Comparison of Four Different Stomatal Resistance Schemes Using FIFE Observations

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ABSTRACT

Stomatal resistance (R_s) calculation has a major impact on the surface energy partitioning that influences diverse boundary layer processes. Present operational limited area or mesoscale models have the Jarvis-type parameterization, whereas the microscale and the climate simulation models prefer physiological schemes for estimating R_s. The pivotal question regarding operational mesoscale models is whether an iterative physiological scheme needs to be adopted ahead of the analytical Jarvis-type formulation.

This question is addressed by comparing the ability of three physiological schemes along with a typical Jarvis-type scheme for predicting R_s using observations made during FIFE. The data used is typical of a C4-type vegetation, predominant in regions of high convective activity such as the semiarid Tropics and the southern United States grasslands. Data from three different intensive field campaigns are analyzed to account for vegetation and hydrological diversity.

It is found that the Jarvis-type approach has low variance in the outcome due to a poor feedback for the ambient changes. The physiological models, on the other hand, are found to be quite responsive to the external environment. All three physiological schemes have a similar performance qualitatively, which suggests that the vapor pressure deficit approach or the relative humidity descriptor used in the physiological schemes may not yield different results for routine meteorological applications. For the data considered, the physiological schemes had a consistently better performance compared to the Jarvis-type scheme in predicting R_s outcome. All four schemes can, however, provide a reasonable estimate of the ensemble mean of the samples considered. A significant influence of the seasonal change in the minimum R_s in the Jarvis-type scheme was also noticed, which suggests the use of nitrogen-based information for improving the performance of the Jarvis-type scheme. A possible interactive influence of soil moisture on the capabilities of the four schemes is also discussed. Overall, the physiological schemes performed better under higher moisture availability.

1. Introduction

Various planetary boundary layer (PBL) and general circulation models (GCMs) are linked with soil–vegetation–atmosphere transfer (SVAT) schemes. Some of these land surface parameterizations presently employed in PBL and GCM studies include Deardorff (1978), BATS (Dickinson et al. 1986), Avissar et al. (1985), SiB (Sellers et al. 1986), Wetzel and Chang (1988), Noilhan and Planton (1989), Acs (1994), Bosilovich and Sun (1995), Viterbo and Beljaars (1995), Pleim and Xiu (1995), and Alapaty et al. (1996a). These models have varying degrees of complexity when describing the energy partitioning at the surface—that is, at the soil and at the vegetation. In addition to these "operational" or "meteorological" schemes, physiologically intensive models for the terrestrial biosphere–atmosphere interactions also exist (see Farquhar and Sharkey 1982). Some of these include Farquhar et al. (1980), Ball et al. (1987), Meyers and Paw U (1987), Lynn and Carlson

(1990), Raupach (1991), Collatz et al. (1991, 1992), Kim and Verma (1991), Baldocchi (1992, 1994), Jacobs (1994), Dougherty et al. (1994), SiB2 (Sellers et al. 1996), Cox et al. (1996), and IBIS (Foley et al. 1996). Although other approaches such as those used by Monteith (1995a,b) and Makela et al. (1996) seem to provide promising insight for understanding the SVAT strategy from observations, they are still evolving and have not been incorporated in weather or climate simulation models yet.

One of the principal differences between the "meteorological" and the "physiological" approach of the SVAT parameterization is the manner in which the stomatal response is modeled. The stomatal response, quantified as stomatal resistance (or conductance), is a measure of the difficulty (or ease) for the vegetation to transpire. Change in the transpiration alters the evapotranspirative/latent heat flux, which due to the surface energy balance constraints in the modeling perspective modifies the sensible heat flux realizations (cf. Alapaty et al. 1996a; Jarvis and McNaughton 1986; DeBruin 1983). The possible impact of the stomatal resistance changes on the coupled atmospheric processes, are quantified in Figs. 1a–c (adopted from Niyogi 1996).

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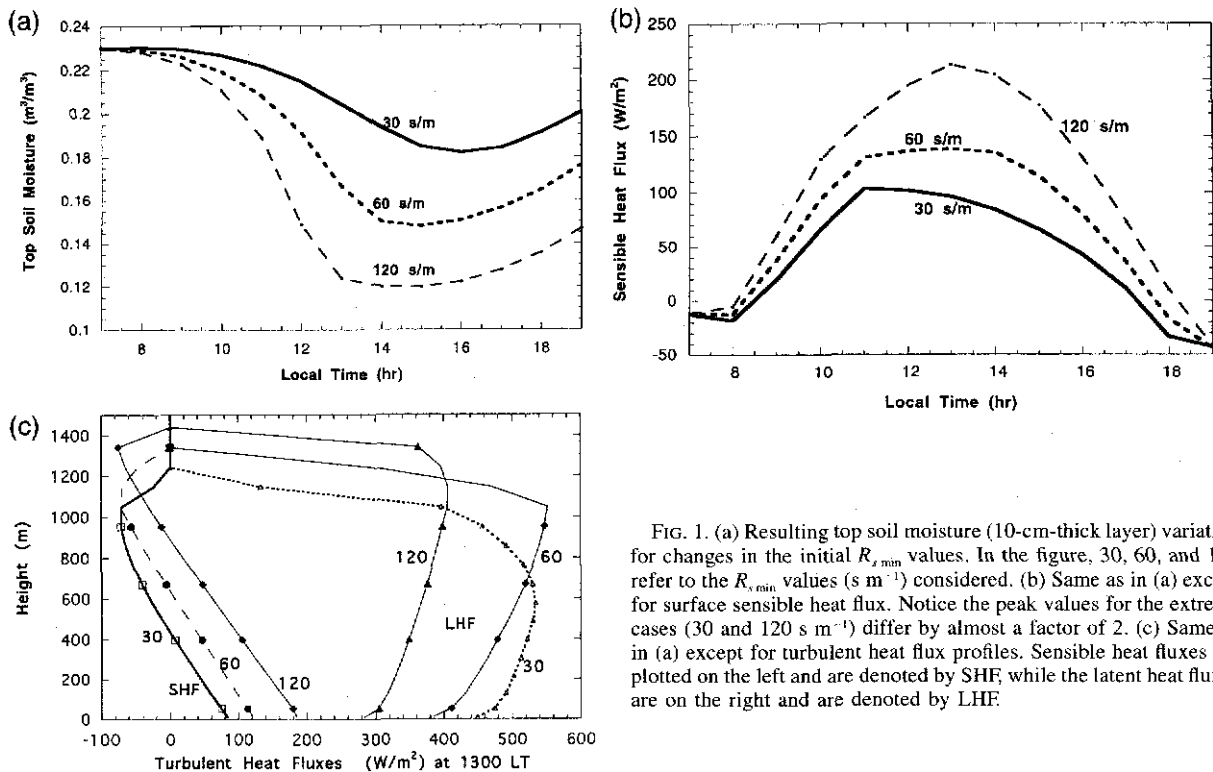E-mail: sethu_raman@ncsu.edu

FIG. 1. (a) Resulting top soil moisture (10-cm-thick layer) variation for changes in the initial $R_{s\,min}$ values. In the figure, 30, 60, and 120 refer to the $R_{s\,min}$ values (s m^{-1}) considered. (b) Same as in (a) except for surface sensible heat flux. Notice the peak values for the extreme cases (30 and 120 s m^{-1}) differ by almost a factor of 2. (c) Same as in (a) except for turbulent heat flux profiles. Sensible heat fluxes are plotted on the left and are denoted by SHF, while the latent heat fluxes are on the right and are denoted by LHF.

