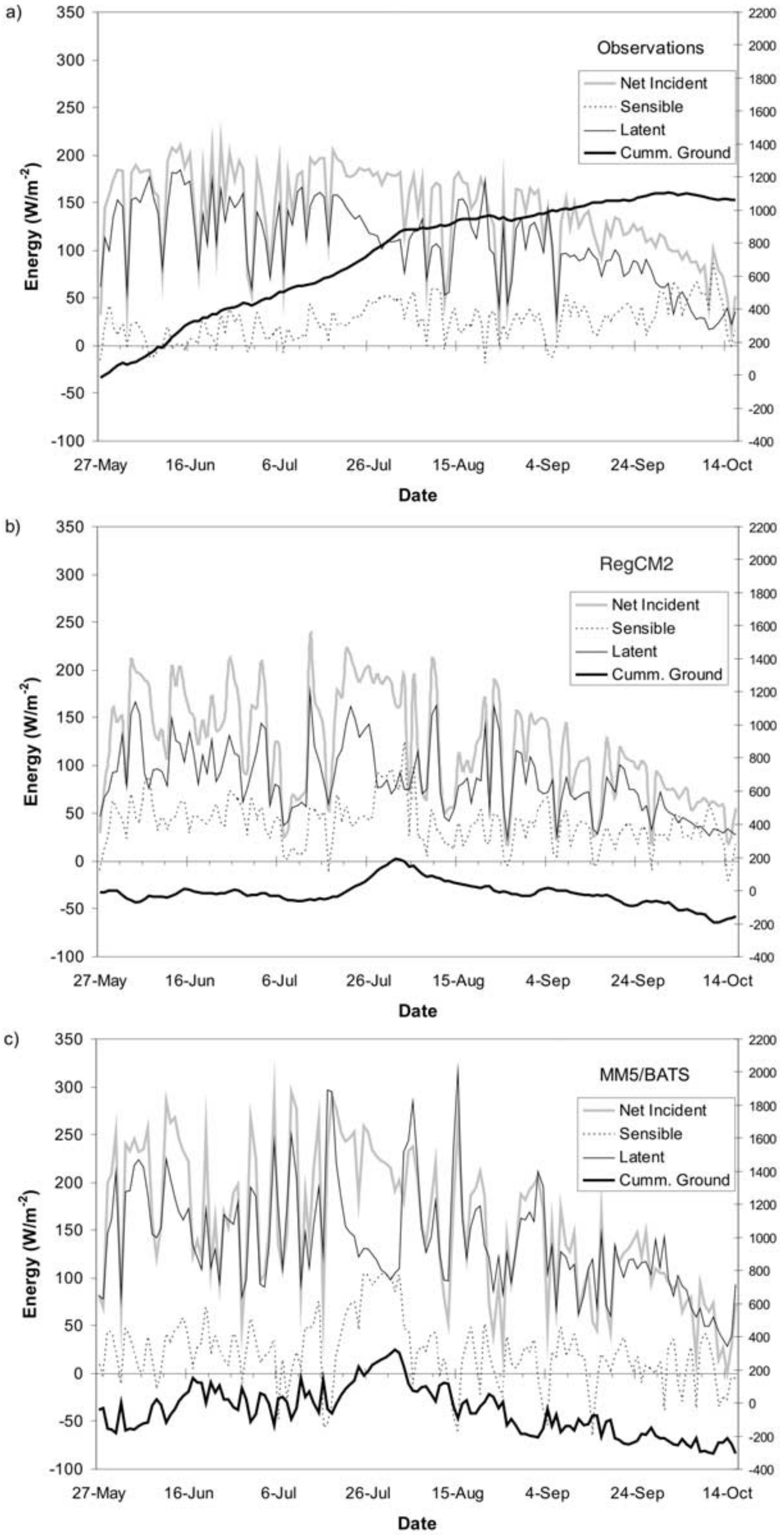

Figure 11. Net incident radiation, sensible, latent (left *y* axis) and cumulative ground heats (right *y* axis) during the 1987 observation period for (a) the observations, (b) RegCM2, (c) MM5/BATS, (d) MM5/SHEELS, and (e) MM5/OSU.

increase due to this ground heat flux would not be confined to the root zone. Nevertheless, the observations show that the soil actually changed its temperature by only a few degrees, much less than the amount required, and these ground heat flux observations remain suspect. MM5/OSU manages to accumulate even more energy in the soil than the observations, making its simulation of ground heat flux even more suspect.

