JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 112, D06106, doi:10.1029/2006JD007455, 2007

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Evaluation of Intergovernmental Panel on Climate Change Fourth Assessment soil moisture simulations for the second half of the twentieth century

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Received 28 April 2006; revised 27 September 2006; accepted 7 November 2006; published 22 March 2007.

[1] Soil moisture trends, particularly during the growing season, are an important possible consequence of global warming. Climate model simulations of future soil moisture changes should be made with models that can produce reliable simulations of soil moisture for past climate changes. In this paper, we compare soil moisture simulations from Intergovernmental Panel on Climate Change Fourth Assessment climate models forced with observed climate forcings for the past century, and evaluate them using in situ soil moisture measurements from over 140 stations or districts in midlatitudes of the Northern Hemisphere. To account for the observed spatial scale of soil moisture variations, we used regionally averaged soil moisture for six regions. The models showed realistic seasonal cycles for Ukraine, Russia, and Illinois, but generally poor seasonal cycles for Mongolia and China. To explore the summer drying issue for the second half of the 20th century, we analyzed the linear trend of soil moisture for Ukraine and Russia. Observations from both regions show increases in summer for the period from 1958–1999 that were larger than most trends in the model simulations. Only two out of 25 model realizations show trends comparable to those of observations. These two trends, however, are due to internal model variability rather than a result of external forcing. Changes in precipitation and temperature cannot fully explain soil moisture increases for Ukraine and Russia, which indicates that other factors might have played a dominant role on the observed patterns for soil moisture. We suggest that changes in solar irradiance (the dimming effect) and resultant changes in evaporative demand explain most of the observed soil moisture trends. To understand such sensitivity, we analyzed soil moisture outputs in a special version of the ECHAM5 model that was capable of capturing the observed radiation pattern as a result of incorporating a sophisticated aerosol scheme. Results suggest that both radiation and precipitation patterns are required to be adequately simulated to reproduce the observed soil moisture trends realistically.

Citation: Li, H., A. Robock, and M. Wild (2007), Evaluation of Intergovernmental Panel on Climate Change Fourth Assessment soil moisture simulations for the second half of the twentieth century, *J. Geophys. Res.*, *112*, D06106, doi:10.1029/2006JD007455.

1. Introduction

[2] Global-warming-induced climate changes are experienced from regional to global scales. How components of the hydrological cycle changed in the past and will evolve in a warming climate will have strong impacts on human society. Higher temperature will accelerate the global hydrological cycle in general [e.g., *Milly et al.*, 2002; *Bosilovich et al.*, 2005]. However, model studies with increased amounts of absorbing aerosol tend to show a slow down of the hydrological cycle [e.g., *Liepert et al.*, 2004]. Unlike other terms in the water budget, however, soil moisture (the water residual) has been relatively less studied because of paucity of available observations, in spite of its importance.

[3] Soil moisture is crucial to agriculture and is an important part of the agricultural drought outlook in many areas of the world. From the perspective of water balance, soil moisture directly influences the rate of evaporation, groundwater recharge and runoff generation. Soil moisture, along with other land surface conditions, also determines the partitioning of available energy at the surface between sensible heat and latent heat. Since there are no global in situ observations, model-simulated soil moisture has been used in many cases as a substitute for observations in climate change studies. A general drying in midlatitude summer was reported in several model simulations [e.g., *Manabe and Wetherald*, 1987; *Gregory et al.*, 1997; *Manabe et al.*, 2004], which, if correct, poses a great threat to future food security. The drying was attributable to earlier snowmelting and higher evaporation in winter and spring

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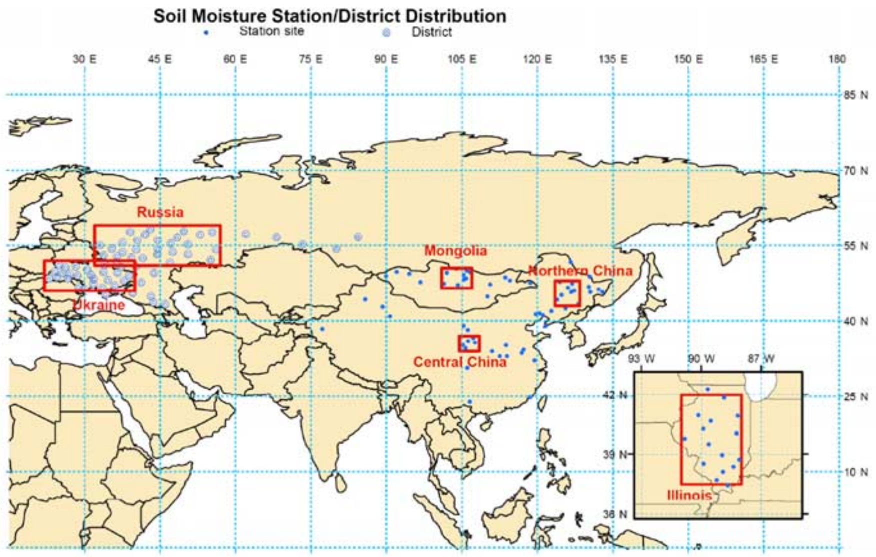

Figure 1. Distribution of soil moisture stations/district centers used in this study. District centers are plotted as double circles and stations are plotted as solid dots. Rectangles are domains used to derive regional averages (Table 1).

and lower precipitation during summer [*IPCC*, 2001]. However, other models presented quite an opposite scenario [e.g., *Meehl and Washington*, 1988; *Seneviratne et al.*, 2002]. These model-dependent predictions cannot be a reliable reference point in explaining the direction of future changes yet [*IPCC*, 2001].

[4] Vegetation plays an important role in the climate system. In response to increasing atmospheric CO_2 concentration, many plant species tend to reduce stomatal openings to reduce water loss through transpiration [*Field et al.*, 1995]. Such a mechanism has profound implication for the hydrological cycle since it potentially leads to an increase for water storage and streamflow [*Gedney et al.*, 2006]. *Wigley and Jones* [1985] analytically illustrated the strong dependence of changes in streamflow on the direct CO_2 effect on plant evapotranspiration which is controlled by stomata. Modeling results suggested that the climatic impact of doubling stomatal resistance could be as large as the effect of doubling atmospheric CO_2 [*Henderson-Sellers et al.*, 1995]. On the other hand, there also exists a compensating mechanism, namely the structural response, which may offset the physiological effects. Increased CO_2 uptake by plants with elevated CO_2 can stimulate plant growth (i.e., increase in root depth and foliage), thus boosting transpiration. This may further enhance the resultant surface cooling through a series of feedbacks in the planetary boundary layer [*Pitman*, 2003]. However, given that our knowledge of these physical processes is rather limited and the parameterizations of these features in climate models are still rather simple, uncertainties concerning the net effect of these two mechanisms on the hydrological cycle remain high. In terms of root-growth feedbacks, *Milly* [1997] demonstrated a 14% decrease of plant accessible water in soil column would generate the same summer dryness comparable to a doubling of atmospheric CO_2.

[5] The ability to calculate accurate soil moisture in a climate model depends on several factors: a good land surface model, and good precipitation and radiation forcing. Both offline experiments [e.g., *Guo et al.*, 2005] and coupled simulations [e.g., *Kanamitsu et al.*, 2002] demonstrate that realistic lower atmospheric conditions are extremely important for accurate soil moisture simulations. By adopting a more realistic radiation scheme, *Wild et al.* [1996] demonstrated that the resultant improvements in radiation and precipitation could attenuate simulated summer desiccation in a climate model. Soil with low field capacity is more prone to reach field capacity in late winter or spring, which ensures that much of the extra precipitation in winter is lost as runoff. Without proper accounting for cold season soil dynamics, models in the Atmospheric Model Intercomparison Project [*Gates*, 1992] were unable to capture the observed month-to-month changes in winter [*Robock et al.*, 1998]. Including soil-water freezing in a

Table 1. Soil Moisture Data Sets

Region	Domain	Record Length (0–1 m)	(0–10 cm)	Number of Stations
Ukraine	46.0–52.0°N, 22.0–40.0°E	1958–1999	1976–1999	26[a]
Russia	51.0–59.0°N, 32.0–57.0°E	1958–1999	1970–1999	29[a]
Mongolia	46.5–50.5°N, 101.0–107.0°E	1970–1999	1970–1999	5
Northern China	43.0–48.0°N, 123.5–128.5°E	1981–1999	1981–1999	8
Central China	34.0–37.0°N, 104.5–108.5°E	1981–1999	1981–1999	5
Illinois	37.5–42.0°N, 88.0–91.0°W	1984–1999	1984–1999	18

[a]District data are derived from 3–6 stations each.