The results are based on a one-dimensional simulation output with a meteorological stomatal resistance (R_s) parameterization (Noilhan and Planton 1989; Alapaty et al. 1996a) using FIFE [First ISLSCP (International Satellite Land Surface Climatology Project) Field Experiment] observations [see Pleim and Xiu (1995) and Alapaty et al. (1996) for the planetary boundary layer model initialization and domain details]. The sensitivity of R_s estimation in the boundary layer turbulent energy flux partitioning and hydrological budgeting is displayed by varying the minimum R_s from 30, 60, and 120 s m^{-1}. Figure 1a shows the change in the predicted top 10-cm-thick surface-layer soil moisture for the three resistances. Around 1300 LT, the top soil moisture for the highest R_s is nearly half of that for the lowest R_s. Similarly, there is a considerable impact on the energy flux estimations (Figs. 1b,c). Once again, the highest resistance has the highest sensible heat flux values (Fig. 1b), which influences other boundary layer parameters such as humidity, surface temperature, and the scalar advection (not shown). Figure 1c shows the changes in the turbulent energy heat fluxes for the entire boundary layer for 1300 LT. Consistent with the earlier results (Figs. 1a,b), a factor-of-4 change in the stomatal resistance value has resulted in a change in the surface and boundary layer parameters by a factor of 2 (see Niyogi 1996 for details). Though these estimates are for a one-dimensional simulation and prone to provide only an upper limit on the changes possible, the results clearly

demonstrate that R_s estimation is perhaps one of the most significant features in the PBL and mesoscale models [see Alapaty et al. (1996) for a comparison of the impact of changes in the turbulence closure in the boundary layer models].

To parameterize the stomatal response in the operational meteorological models, a simple resistance approach as developed by Jarvis (1976) is often employed (cf. Noilhan and Planton 1989; Pleim and Xiu 1995; Viterbo and Beljaars 1995; Bosilovich and Sun 1995; Alapaty et al. 1996). In these models, the stomatal response is modeled as a function of meteorological parameters such as air temperature, ambient vapor pressure, radiation, and soil moisture availability. However, the tendency of the present biophysical routines in the numerical models, particularly for climate analysis, is to use the physiological schemes, which employ more rigorous plant gas-exchange responses such as carbon-assimilation rates, night respiration, or plant biochemical symptoms through ribulose-1,5,-bisphosphate carboxylase-oxygenase (RuBisCO), or abscisic acid (ABA) signals (cf. Sellers et al. 1996; Foley et al. 1996; Cox et al. 1997). Recent model analyses (e.g., Sellers et al. 1996) suggest the two approaches could give different feedback for changes in CO_2 levels. Thus, present modeling efforts are oriented toward adapting the physiological approach within a meteorological or climate model (Monteith 1995a). The significance associated with these schemes at the mesoscale (few kilometers

spatial and few days in temporal resolution) is still exploratory. Additionally, perhaps due to larger abundance of C3 vegetation globally efforts are apparently biased toward studying the C3 vegetation (cf. Leuning 1990, 1995). However, within the meteorological or climate perspective, C4 vegetation has special significance as it is the predominant vegetation type within the active convection regions such as the semiarid Tropics or the central plains and southern grasslands of the United States. Hence, though the principal C4 related studies (cf. Collatz et al. 1992; Knapp 1993; Henderson et al. 1994) attempt to unravel the species dominance and the hydrological mechanisms, the question pivotal to the meteorological models is how the two approaches for stomatal representation compare for surface energy budget.

Thus, some of the questions that need to be addressed before the biophysical modules in the mesoscale models are altered include the following. (a) Does the present Jarvis-type approach significantly differ in terms of its outcome as compared to the physiological approach? (b) What are the constraints of the meteorological and physiological approaches in terms of the scenario estimation? (c) What is the impact of the uncertainty associated with the input information for these schemes at a regional scale (cf. Alapaty et al. 1997; Niyogi et al. 1997, manuscript submitted to *Bound.-Layer Meteor.*)? (d) Can the constants used in the Jarvis-type meteorological approach be better parameterized through a nutrient database such as regional or leaf nitrogen content (cf. Schulze et al. 1994; Dewar 1996)? To focus on these and related aspects of the tropical SVAT mechanism, the underlying approach we have adopted is to analyze observations and the scenario predictive ability of various biophysical equations. In this paper, we present the first results of this ongoing analysis to view the stand-alone ability of the different stomatal resistance schemes in predicting the stomatal resistances for C4 grasslands. Another study under way (Niyogi et al. 1997, manuscript submitted to *J. Appl. Meteor.*) aims at explicitly resolving the direct and indirect interactions within the two approaches using a fractional factorial approach (cf. Henderson-Sellers 1993; Niyogi et al. 1997; Niyogi 1996). This interaction-explicit analysis will prescribe scenario uncertainties in the stomatal resistance estimations using different schemes under diverse surface combinations. Another related study to be reported soon (Niyogi et al. 1997, manuscript submitted to *Geophys. Res. Lett.*) concerns the test of the leaf nitrogen content coupled with the Jarvis-type approach as a stomatal resistance predictor using observations made during a tropical field experiment: Vegetation and Energy Balance Experiment (Raman et al. 1997). Finally, these schemes will be tested in a three-dimensional model with feedback from the meteorological and surface parameters with explicit convective forcing and radiation and cumulus parameterization (cf. Leach et al. 1997; Hong et al. 1995).

In this paper, however, responses of the following four schemes are evaluated using observations from FIFE: Jarvis (1976), as in Noilhan and Planton (1989; denoted as JNP); Ball et al. (1987; denoted as BBM); Kim and Verma (1991; henceforth KV91); and Jacobs (1994; denoted as CJ94). The observations and model predictions are for the C4-type grasslands over the FIFE site. Section 2 outlines the experimental framework for this study principally describing the equations associated with each of the four schemes. Section 3 describes the measurements and site characteristics during FIFE that are used as a reference for the model scenario predictive ability. Section 4 presents the model comparisons and the results from this study, and section 5 summarizes the conclusions.

2. Parameterizations

In this section, we will describe the two R_s parameterization related approaches, meteorological and physiological, in greater detail. The meteorological approach for modeling the stomatal response attempts to modify a minimum R_s, defined a priori, through external factors such as moisture and radiation availability (Jarvis 1976; Monteith 1995a). The Jarvis-type approach as extended by Noilhan and Planton (1989) for mesoscale applications is tested in this study. The physiological schemes, on the other hand, are governed by the gas-exchange aspects. The three physiological schemes used in the study are those developed by Ball et al. (1987) (referred to as the Ball–Berry model or BBM), Kim and Verma (1991, KV91), and Jacobs (1994, CJ94). These schemes represent a different modeling philosophy in the manner in which the stomatal response is linked to humidity stress. Additionally, they have been tested or applied for different scales of meteorological scenarios. For example, the BBM-like approach is linked in recent climate models such as the SiB2 (Sellers et al. 1996); KV91 was developed and tested for canopy-scale interactions (Kim and Verma 1991); and CJ94 was effectively applied for a regional-scale analysis (Jacobs 1994). The equations presented below often form a part of a closed set of equations for variables such as radiation, leaf temperature, and surface energy budget coupled together (cf. Nikolov et al. 1995; Sellers et al. 1996). For details, the reader is referred to the original references of each scheme.

a. Meteorological approach (JNP scheme)

The JNP scheme is taken as representative of this approach in the mesoscale models. The features and limitations of the meteorological Jarvis-type scheme used in this study is described below.

The stomatal response is represented through an environmental modulation of a prescribed constant: minimum stomatal resistance ($R_{s\,min}$). Here, $R_{s\,min}$ is the minimum resistance of the foliage to water vapor transfer under stress-free (optimum soil moisture, ambient vapor

pressure, temperature, and radiation availability) conditions. This scheme, originally proposed by Jarvis (1976) and extended by Noilhan and Planton (1989) for use in mesoscale atmospheric models has the following governing equation:

$$R_s = R_{s\,min}\, LAI^{-1}\, F_1 F_2^{-1} F_3^{-1} F_4^{-1}, \quad (1)$$

where for a prescribed $R_{s\,min}$ and LAI value,

$$F_1 = \frac{1+f}{f + R_{s\,min}/R_{s\,max}} \quad \text{with} \quad f = 0.55 \frac{R_n}{R_{nl}} \frac{2}{LAI} \quad (2a)$$

$$F_2 = \begin{cases} 1, & w_2 > 0.75 w_{sat} \\ \dfrac{w_2 - w_{wilt}}{0.75 w_{sat} - w_{wilt}}, & w_{wilt} \le w_2 \le 0.75 w_{sat} \\ 0, & w_2 < w_{wilt} \end{cases} \quad (2b)$$

