The Influence of Initial Soil Wetness on Medium-Range Surface Weather Forecasts

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ABSTRACT

The influence of initial soil wetness on surface weather forecasts was quantitatively assessed through the use of the Center for Ocean–Land–Atmosphere Interactions (COLA) general circulation model with an advanced simple biosphere model. The sensitivity of the COLA GCM to changes in initial soil wetness (ISW) is determined by repeating three 10-day integrations with the same initial and boundary conditions as the control runs except the values of ISW, which are revised at 69 model grid points covering much of the continental United States. It is found that the relationship between the changes in the 5-day mean forecasts of surface air temperature and surface specific humidity and the changes in ISW depends upon vegetation type and the values of ISW, and is approximated by regression equations. With the ISW revised based on these regression equations, the first 5-day mean surface air temperature and mean surface relative humidity forecast errors over the relatively dry western portion of the domain are reduced from 2.9° to 1.1°C and from 15% to 7.6%, respectively. Somewhat smaller surface forecast improvements occur for the following 5 days. The impact on the upper atmosphere is small and is largely confined to lower levels.

It is also found that the model soil wetness has strong persistence. Therefore, additional forecast experiments are carried out in which the initial soil wetness for a 10-day integration is revised based on the surface forecast errors for the preceding 5-day mean. This results in a reduction of the first 5-day mean surface air temperature and surface relative humidity forecast errors from 2.4° to 1.3°C and from 15% to 8%, respectively, averaged over the dry region.

This study suggests the importance of accurate initial soil wetness for medium-range surface weather forecasts. The regression method developed in this study could be readily used operationally to initialize the soil wetness field for medium-range forecasting.

1. Introduction

The influence of land surface boundary conditions, particularly the evaporation process, on climate has been recognized for quite some time (Namias 1959, 1960; Rasmusson 1968; Anthes 1984). Since the development of general circulation models (GCMs) in the 1970s, meteorologists have been using these numerical models to investigate the influence of land surface conditions on precipitation, temperature, and atmospheric circulation. In the early GCM studies, the land surface conditions were simply prescribed by three independent parameters: surface albedo, soil wetness, and surface roughness. And the separate influence of changes in these parameters was investigated. Of these three parameters, the soil wetness has perhaps attracted the most attention. These GCM studies, as reviewed by Mintz (1984), have shown that the variation of soil wetness has considerable influence on the precipitation, temperature, and atmospheric circulation for various time scales (Shukla and Mintz 1982; Walker and Rowntree 1977; Rowntree and Bolton 1983). The persistence of the soil wetness anomaly and the degree of the feedback caused by the anomaly vary widely depending on the latitude of the anomaly and the prevailing flow in the tested region (Rind 1982; Sud et al. 1982; Yeh et al. 1984).

The impact of changes in soil wetness on medium-range forecasts was first investigated by Miyakoda et al. (1979), who performed a series of two-week forecast experiments during summer with a version of the Geophysical Fluid Dynamics Laboratory (GFDL) GCM. Their control simulations used an arbitrarily chosen soil wetness value of 0.5 globally. In their test simulations the soil wetness was specified from past precipitation data. They concluded that this simple procedure for specifying soil moisture improved the forecasts of precipitation and evaporation.

More recently developed surface biosphere models include a more realistic parameterization of evaporation. The Biosphere–Atmosphere Transfer Model (BATS, Dickinson 1984), and the Simple Biosphere Model (SiB, Sellers et al. 1986), have explicitly included vegetation and improved the simulation of surface evaporation when coupled with GCMs. Sato et al. (1989) implemented SiB into a version of the Center for Ocean–Land–Atmosphere Interactions (COLA)

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GCM and showed that the simulation of surface fluxes and precipitation is superior to that generated by the same GCM without SiB. They also found that the model climate is sensitive to the initial soil wetness by comparing two 30-day GCM simulations differing only that in one integration the initial soil wetness was set to 0.45 wherever it exceeded this value over North America.

This study is motivated by past verifications of surface weather forecasts with the COLA GCM. In particular, a study by Frederickson (1989) showed that both too high surface temperature and too low relative humidity were forecast over dry regions. The initial soil wetness (ISW) used by the GCM is generated from climatological data using a simple bucket hydrology model similar to that used by Mintz and Serafini (1984) and is therefore somewhat arbitrary. Thus, we hypothesize that some of these surface forecast errors are due to unrealistic ISW. We test this hypothesis with the COLA GCM by developing a quantitative method to revise the ISW field so as to improve the 10-day surface forecasts.

The paper is organized as follows. In section 2, the experimental design and the process that generates the ISW field for the model are described. Section 3 addresses the model sensitivity to ISW, which underlies the development of the method for revising the ISW. Section 4 describes the impact of the changes in ISW on surface weather forecasts. In section 5 the impacts of the changes in ISW on the surface energy and hydrology, as well as on the upper atmosphere, are analyzed. A summary and discussion are given in section 6.

2. Experimental design and the soil moisture initialization

a. Experimental design and observed data

We first compare three 10-day GCM forecasts (to be referred to as "control runs") of surface meteorological variables with the observed data over 69 model grid boxes in the United States to determine how the distribution of the forecast errors is related to the distribution of the ISW. We hypothesize that the surface weather forecast errors are in part caused by the errors in the ISW field, and then revise the ISW to see its impact on the forecast error. The integrations are then repeated using the revised ISW. An analysis of the original and revised integrations reveals the model sensitivity to the ISW. Finally, we develop a method to modify the current soil wetness initialization based on the knowledge gained from the preceding analysis.

The GCM model used here is the same as used in the sensitivity experiments by Sato et al. (1989). It is a spectral model with rhomboidal truncation at wavenumber 40 and has 18 sigma layers in the vertical, with the lowest 12 levels carrying water vapor. The surface land processes are described by SiB. The radiatively active clouds are prescribed from a zonally symmetric seasonally varying climatology. The control runs are three 10-day GCM integrations from 1200 UTC 11 June to 21 June 1979 (hereafter CON 1), 0000 UTC 10 July to 20 July 1983 (hereafter CON 2), and 1200 UTC 15 June to 25 June 1986 (hereafter CON 3).

For 69 GCM grid boxes that cover much of the United States (Fig. 1), the observed grid box values were obtained by averaging the observations of the stations located within the corresponding grid area, about 200 km × 250 km (Frederickson 1989). Hourly synoptic station observations over the United States were provided by the National Meteorological Center (NMC), Techniques Development Laboratory. NMC analyses were used to verify the model forecast fields aloft.

There are large differences between the model grid box topographic heights and the averaged observation station heights in the northwestern portion of the study region. In this region, the differences in height are generally greater than 600 m, as shown in Fig. 1. To compare the model forecasts with the observations, we used an air temperature lapse rate of 6.5°C km^{-1} to adjust the model forecast temperature for each grid box.

b. The soil wetness initialization of the model

The ISW field of the GCM is derived from that of Mintz and Serafini (1984), who computed this quantity by forcing a simple water budget equation (bucket model) with observed climatological monthly mean precipitation and surface air temperature. Essentially, the field is a climatological field that contains great uncertainty due to the overly simple method used to derive it. Since the formulation of the three-layer soil wetness in SiB is different from that of the single-layer bucket model, the original Mintz and Serafini soil moisture field (1984) is transformed into a SiB compatible soil wetness field under several assumptions (Sato et al. 1989). As pointed out by Sato et al., these assumptions give rise to a high degree of uncertainty in addition to that already present in the original soil moisture field. One of these assumptions is that the derived SiB initial soil wetness is uniformly distributed in the vertical; thus, the same ISW is assigned to all three layers. The Mintz and Serafini soil wetness fields vary unrealistically from 0 to 1. The derived SiB soil wetness values vary between the unavailable soil wetness (roughly 0.25) and the saturated soil wetness (roughly 0.8).

Additional potential sources of error in the model soil wetness field are the use of climatological rather than real-time data and the possible misrepresentation of the soil wetness in the physical processes of the model itself. Since there are no large-scale soil moisture observations, it is hard to verify the model soil wetness field.