Table 2. IPCC AR4 Climate Models Analyzed

Model Name	Organization	Land Surface Model, Resolution	Number of Ensemble Members	Reference
MIROC3.2 (medres)[a,b]	CCSR (University of Tokyo),	MATSIRO (no tiling), ~2.8°	3	*Takata et al.* [2003]
MIROC3.2 (hires)[b]	NIES,and FRCGC (JAMSTEC), Japan	MATSIRO (2 × 2 tiling), ~0.56°	1	
GISS – EH[a,c]	NASA/GISS, USA	Land Surface Model, 4° × 5°	5	*Rosenzweig and Abramopoulos* [1997],
GISS – ER[a,c]			9	*Friend and Kiang* [2005]
MRI-CGCM2.3.2[a,b,c]	MRI, Japan	SiB L3, ~2.8°	5	*Sellers et al.* [1986], *Sato et al.* [1989]
FGOALS-g1.0[a,c]	LASG/IAP, China	CLM2.0, ~2.8°	3	*Bonan et al.* [2002]
CGCM3.1 (T47)[a]	CCCMA, Canada	CLASS, ~3.75°	5	*Verseghy et al.* [1991]
CCSM3, USA[a,b,c]	NCAR, USA	CLM3.0, ~1.4°	6	*Oleson et al.* [2004]
PCM1, USA[b,c]	NCAR, USA	LSM1.0, ~2.8°	4	*Bonan* [1996]
GFDL_CM2_0[b,d]	GFDL, USA	LM2, 2.0° × 2.5°	3	*Milly and Shmakin* [2002]
GFDL_CM2_1[b,d]	GFDL, USA			
UKMO-HADCM3[a,c]	Hadley Centre, Met Office, UK	MOSES-I, 2.5° × 3.75°	2	*Cox et al.* [1999]
UKMO-HADGEM1[a,c]		MOSES-II, 1.25° × 1.875°	2	*Essery et al.* [2001]

[a]Model has top 0–10 cm soil moisture output.
[b]Model has top 0–1 m soil moisture output.
[c]Model includes carbon fertilization effects.
[d]Model reported root-zone level (about 1 m) plant-available soil moisture.

model can also improve the simulation of the soil thermal state [*Luo et al.*, 2003].

[6] In July 2004, the Working Group on Coupled Models Climate Simulation Panel invited voluntary groups to analyze climate model outputs [*Meehl et al.*, 2004]. These analyses will lead to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). These coupled models represent the latest model developments with improved parameterizations of physical processes of the climate system.

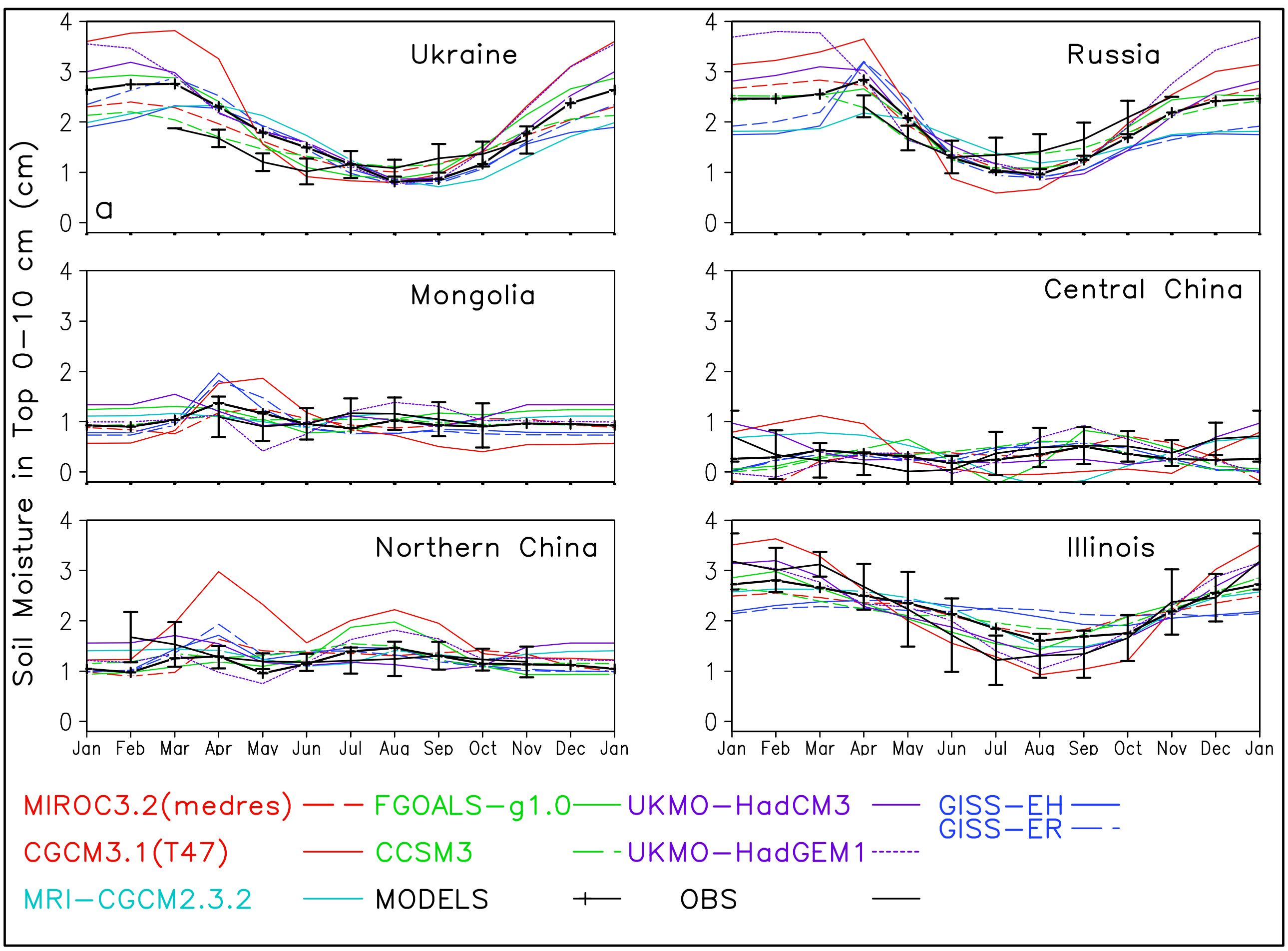

Figure 2a. Mean soil moisture seasonal cycle for top 10 cm (units: cm).