$$F_3 = 1 - 0.025D \quad (2c)$$

$$F_4 = 1 - 0.0016(298.0 - T_a)^2. \quad (2d)$$

In the above, R_n is the solar radiation flux (W m^{-2}) reaching the foliage, and R_{nl} is the radiation limit at which photosynthesis is assumed to start. In this study, R_{nl} is taken as 100 W m^{-2} as a representative value for crop-like vegetation (Noilhan and Planton 1989). Here, R_{smax} is the maximum stomatal resistance and is set at a constant value of 5000 s m^{-1} following Jacquemin and Noilhan (1990). In the F_2 term, w_2 is the deep soil moisture (volumetric water content at 1 m below the surface) and w_{wilt} and w_{sat} are the wilting and saturated soil moisture values for the soil. Following Clapp and Hornberger (1978) and Cosby et al. (1984), values assigned in this study are 0.218 m^3 m^{-3} for w_{wilt} and 0.477 m^3 m^{-3} for w_{sat} (also see Alapaty et al. 1996). In the remaining terms, D is the vapor pressure deficit given by $e_{sat}(T_s) - e_a$, where $e_{sat}(T_s)$ is the saturated vapor pressure at the surface temperature T_s (dry-bulb temperature) and e_a is the vapor pressure. The vapor pressure values were calculated from temperature data following Stull (1995).

The other three schemes used in this study are physiological in philosophy and are described in the next section with the constants and the assumptions used in each.

b. Physiological approach

The three physiological schemes examined in this study are the Ball–Berry model (BBM), Kim and Verma (1991; KV91), and Jacobs (1994; CJ94). An important aspect of these models is that, though in theory they tend to mimic the physiological response, they are still empirical in nature and need not represent a causal relation (cf. Cowan 1982) between the parameters.

1) BBM SCHEME

The principal equation for stomatal conductance (inverse of resistance) in this scheme is

$$g_s = m\frac{A_n\, RH}{C_s} + g_0. \quad (3)$$

Here, g_s is the stomatal conductance, A_n is the net CO_2 assimilation or the photosynthesis rate, RH is the relative humidity at the leaf surface, and C_s is the CO_2 concentration at the leaf surface. The remaining terms m and g_0 are constants based on linear gas-exchange considerations (Ball 1987). In this study, the value of m is taken as 1.6 (cf. Jacobs 1994) and g_0, the cuticle resistance of the leaf, is taken as 0.01 mol m^{-2} s^{-1} (Vogel et al. 1995). Other parameters, A_n, C_s, and RH, are based on observations of Polley et al. (1992) and the analytical solution of Su et al. (1996) and are described in section 3.

The BBM scheme is being applied in increasing numbers of studies (cf. Leuning 1990, 1995; Collatz et al. 1991; Nikolov et al. 1995; Su et al. 1996). However, the ability of RH to provide a description of the humidity response to stomatal resistance has been the principal concern (Aphalo and Jarvis 1991; Mott and Parkhurst 1991; Nikolov et al. 1995; Monteith 1995a,b). Also, the outcomes are sensitive to prescribed values of m (cf. Nikolov et al. 1995). However, for meteorological applications, the RH-related feature delineated by Mott and Parkhurst (1991) need not necessarily be a drawback for routine practical applications (Baldocchi 1996, personal communication). Also, unlike $R_{s\,min}$ in the JNP scheme, the gas-exchange constant m is measurable in the laboratory quite accurately (Ball 1987). [The range of m is small for C4 plants (around 1.6–2; Jacobs 1994) as compared to the C3 plants (around 6–16, Nikolov et al. 1995) and hence not a major concern in the present study.]

2) KV91 SCHEME

Unlike BBM, which uses relative humidity as a descriptor, KV91 uses the vapor pressure deficit approach. The model equation used is

$$g_s = g_0 + \left(1 - \frac{D}{D_{max}}\right) 1.6 \frac{A_n}{C_s - C_i}, \quad (4)$$

where A_n is the net CO_2 assimilation and C_s and C_i are the CO_2 concentrations at the leaf surface and within the leaf, respectively. The values used in this study are based on the FIFE observations. As in BBM, g_0 is taken as 0.01 mol m^{-2} s^{-1}, D is as described in the JNP scheme, and D_{max} is taken as 45 g kg^{-1} following Choudhury and Monteith (1986) and Jacobs (1994).

The principal feature of the scheme is its inherent simplicity in assuming the diffusivity through a constant. However, in the operational sense, the iterative method is computationally expensive (as any other physiological scheme), particularly since compared to BBM, an additional variable C_i needs to be computed, but no conceptual drawback is apparent with this scheme (however, also see Monteith 1995a,b).

3) CJ94 SCHEME

Similar to KV91; CJ94 uses the vapor pressure deficit approach. The principal change is the introduction of a smoother transition, unlike the linear variation of D/D_{max} ratio in KV91. This transition is introduced by taking two linear terms together. The equation used in this study is

$$g_s = g_0 + \left[f_0 \left(1 - \frac{D}{D_{max}} \right) + f_{min} \left(\frac{D}{D_{max}} \right) \right] 1.6 \frac{A_n}{C_s - C_i}, \tag{5}$$

where values of g_0, D, and D_{max} are similar as in KV91; f_0 is taken as 0.5; and f_{min} as 0.16 for the C4 vegetation (Jacobs 1994).

This formulation has been tested against observations by Jacobs (1994) for a sparse vineyard in Tomelloso, Spain.

3. Site characteristics and measurements

Results using the four schemes outlined in the earlier section are compared with the stomatal resistance observations during FIFE (Sellers et al. 1988, 1992; Polley et al. 1992) as the reference. The observations are considered representative of a typical prairie grassland region widely covering a vast portion of the continental United States or semiarid Tropics (Polley et al. 1992). The vegetation shows a C4-type of photosynthesis mechanism. The observation site and the measurement procedures are described in the FIFE Information System documentation (available on-line at http://www-eosdis.ornl.gov/FIFE/) and by Kim and Verma (1990, 1991), Polley et al. (1992), Stewart and Gray (1989), and Stewart and Verma (1992). During FIFE, four intensive field campaigns (IFCs) were conducted to study the biophysical processes related to different vegetation growth stages. The data used in this study is from the observations for the Julian days 157 (IFC 1: early growth), 187 (IFC 2: peak growth), and 227 (IFC 3: early senescence), each representing a different vegetation stage (Sellers et al. 1992). For the days considered, CO_2 assimilation rates and stomatal conductances were measured using a closed system gas analyzer, whereas the meteorological parameters such as radiation, air temperature, and humidity were measured through a portable automated meteorological station. The CO_2-related parameters are known to follow the von Caemmerer and Farquhar (1981)–type relations (for details see Polley et al. 1992). The conductance values measured in moles per square meter per second are converted into meters per second by multiplying with the factor 8.309 $T_a P^{-1}$; where T_a is the air temperature (K) and P is ambient surface pressure (Pa) (Nikolov et al. 1995).

In this study, the foliage has not been categorized in terms of individual families; it has been taken as a single group of C4 vegetation. This was done because an ear-lier study by Polley et al. (1992) has shown there is no significant difference in the three varieties of C4 grass found on the site [*Andropogon gerardii* Vitman, *Panicum virgatum* L., and *Sorghastrum nutans* (L.) Nash]. Second, the JNP scheme in the form used in the mesoscale models cannot discriminate between different vegetation types [unless there is a change in the land-use type for the model grid; in which case the $R_{s\ min}$ value is altered (cf. Dickinson et al. 1986)]. Hence, all the observations are reported in a combined manner irrespective of the vegetation type. Additionally, only the daytime observations are considered in the present study.