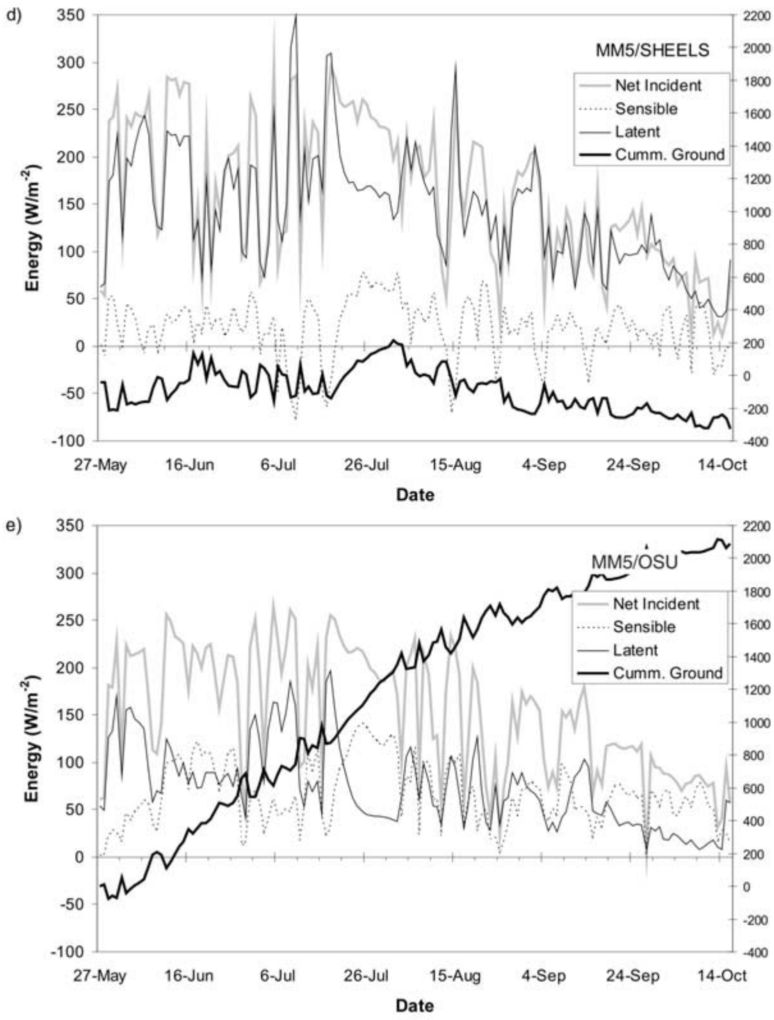

Figure 11. (continued)

[77] Since they essentially share land surface parameterizations, differences in the latent and sensible heat fluxes simulated by RegCM2, MM5/BATS, and MM5/SHEELS are explained largely in terms of the driving forces. These include the net longwave radiation, near-surface winds, and precipitation as discussed above. The difference between surface fluxes simulated by MM5/OSU and the other MM5 based RCMs, while influenced by differences in the driving forces, can be explained by the surface parameterization, in particular, the formulation of latent heat. MM5/OSU consistently simulates higher vegetative resistance to ET than any of the other models, decreasing the ET and associated precipitation feedback while increasing the sensible heat.

[78] Over the entire annual cycles of 1987 and 1988 (not shown), RegCM2, MM5/BATS, and MM5/SHEELS come close to closing the energy budget with the ground required to give up a small amount over the course of a year to maintain a balance. For MM5/OSU, however, a significant surplus of energy exists in both years, requiring the ground to absorb a significant amount of energy in order to maintain a balance. While MM5/OSU simulates the largest increase in ground temperature between 1987 and 1988, it does not account for all of the energy available, implying that the energy budget is not closed in MM5/OSU.

6. Summary and Conclusions

[79] In this study, four regional climate models (RegCM2, MM5/BATS, MM5/SHEELS, and MM5/OSU) were run on a fairly small domain covering a relatively homogenous area in Kansas, United States, including the FIFE site. The models were integrated for a 2-year period covering 1987 and 1988. As well as intercomparing the models, the results were evaluated against data collected at the Konza Prairie LTER and over the summer observation periods of FIFE.

[80] When considering the entire period and the collection of surface variables for which observations are available, no one model was found to consistently perform better than the other models as has been found in several other model intercomparison studies. There are, however, several conclusions which can be drawn from the study.

[81] The observations show that 1987 was a normal (wet) year while 1988 had drought-like conditions (dry) providing quite a good test of the models' performance under sub-

stantially different conditions. The need to test these complex models under various and even extreme conditions has been recognized by others, and, indeed, previous studies such as PIRCS have evaluated models for short time integrations under flood and/or drought conditions. Here the models' ability to transition from a wet year to a dry year is evaluated and often found wanting. The models generally had difficulty reproducing the interannual changes seen in the observations, as they seem unable to simulate any particular variable well under both wet and dry conditions. The RCMs seem able to capture the difference in only a qualitative sense. This inability to reproduce the interannual changes is particularly evident in the variance of the surface flux variables. The models generally move the means of variables such as the sensible and latent heats in the same direction as that observed; however, the modeled change in variance is often a change in the opposite direction to that observed.

