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Soil moisture simulations in revised AMIP models

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Abstract. Soil moisture is important both in its influence on climate and for assessing impacts of future climate change. It is therefore necessary to simulate it correctly in global climate models. We have used the revisit simulations contributed by six of the Atmospheric Model Intercomparison Project 1 participating modeling groups to examine the impacts of model revisions, particularly the land surface representations, on soil moisture simulations, by comparing the simulations to actual soil moisture observations. The revised models do not show any systematic improvement in their ability to simulate observed seasonal variations of soil moisture over the regions studied. Many of the revised models continue to have a strong tendency toward dry soil conditions during Northern Hemisphere summer months, both globally and regionally. There are no indications of conceptually more realistic land surface representations producing better soil moisture simulations in the revised climate models. As the revised models continue to produce incorrect simulations of the seasonal cycle of regional precipitation, it is not possible to isolate the effect of land surface schemes on the simulations. The European Centre for Medium Range Weather Forecasts and National Centers for Environmental Prediction/National Center for Atmospheric Research reanalyses, however, which are driven by observed precipitation, do capture some of the observed interannual variability of soil moisture over Illinois.

1. Introduction

Soil moisture variations can significantly influence climate by modulating the fluxes at the lower boundary of the atmosphere. *Charney et al.* [1977] and *Walker and Rowntree* [1977] provided pioneering demonstrations of the impact of land surface changes on simulated climate. Since then a number of studies related to land surface and climate, using general circulation models (GCMs), have been carried out. GCM experiments have illustrated the influence of land surface processes on the variability of precipitation over land [*Koster and Suarez,* 1995], the possible role of soil moisture feedback on the Asian monsoon [*Yang and Lau,* 1998; *Shen et al.,* 1998], and the potential for seasonal prediction of temperature using soil moisture anomalies [*Huang et al.,* 1996]. Future changes in soil moisture are considered important for assessing the impacts of climate change on vegetation, and GCMs are the principal tools being used to make these projections. In view of the importance of soil moisture simulations made by GCMs, it is necessary to evaluate and improve them. Simpler land-surface parameterization schemes are being replaced by conceptually realistic treatments [e.g., *Mahfouf et al.,* 1995; *Pitman and Desborough,* 1996; *Govindaswamy,* 1999]. Improvements gained by such changes are, however, not very apparent [*Robock et al.,* 1995, 1998]. *Gates et al.* [1996] while summarizing an evaluation of GCMs for the Intergovernmental Panel on Climate Change state that "Clouds, the hydrological cycle, and the treatment of the land surface remain the largest areas of uncertainty in climate models, and are generally the cause of the largest inter-model differences in both control and sensitivity experiments." Coordinated efforts such as the Atmospheric Model Intercomparison Project (AMIP) [*Gates,* 1992; *Gates et al.,* 1999], the Project for Intercomparison of Land-surface Parameterization Schemes (PILPS) [*Henderson-Sellers et al.,* 1993, 1995, 1996], and the Global Energy and Water Cycle Experiment Global Soil Wetness Project (GEWEX GSWP) [*Koike et al.,* 1999; *Dirmeyer et al.,* 1999] for intercomparing models are important steps toward resolving these issues.

The AMIP project, which is the context for this study, focuses primarily on intercomparison of atmospheric GCM simulations forced by observed sea surface temperatures (SSTs) for the 10 year period, 1979-1988. Following the AMIP 1 original simulations, some of the modeling groups contributed revised runs during 1995, which included several modifications. The significant changes incorporated in the revised simulations, or "revisits," considered in this study are listed in Table 1 (compiled on the basis of details given by *Phillips* [1994] and the AMIP web site at http://www-pcmdi.llnl.gov/amip/). *Sperber et al.* [1999], examining the same revisits as studied in this paper, found improvement in the revised model simulations of rainfall variability (March-May average) over the Nordeste (Northeast Brazil)

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Table 1. Changes Made in the Revised AMIP Runs Compared to the Originals

Model	Atmosphere	Land Surface
BMRC R31L9	original	bucket hydrology, two-layer thermal, with prescribed deep temperature
BMRCa R31L17	vertical resolution, clouds, convection, diffusion	bucket hydrology, three-layer thermal with no flux at the bottom, mosaic vegetation for roughness, albedo, fractional snow
CNRM T42L30	original EMERAUDE	two-layer force-restore, with prescribed deep temperature
CNRMa T42L30 ARPEGE cy11	numerics (especially the horizontal representation), horizontal diffusion, gravity-wave drag, cloud formation	ISBA, vegetation affects canopy interception, stomatal resistance, turbulence, rooting depth
DERF T42L18	original	bucket, force-restore
DERFa T42L18	smoothed orography, cloud formation	three-layer model with deep moisture prescribed from *Mintz and Serafini* [1992]
DNM 4°x5° L7	original	bucket, prescribed deep temperature and moisture
DNMa 4°x5° L7	time integration, horizontal diffusion, penetrative convection	bucket but with vegetation canopy storage; runoff is partitioned into surface and deep components
LMD 3.6°x5.6° L11	original	bucket, one-layer temperature
LMDa 3.6°x5.6° L11	diurnal cycle, precipitation, cloud formation and optical properties	SECHIBA, vegetation canopy, seasonal vegetation depends on temperature, two-layer moisture, seven-layer temperature
LMDb 3.6°x 5.6° L11	same as LMDa	same as LMDa but soil hydrology simulated with one layer
YONU 4°x5° L5	original	bucket
YONUa 4°x5° L7	vertical resolution	bucket

region, but the same was not apparent for Indian rainfall (June-September) or Sahel rainfall (July-September). They also found that revised models that were better able to simulate the observed mean state were also better at simulating interannual variability.