4. Results

Figure 2 gives a summary of the parameters in this study through the box–whisker plots. These plots show the 5th and 95th percentile values within a bracket shape, while the 50th percentile value is the white band within the 10th and 90th percentile box. The horizontal lines beyond the 95th percentile limit are simply reported as above the 95th percentile. Thus, for example, for the temperature data considered in this study, only 5th percentile values were below 24°C, whereas the 95th percentile value corresponds to a value around 34°C with the 50th percentile value around 31°C. The data from the 10th to 90th percentile is from 27°C to a value close to 34°C. Note that the principal aim of these plots is to show the scatter in the observations and the model outcome and also to pick an outlier, if any. Accordingly, one photosynthesis rate value ($>50\ \mu$mol CO_2 m^{-2} s^{-1} units) is taken as an outlier for the dataset and the observations or model outcome corresponding to this value are not considered in any of the analysis ahead. Also, a significant scatter is seen (Fig. 2) in the observed leaf CO_2 concentrations and the estimated vapor pressure deficit and relative humidity values. These affect the observed and predicted R_s values and cause the scatter noticed in the plots (discussed ahead).

Corresponding to the data delineated in Fig. 2, Fig. 3 shows a combined plot for the measured and the observed stomatal resistance for all three IFCs. The x axis starts with IFC1 data points and ends with the IFC3 samples, as shown. The principal feature of this plot is the distinct difference between the meteorological and physiological schemes. The first obvious difference in the two schemes is in terms of the variation or sensitivity of the R_s predictions, with the JNP outcome showing a gradual change with time, whereas the physiological schemes respond rapidly to the prescribed ambient conditions. Thus, the lack of a feedback mechanism in the JNP scheme, as compared to the physiological, is apparent (cf. Jacobs 1994). Second, the JNP outcome shows a significant steplike change for the IFCs, which can be linked to the change in the vegetation features and hydrology, as discussed later. Figure 4 shows the comparative performance of each model individually
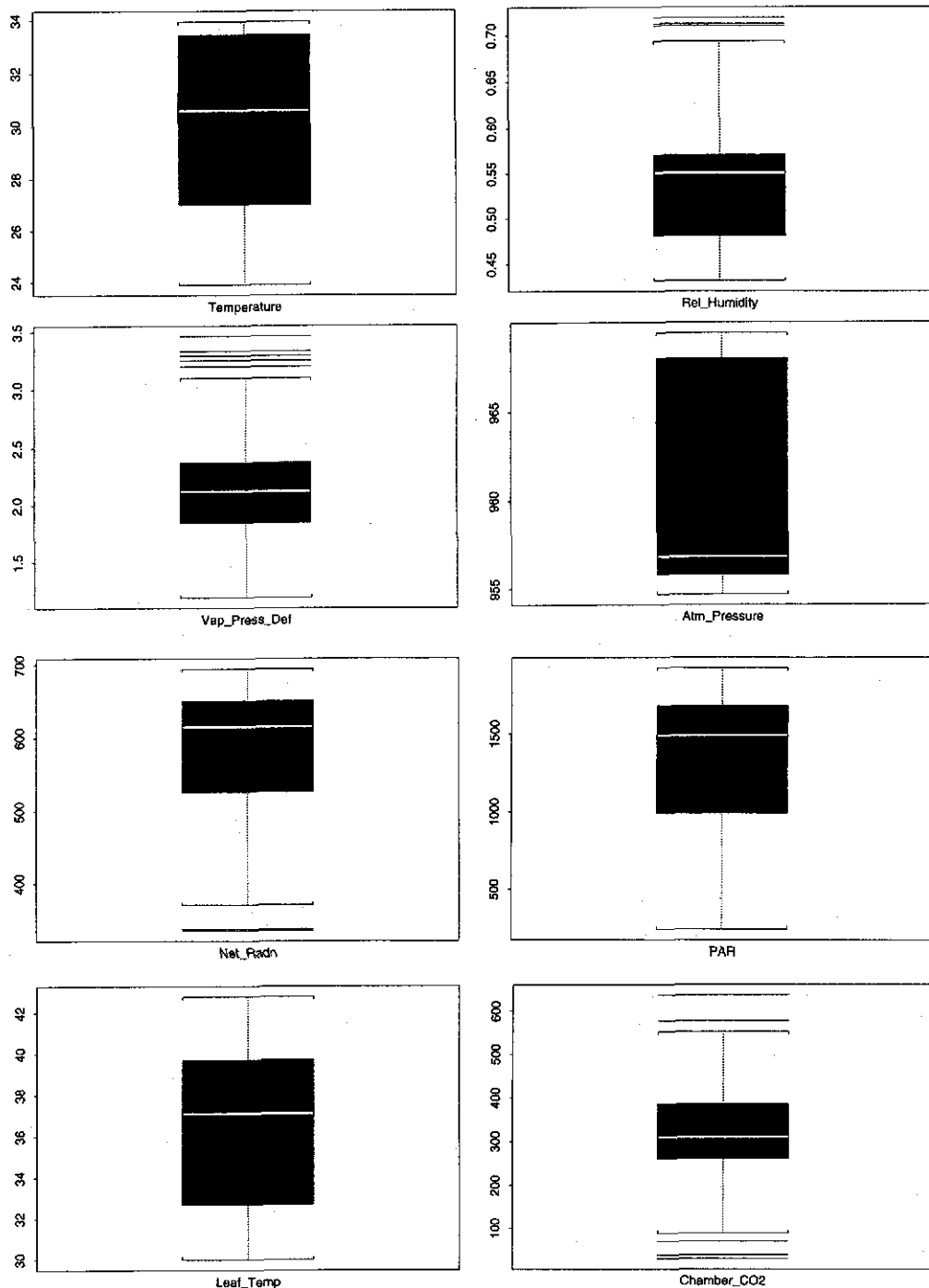
FIG. 2. Box and whisker plots for the data considered and resulting output. Temperatures are in degrees Celsius, RH in decimal fraction, vapor pressure deficit in grams per kilogram, pressure in millibars, net radiation in watts per square meter, PAR in microeinsteins per square meter per second, CO_2 is in micromoles per square meter per second, stomatal resistances denoted by R_s are in seconds per meter, photosynthesis is in micromoles per square meter per second of CO_2, and D/D_{max} is a ratio.

with the observations for all the three IFCs. Two features deserve special mention. First, there is a significant difference, in the overall sense, in the meteorological and physiological realization of the stomatal response for the present models and data considered. The perfor- mance of the JNP (meteorological) approach used in the present mesoscale models cannot be considered equiv- alent of the observations for the dataset referenced. A related feature for the JNP scheme concerns the sys- tematic underprediction in the earlier IFCs and then a
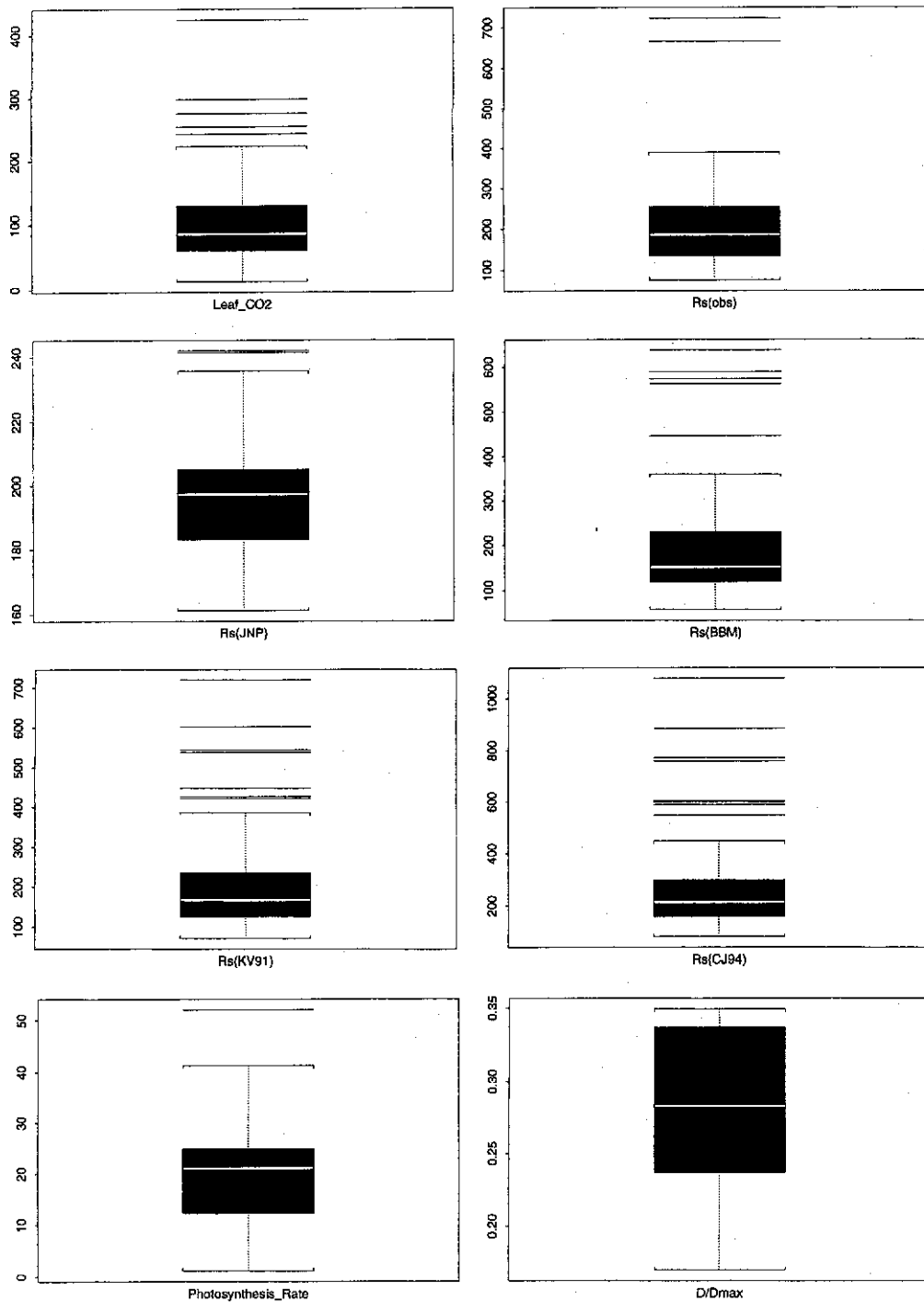
FIG. 2. (*Continued*)