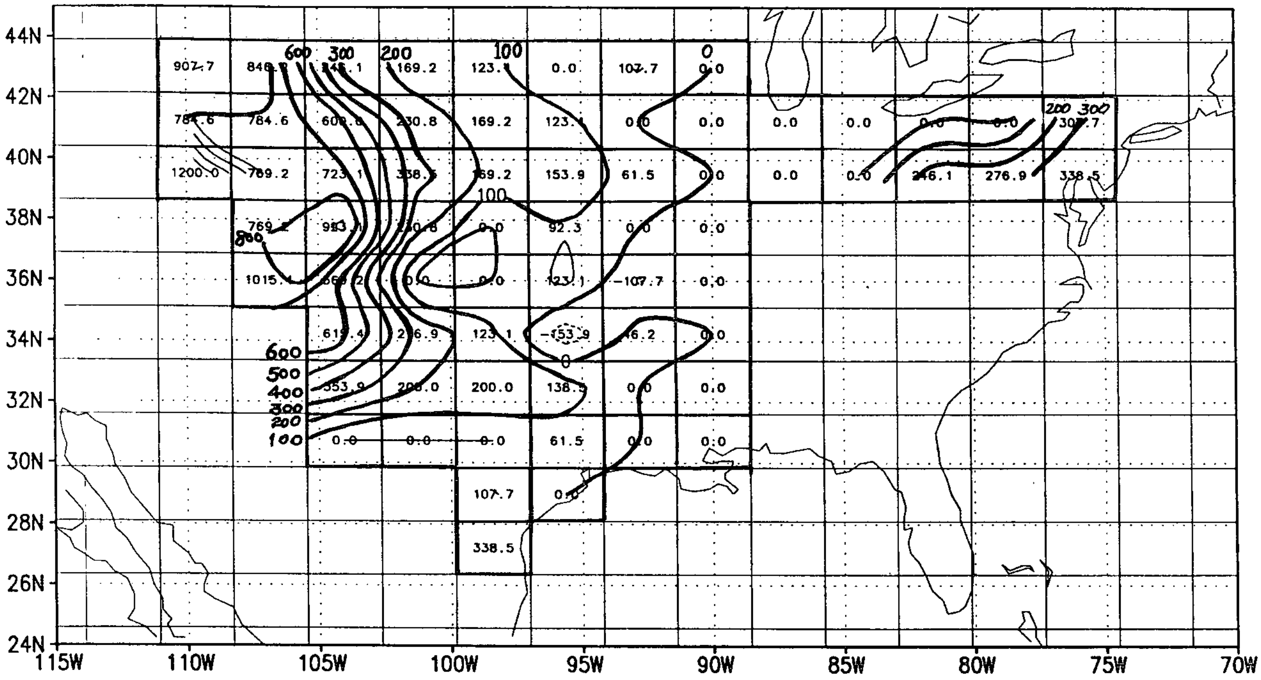

FIG. 1. The 69 model grid boxes used in this study. Isopleths are for the differences of height between the model topography and the observed station elevation. Contour interval is 100 m.

3. The model sensitivity to the changes in initial soil wetness

a. Surface forecast error analysis

We analyze the first 5 days and the second 5 days of the 10-day forecast separately. We analyze 5-day rather than shorter time period means in order to isolate the impact of the relatively steady soil wetness forcing as opposed to more transient forcing unrelated to ISW. Figure 2a shows the distribution of the first 5-day mean surface air temperature forecast error (forecast minus observation) for the 11 June 1979 initial condition (CON 1). Compared with the distribution of the ISW of CON 1 (Fig. 2b), the area with ISW less than or equal to 0.45 (to be referred to as the "dry area") overlaps the area with large surface air temperature forecast errors, where the 5-day mean forecast temperature is higher than the observed by more than 3°C. Large surface air temperature forecast errors also occur in the dry areas of CON 2 and CON 3 (not shown). The dry area covers most of the western Great Plains, and the wet area (defined as the area with ISW larger than 0.45) extends from the eastern Great Plains eastward. Hourly values of surface air temperature and surface relative humidity averaged over the dry area for CON 1 are shown in Fig. 3, along with the corresponding observations. The forecast surface air temperature (Fig. 3a) [surface relative humidity (Fig. 3b)] is consistently higher (lower) than the observations throughout the 10-day period. The amplitude of the forecast surface air temperature diurnal cycle is close to that of the observed. The surface forecast errors in the wet area are much smaller and are close to the observations (not shown).

The forecast precipitation in the dry area is approximately 1 mm day^{-1} lower than that observed, but the precipitation in the wet area is close to the observations (not shown).

Based on the preceding features of the forecast errors in dry areas, we conjecture that the errors are related to unrealistically low model soil wetness. Since at this time we have no independent method to eliminate ISW errors a priori, our strategy is to revise ISW a posteriori, that is, to revise the ISW based on correcting the first 5-day forecast errors and then to repeat the integration for 10 days.

b. Simple regression equation for initial soil wetness

The SiB surface model was integrated both alone and coupled to the COLA GCM. Running alone, the SiB surface model is forced by atmospheric variables from the lowest GCM level. The GCM variables used to force SiB are temperature, humidity, precipitation, downward radiative fluxes, and wind speed. For each vegetation type, SiB computes eight forecast variables: canopy temperature, ground temperature, deep soil temperature, liquid water storage for both the canopy foliage and the ground foliage, and soil wetness for the three soil layers.

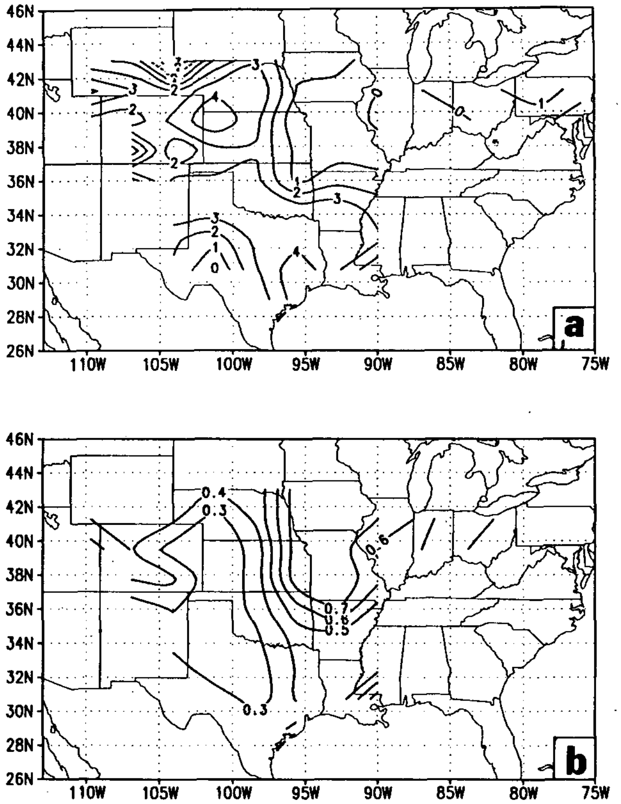

FIG. 2. (a) The distribution of 5-day mean surface air temperature error, control minus observation, and (b) the distribution of ISW, for CON 1. Contour intervals are (a) 1°C and (b) 0.1.

The SiB surface model was first repeatedly integrated alone to obtain a preliminary relation between changes in ISW and changes in surface air temperature, as a function of vegetation type. The surface temperature generally decreases when ISW increases but not when ISW is below 0.3 or higher than 0.6–0.7. We assume we can correct the GCM 5-day mean temperature errors of a control run (CON 1) by adjusting the ISW at each grid point by the amount obtained from this preliminary relation. The 10-day GCM integration was repeated with the same initial and boundary conditions as CON 1 except that the ISW values were revised. Comparing this revised integration with the original CON 1 yields the change of mean surface air temperature versus the change in ISW for GCM runs, which was then used to revise the ISW of CON 2 and CON 3 for the two new GCM integrations.

The results from these three pairs of model integrations are used to examine the relationship between changes in ISW and the changes in the 5-day mean surface air temperature, which is shown in Fig. 4. The abscissa is the change in ISW (new minus old); the ordinate is the change in the first 5-day mean surface air temperature. The plotted numbers are the values of ISW from the control integration for grid points with vegetation type 12. These values have been multiplied by 10 and rounded to one digit before plotting. It can be seen that the change in the mean surface air temperature depends upon the value of the control ISW. When the value is large, such as 7 or 8 (upper left of Fig. 4—that is, the ISW value is 0.7 or 0.8)—a moderate increase or decrease in ISW does not produce a perceptible change in surface air temperature. Whereas, when the value is small, such as 4 or less (lower right of Fig. 4), a moderate increase in ISW can cause a large change in surface air temperature. The relationship also depends on vegetation type and can be approximated by a linear regression equation. For vegetation type 12 (broadleaf deciduous trees with winter wheat, Fig. 4), the correlation coefficient derived from a sample size of 64 is −0.87, and the regression equation for the increment of ISW is

$$\Delta \mathrm{ISW} = -0.09 + 0.10\Delta T. \qquad (1)$$

Here, ΔISW is the increment of ISW for the new run (new ISW minus the old) and ΔT is the 5-day mean surface air temperature error of the control run (forecast minus observation).