Many of the revised models included revisions in their land-surface representations (Table 1), which presents an opportunity to examine their impact on simulations. In an earlier study, soil moisture simulations from 30 GCMs participating in AMIP 1 were compared with each other and with observations by *Robock et al.* [1998]. In this study we aim to intercompare the revised simulations of soil moisture with their original runs and observations to bring out the influence of modifications pertaining to the land-surface. Although it is difficult to isolate the impact of changes in land surface schemes (LSSs), because they were not the only modifications made in the revised simulations (except in LMDb), our study shows that some general conclusions are possible.

Observed soil moisture data sets used for the study and the subset of model simulations used are described in section 2. Influences of model revision on global soil moisture simulations are then presented. The following section describes the comparison of original and revised model simulations with observations of soil moisture over specified regions.

2. Data Sets

2.1. Observations

Observed soil moisture data sets from China, the former Soviet Union (FSU) and Illinois, United States, available from the Global Soil Moisture Data Bank (http://climate.envsci.rutgers.edu/soil_moisture) were used for this study. *Vinnikov and Yeserkepova* [1991], *Hollinger and Isard* [1994], *Entin et al.* [1999], and *Robock et al.* [2000] describe these data sets in detail. We have used the monthly average top 1 m plant-available soil moisture, which is based on three observations taken each month at 10 day intervals. The Chinese data set consists of 43 stations in China, for the period 1981-1991. Ten different stations in the central China region (30°-40°N, 105°-120°E) showed remarkable similarity in their seasonal variation, implying that large spatial scale variation of soil moisture is controlled by large-scale atmospheric forcings. Observations from stations in Northeastern China and Mongolia show lesser similarity in their seasonal cycles, which may be attributable to several reasons, including the mountainous terrain as pointed out by *Entin et al.* [2000] for Mongolia. Coherence in seasonality exhibited by the central China stations led to the choice of this region to make comparisons with model simulations. Observations from stations in the FSU and Illinois have been analyzed and found to be homogenous, and their area averages have been used in an earlier evaluation of AMIP 1 soil moisture simulations [*Robock et al.*, 1998].

In addition to the comparison of seasonal cycles, we also compared the interannual variation for the Illinois region. This region is adequately represented by 18 stations where the observations were made in grassland plots [*Hollinger and Isard*, 1994]. For this region observations were optimally averaged over space using the technique of *Kagan* [1979] to obtain representative values for the region to compare with model simulations.

2.2. Model simulations

The AMIP archive at the Lawrence Livermore National Laboratory was the source for the simulated data sets of AMIP 1 original and revised runs contributed by some modeling groups. Soil moisture fields produced by different GCMs are not always comparable. This is because the various LSSs employ different

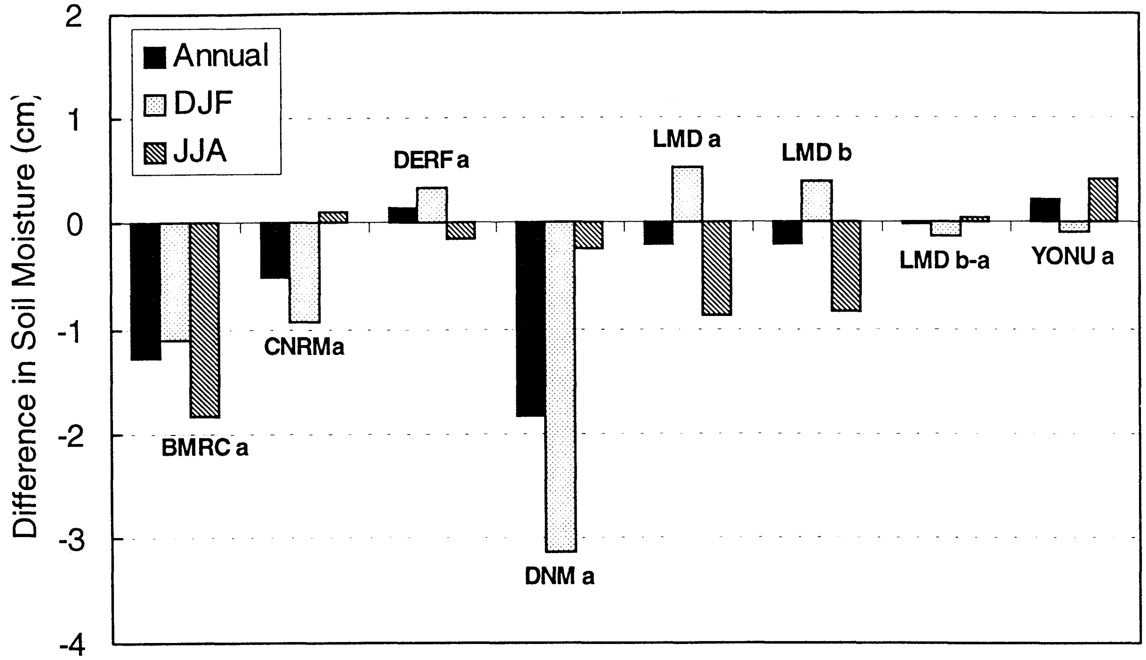

Figure 1. Difference in globally averaged soil moisture (revised minus original model simulations) over the 1980-1988 period for annual, winter (DJF), and summer (JJA) periods.