consistent overprediction in the IFC3. This can perhaps be explained by the "excepted" seasonal changes in $R_{s\,min}$ (cf. Dorman and Sellers 1989) and the sensitivity of soil moisture for the three regimes, as discussed ahead. The second feature realized from the plots shown in Fig. 4 is the qualitative similarity in the outcome of all the three physiological schemes. As mentioned earlier, the physiological schemes considered in this study represent two different philosophies in terms of representing the humidity response. The results suggest there is apparently no major difference in the application of the vapor pressure deficit approach or the relative humidity–based
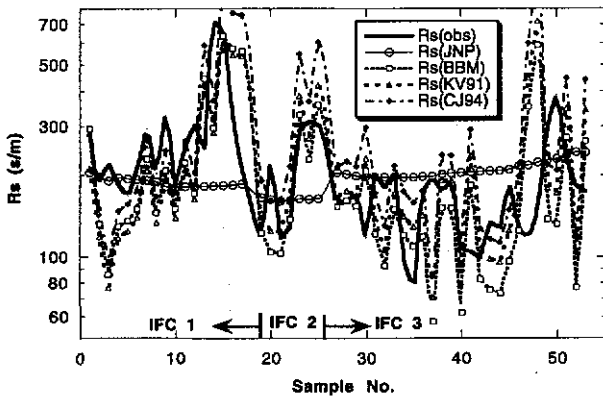
FIG. 3. Predicted and observed stomatal resistance outcome for the FIFE observations. The sample points (x axis) start with IFC1 data and end with IFC 3 data points. The $R_{s\,min}$ value used for the JNP prediction was 60 s m^{-1}.

descriptor, as in the empirical equations used in this study, for meteorological applications. We acknowledge, however, that there can be different constraints in terms of the limits for scenario predictive ability of the two humidity representations based on their respective indirect interactions with other parameters [detailed in Niyogi et al. (1997, manuscript submitted to *J. Appl.*

Meteor.)]. But in terms of the overall scenario, the results suggest that there is no apparent difference in applying vapor presure deficit or relative humidity as a descriptor for meteorological applications such as short-term weather forecasting in limited-area models.

To have a quantitative measure of the model performance, various statistical descriptors are calculated as shown in Table 1. In the table, d represents the index of agreement (Wilmott 1982):

$$d = 1 - \left[\frac{\sum\limits_{i=1}^{N} (P_i - O_i)^2}{\sum\limits_{i=1}^{N} (|P_i'| + |O_i'|)^2} \right], \qquad (6)$$

where P_i and O_i refer to the ith prediction and observation. The primed parameters (P_i' and O_i') equal the deviation from the population mean of N samples. Higher d indicates a larger agreement between the model predictions and observations and hence a good model performance. Thus, from this analysis it follows that the performance of the four schemes is fair in terms of predicting the ensemble *mean* R_s, consistent with the conclusions of Choudhury and Monteith (1988) and also Shuttleworth and Wallace (1985). JNP is not very sen-
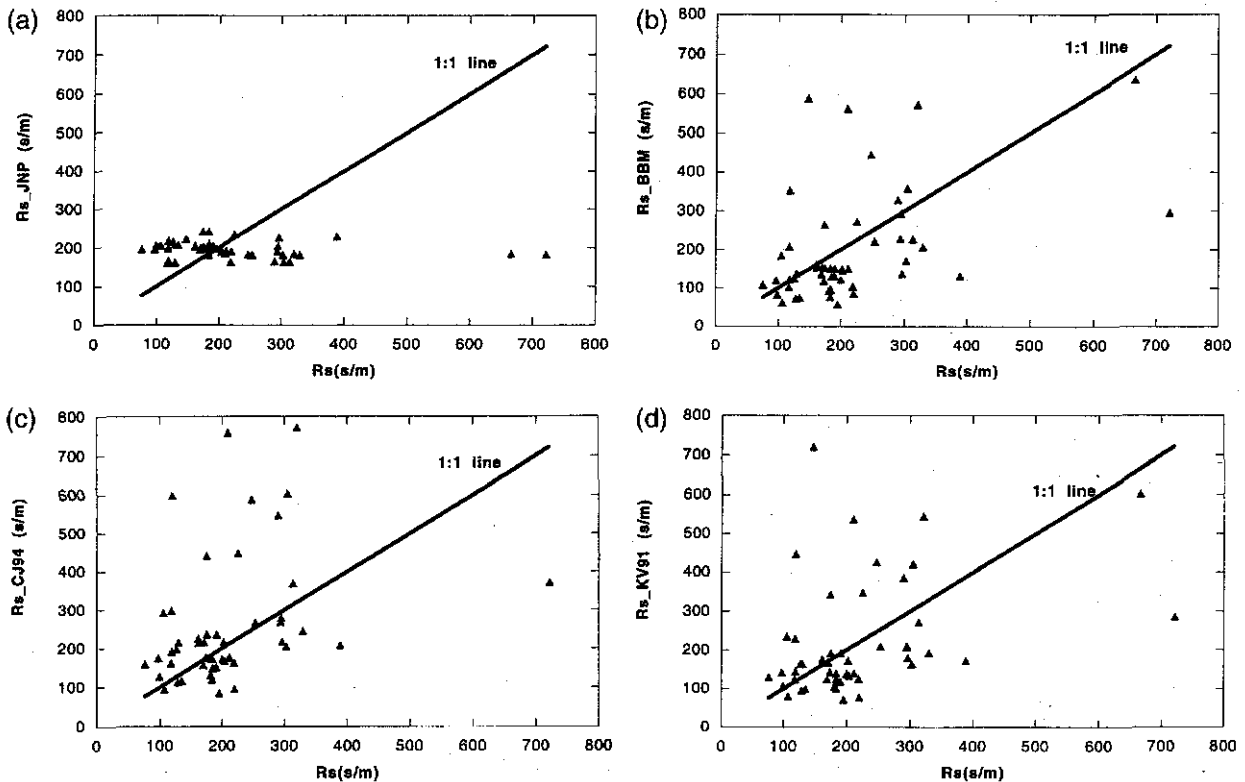

FIG. 4. The predicted outcomes from the four schemes (y axis) are compared with observations (x axis) corresponding to Fig. 3. The data was transformed and all the IFCs outcomes are combined in the sorted transformation for (a) Jarvis-type scheme, (b) Ball–Berry model, (c) Kim–Verma model, and (d) Jacobs scheme.