For vegetation type 7 (ground cover), the correlation coefficient derived from a sample size of 24 is −0.9 and the regression equation is

$$\Delta \mathrm{ISW} = -0.08 + 0.076\Delta T. \qquad (2)$$

These equations show that the rate of change of temperature with ISW for vegetation type 7 is larger than that for vegetation type 12. The high linear correlation demonstrates that ISW has a strong effect on the surface air temperature forecast. The nonzero constant in the equations denotes in part that the change in ISW around the area adjacent to a point may affect the surface air temperature at the point even if its ISW does not change. Because the study region on average was warm and dry, the soil wetness on average was increased, and the area average temperature was reduced. The negative constant in the regression equations acts to reduce the soil wetness at each point, thereby raising the temperature, in opposition to the regional cooling effect. As an alternative, the constant could have been set to zero, implying that the temperature error at a point is due only to the ISW error at that point. We believe that for a limited region such as that studied here, including the constant and thus allowing for the regional influence is a good approach. However, we should note that this constant may vary if the regression equation was derived for a different region or season.

c. *Multiple-regression equation for initial soil wetness*

In an attempt to improve the ISW revision method, we developed multiple-regression equations for the change in ISW from two predictors: the mean surface

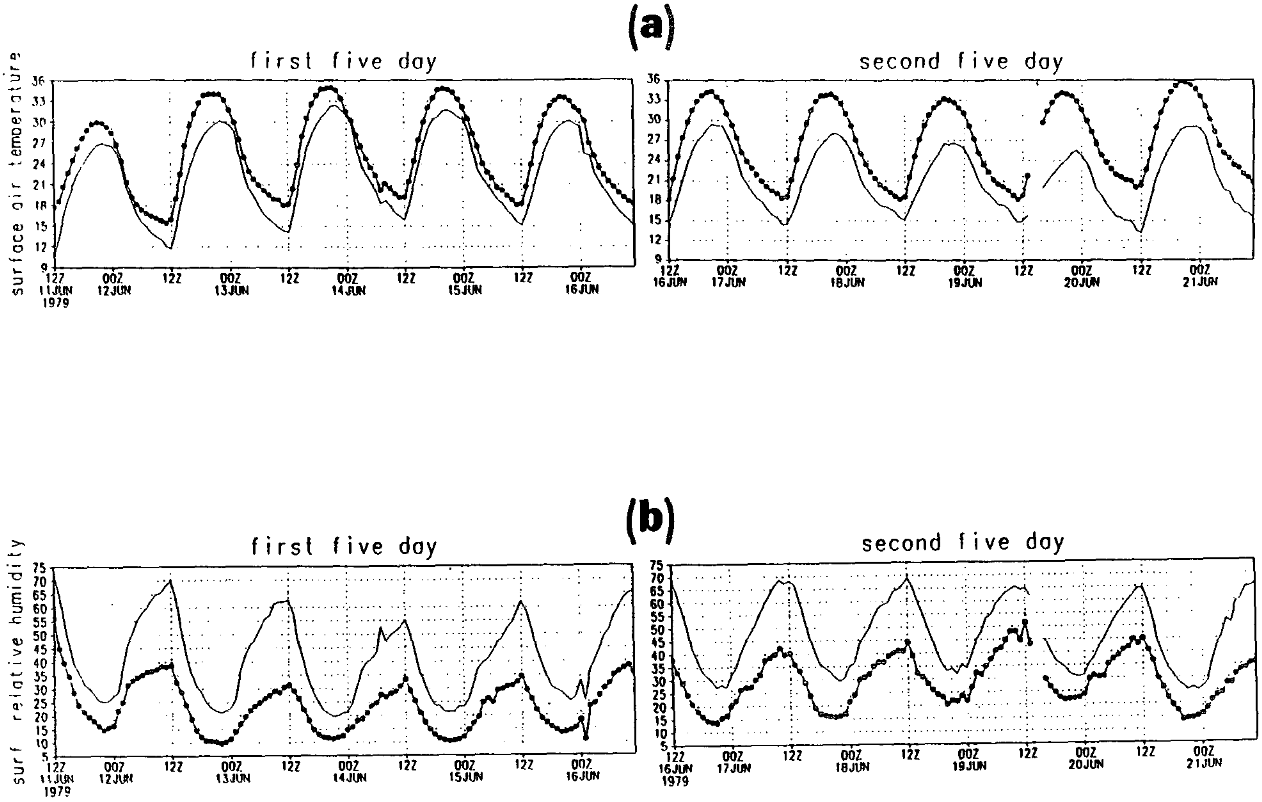

FIG. 3. The diurnal cycles of (a) surface air temperature (°C) and (b) surface relative humidity (%), averaged for all grid points in the dry area. The solid line is for observations, and the dotted line is for CON 1.

air temperature error and the mean surface specific humidity error.

We first compared the forecast specific humidity with observations. Figure 5 shows the ensemble 5-day mean specific humidity error from the three control runs. During the first five days (Fig. 5a), the specific humidities of the control runs are lower than the observations in the dry area with a maximum difference of 3.9 g kg^{-1} in northern Texas, whereas along the northern and eastern boundaries of the study area the specific humidities are somewhat higher than the observations. During the second five days (Fig. 5b), the forecast specific humidities are drier than the observations in the southern Great Plains and erroneously low specific humidities occur across the entire central part of the tested area. Thus, the control runs have erroneously low specific humidity over most of the previously discussed dry area. This specific humidity analysis is in agreement with a similar relative humidity analysis (not shown).

Similar to the previous regression equations, the multiple-regression equation for each vegetation type is derived from three control and three revised runs. For vegetation type 12, the equation is

$$\Delta \mathrm{ISW} = -0.055 + 0.06\Delta T - 0.024\Delta Q. \quad (3)$$

For vegetation type 7, the equation is

$$\Delta \mathrm{ISW} = -0.066 + 0.06\Delta T + 0.001\Delta Q. \quad (4)$$

Here, ΔQ is the forecast surface specific humidity error (forecast minus observation) of the control run. The multiple-regression equations are different from the simple regression equations in that the constant and the temperature error coefficient are both reduced in magnitude and the temperature error is now equally important for the two vegetation types. The coincident reduction in the magnitude of the constant and the temperature error coefficient is consistent with the constant being an artifact of the previously described regional cooling effect.

4. Impacts of the changes in initial soil wetness on surface weather forecasts

In this section, we will describe the improvement in the surface weather forecast as the result of revising ISW in both sensitivity tests and a forecast experiment. In the sensitivity tests, the ISW is revised based on the first 5-day surface air temperature forecast error—that is, correcting ISW a posteriori—and the same 10-day integration is then repeated with the revised ISW. In the forecast experiment, the ISW for a 10-day integra-

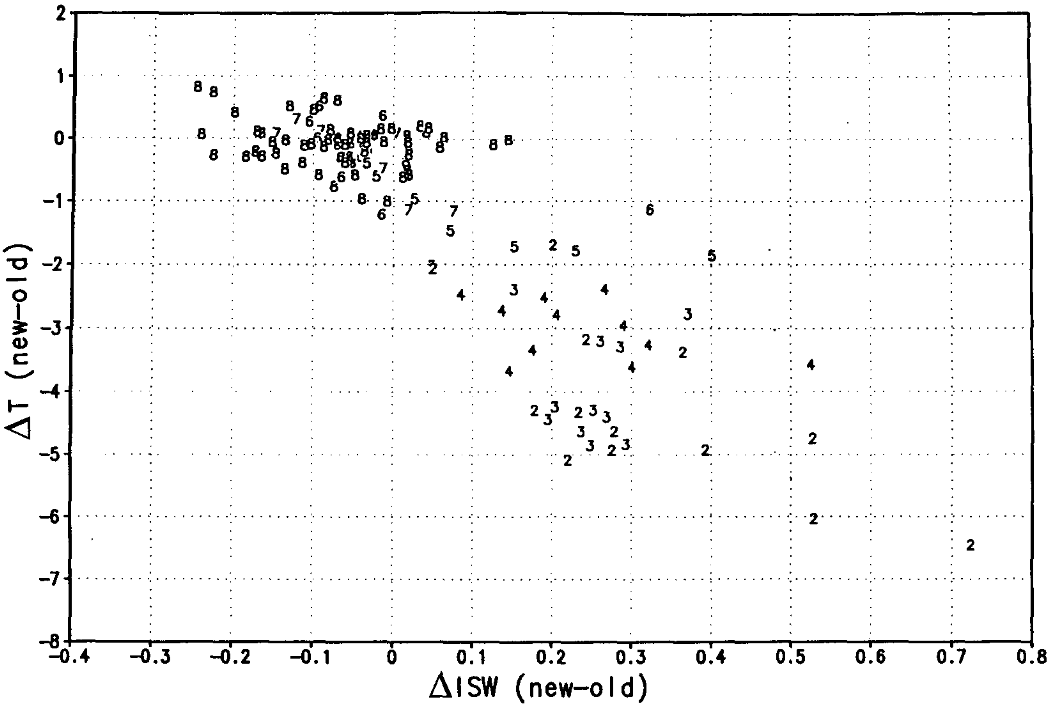

FIG. 4. The relation between the change of 5-day mean surface air temperature (ΔT, the vertical axis) and the change in ISW (ΔISW, the horizontal axis), new minus old, derived from the three pairs of GCM integrations for the grid points with vegetation type 12. Plotted are the ISW values used in the control runs multiplied by 10.