soil column characteristics resulting in slightly varying definitions for soil moisture. LSSs using explicit vegetation or spatially varying soil characteristics have different soil column depths. It was therefore necessary to convert simulated soil moisture to an equivalent quantity (plant-available soil moisture in the top 1 m) to enable intercomparisons and to compare with observations. Not all of the revised model simulations could be used for reasons including availability of sufficient information to make such conversions and problems with archived data.

We have not used the whole 10 year AMIP period because many of the models have spin-up-related problems during the initial months of their simulations [*Srinivasan et al.*, 1995; *Robock et al.*, 1998]. The first-year simulations are discarded from our analysis and we use only the 1980-1988 period. The time periods of data availability for model simulations and observation do not correspond exactly. In the case of China and Illinois the observed data used are for the period 1981-1988 and overlap well with the simulated period. For the FSU, however, the observed data are only available for the period 1979-1985.

3. Mean Soil Moisture Fields

Figure 1 shows the differences in globally averaged soil moisture fields for annual, Northern Hemisphere (NH) winter (DJF) and summer (JJA) periods between the revised simulations and the original runs. Hereinafter, the summer and winter periods pertain to the NH and refer to JJA and DJF averages. Revisions made in the BMRCa, CNRMa, and DNMa runs result in mean soil moisture simulations that are drier than their respective original simulations. In BMRCa the revisions produced summer and winter drying, but CNRMa and DNMa show drying mainly in winter. In BMRCa and DNMa, revisions were made in their bucket hydrology scheme to represent vegetation, and in CNRMa an improved LSS was introduced with explicit treatment of vegetation using the Interactions between Soil-Biosphere-Atmosphere (ISBA) scheme of *Noilhan and Planton* [1989] and *Mahfouf et al.* [1995]. For DNMa the LSS revision also included partitioning of runoff into faster surface and slower deep-soil components. Compared to BMRCa and DNMa, the other model revisions show relatively smaller changes in simulated global mean soil moisture. Winter simulations of DERFa are slightly wetter and summer simulations are drier with respect to the original. This pattern is perhaps linked to the revision made in the LSS to prescribe deep soil moisture from the *Mintz and Serafini* [1992] climatology. Studies by *Chen and Mitchell* [1999] and *Roads et al.* [1999] have shown that relaxation to this climatology produced wetter winter and drier summer conditions in simulations. YONUa revised run soil moisture simulations are higher during summer and slightly lower during winter as compared to the original runs.

LMDa and LMDb revised simulations are important because other than the changes from the original model common to both, they differ only in the hydrological component of the LSSs. Both of the models are wetter during winter and drier during summer as compared to the original simulation (Figure 2), but these differences are not statistically significant. LMDa and LMDb soil moisture simulations show very little difference (Figure 2). Changes in precipitation rates associated with the change in LSS are, however, noticeable, with LMDb producing higher continental precipitation rates (+0.4 mm d^{-1}), especially during the summer period.

4. Comparison of Observations and Simulations

Soil moisture simulations from revised and their respective original runs were compared with observations from three different regions, central China, Illinois, and the FSU. Area-averaged model simulations for the central China region (30°-40°N, 105°-120°E) were compared with observations averaged for the 10 stations in the region. The seasonal cycle of observed soil moisture shows a minimum around the May-June period and maximum around December-January (Figure 3). None of the original model simulations or their revisions (Figure 3) reproduce the observed seasonal cycle. We have also included the National