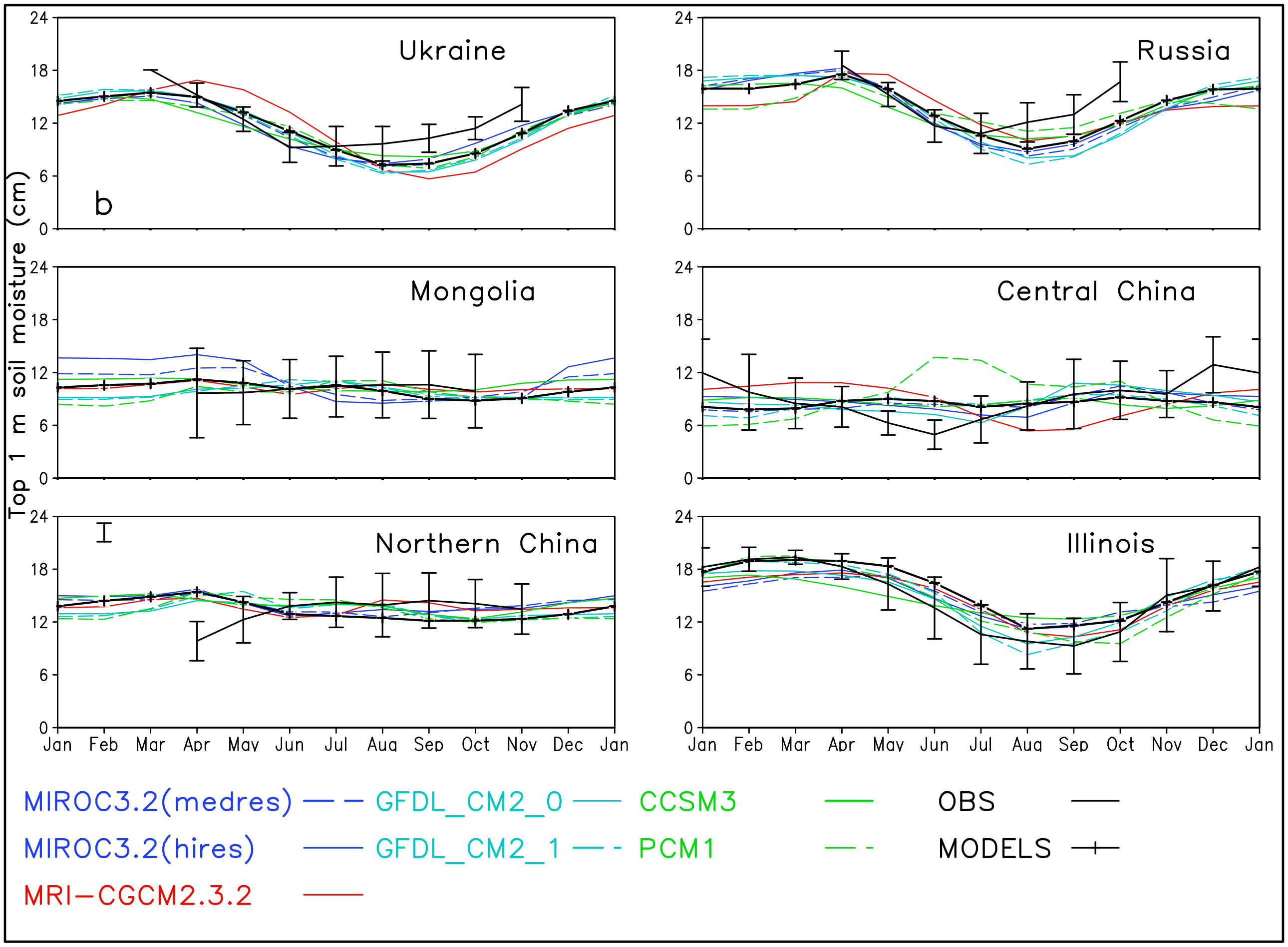

Figure 2b. Mean soil moisture seasonal cycle for top 1 m (units: cm).

[7] Recent updates at the Global Soil Moisture Data Bank, especially several long-term observations from the former Soviet Union (FSU), make it possible to use these benchmark observations to evaluate the soil-moisture-related climate change in these models. In this study, we focus on the second half of the 20th century when most observations are available. We will address the following scientific questions with an emphasis on the second one: (1) How realistic are the seasonal cycle of the model simulated soil moisture? and (2) Can IPCC models capture observed soil moisture trends in the summer? The data sets are described in section 2. Comparisons between observations and model outputs in terms of seasonal cycle are presented in section 3. Analysis of long-term soil moisture in summer is given in section 4, with a summary in section 5.

2. Data Sets

[8] Soil moisture observations from FSU, China, Mongolia, and Illinois (Figure 1 and Table 1) from the Global Soil Moisture Data Bank [*Robock et al.*, 2000] were used in this study. We used a subset of the FSU soil moisture (now called Russian and Ukrainian data), measured separately for winter cereal crops and spring cereal crops, composed of 66 district averages at 0–20 cm and 0–100 cm depth. There is a good agreement between these two independent observations taken in winter cereal and spring cereal crop fields [*Entin et al.*, 1999; *Robock et al.*, 2005]. Since the data for winter cereal crops contain fewer missing values, we only used soil moisture for winter cereal crops in our analysis. Measurements for top 1 m soil moisture began in 1958 and started in the 1970s for the top 0–20 cm. We recently updated the Ukrainian data through 2004. The Chinese soil moisture consists of 40 stations and spans the period of 1981–1999 [*Li et al.*, 2005]. There are 17 stations for Mongolia for the period of 1970–2002; a few of them started in the 1960s. The state of Illinois has been measuring soil moisture since 1981 at 19 stations [*Hollinger and Isard*, 1994]. The data for the first three years are inhomogeneous with the rest of the data so were excluded from our analysis. The data sets are describe in more detail by *Hollinger and Isard* [1994], *Vinnikov et al.* [1996, 1997], *Robock et al.* [2000, 2005], and *Li et al.* [2005]. These quality-controlled data sets have been widely used in various aspects of model evaluation [e.g., *Robock et al.*, 1998; *Entin et al.*, 1999; *Srinivasan et al.*, 2000; *Schlosser et al.*, 2000; *Luo et al.*, 2003; *Dirmeyer et al.*, 2004]. Monthly mean observations were calculated to be compatible with model outputs. In addition to soil moisture, monthly mean precipitation and temperature from the Climate Research Unit at the Univer-

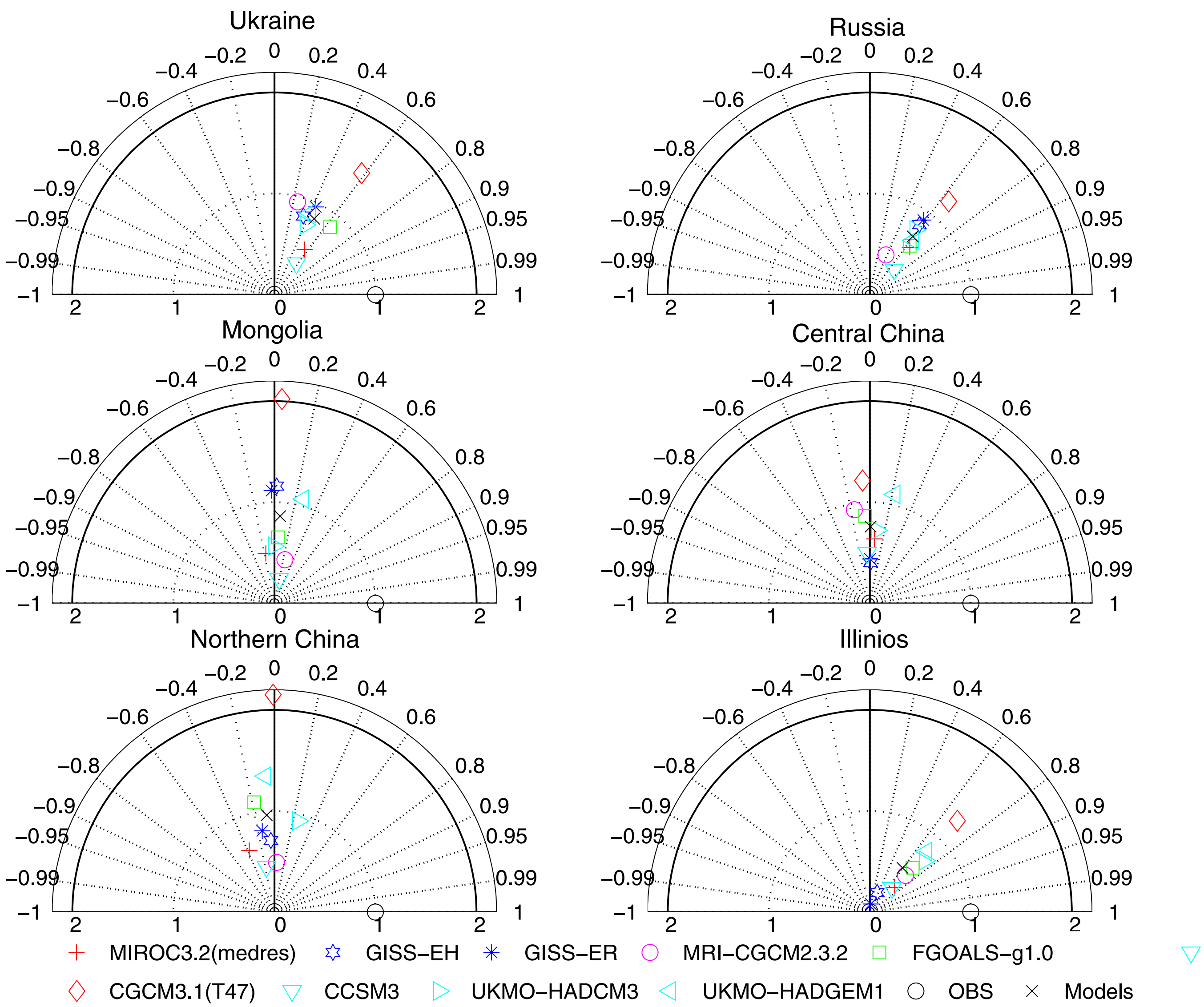

Figure 3. Taylor diagrams for top 10 cm soil moisture. Azimuthal angle represents correlation coefficient and radial distance is the standard deviation normalized to observations.

sity of East Anglia [*New et al.*, 1999, 2000] and monthly precipitation data from the University of Delaware [*Legates and Willmott*, 1990] were utilized to evaluate corresponding model fields.

[9] Eighteen modeling groups sent their latest IPCC results to the Program for Climate Model Diagnosis and Intercomparison of Lawrence Livermore Laboratory. Each group was asked to report soil moisture in the top 10 cm and in the total soil column. Because of large intermodel differences, not all models produced top 10 cm values and the depth of the total soil column varied from model to model. To ensure consistence, we selected nine models that had multiple simulations and outputs for the top 10 cm and seven models for the top 1 m for this study (Table 2). For the 20th century runs, models were initialized from conditions derived from preindustrial control runs. Each realization differed only in initial conditions. Thus ensemble averages from multiple simulations can better detect signal from noise. The models differed not only in land surface schemes but also in resolution. We calculated regional averaged soil moisture to account for the scale of soil moisture variances and the differences in model resolutions (see Figure 1 for the domain and Table 1 for details).