tion is revised a priori by correcting the 5-day surface forecast error of an integration over the previous 5 days.

a. A posteriori revision of the initial soil wetness

The simple regression equations (1) and (2) were used to revise the original ISW for three 10-day integrations from the same initial atmospheric states described earlier (hereafter REV 1, REV 2, and REV 3). The forecast surface air temperature was adjusted for the height difference between the model topography and mean elevation of the observation stations as described in section 2. Equation (1) was used for the grid points with vegetation types 12, 4 (needle-leaf evergreen trees), 2 (broadleaf deciduous trees), and 3 (broadleaf and needle-leaf trees). The equation for vegetation type 4 is close to the equation of vegetation type 12, and the equations for types 2 and 3 are not reliable due to small sample sizes. Equation (2) is used for the grid points with vegetation types 7 and 8 (broadleaf shrubs with ground cover), as the equations for these two vegetation types are approximately the same. A summary of some of the key morphological parameters for each vegetation type used in this study is given by Table 1. The morphological parameters of vegetation types 2, 3, 4, and 12 are similar, as are those of vegetation types 7 and 8. The vegetation distribution is shown in Fig. 6, where 42 of the 69 grid points are of vegetation type 12, and 14 of the 69 grid points are of vegetation types 7 and 8.

We have examined the three pairs of runs individually and found that the results are quite consistent. Therefore, we will present only the ensemble means of the three cases.

Figure 7 shows the difference in ensemble mean ISW between the revised and control runs, scaled by the standard deviation of soil wetness. (The standard deviation is based on hourly values for 10 days.) In most of the area where the control ISW was lower than 0.45 (shaded area), the ISW values were changed by more than one standard deviation. The mean ISW for all the points where the new ISW was increased (hereafter called the "dry" category) changed from 0.42 in the control to 0.58 in the revised runs. In the area where the ISW was decreased (hereafter called the "wet" category), the mean ISW changed from 0.67 in the control to 0.59 in the revised runs. The improvements in the surface air temperature and surface relative humidity forecasts made by the revised runs for the first 5-day mean are shown in Figs. 8 and 9, respectively.

The first 5-day mean surface air temperature forecast error of the control ensemble is shown in Fig. 8a; that of the revised ensemble is shown in Fig. 8b. The 5-day mean surface air temperature forecast of the control runs is consistently higher than the observations in the

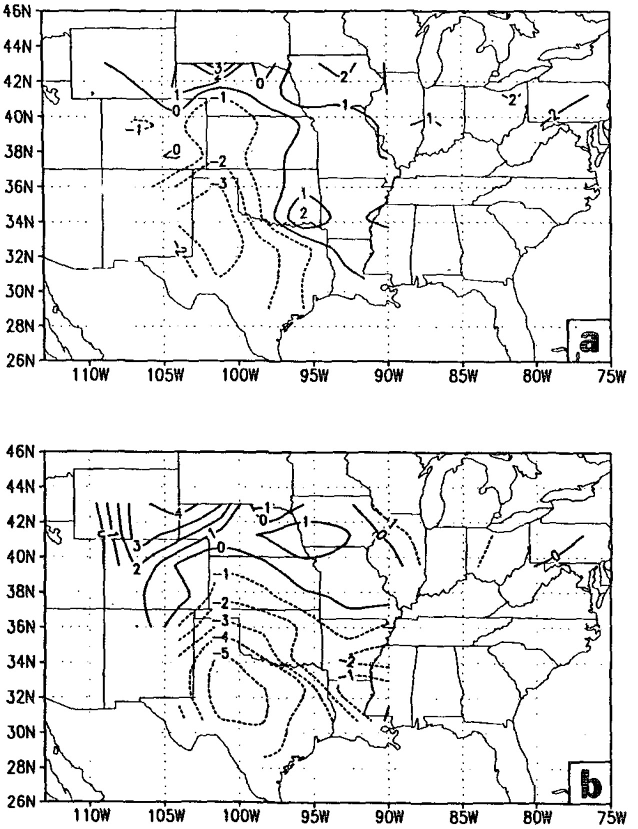

FIG. 5. The 5-day mean surface specific humidity forecast error of the ensemble control runs, forecast minus observation, for (a) the first five days and (b) the second five days. Contour interval is 1 g kg^{-1}.

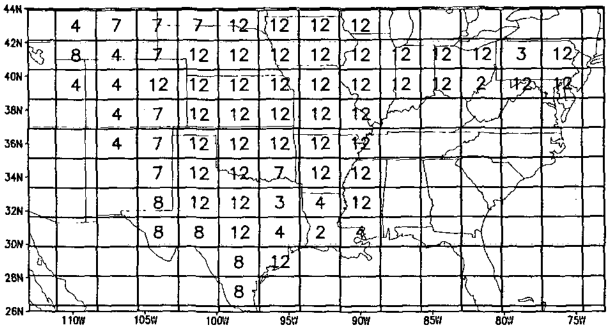

FIG. 6. The distribution of SiB vegetation types in the tested region.

region west of 95°W, especially in the western Great Plains, where the surface air temperature errors reach up to 5°C. In the revised runs the surface air temperature forecast improved remarkably in the western Great Plains, with surface air temperature errors in most of the region less than 1°C. However, the forecast surface air temperatures of the revised runs are somewhat lower than the observations. Improvements also occurred in the root-mean-square error (rmse) of the hourly forecast surface temperature (not shown). The rmse's of the control runs in the region west of 95°W range from 3° to 6°C, whereas in the revised runs, the range from 2° to 3°C. The mean surface air temperature differences between the revised and control runs in the eastern region (wet area) are generally less than 0.5°C.

Improvements in the surface relative humidity forecast are also exhibited by both 5-day means and rmse of surface relative humidity. The 5-day mean surface relative humidity forecasts of the control runs (Fig. 9a) are lower than those observed in the region west of 97°W, especially in the western Great Plains, where the errors are larger than 15%, with a maximum error of 30% in northern Texas. The absolute value of the surface relative humidity errors of the revised runs (Fig. 9b) are consistently lower than those of the control runs and are less than 10% in most of the western Great Plains. However, the revised forecast surface relative humidities are somewhat higher than those observed (as shown by positive values). The rmse's of the control runs (not shown) in the Great Plains are larger than 20% with a maximum of 30%, whereas the rmse's of the revised runs in this region are generally less than 20%. The differences between the control and revised runs in the wet area are negligible.

During the second five days, the improvements in the forecasts of mean surface air temperature (Fig. 10) and mean surface relative humidity (Fig. 11) made by the revised runs are still prominent in the western Great Plains, where the 5-day mean forecast errors of the revised runs are generally smaller than those of the control runs by about 2°–3°C for surface air temperature

TABLE 1. Key morphological parameters of vegetation types used.

Vegetation type	Classification	Height of canopy (m)	Surface roughness length (cm)	Vegetation cover (%)
2	broadleaf deciduous trees	20	83	75
3	broadleaf and needle-leaf trees	20	118	75
4	needle-leaf evergreen trees	17	88	75
7	ground cover	0.6	8	30
8	broadleaf shrubs with ground cover	0.5	6	52
12	broadleaf deciduous trees with winter wheat	20	31	90