TABLE 1. Descriptive statistics for model performance evaluation for all the IFCs combined.

Data	Mean (s m^{-1})	Median (s m^{-1})	Std. deviation (s m^{-1})	d
Observed	215.87	185.45	120.94	—
Jarvis type (JNP)	196.34	197.22	19.70	0.4238
Ball–Berry model (BBM)	200.74	150.45	142.04	0.6661
Kim and Verma (1991; KV91)	218.06	166.67	146.38	0.599
Jacobs (1994) (CJ94)	288.33	204.93	214.06	0.5241

sitive to the ambient changes, as is reflected in the low standard deviation of the predicted outcome. CJ94, on the other hand, is the most sensitive scheme and hence though it has been able to create various R_s scenarios quite accurately, there is large scatter in the outcome lowering the d value in Table 1. A similar scatter for CJ94 was also reported in a detailed analysis by Jacobs (1994). Thus, following the statistical descriptors, BBM has the best overall performance, closely followed by KV91, followed by CJ94, and then the meteorological JNP. But again one should be cautious about the outcomes as the number of samples considered in this study are limited ($n = 51$).

As yet, we have studied the performance of the four schemes in the overall sense for all the three IFCs. This can be considered as an effective performance when subgrid-scale heterogeneities or the temporal scenarios are averaged. However, each of the IFCs during FIFE represent a different physiological and hydrological regime, hence it will be interesting to see how the models perform for each of the IFCs independantly. Figures 5a–c show the observed and the predicted R_s values for the three IFCs. Corresponding to these data points (shown in Figs. 5a–c), Tables 2a–c summarize the descriptive statistics. Figure 5a, for IFC1 ("green-up" phase), shows for prenoon that the physiological schemes underpredict observations, whereas the meteorological models slightly overpredict the observations. Beyond afternoon, the physiological model follows the observations fairly well, whereas the meteorological scheme underpredicts considerably. For these data points, CJ94 predictions closely follow observations around noon but the morning underpredictions and the evening overpredictions lower the overall "index of agreement" (Table 2a). Also from Table 2a, the physiological schemes have a nearly similar performance, with BBM being slightly better of the three, statistically. Figure 6, which shows the one to one correspondence for the observed and predicted data points for each of the schemes, confirms the earlier result for the IFC1 data points, particularly the similarity of the outcomes for each scheme, which can deviate considerably from the observations. Figure 5b, for the IFC2 ("full-green") phase, strengthens the conclusion that the physiological schemes be-
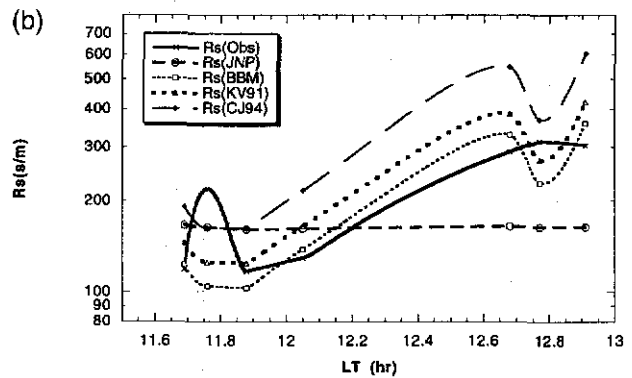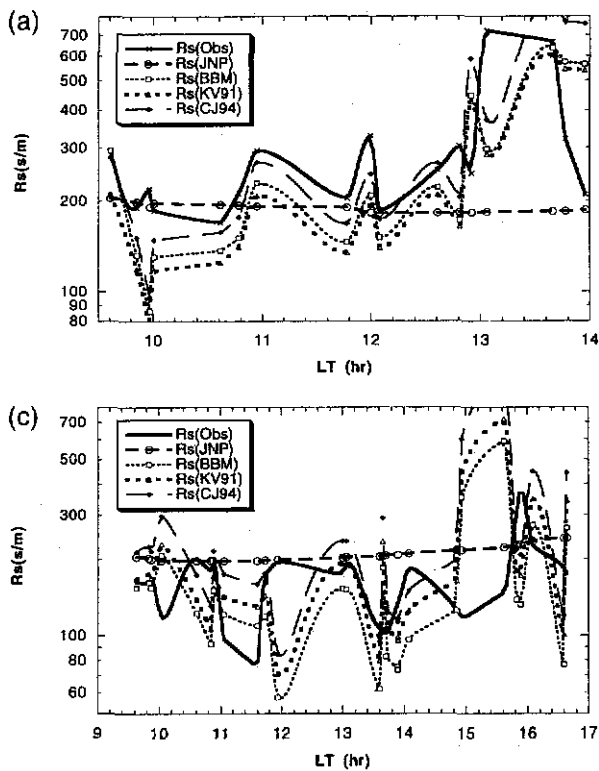

FIG. 5. (a) Same as Fig. 3 except for IFC1 data points alone. (b) Same as Fig. 3 except for IFC2 data points alone. (c) Same as Fig. 3 except for IFC3 data points alone.

TABLE 2a. Descriptive statistics for model performance evaluation for IFC1 data points.

Data	Mean (s m^{-1})	Median (s m^{-1})	Std. deviation (s m^{-1})	d
Observed	294.22	246.59	159.12	—
Jarvis type (JNP)	188.61	186.13	6.92	0.3469
Ball–Berry model (BBM)	268.97	208.21	176.05	0.4816
Kim and Verma (1991; KV91)	249.07	193.27	169.52	0.4832
Jacobs (1994) (CJ94)	335.88	245.45	251.47	0.4806

TABLE 2b. Descriptive statistics for model performance evaluation for IFC2 data points.

Data	Mean (s m^{-1})	Median (s m^{-1})	Std. deviation (s m^{-1})	d
Observed	213.05	219.04	34.3	—
Jarvis type (JNP)	163.53	163.65	1.67	0.297
Ball–Berry model (BBM)	197.91	138.18	109.02	0.8169
Kim and Verma (1991; KV91)	234.26	164.75	126.66	0.8204
Jacobs (1994) (CJ94)	321.8	216.08	188.00	0.8144

have similarly and follow the observations better than the meteorological scheme. Once again JNP shows no feedback and hence a very low variance in the outcome (Table 2b). Also, as seen in Fig. 7, BBM and KV91 have a nearly similar performance for this IFC (also see Table 2). The IFC3 data points (shown in Figs. 5c and 8) once again confirm the earlier observations regarding the poor feedback for the JNP and the similar performance for all the physiological schemes. However, another aspect revealed in these plots (particularly Fig. 5c) relates to the underprediction of R_s in the morning and overprediction in the early evening. For these IFCs, note that there are two changes taking place during the field