[10] Meanwhile, surface layer Russian soil moisture data was archived for the 0–20 cm top layer. Some conversion was needed to get top 0–10 cm soil moisture. By analyzing the data from other places where soil moisture at both levels is available, we found that top 10 cm soil moisture is highly correlated with that in 0–20 cm with a mean correlation coefficient of 0.98. This might be explained by strong vertical interaction in the near surface zone. Moreover, the magnitude of top 20 cm soil moisture was roughly twice that in the 0–10 cm layer. Thus we divided the 0–20 cm soil moisture by 2 to approximate the value for the 0–10 cm layer. As our focus was on the seasonal pattern and interannual changes that are not dependent on

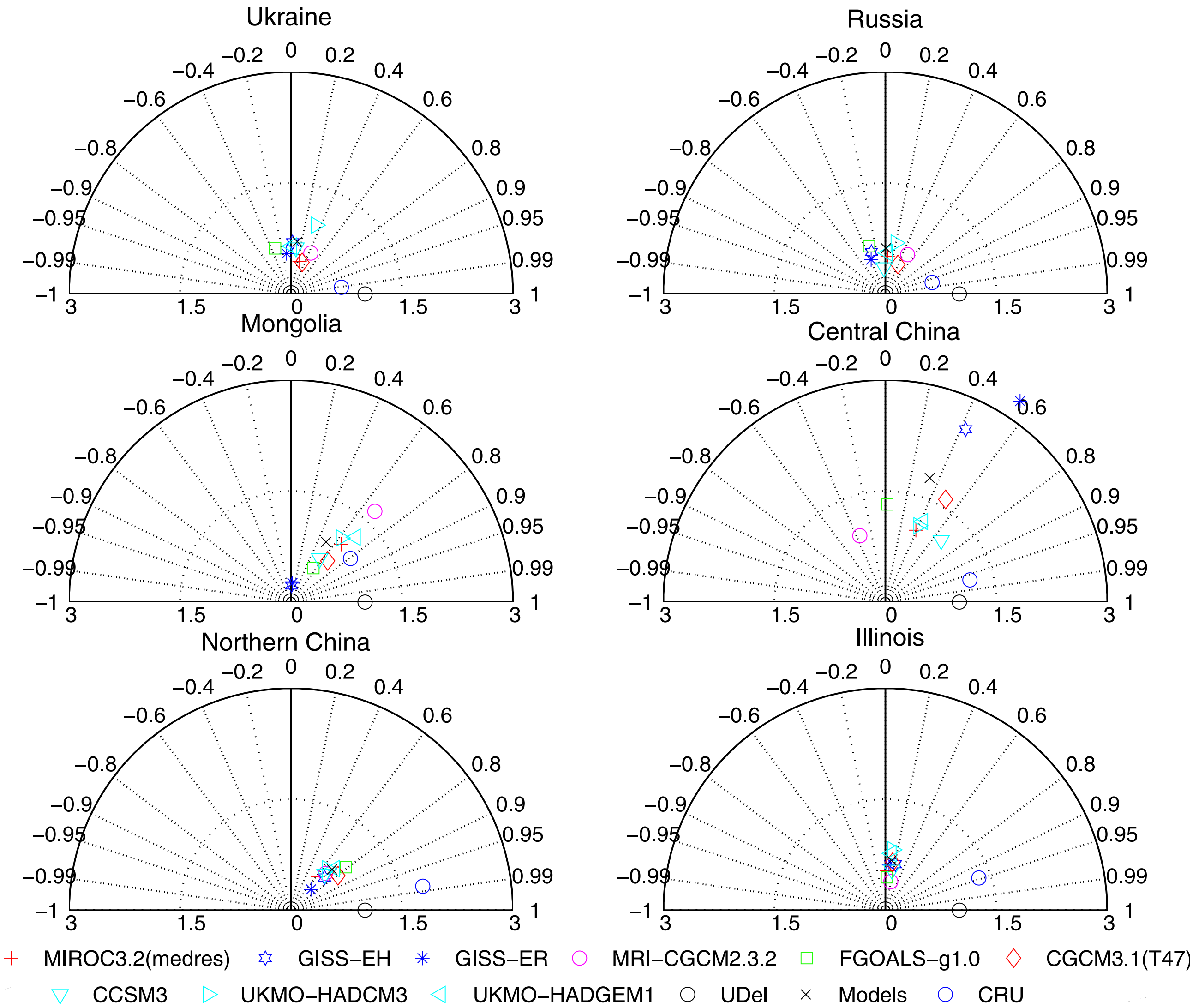

Figure 4. Taylor diagram for precipitation.

absolute values, this procedure will not affect our analysis in general.

3. Seasonal Cycle

[11] Figures 2a and 2b give the soil moisture seasonal cycles for the top 0–10 cm and top 0–1 m for the models and observations. As models tended to have their own climatology or effective range [*Koster and Milly*, 1997], we adjusted soil moisture simulations from each model according to the difference between the averages of monthly mean values of that model and observations. In terms of correlation coefficient, model-simulated seasonal patterns are in better agreement with those of observations for Ukraine, Russia, and Illinois where seasonal cycles are qualitatively reproduced by the models, particularly for the 0–1 m depth where the signal-to-noise ratio is larger. For the other locations, there were relatively large intermodel differences and model-to-observation differences. Another conspicuous feature is that the warm season climatology shows less intermodel disparity than that for cold season, with large spread between the models, particularly for top layer soil moisture of Russia and Illinois. The variety of schemes for frozen soil treatment in land surface models, even driven by identical meteorological forcing in stand-alone mode, can bring about large disparities of simulated soil temperature and snow water equivalent [*Luo et al.*, 2003]. Spread of the duration and extent of global snow cover in climate models may further exacerbate differences in simulated soil moisture. Detailed analysis about the cold season soil moisture is of special interest but is beyond the scope of this paper.

[12] To quantitatively understand how good model simulations were compared to observations, we utilized Taylor diagrams [*Taylor*, 2001], which nicely summarize several important statistical quantities in just one plot. In Figure 3, the azimuthal angle (clockwise angle from north) represents the correlation coefficient between monthly means of model ensembles and observations, and the radial distance from the origin is the standard deviation normalized by that of observations. Correlation coefficients were generally higher for the Russian regions and Illinois where the