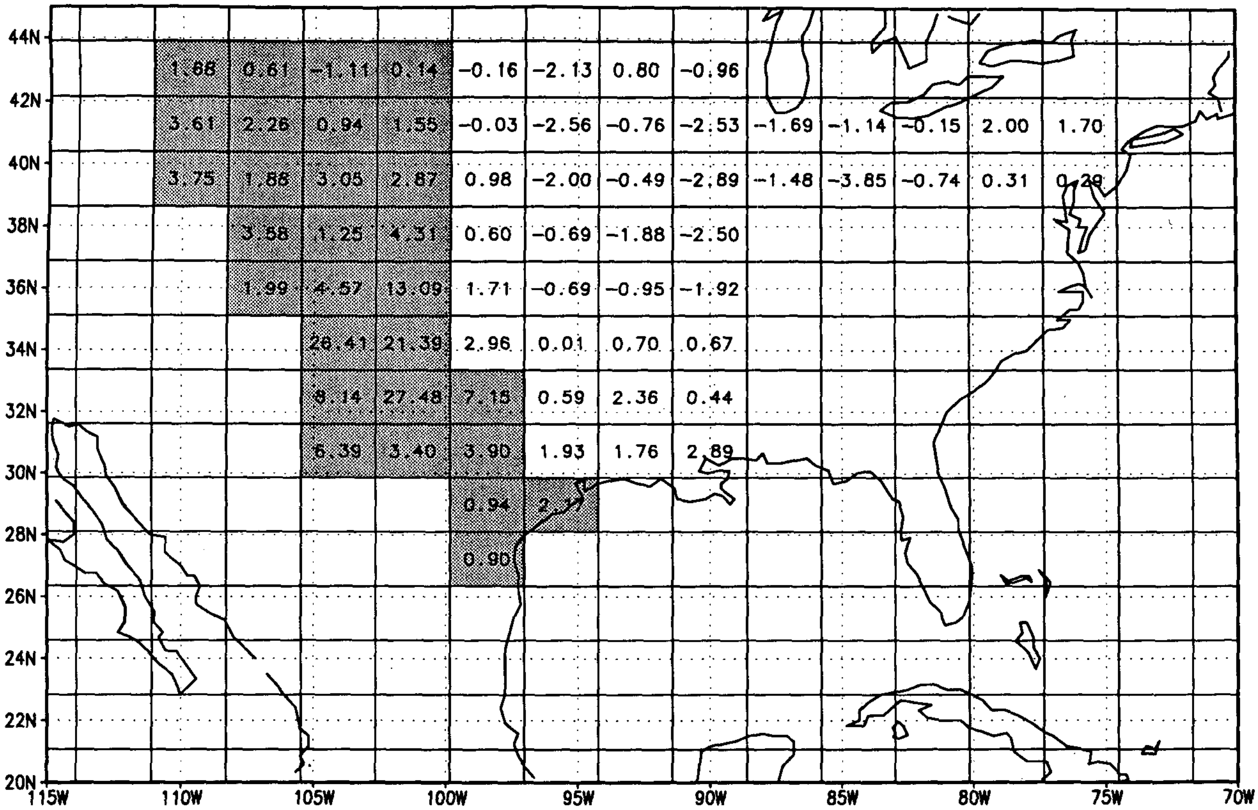

FIG. 7. The difference between the ensemble revised ISW and the control ISW. Units are in standard deviations of hourly values of soil wetness of the control runs. The shaded area denotes where the control ISW is less than 0.45.

and by 10%–20% for surface relative humidity. The improvements in the rmse (not shown) are smaller than those in the first five days.

Figures 12 and 13 depict the diurnal cycles of surface air temperature and surface relative humidity of the ensemble control and ensemble revised forecasts, and of the observations during the 10-day period. Each curve represents the quantity averaged over the grid points in the dry category. Throughout the 10 days, the forecast surface air temperature (Fig. 12) of the control runs (short dashed line) is consistently higher than observed (solid line). The revised runs (long dashed line) reduce the temperature errors and are close to the observations. The surface relative humidity forecasts of the control runs are too low and the revised ones are closer to observations (Fig. 13). It is noteworthy that both the daily maxima and minima were improved in the revised forecast.

The ensemble mean statistics for the dry category are listed in Table 2. The third (fifth) column of Table 2 contains the absolute value of the 5-day mean error of surface air temperature (surface relative humidity), and the fourth (sixth) column contains the corresponding rmse of surface air temperature (surface relative humidity). The last column contains the mean number of grid points in the dry category. These statistics are given for CON, REV, and the difference $R - C$ ("revised" minus "control"), which is negative for a forecast improvement. The improvement in the 5-day mean surface air temperature forecast is consistent with that of the hourly values (rmse), with greater improvement in the first 5-day mean. The mean error of surface air temperature of the revised runs is 1.1°C during the first five days, which is 1.8°C smaller than that of CON, and is 2.1°C during the second five days, which is 1.2°C smaller than that of CON. The improvement in surface relative humidity forecast persists throughout the 10-day period.

In the wet category (Table 2b) the differences between CON and REV are small, because the values of mean ISW of both runs are high, and the surface variables are not sensitive to the small variations of such high ISW values. However, the surface forecasts of the revised runs are slightly closer to the observations than the control. For both ensembles the 5-day mean errors of surface air temperature (surface relative humidity) are less than 0.7°C (8%) during the first five days and are less than 2.1°C (9.3%) during the second five days. The rmse values of both the control and revised ensembles are also consistently small.

The forecast precipitation is also changed in the revised runs. For the dry category, the first 5-day mean

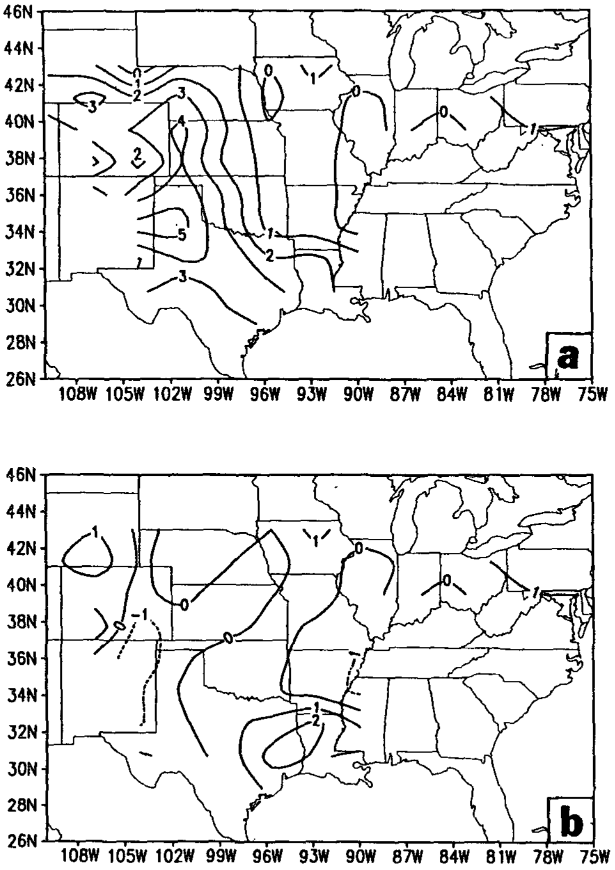

FIG. 8. The distribution of the first 5-day mean surface air temperature forecast error of (a) the three control runs and (b) the three revised runs. Contour interval is 1°C.

precipitation increased from 1.53 mm day^{-1} for CON to 2.26 mm day^{-1} for REV, comparable to the observed value of 2.53 mm day^{-1}. The second 5-day mean precipitation increased from 3.10 mm day^{-1} for CON to 3.61 mm day^{-1} for REV, both higher than the observed value of 2.8 mm day^{-1}. For the wet category the precipitation of both the CON and REV integrations was higher than the observations.

b. A priori revision of initial soil wetness

From the sensitivity tests it is apparent that the soil wetness is very persistent. Figure 14 shows the hourly mean soil wetness of the first two soil layers for two pairs of experiments (CON 2 and CON 3, REV 2 and REV 3) averaged for all grid points in the region. Over the 10-day period each curve varies by no more than 0.06. If the forecast error is related to an ISW error, it may persist for the following 5–10 days because the soil wetness error will persist. Therefore, *we can use the previous 5-day mean surface weather forecast error to revise the soil wetness at the end of the 5 days and take it as the ISW for the following 10-day integration.* With this kind of revised ISW, a series of 10-day forecast integrations was performed.

Two 5-day control runs are performed, one starting at 1200 UTC 6 June 1979, another at 0000 UTC 5 July 1983. Both the multiple-regression and simple regression equations were applied to adjust the soil wetness at the end of the five days based on correcting the previous 5-day mean surface air temperature and surface specific humidity errors. The revised runs with the ISW corrected based on the multiple-regression equations will be described because they generated better surface forecasts than the runs with ISW corrected with the simple regression equations.

Similar to the previous description, the results in the dry and wet categories will be described separately. Table 3 lists both the absolute value of the 5-day mean forecast error and the rmse of surface air temperature and surface relative humidity, which were averaged for the two revised runs and the two control runs for the 45 points in the dry category. Compared with the control runs, the mean ISW value of revised runs is increased from 0.46 to 0.61 (seventh column). As a result of this increase, the 5-day mean surface air tem-

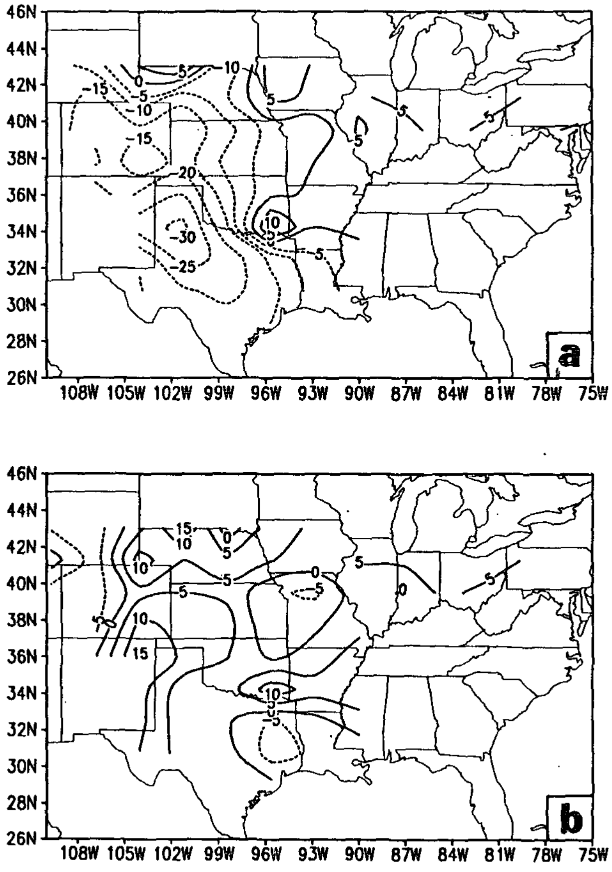

FIG. 9. The distribution of the first 5-day mean surface relative humidity forecast error of (a) the three control runs and (b) the three revised runs. Contour interval is 5%.