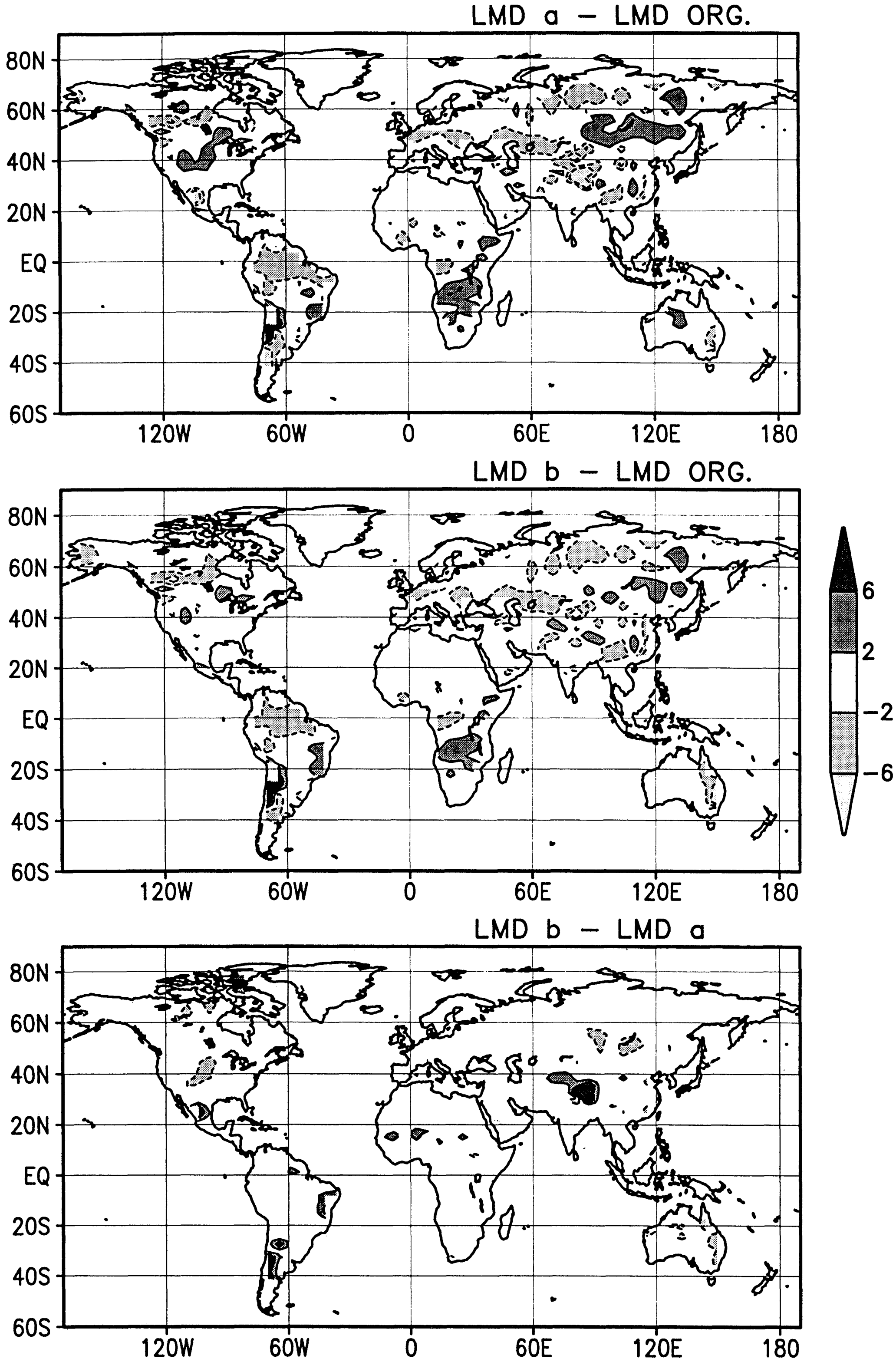

Figure 2. Difference in simulated plant-available soil moisture (centimeters) in the top 1 m averaged for 1980-1988 period among the three LMD runs.

Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) [*Kalnay et al.*, 1996] and European Centre for Medium Range Weather Forecasts (ECMWF) (ERA-15) [*Gibson et al.*, 1997] reanalyses, and the commonly used *Mintz and Serafini* [1992] climatology, which are all also model results but forced with observed precipitation and meteorology. The NCEP/NCAR reanalysis soil moisture is nudged to the Mintz and Serafini data to correct for model drift, and the ERA-15 reanalysis is nudged to compensate for surface relative humidity drift. This essentially makes up for errors in