observations. One, the vegetation is maturing from the first to the third IFC; thus there is growth and greenness to attribute for in the scenario. Second, feature changing, which could be equally important (cf. Makela et al. 1996; Berninger et al. 1996), is the soil moisture availability during the IFCs. Also, though there is heterogeneity in the soil moisture availability for the FIFE domain, there was an "unusual wet spell in 1987" (Sellers et al. 1992) and hence there is less diversity in the soil moisture regimes than one would have anticipated and desired. Thus, the soil moisture content is around 60%–65% of saturation with IFC1 (day 157) and IFC3 (day 227) being generally drier compared to IFC2 (day
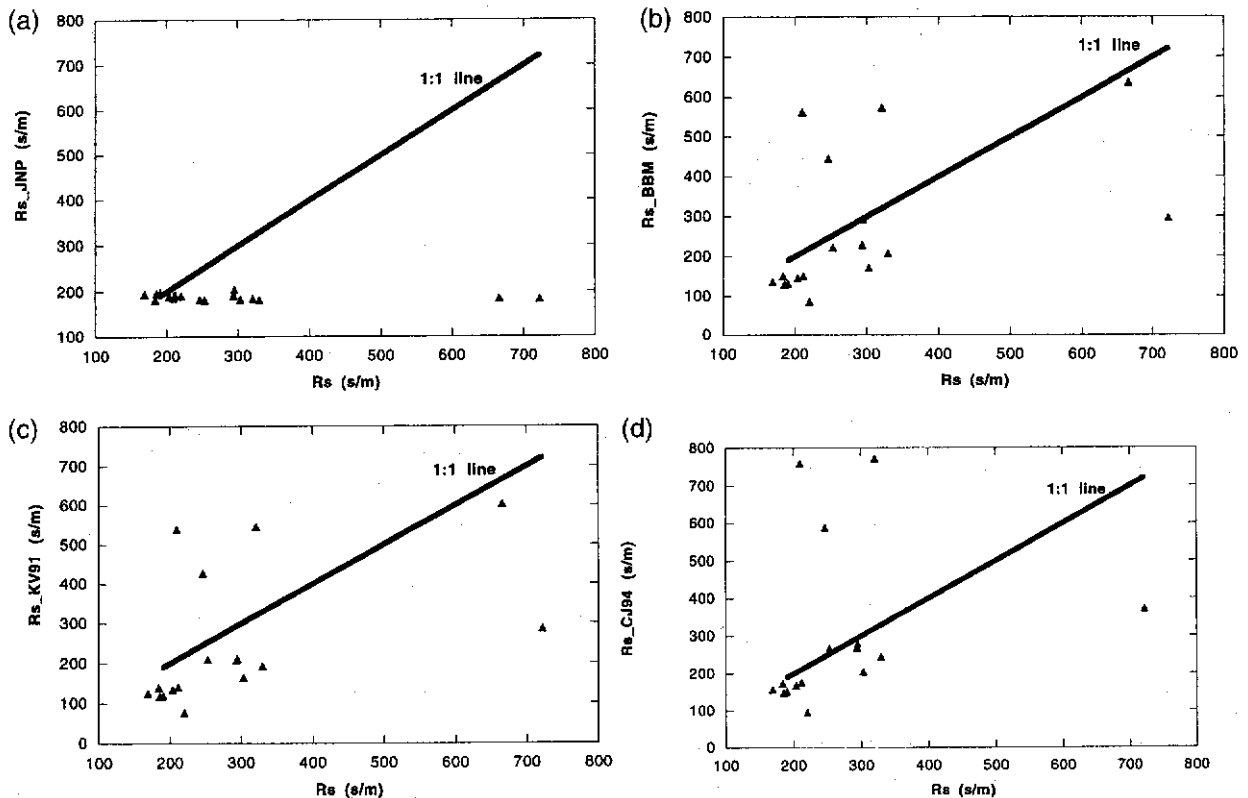

FIG. 6. Same as Fig. 4 except for IFC1 data points.

Data	Mean (s m^{-1})	Median (s m^{-1})	Std. deviation (s m^{-1})	d
Observed	167.27	170.49	64.62	—
Jarvis type (JNP)	209.71	204.75	14.21	0.103
Ball–Berry model (BBM)	158.52	132.47	109.9	0.2297
Kim and Verma (1991; KV91)	194.33	166.67	136.15	0.189
Jacobs (1994) (CJ94)	249.71	208.43	202.46	0.209

187), which was relatively moist. For the JNP, this impact is more apparent with the IFC2 values (Figs. 2 and 5b), showing the least resistance as compared to the other two IFCs. Overall, however, the changes in the soil moisture values are not quite large and hence are not reflected directly in the R_s values compared to the phenological features associated with the changes in the range of stomatal resistance for the IFCs (Figs. 5a–c). Table 2, which summarizes the statistics of the performance of the four models, however, brings out the significance of soil moisture for R_s estimation. As that, for all the physiological models, the overall performance seems to deteriorate with decreasing soil moisture avail-

ability. For the "wet" IFC2, the agreement is fairly high, whereas for the "dry" IFC3, the performance is less appreciable. (Note that the difference in the number of sample points and the temporal coverage for the two cases could also result in altering the index, but the conclusion we draw here is also supported by Figs. 5a–c). As for the JNP, the performance is relatively better for IFC1 where the soil moisture availability is "intermediate" (as compared to the other two IFCs). This is in agreement with the conclusions obtained from an interaction-explicit study by Niyogi et al. (1997) and also from observations of Avissar (1993). The linear vapor pressure deficit dependence in the JNP scheme could possibly result in such an outcome and needs to be confirmed (cf. Avissar 1993). Also, the prediction of the high resistances observed for the midafternoon or early evening [cf. Collatz et al. (1991) for C4 plants] was the main feature that could not be captured by the JNP in either of the IFCs. As for the physiological schemes, particularly CJ94, most of the predictions for afternoon conditions were fairly accurate; it was only in the morning or evening that the outcome was significantly different for all three schemes (Figs. 5a–c). This makes us tentatively suggest a possible role of available soil moisture and the vegetation photosynthesis rate in the poor model outcome for these conditions. As mentioned, the R_s values are closely correlated to
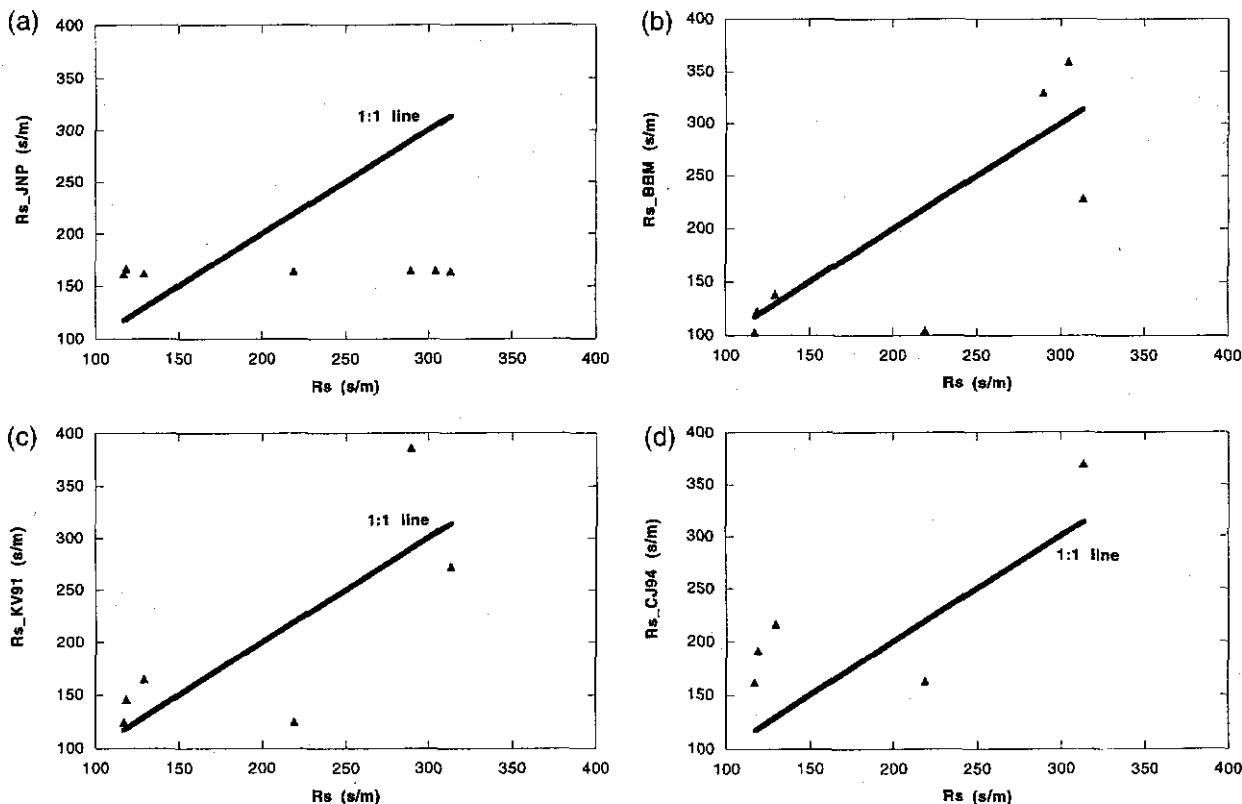