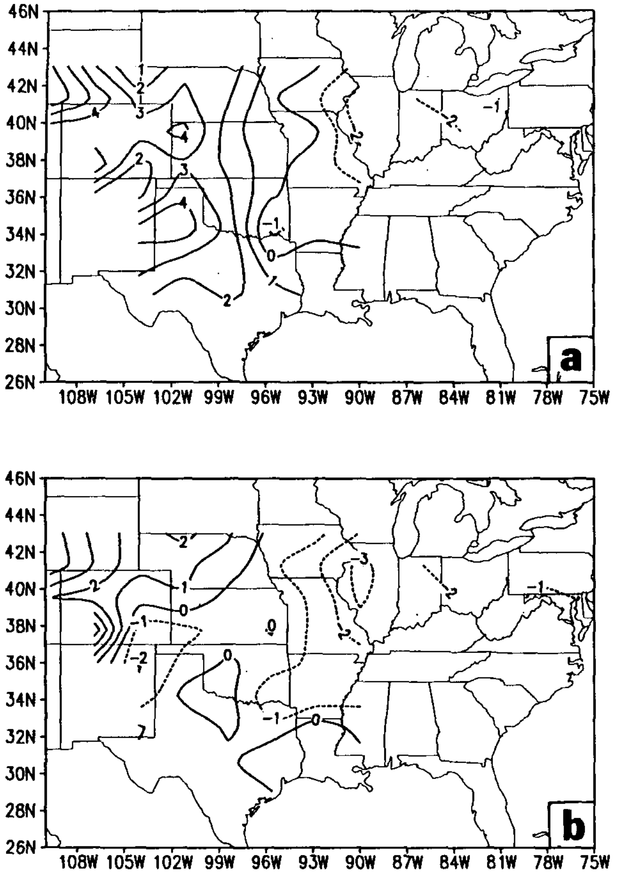

FIG. 10. The distribution of the second 5-day mean surface air temperature forecast error of (a) the three control runs and (b) the three revised runs. Contour interval is 1°C.

perature error is reduced by more than 1.2°C in the first 5 days, and by 0.8°C in the second 5 days; the 5-day mean surface relative humidity error is reduced by 6% in the first 5 days, and by 5% in the second 5 days. The improvement in the second 5-day mean surface air temperature depends on the individual case, large in 1979, small in 1983 (not shown).

The improvement mainly appeared in dry areas. Figure 15 shows the first 5-day mean forecast surface air temperature error of the ensemble control (Fig. 15a) and revised runs (Fig. 15b). Over the western region, the forecast temperature of the control runs is higher than the observations by more than 2°C. The forecast errors are larger than 3°C in eastern Colorado and northern Texas. The forecast surface air temperature errors of revised runs are generally smaller than 2°C except for a few grid points. The revised runs improved the forecast temperature in eastern Colorado and northern Texas considerably, the errors being within 1.5°C. The improvements persist for the second five days (not shown) but are smaller than in the first 5 days.

The surface relative humidity forecast is also improved. The first 5-day mean surface relative humidity of the control runs is consistently lower than the observations in the western half of the region, especially in Texas, where the forecast surface relative humidity is lower than the observation by more than 20% (Fig. 16a). The surface relative humidity of the revised runs is increased and the forecast error is generally smaller than 15% in the western half of the region (Fig. 16b). Compared with the control, the surface relative humidity forecast errors of the revised runs in Texas and Colorado are much smaller.

Over the eastern wet region, the differences between the results of the control and the revised runs are small throughout the 10 days.

The revised forecast runs using the simple regression equations (based on correcting surface temperature error only) also improved the surface air temperature forecast considerably, but only slightly improved the surface relative humidity (not shown). This is because the forecast surface relative humidities of the revised runs are consistently higher than the observations as the result of a large increase in ISW (from 0.55 in the control runs to 0.76 in the revised runs). The ISW revision method based on multiple regression is better

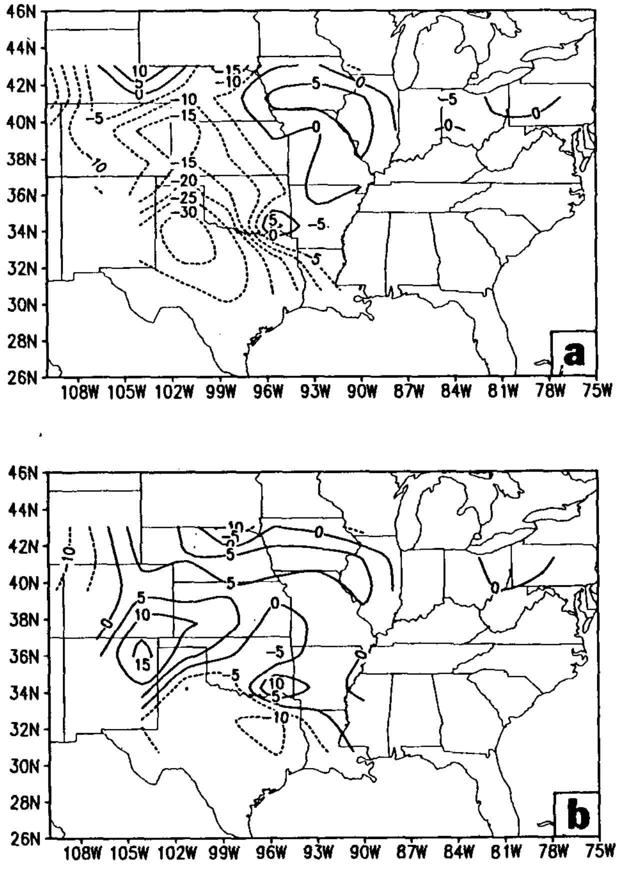

FIG. 11. The distribution of the second 5-day mean surface relative humidity forecast error of (a) the three control runs and (b) the three revised runs. Contour interval is 5%.

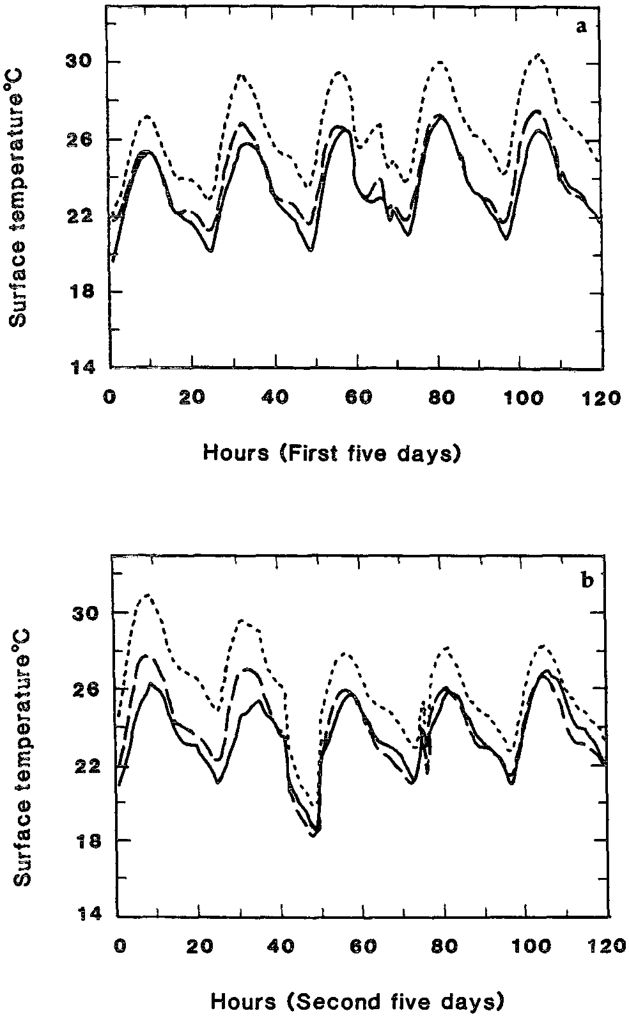

FIG. 12. The diurnal cycles of hourly mean surface air temperature (°C) among the observations (solid line), control forecast (short dashed line), and revised forecast (long dashed line) for (a) the first five days and (b) the second five days. The curves are averaged for all the grid points in the dry category.

than that based on simple regression because it considers two independent variables related to the local soil moisture. The simple regression equation method can result in the addition of too much moisture in dry areas because of the implicit assumption that erroneously high forecast surface temperature is entirely due to the dry soil.