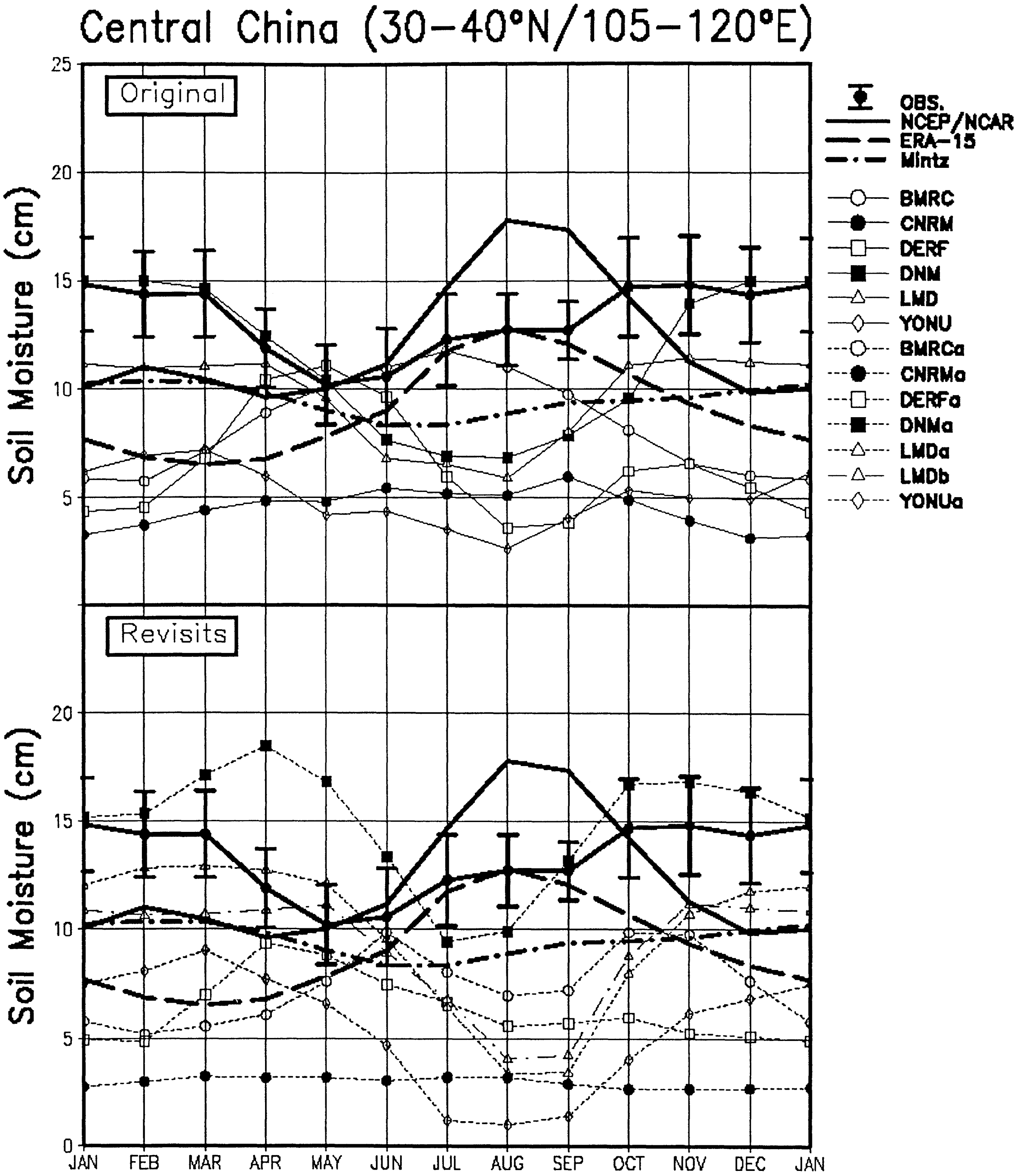

Figure 3. Observed seasonal cycle of soil moisture over the central China region (based on 1981-1988 averages) compared to original and revisit simulations (based on 1980-1988 averages). Error bars on observations are the standard deviation of the values of the 10 individual stations about the mean for the region.

model-generated precipitation, which in general was found to be too small [*Betts et al.*, 1998a, 1998b]. The reanalyses are also unable to completely capture the observed seasonal cycle (Figure 3). Although the Mintz and Serafini climatology captures some of the phase of the observed variations, it does not reproduce the amplitude and is comparatively dry. The NCEP/NCAR reanalysis, although nudged to *Mintz and Serafini* [1992], is substantially wetter in the summer, which must be due to large precipitation forcing (shown later in Figure 5). ERA-15 captures the observed phase of the annual cycle but is too dry in winter and fall. The FSU and Illinois regions gave similar results (not shown here). In an earlier study, *Robock et al.* [1998] used the same regions in the FSU and Illinois to compare soil moisture simulations from 30 AMIP models and found that the models could not reproduce the observed seasonal cycles. While this status remains unchanged, our results from the present study show that some of the revised runs actually become drier in the summer as compared to their original runs, thus exacerbating the problem of excessive midlatitude summer soil dryness.

The ideal spatial and temporal coverage of the Illinois data set enables comparison of interannual and seasonal variations during the overlapping 1981-1988 period when both observations and