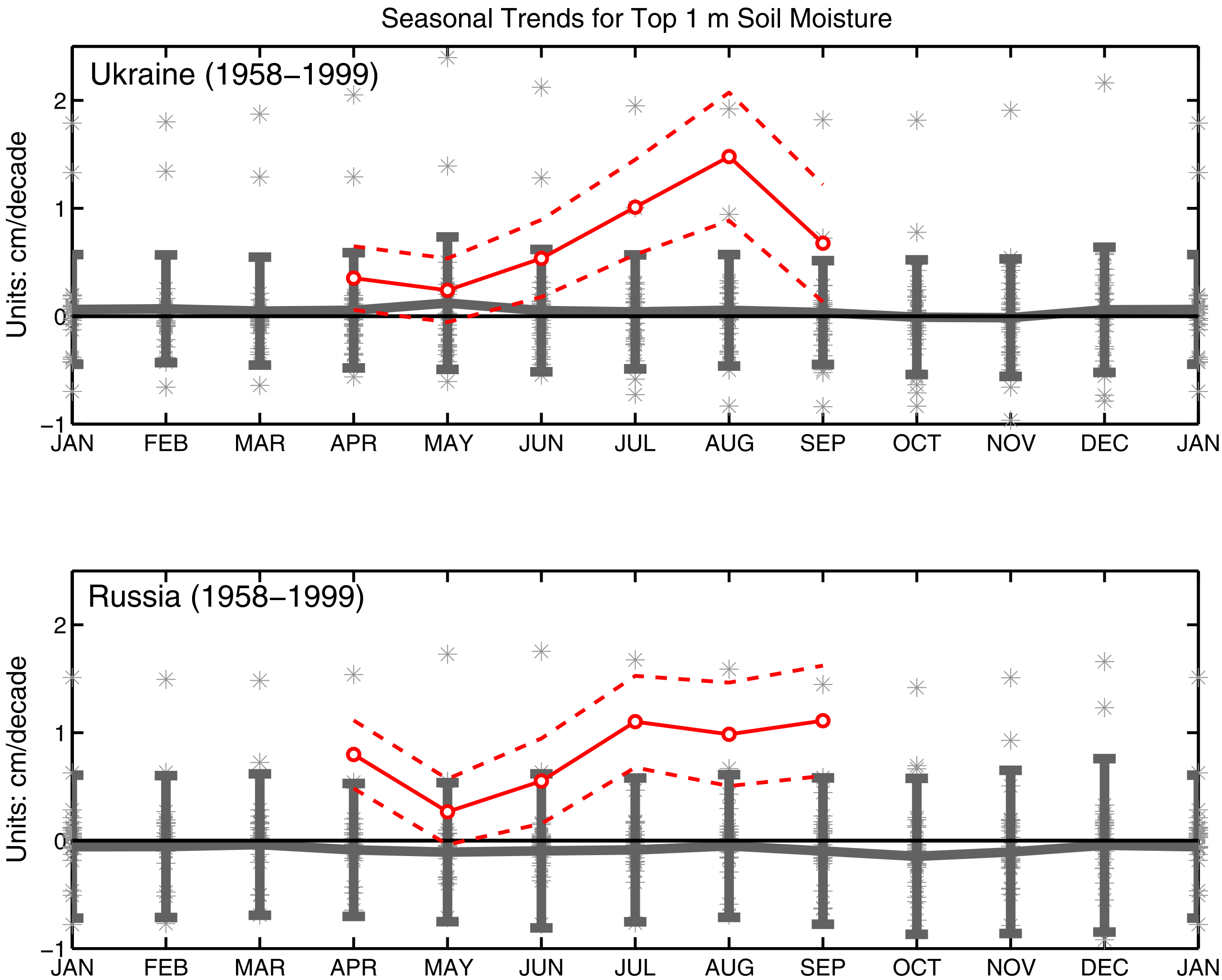

Figure 5. Seasonal cycle of top 1 m soil moisture trends for 1958–1999. Observations are circles, 90% confidence intervals are dashed lines, dark gray lines represent mean trends for individual model realizations (see Table 2 for list of models), and error bars show standard deviation for trends. Light gray symbols are estimated trends for individual realizations. For location of Ukraine and Russia boxes, see Table 1 and Figure 1.

models also showed a better and strong climatology. In terms of interannual variability, the two UK models had variability comparable to observations for all six regions. The Canadian model exhibited stronger interannual variability in all climates. To investigate whether precipitation has a similar pattern to soil moisture, we plotted the Taylor Diagram for monthly precipitation (Figure 4). The precipitation fields for China and Mongolia actually were better, probably because of the strong seasonality of the Asian monsoon and that we did not have winter soil moisture observations for comparison to models. In Russia and Illinois, precipitation was not simulated well. Further analysis of the precipitation climatology indicates models capture the seasonal cycles better for Mongolia and China, where seasonal changes are also strong. Similar to soil moisture analysis, this suggests a better climatology to a large extent explains higher correlation coefficients between models and observations (for soil moisture and precipitation). Better precipitation forcing does not guarantee more realistic soil moisture in coupled models.

4. Trends

[13] Because soil moisture simulations were more realistic for the two FSU regions and those two regions had relatively long measurements available (over 40 years), we chose Russia and Ukraine for long-term trend analysis. We used the least squares method for trend detection. An additional analysis by nonparametric Mann-Kendall method [*Hirsch et al.*, 1982] showed similar results. We calculated the monthly trends for Ukraine and Russia (Figure 5). There was a general increase in April, June, July, August, and September for observations for both regions (10% significance level). The mean trends of models showed a slight increase for Ukraine but a small decrease for Russia. The number of realizations that show an increase is roughly equal to that exhibiting a decrease. The observed trends in

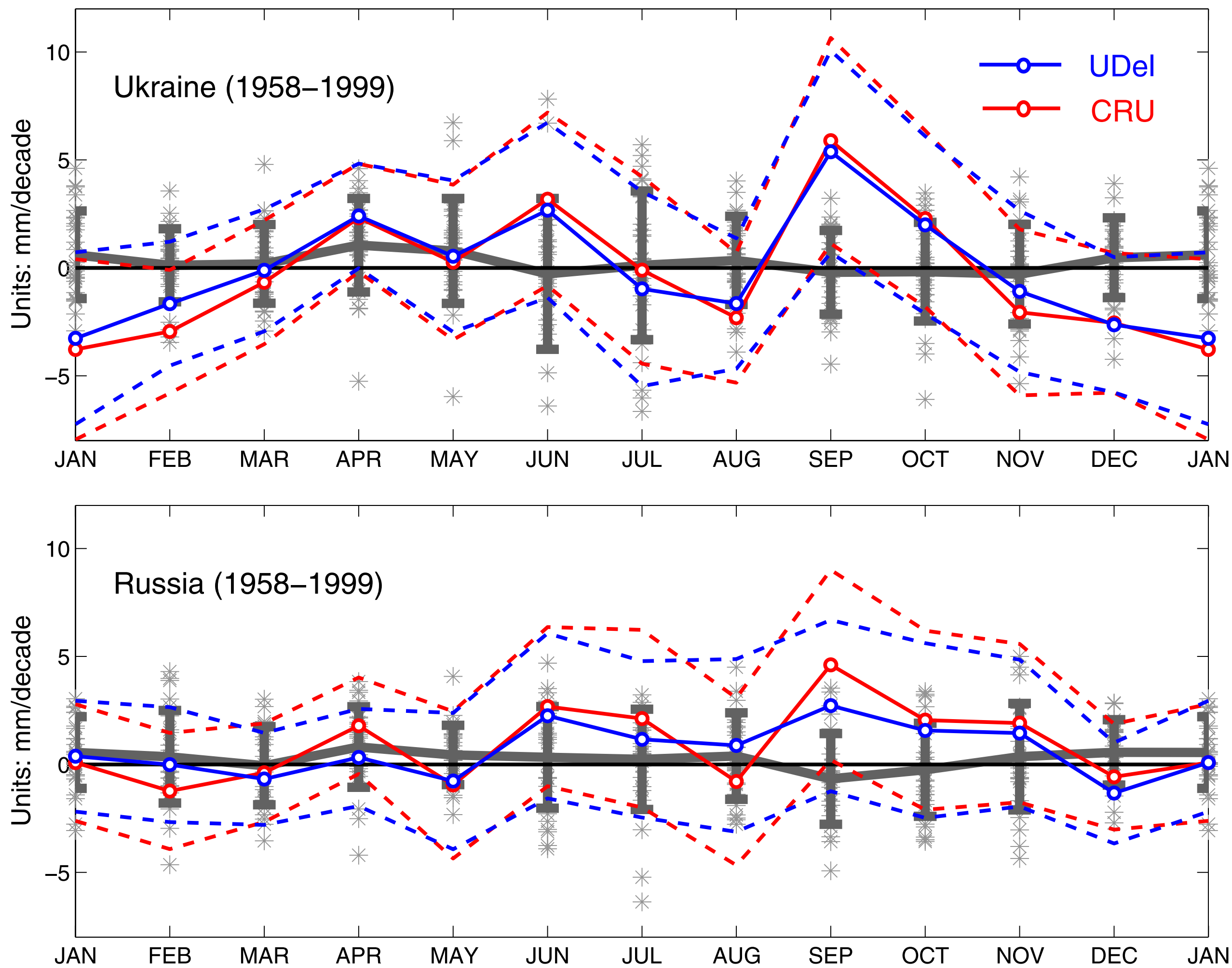

Figure 6. Same as Figure 5, but for precipitation. See text for references to CRU and UDel data.

April and May are relatively well captured by models. However, in the warm months of July and August, less than 8% of model realizations have trends comparable to the observed patterns.

[14] To see whether similar patterns exist in precipitation and temperature, we analyzed the monthly trends for precipitation and temperature, too (Figures 6–7). In general, there are small upward trends in the observed precipitation, which is characterized by large interannual variations. Mean trends from models indicate a weak increase, relatively larger in spring and late winter. The observed temperature increased slightly in the warm season. Models simulated an almost ubiquitous increase of temperature for all seasons, larger in winter and smaller in summer. There was a good agreement between models and observations for summer months. Observed temperature trends lay within model predictions fairly well from July to October (Figure 7), which validates the model-predicted warming. In terms of solar irradiance, there was an overall small decrease for the model ensemble. Models tended to agree with each other well in winter but there was a large spread in the warm seasons (not shown). We do not have observations for these regions, but the downward model trends of insolation are an order of magnitude lower than those observed for nearby regions in Europe [*Wild et al.*, 2005].