As expected, the forecast errors of the revised runs here are consistently larger than the forecast errors of the sensitivity tests with ISW revised a posteriori as described in section 4a.

In summary, a moderate increase in ISW over a limited area has brought out a remarkable improvement in the forecasts of surface air temperature and surface relative humidity, especially during the first five days. The forecasts along the eastern slope of the Rocky Mountains and in Texas are greatly improved by increasing the soil moisture. The great sensitivity of the surface weather to soil moisture in the Great Plains found by this study was also found by Walsh et al. (1985) and McCorcle (1988).

5. Soil wetness impact on surface energy, surface hydrology, and the upper atmosphere

The results of the sensitivity experiments in which the ISW was revised a posteriori have been analyzed to determine the impact of the change in ISW on the surface energy and hydrology balances and on the upper atmosphere.

The surface sensible and latent heat fluxes are the quantities most sensitive to the change in ISW. The first 5-day mean surface latent heat flux of the revised runs

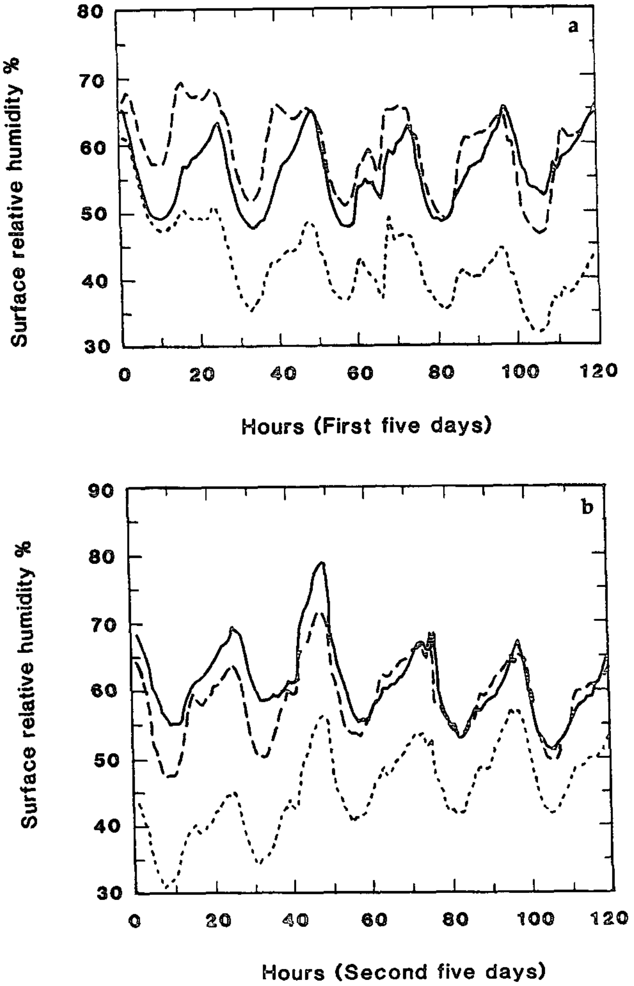

FIG. 13. The diurnal cycles of hourly mean surface relative humidity (%) among the observations (solid line), control forecast (short dashed line), and revised forecast (long dashed line) for (a) the first five days and (b) the second five days. The curves are averaged for all the grid points in the dry category.

TABLE 2. The ensemble statistics of surface air temperature and surface relative humidity errors of the three control and three revised runs for (a) the dry category and (b) the wet category, in the sensitivity test. AME denotes the absolute value of the 5-day mean error, and NUM denotes the mean number of grid points included.

		Temperature		Relative humidity		
		AME	rmse	AME	rmse	NUM
(a) Dry category						
1–5 days	CON	2.91	4.20	15.05	22.26	42
	REV	1.08	3.02	7.58	16.95	42
	$R - C$	−1.83	−1.18	−7.47	−5.31	
6–10 days	CON	3.23	5.23	18.55	26.71	42
	REV	2.08	4.08	10.29	19.21	42
	$R - C$	−1.15	−1.15	−8.26	−7.50	
(b) Wet category						
1–5 days	CON	0.63	2.77	7.45	15.57	27
	REV	0.59	2.72	6.72	15.04	27
	$R - C$	−0.04	−0.05	−0.73	−0.53	
6–10 days	CON	2.09	3.94	9.24	17.41	27
	REV	2.00	4.00	7.90	16.82	27
	$R - C$	−0.09	0.06	−1.34	−0.59	

is increased by 88% and the surface sensible heat flux is decreased by 45%, averaged for points in the dry category. During the second five days, the differences between the control and revised runs are somewhat smaller than those during the first five days, implying a weakening of the influence of the ISW change. Nevertheless, the ensemble means of latent and sensible heat fluxes are still changed by 62% and −35%, respectively.

In the wet category, for which the ISW was decreased slightly, the changes of the latent heat and sensible heat fluxes are of opposite signs of those in the dry category and are of small magnitude.

The changes in evaporation are strongly spatially correlated with the changes in the soil wetness. The area with a 1.5–2.0 mm day^{-1} increase in evaporation (not shown) very closely corresponds to the previously discussed dry area (shaded area in Fig. 7). Whereas the changes in precipitation are not as strongly correlated with the changes in soil wetness, particularly during the second five days. During the first five days, a region with largely increased precipitation (>1 mm day^{-1}) occurs in the midwestern Great Plains, where the evaporation was increased during the same period. For the second 5-day mean the region with increased precipitation is to the northeast of the region with the largest increase in evaporation.

Averaged over all the points in the dry category, the ensemble mean ISW is increased by 0.16 in the revised runs. The ensemble mean evaporation is increased by about 2 mm day^{-1} during the first five days and by 1.5 mm day^{-1} during the second five days. The ensemble mean precipitation is increased by about 0.65 mm day^{-1} during the first five days and by 0.4 mm day^{-1} during the second five days. Thus, about 30% of the moisture supplied to the atmosphere by increased evaporation contributes to increased precipitation.

In the wet category, the overall mean evaporation rate is decreased by a small amount (0.3 mm day^{-1}) due to a decrease of 0.08 in soil wetness. The mean precipitation in the WET category is increased even though the local evaporation is decreased, because of increased moisture flux convergence into the wet category region.

The precipitation of both the control and revised runs was mainly composed of convective precipitation, and the increased precipitation of the revised runs is due to enhanced convection.

The impact of the change in ISW on the upper atmosphere is small and is mainly confined to the dry area and to the lower atmosphere (up to 700 mb). Above 500 mb the differences between the control and revised runs are no more than 0.5°C for temperature and no more than 10% for relative humidity. The influence is somewhat enhanced in both spatial scale and vertical scale during the second five days compared to the first five days.

6. Summary and discussion

The relationship between the changes in the first 5-day mean surface air temperature and the changes in ISW depends upon vegetation type and the value of the ISW and can be approximated by linear-regression equations. These equations were applied to revise the ISW at 69 United States grid points for three 10-day numerical integrations. With the revised ISW, the first 5-day mean temperature forecast error is reduced by 1.8°C and the surface relative humidity forecast error is reduced by 7.4%, for the grid points in the dry cat-