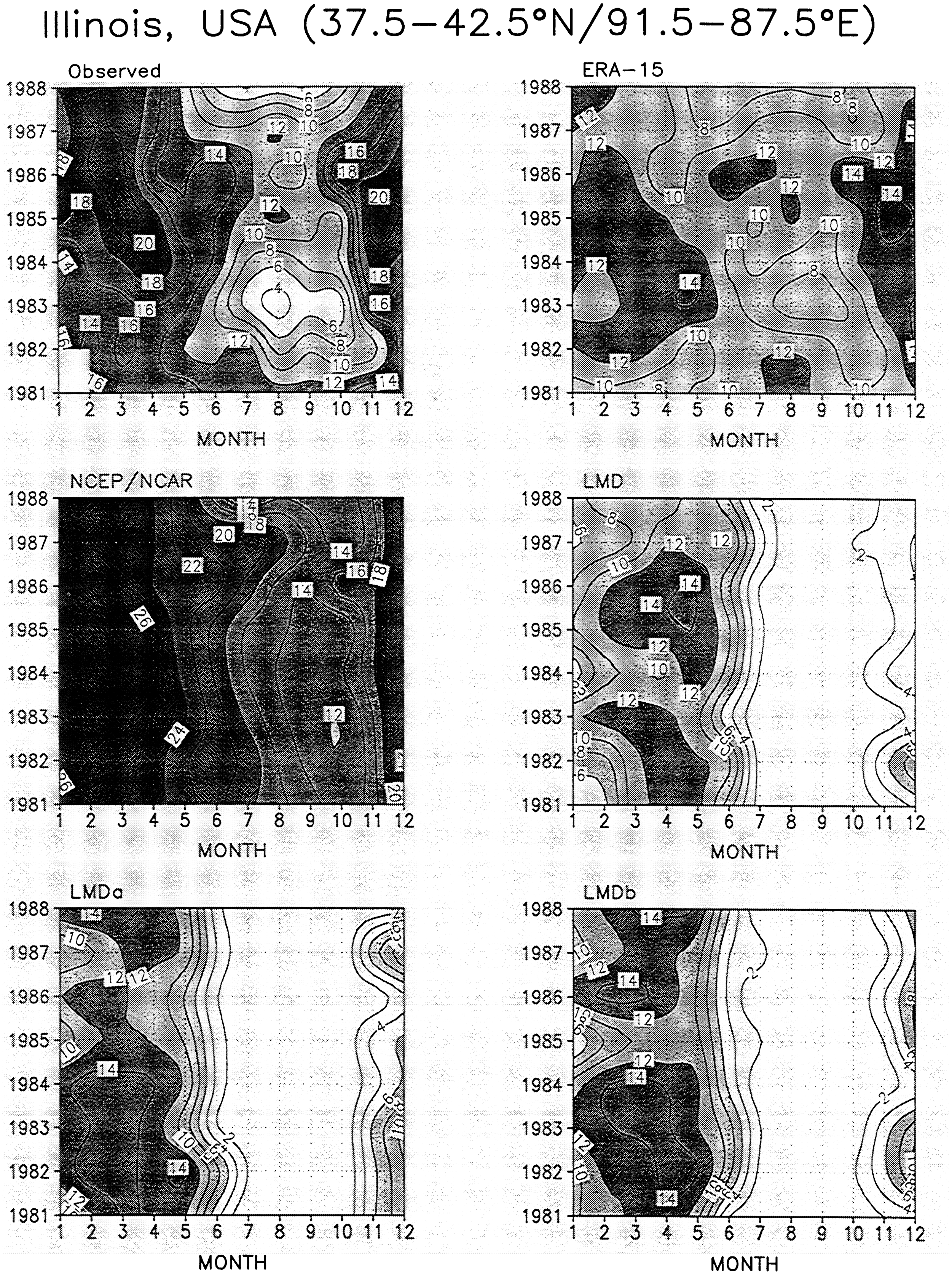

Figure 4. Year-month plot of observed and simulated plant-available soil moisture (centimeters) in the top 1 m over Illinois, United States (averaged over the region 37.5°-42.5°N, 87.5°-91.5°E), for the period 1981-1988.