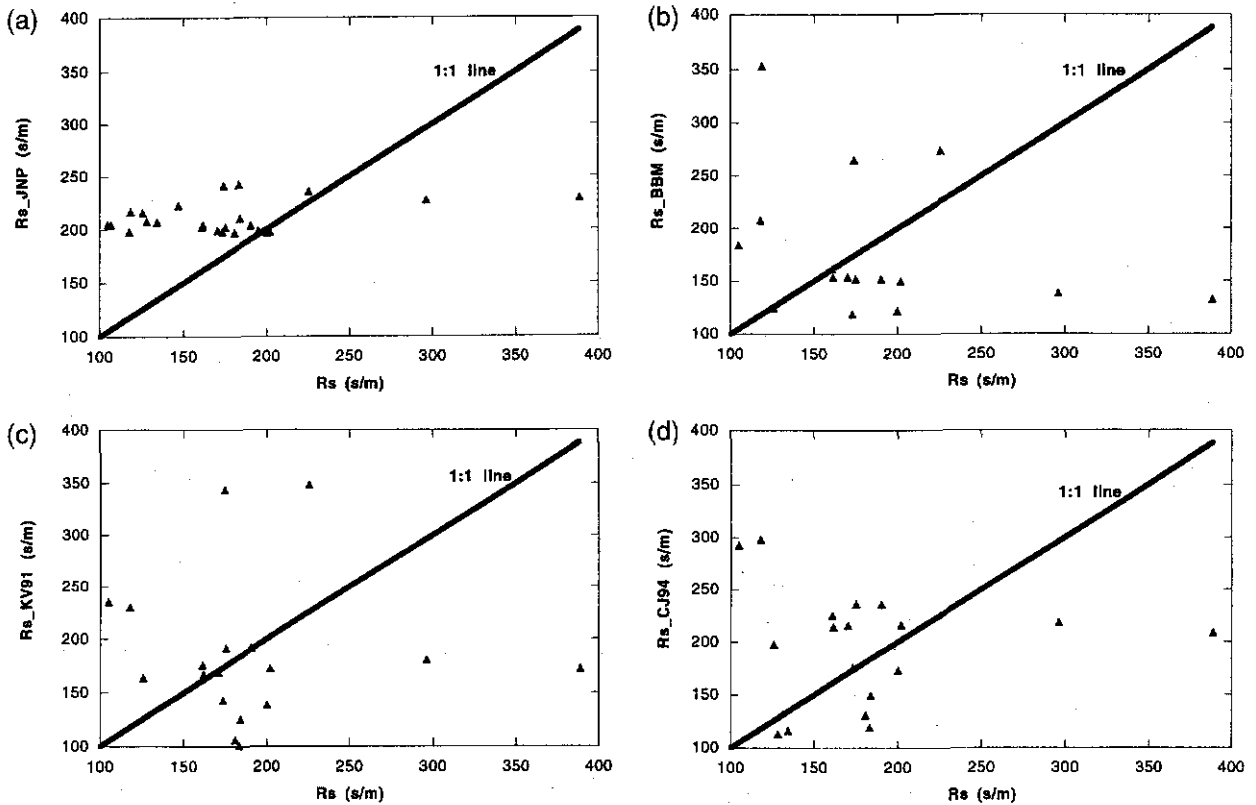FIG. 7. Same as Fig. 4 except for IFC2 data points.

FIG. 8. Same as Fig. 4 except for IFC3 datapoints.

the photosynthesis rate for the observations (Polley et al. 1992) as also for the model results. This feature is captured particularly around midafternoon for all the three IFCs and the three models. However, the underpredictions in the morning and overpredictions in the evening even when the photosynthesis rate is low need to be explained further. It can be fairly assumed, based on various observations (cf. Sellers et al. 1992) and numerical simulations (cf. Fig. 1a) in the morning, that the relative soil moisture availability is highest for the top soil layer and, as the day progresses, the soil moisture depletes and later in the evening gets replenished around sunset. Assuming this scenario valid for the three days (157, 187, and 227) considered, it appears, when the soil moisture availability is high, the predicted R_s is lower, whereas for the late afternoon, when the soil moisture availability is lower, for low photosynthesis rate regimes particularly, the predicted R_s is overestimated. This suggests a possible strong synergistic interaction between photosynthesis rate and soil moisture, which is manifested in the physiological schemes and needs to be verified (cf. Leuning 1995; Niyogi et al. 1997, manuscript submitted to *J. Appl. Meteor.;* Ellsworth 1982).

5. Conclusions

For active convection regions such as the Tropics and semiarid grasslands of the southern United States, the vegetation has a predominant C4-type pathway. The parameterization of stomatal resistance R_s for such vegetation has a profound impact on the energy partitioning and the prediction of boundary layer fluxes and surface parameters such as temperature and humidity, through the transpiration regulation. For typical one-dimensional simulation outcomes, change in the stomatal response by a factor of 4 can change the predictions of energy fluxes and boundary layer parameters by a factor of 2.

In the mesoscale models presently, a Jarvis-type parameterization is employed (cf. Noilhan and Planton 1989), whereas in the climate (cf. Sellers et al. 1996) and microscale models (cf. Su et al. 1996), physiological representation involving a photosynthesis-transpiration iterative function is being adopted. In an attempt to understand the constraints and abilities of the two approaches, this study compares the performance of four different schemes in predicting R_s through a mesoscale modeling perspective over C4 grasslands typical of southern United States and semiarid Tropics. The four schemes studied are the exisiting Jarvis-type scheme as extended by Noilhan and Planton (1989; referred to as JNP), and the physiological schemes of Ball et al. (1987; referred to as BBM), Kim and Verma (1991; KV91), and Jacobs (1994, CJ94). Observations made by Polley et al. (1992) as a part of FIFE (Sellers et al. 1992) are used as the reference for comparing the performance of

the four schemes. Modeled and observed data from three IFCs, each representing a different physiological and hydrological regime, are compared, first in a combined manner and then for each IFC individually.

Overall, there was a significant difference in the outcomes of the meteorological JNP scheme and the three physiological schemes. Qualitatively, the three physiological schemes followed similar trends in the R_s outcome and predicted observed R_s better than the meteorological scheme consistently. However, there was a large variability in the estimated R_s values for the physiological schemes. On the other hand, all the schemes (including JNP), predicted the ensemble *mean* in a fair manner. This suggests that the confidence associated with the predictions can largely depend on the temporal frequency of the predictions. This conclusion, though not surprising, is of practical importance for short-range weather, and mesoscale forecasting indicating features such as the model resolution and the subgrid-scale heterogeneity will alter the performance of the schemes in the operational models. Thus, no single scheme can be considered better or worse than others ubiquitously. These aspects will be tested in a future study using a three-dimensional version of an operational model with coupled feedback.

Additionally, we also found an expected "seasonal" change in the $R_{s\ min}$ embedded in the meteorological model outcome. It was also highlighted that the boundary layer parameters are largely sensitive to the $R_{s\ min}$ specification in the meteorological approach. These two features combined together suggest that the performance of the Jarvis-type meteorological models can be significantly enhanced by modulating $R_{s\ min}$ through phenological information such as the nitrogen content (cf. Schulze et al. 1994; Niyogi et al. 1997, manuscript submitted to *Geophys. Res. Lett.*; Baldocchi 1996, personal communication).

It was also found that the three physiological schemes performed remarkably similarly in a qualitative manner, suggesting there is no apparent difference, in the operational sense, regarding the use of the vapor pressure deficit approach or the relative humidity based description of the humidity stress in the empirical models (cf. Monteith 1995a,b). This conclusion is however, based on the outcome without resolving interactions in the system (cf. Alpert et al. 1995; Niyogi 1996; Niyogi et al. 1997). A follow-up study (Niyogi et al. 1997, manuscript submitted to *J. Appl. Meteor.*) views the interactions associated with the humidity descriptors using a fractional factorial approach (cf. Henderson-Sellers 1993) and will discuss further constraints or similarities within the stomatal resistance schemes. Additionally, it was hypothesized that soil moisture and photosynthesis rate form an interactive term in the physiological models, which manifests in some of the extreme outcomes— that is, in terms of underpredictions in the morning and overprediction in the evening—and needs to be resolved from observations in a future study.

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