[15] *Robock et al.* [2005] reported an increase in summer soil moisture for Ukraine from 1960s to 1990s but this pattern started to level off at the end of the period. Here we extend their study to both Ukraine and Russia, using these Russian data for the first time. Figure 8 gives the soil moisture anomaly time series (JJA average) for observations and each model, and the linear trend estimations. The amplitude of the upward trends in top 0–1 m observations is about 8.0 mm/decade for Ukraine and 8.6 mm/decade for Russia. The IPCC models, however, simulated a very small upward trend for Ukraine and essentially no trend for Russia in terms of mean trends. In both cases, the observed trends were larger than most trends of the model simulations. Only two out of 25 model realizations have trends comparable to those of observations. These two realizations come from different climate models and other realizations from those two models do not show similar patterns. Thus the two trends are due to internal model variability as different realizations for the same model only differ in initial conditions. Similar to the model trends discussed earlier, there

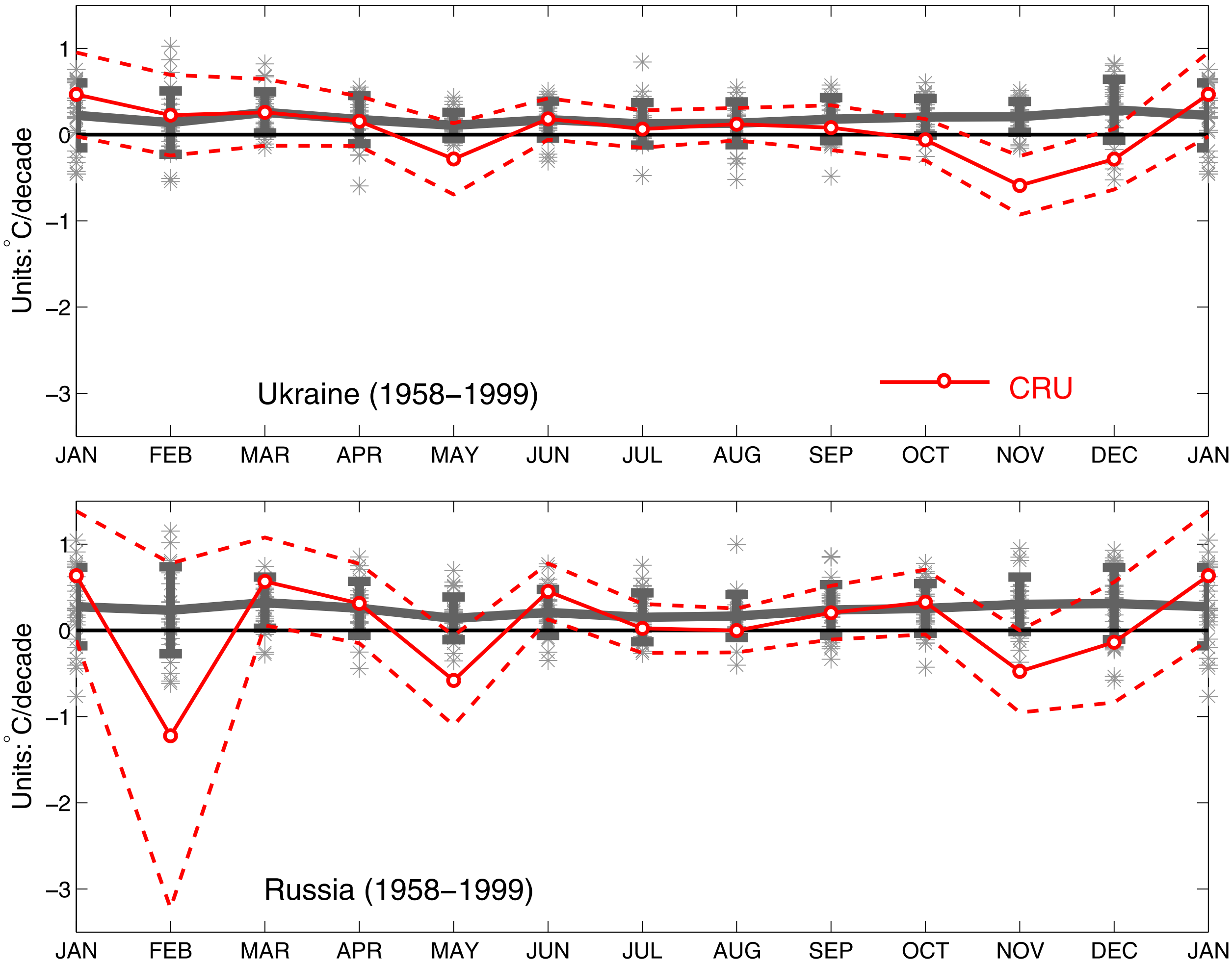

Figure 7. Same as Figure 5, but for temperature. See text for references to CRU data.

was a slight increase in both precipitation and temperature (not shown). Again, the observed temperature pattern is well constrained in model results, highlighting the reliability of the model-simulated warming.

[16] An interesting question remains about what drives the observed pattern in soil moisture. Precipitation and solar radiation are the driving forces for the water cycle. A phenomenon called "from dimming to brightening" has been observed for solar radiation data from both ground stations [*Wild et al.*, 2005] and satellite measurements [*Pinker et al.*, 2005] for many places around the world. A widespread decrease for shortwave radiation for 1950s to 1990s was observed and followed by a gradual recovery since 1990s. Such a pattern (solar dimming) may well explain the observed soil moisture change for FSU regions. *Peterson et al.* [1995] reported a decrease in pan evaporation in FSU around the same period. Showing evidence from the observed decreases in solar irradiance and associated changes in diurnal temperature range and vapor pressure deficit, *Roderick and Farquhar* [2002] suggested that the decrease in pan evaporation was in line with the change of evaporation. The upward trend in soil moisture is consistent with these results, as suggested by *Liepert et al.* [2004] and *Robock et al.* [2005]. Using a sophisticated land surface model, *Robock and Li* [2006] demonstrated that changes in precipitation and temperature are not enough to explain the amplitude of the observed soil moisture increases. They further quantitatively showed that solar dimming from tropospheric pollutions is the main cause for the soil moisture trends. In other words, soil moisture increases for Ukraine and Russia are likely externally forced rather than due to model internal variability as suggested by the IPCC models we analyzed here. The lack of solar dimming in the IPCC models explains their inability to model the soil moisture trends.

[17] The failure to capture the observed dimming effects for many models might be partly attributable to the lack of an adequate representation of aerosol. Scientists at the Max Planck Institute recently developed a special version of the ECHAM5 model that incorporates a sophisticated treatment of aerosol effects based on a flexible microphysical approach (ECHAM5-HAM, *Stier et al.* [2005]). Sulfate aerosols, black carbon, particulate organic matter, sea salt, and mineral dust are included in the aerosol scheme. By comparing the special version to the standard ECHAM5 model [*Roeckner et al.*, 2003], which only prescribes direct and the first indirect effect of sulfate aerosols, the soil moisture sensitivity to changes in solar radiation caused by aerosol might be understood.