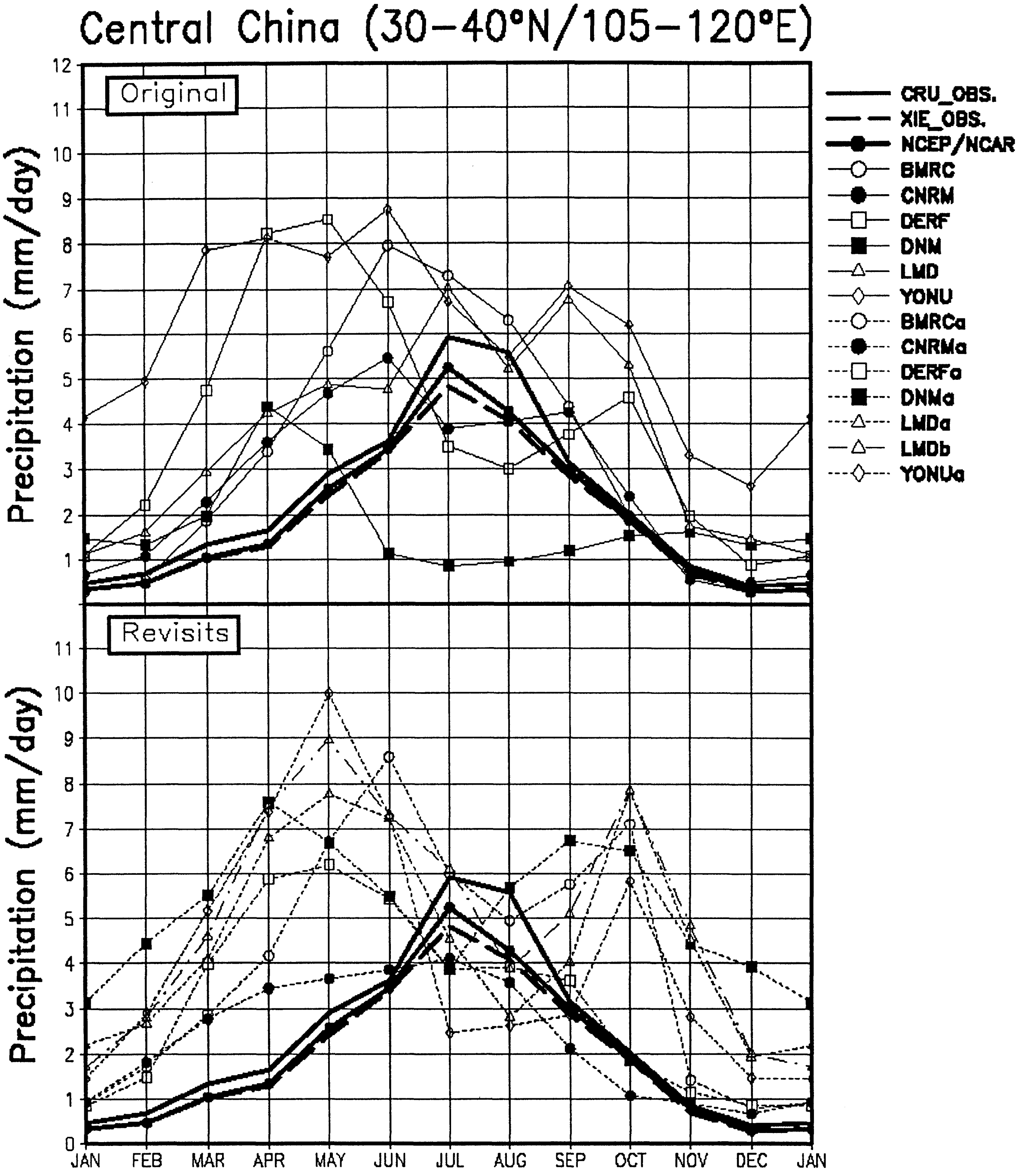

Figure 5. Observed seasonal cycle of precipitation over the central China region compared to original and revisit simulations based on averages for the period 1980-1988. Also shown are the NCEP/NCAR reanalysis [*Kalnay et al.*, 1996], and observations from *Xie and Arkin* [1997] and *Hulme* [1994], labeled NCEP/NCAR, XIE_OBS, and CRU_OBS, respectively.

model simulations are available (Figure 4). The observations clearly show the summer dryness associated with the droughts in 1983 and 1988 in the region and the wet years of 1986 and 1987. The ERA-15 reanalysis shows the correct interannual variability, although not so pronounced as observed, in agreement with findings for the entire United States [*Viterbo and Betts*, 1999]. The NCEP/NCAR reanalysis is too wet overall and has too little interannual variability but also shows the correct relatively wet and dry years. The LMD model is a typical case to illustrate the problem of excessive summer dryness produced by the GCMs. LMDa, where the revisions included a more realistic LSS, and LMDb also show excessive drying in summers. In general, the simulated soil moisture values are much lower than the observations. The LMD models, however, seem to be catching some of the interannual variations in the observations during the spring season but are entirely wrong for 1982 both in the spring and in the fall.

From the water balance perspective, soil moisture simulation is greatly influenced by the simulation of other hydrological components, including precipitation, evapotranspiration, and

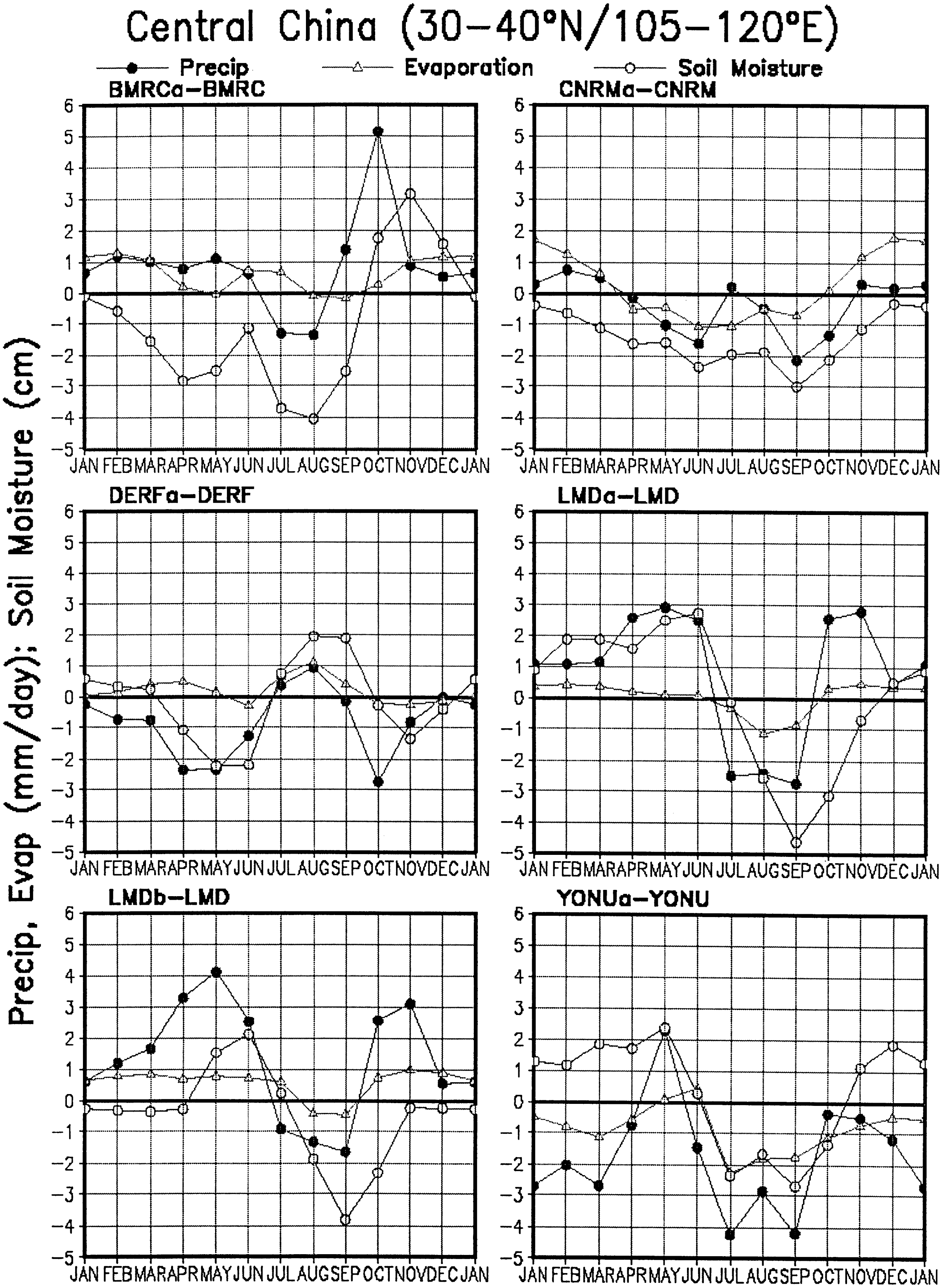

Figure 6. Seasonal cycle of changes in precipitation, evapotranspiration, and soil moisture for each model (based on 1980-1988 averages).