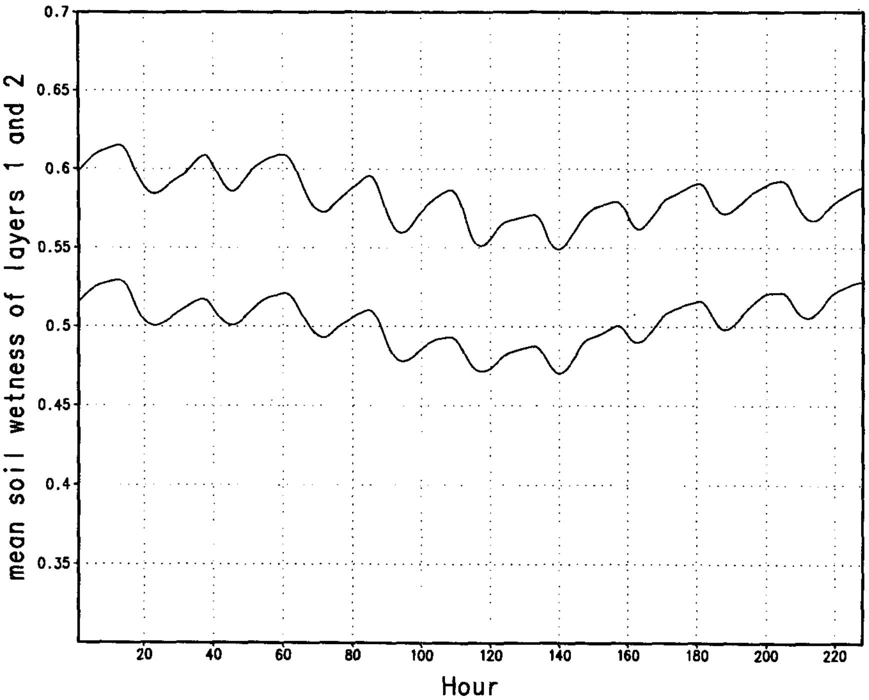

FIG. 14. The hourly mean soil wetness of the first two model soil layers for CON 2 and CON 3, REV 2 and REV 3 averaged for all grid points in the region. The top line is for the revised run and the bottom line is for the control run.

egory. These improvements persist for another five days but are smaller than in the first five days. The hourly forecast of the revised runs is also improved, especially in the first five days.

For the wet category, the differences in surface temperature and humidity between the control and revised runs are small because the values of ISW are outside the band of high model sensitivity.

Because of the strong persistence of soil wetness, we applied the ISW revision methods to forecast experiments. In addition to simple regression equations, multiple-regression equations, which include the 5-day mean specific humidity forecast error as another predictor, were derived and applied to correct the soil wetness at the end of the 5-day integration. Results for the subsequent 10-day forecast show that the surface air temperature and surface relative humidity forecast errors of the revised runs are reduced by 1.2°C and 6%, respectively, averaged for the dry category during the first five days. Somewhat smaller improvements occurred during the second five days.

The influence of variations of ISW on surface energy components and hydrological components is large when the variations are in the model soil wetness sensitivity band, ranging from 0.3 to 0.6. As expected, an increase in ISW causes an increase of surface latent heat flux and a decrease of surface sensible heat flux. Changes in downward longwave radiation and short-

TABLE 3. Ensemble statistics of the absolute 5-day mean error and the root-mean-square error of surface air temperature and surface relative humidity for the dry category in the forecast experiment. Also listed are the values of ISW and the number of points included.

		Temperature		Relative humidity			
		AME	rmse	AME	rmse	ISW	NUM
1–5 days	CON	2.44	3.72	14.67	21.08	0.46	45
	REV	1.15	2.96	8.54	16.83	0.61	45
	R − *C*	−1.29	−0.76	−6.13	−4.25	0.15	
6–10 days	CON	3.02	5.18	15.35	24.63	0.46	45
	REV	2.21	4.26	10.20	19.16	0.61	45
	R − *C*	−0.81	−0.92	−5.15	−5.47	0.15	

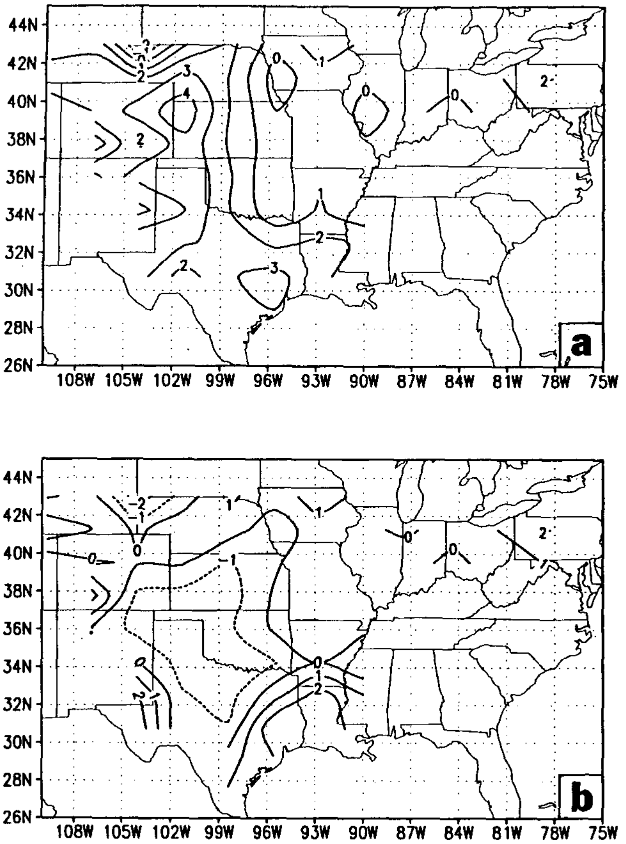

FIG. 15. The first 5-day mean surface air temperature errors of (a) the two control runs and (b) the two revised runs, used in the a priori forecast experiment. Contour interval is 1°C.

wave radiation are negligible, because the radiatively interactive clouds are prescribed.

Almost all the increased precipitation simulated in the revised runs is convective precipitation. The increased precipitation is due to increases in both the frequency and magnitude of precipitation events. This implies that two mechanisms are involved: one is to induce moist static instability of the atmospheric column by entraining moist air at low levels; the other is to simply supply more moisture available for precipitation. This agrees with the arguments proposed by Mintz (1984), who found a positive impact of evaporation on precipitation in the eastern and central United States.

Because the change in ISW is of small spatial scale and small magnitude, its influence is mainly confined to low levels over the dry area. The fact that the circulation field does not change much denotes that the large-scale synoptic systems and dynamic processes between the revised and control runs are quite similar.

The improvements in the surface forecast depend on the model surface forecast systematic errors. Thus, the coefficients of the regression equation used to correct the ISW are dependent on the model used, as well as on the region and season for which the equation was derived. To be correctable by these methods the surface forecast errors must be mutually consistent with the possible soil wetness error, such as too high temperature and too low relative humidity. In the ISW revision methods an assumption is made that the surface air temperature and surface relative humidity forecast errors are due solely to the error in ISW. Actually, other possible sources of model errors, such as errors in advection or surface radiative flux, account for a portion of the surface forecast errors. This is perhaps why the ISW revision method tended to slightly overcompensate for the original surface forecast errors.

This study suggests the important role of accurate ISW for medium-range surface forecasts. However, obtaining a good global soil wetness field is a challenging task. The methods used here could be refined over a limited region for which observed soil wetness data is available. The surface forecast errors of any GCM over a given region can be analyzed, to see if the model surface forecast errors are related to the model soil wetness errors. Based on this analysis, a revised method could be developed to produce a suitable ISW field for the regional medium-range forecast. If successful, this method could then be applied to produce a global soil

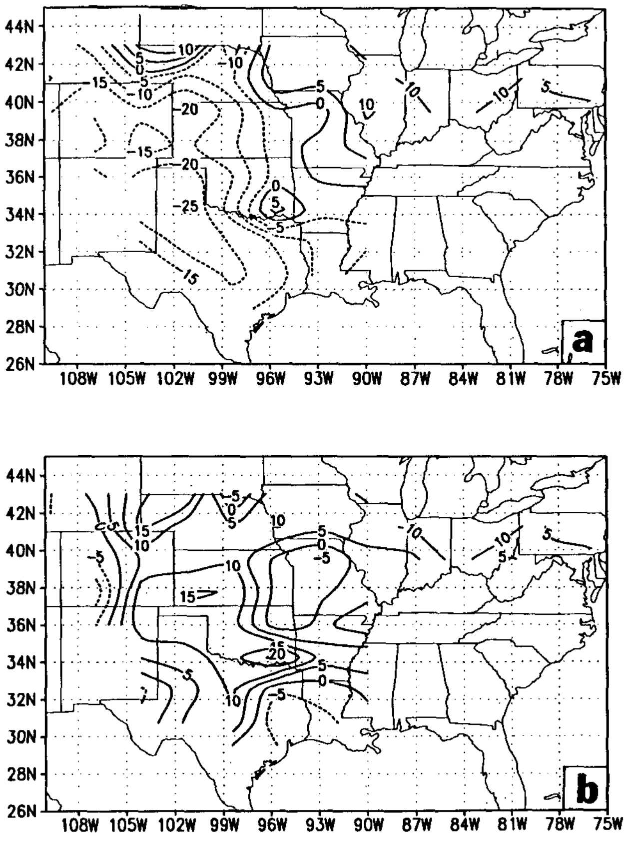

FIG. 16. The first 5-day mean surface relative humidity errors of (a) the two control runs and (b) the two revised runs, used in the a priori forecast experiment. Contour interval is 5%.

wetness field based on the global surface forecast errors.

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