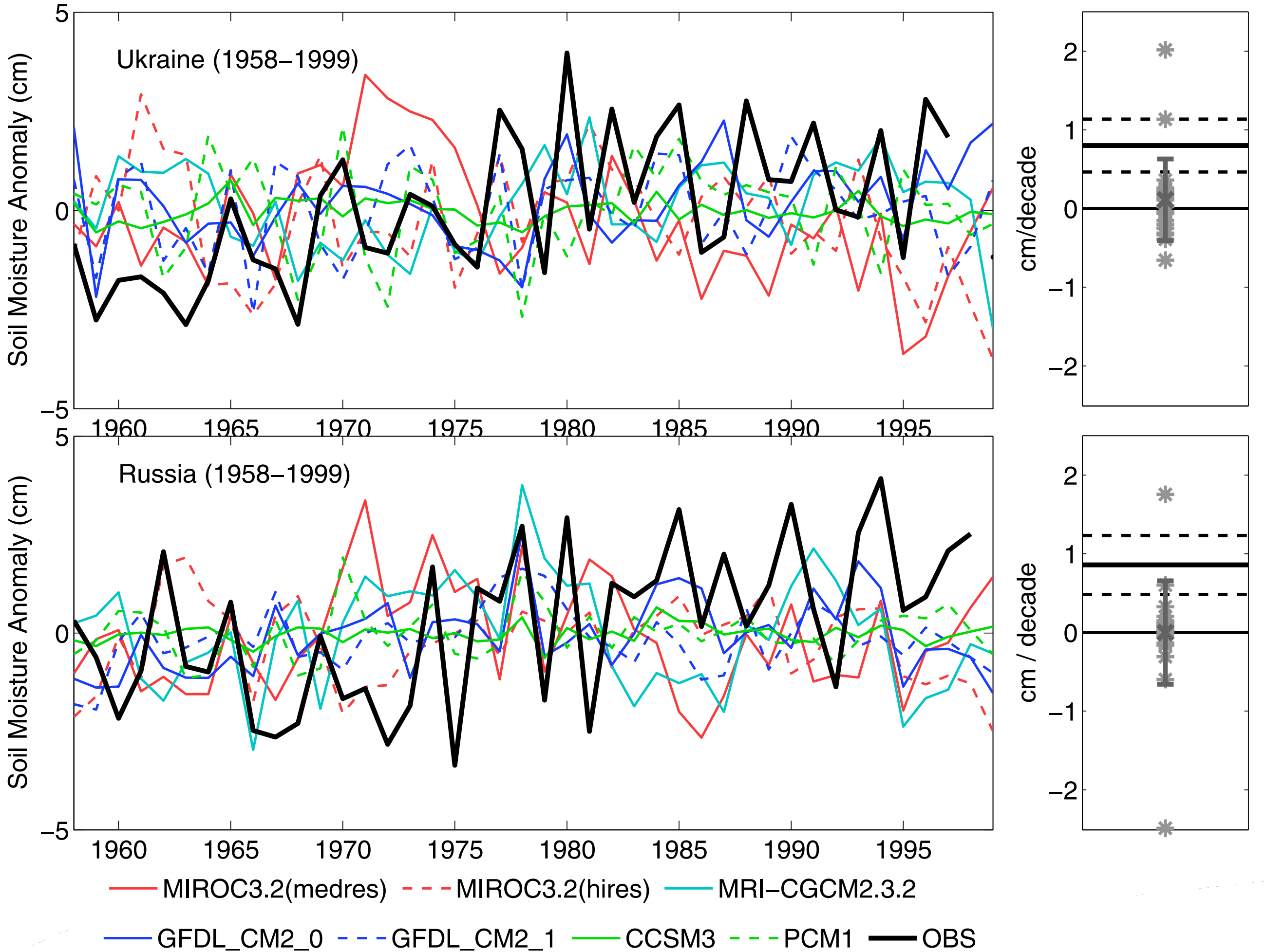

Figure 8. Summer (JJA) soil moisture changes for Ukraine and Russia for the period of 1958–1999 from observations and model ensembles, expressed as anomalies relative to the 1961–1999 means. Right panel shows linear trends. Thick solid lines are estimated trends for observations and 90% confidence intervals are dashed lines. Trends from individual model realizations (Table 2) are plotted as asterisks in light gray. Error bar represents the standard deviation of the trends from 25 realizations.

[18] Figure 9 gives the JJA soil moisture from 1958–2002 for both models and the observations for Russia and Ukraine. Soil moisture decreased slightly for both models in contrast to the general increases found in observations. Measurements from a nearby station indicate that solar radiation decreased until 1980 and began to gradually recover afterward [*Wild et al.*, 2005]. Accordingly, we split the data into two equal periods to investigate how soil moisture evolved. We found an increase in observations for both regions from 1958–1980. The standard ECHAM5 model also had an increase in soil moisture. However, the special version showed a drying pattern. For the second period from 1980 to 2002, observed soil moisture started to level off for Ukraine but continued to increase for Russia. There was a downward trend for the special version but an upward pattern for the standard model for Ukraine. An increase was found for the special version but a decline in the standard model for Russia.

[19] We further analyzed the clear-sky shortwave radiation and precipitation fields for both models to explore probable causes of the differences between the models and observations. Clear-sky shortwave radiation for both models exhibited the process from dimming to brightening but the special version showed a much stronger signal and more closely resembled the observations. At the same time, the clear-sky shortwave radiation for the special version is noticeably higher than that of the standard one (Figure 10a). However, in terms of precipitation, simulated precipitation decreased over the entire period of 1958–2002 for both models for Ukraine. Also, there was a conspicuous dry bias for the special version (Figure 10b). We conclude that these unfavorable conditions simulated by the special version may create a more water limited rather than energy-limited climate in which precipitation plays a dominant role. Therefore the simulated soil moisture patterns more closely follow those of precipitation. The same reasoning can be used to explain the pattern of simulated soil moisture by the special version for Russia, too. To conclude, neither the special version model nor the standard version model can simulate the precipitation well. This explains the disparity

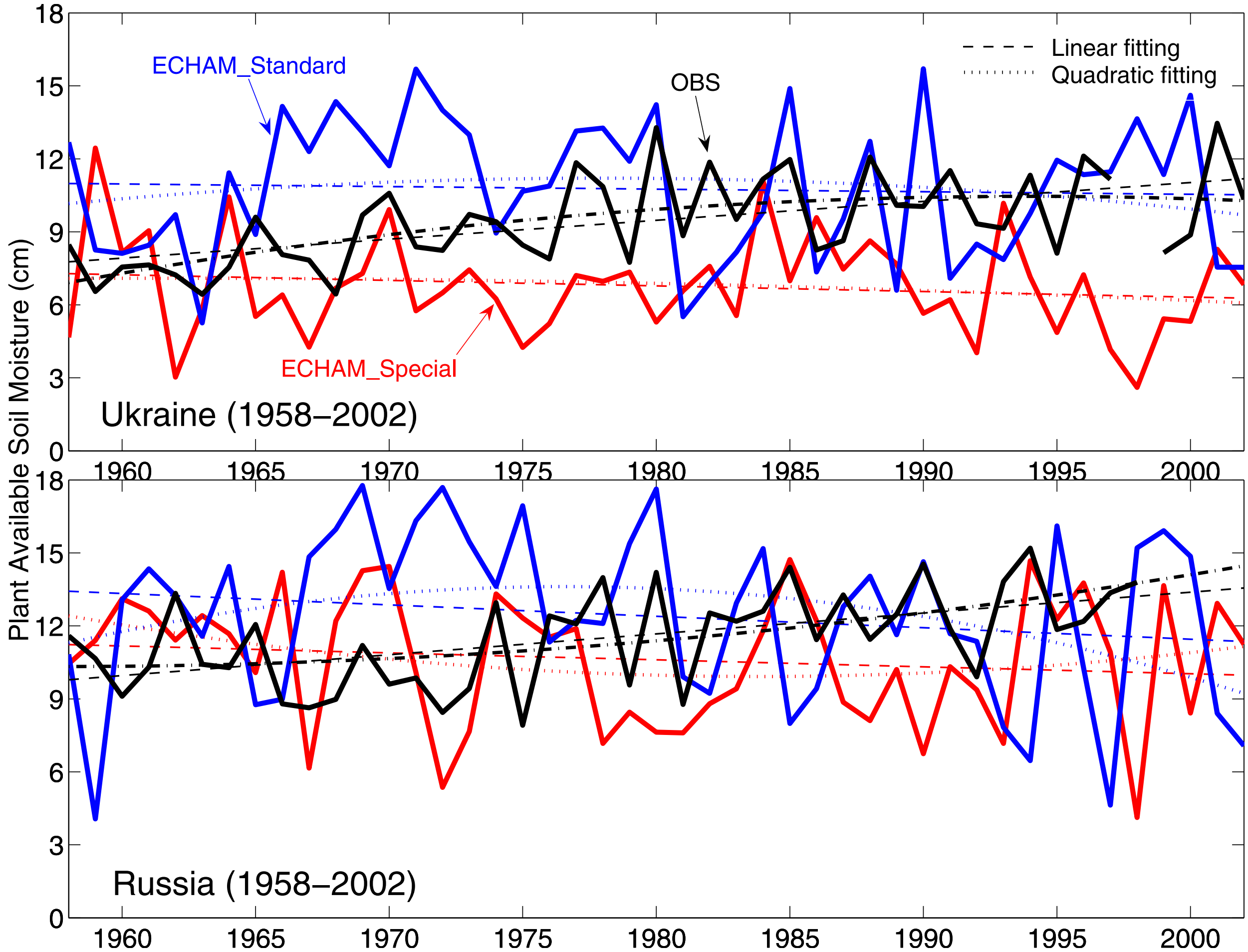

Figure 9. Summer (JJA) plant-available soil moisture for the top 1 m for special version of ECHAM5-HAM model, standard ECHAM5 model, and observations. Also shown are linear and quadratic fitted trend lines.

between simulated soil moisture patterns and the observed ones to large extent.

5. Summary

[20] To investigate how realistic the soil moisture simulations in IPCC models are, we compared the seasonal cycle and long-term pattern in summer for observations and model outputs. Generally, IPCC models have limited capacity to reproduce observed seasonal cycle, although better simulations are found for Russia, Ukraine, and Illinois than for Mongolia and China with respect to seasonal cycle.

[21] To capture the observed soil moisture trends, we need realistic forcings, particularly both precipitation and radiation, in addition to a good land surface scheme. Regarding water balance, either precipitation increase or evaporation decrease may result in soil moisture increase, and the latter is closely related to available energy. The observed solar dimming can dampen the evaporative demand of atmosphere and lead to water storage increase, which may explain the observed soil moisture patterns for Ukraine and Russia. Our analysis of the ECHAM5 model simulations supports the argument that including a comprehensive representation of aerosol effects may exert considerable impacts on the hydrological cycle [*Liepert et al.*, 2004]. Through incorporating a sophisticated aerosol scheme, the special ECHAM5 model showed promising results with respect to the simulated radiation fields. However, the explicit treatment of aerosol-cloud interactions remains a challenge [*Stier et al.*, 2005].