runoff. Unfortunately, the absence of runoff information in AMIP 1 and revised runs and of evapotranspiration observations makes it impossible to do the water closure either with the models or with the observations over one region. We also examined the precipitation simulated by revised and original simulations over the regions where we made comparison with observed soil moisture. Figure 5, for example, shows the seasonal changes in precipitation over the central China region. The plots include the

NCEP/NCAR reanalysis and the observed seasonal cycle for the same time periods from two global data sets [*Hulme et al.*, 1994; *Xie and Arkin*, 1997]. Figure 5 shows that over the central China region, neither the original nor the revised simulations correctly reproduce the observed sharp increase during April to June followed by a peak in July. The FSU and Illinois regions also indicate similar problems. Obviously, one of the reasons for improper soil moisture simulations of the AMIP GCMs examined is related to poor regional-scale simulations of the seasonal cycle of precipitation. It is curious that the revisits seem to cluster more closely than the original runs, a result also shown for the Nordeste by *Sperber et al.* [1999, Figure 1]. As they briefly discuss, this is related to the models' ability to simulate the continental precipitation pattern related to the Asian monsoon. They showed that the simulations of the June-September mean were improved for India, a result also seen in our Figure 5 for China, but clearly, the entire seasonal cycle must be considered. If each month is considered separately, this "improvement" is overshadowed by the errors in the other months.

Figure 6 shows the seasonal cycle of difference of precipitation, evapotranspiration, and soil moisture over central China produced by the revised runs compared to the original ones. Careful examination of the panels for each model shows that precipitation differences lead soil moisture changes by about a month and that evapotranspiration changes are simultaneous or follow soil moisture changes by about 1 month. Therefore it seems that precipitation errors drive soil moisture errors, and there is no evidence for local soil moisture feedback on precipitation. Therefore unless regional-scale precipitation is improved, the soil moisture field cannot be correctly produced no matter how complex the land surface model is.

We also looked at seasonal averages for India and other regions and found that when considering seasonal averages, based on several months as in the work of *Sperber et al.* [1999], such model discrepancies are not so apparent. For soil moisture simulations, however, the timing of summer precipitation is crucial to produce an accurate summer soil moisture simulation.

5. Discussion and Conclusions

We have examined soil moisture simulations from a set of revised atmospheric GCMs, which include changes in the land surface representation in additions to other significant changes. There are no systematic improvements in soil moisture simulations produced by the revised models in the regions we studied. The GCMs are unable to reproduce the observed seasonality in the precipitation at regional scales. *Mahfouf et al.* [1995], on the basis of the ARPEGE model results using a revised LSS, also report a similar problem.

The tendency toward unrealistic summer drying in several models could be possibly linked to availability of excess energy at the surface. Such a spuriously large forcing may not allow the LSS to retain moisture irrespective of its complexity. The finding of *Wild et al.* [1998] that the current generation of GCMs may be underestimating atmospheric solar absorption by 10-20 Wm^{-2} documents the presence of excess radiative energy in the models.

The findings of this study can be summarized as follows:

1. Soil moisture simulations in atmospheric GCMs forced by SSTs are poor despite revisions, including those involving improvements in land-surface representations. Not only are the mean seasonal cycles poorly simulated but also there is no evidence that the simulations of interannual variations have improved from those shown by *Robock et al.* [1998].

2. There is a tendency toward drier soil conditions, especially during summers, among both the original and the revised models. This is particularly relevant in view of the summer desiccation projected by GCMs considered in future assessments of climate change [*Manabe et al.*, 1981; *Mitchell and Warrilow*, 1987].

3. Improper simulation of the seasonal cycle of precipitation at regional scale and surface radiation forcing may be responsible for the incorrect soil moisture simulations.

4. The reanalyses, which are driven by observed precipitation, do capture some of the observed soil moisture variations, but the nudging damps out the amplitude of the variations.

As models are being constantly improved, it should be noted that these results might not be indicative of the current status of the GCMs or reflect the overall performance of the models studied. As it is difficult to evaluate LSS improvements in the context of forcing produced by a GCM, this study highlights the need for continued off-line intercomparisons in the style of PILPS phase 2 [e.g., *Henderson-Sellers et al.*, 1995; *Schlosser et al.*, 2000] or the Global Soil Wetness Project [*Dirmeyer et al.*, 1999] in which all the models receive the same forcing from observations. The differences between the models can then be interpreted based only on their different formulations. Land-surface schemes developed and improved in this way and then introduced into GCMs may then help to improve the GCM simulations of precipitation and cloudiness.

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