[82] In terms of precipitation the models are able to reasonably capture the interannual difference between 1987 and 1988. How the models split this precipitation between stable and convective contains significant variation. All of the models do, however, simulate much more convection during summer than winter. Overall, the models reproduce the size distribution of events reasonably well. The MM5 based models tend to underestimate the number of small events, while RegCM2 overestimates this but underestimates the number of large events. This difference between the models can be largely traced to differences in the stable precipitation parameterization with RegCM2 simulating only ''warm rain,'' while the MM5 based models contain an ice phase. The consistent underestimation of precipitation by MM5/OSU is related, through a feedback mechanism, to its consistent underestimation of ET.

[83] All of the models have major difficulty reproducing magnitudes and timing of runoff even on a monthly basis and are certainly incapable of simulating a realistic hydrograph on shorter timescales. The consistent overestimation of runoff by the RCMs throughout the winter, along with an apparent overestimation of ET, results in a significant underestimation of soil moisture in spring 1988. This dry anomaly persists throughout the summer, causing biases in the various land surface–atmosphere fluxes. Thus while winter is the low ET time of year and runoff is often considered merely a residual of the water balance by atmospheric modelers, small but systematic bias in these quantities can accumulate and affect other aspects of the climate system. Addressing these model issues would require field data, such as that collected during FIFE, to be collected over more than an annual cycle, thus allowing the model biases identified above to be investigated, tested, and corrected. It may also be important to consider runoff as an important physical process in its own right, rather than just considering it a residual of the water balance. Some early attempts to do so, such as the inclusion of the Simple Water Balance (SWB) model in the OSU land surface scheme used here, have not been particularly successful in reproducing observed runoff behavior. In this case the SWB model has been coupled to OSU via a precipitation threshold mechanism, which results in behavior similar to that obtained by the other land surface schemes as discussed by *Evans* [2003].

[84] With no systematic way to take antecedent conditions into account, the initial model soil moisture varies considerably between the models, as does the soil moisture range used by each model. The modeled soil moisture tends to be most similar under low soil moisture conditions. The SHEELS many layer approach simulates the largest interannual difference in soil moisture dynamics, with soil moisture moving readily in the wet year but this movement being retarded considerably as moisture becomes scarce. This seems to provide SHEELS with some advantage in dealing with the upper layer soil moisture; however, this advantage is no longer apparent once you reach the root zone depth.

[85] Another notable difference between the models occurs in the downward longwave radiation. None of the models is able to reproduce the observed interannual variability. The MM5 based models tend to overestimate the downward longwave radiation and demonstrate inadequate sensitivity to the radiation-cloud interaction. RegCM2 tends to underestimate the downward longwave radiation with the radiation's lack of interannual variability being inherited from the models cloud field which varies little between years.

[86] The models simulation of low-level winds has substantial effects on the surface fluxes. This sensitivity to the winds can be amplified if, as is often done, the land surface scheme is coupled to the wind field of the lowest level of the atmospheric component which is often around 50 m above the surface even though it was developed using wind field data from much closer to the surface. The sensible heat flux can be particularly sensitive to the wind, depending on the stability formulation such as is seen with MM5/BATS and MM5/SHEELS. The impact of parameterizations which couple the atmospheric and land surface together, such as the wind fields and the stability dependence of the surface drag coefficients, can be large enough, under the right conditions, to dominate the effects of the land surface scheme itself. This can be seen several times in the MM5/BATS and MM5/SHEELS simulations, highlighting the need for testing of the coupled modeling system during the development phase rather than merely testing each component in isolation. This sensitivity in the sensible heat flux allows these models to convert energy from sensible heat to latent heat much more readily than is observed.

[87] MM5/OSU sensible heat is closely related to its latent heat through the latent heat's effect on the surface temperature. Hence the canopy resistance formulation has a strong impact on both the latent and sensible heats. MM5/OSU consistently produces a canopy resistance high enough to cause an underestimation of latent heat which leads to an overestimation of sensible heat. This consistent bias in the Bowen ratio and evaporative fraction causes feedback to the atmosphere, largely through the reduced moist static stability and hence convective precipitation. During dry conditions, all of the models have a tendency to underestimate the evaporative fraction.

[88] The observations of latent and sensible heat are well constrained by the net surface radiation. RegCM2 and MM5/OSU latent and sensible heats are both also well constrained by their net radiation while MM5/BATS and MM5/SHEELS are not, and either flux can be larger than the radiation. Even so, RegCM2, MM5/BATS, and MM5/

SHEELS all manage to maintain the surface energy balance with only minor contributions from the ground heat flux, while MM5/OSU requires a much more significant (unrealistic) contribution to the ground heat in order to maintain the surface energy balance. The MM5/OSU simulated change in soil temperature is much smaller than would be required to account for this ground heat flux implying that the energy budget fails to close.

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