[22] *Wang* [2005] analyzed soil moisture in IPCC models in a future scenario. Interestingly, her results showed that FSU regions were the places where models disagreed most, highlighting the sophisticated nature of sensitivity of land hydrology to elevated CO_2 concentrations in models. In response to elevated CO_2 concentrations, many plant species reduce their stomatal openings [*Field et al.*, 1995], leading to a reduction in evaporation to the atmosphere. More water is likely to be stored in the soil or run off consequently. Figure 11 shows the relative change of summer soil moisture for a future scenario from our IPCC models. The relative change is defined as the difference between the mean of 2060–2099 (scenario SRESA1B) and that of 1960–1999 normalized by the average of 1960–1999. In spite of large spatial differences, many models did not produce summer desiccation. The response of plants to elevated CO_2 concentrations might explain why some

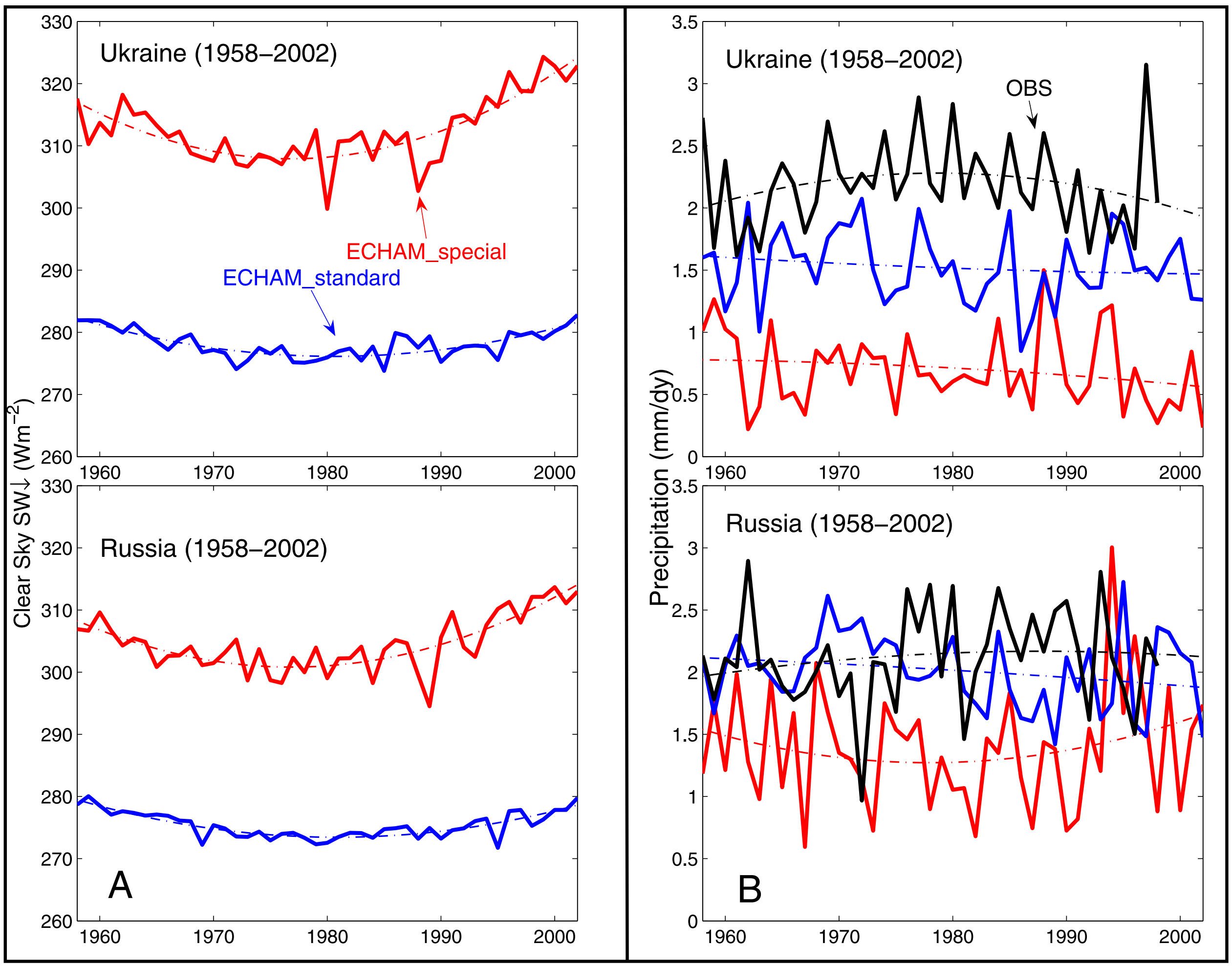

Figure 10. Same as Figure 8 but for clear sky downward shortwave radiation (a) and precipitation (b).

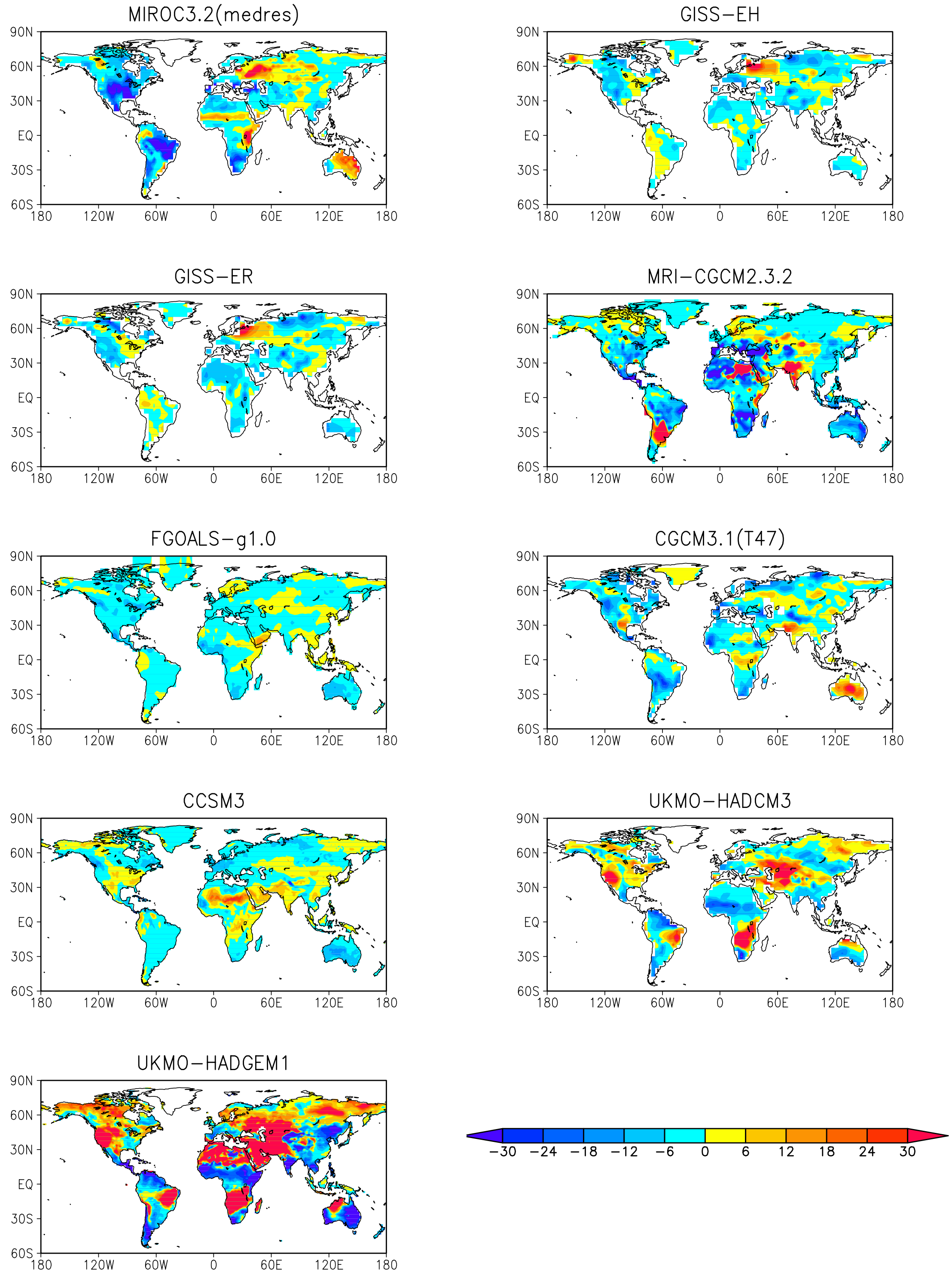

Figure 11. Relative change of soil moisture in summer (JJA) between 2060–2999 and 1960–1999 for models forced with the SRES A1B scenario, normalized by the average of 1960–1999. Units are in percent.

models project wetter land surface for some regions. Recent modeling results also demonstrated the direct carbon dioxide effects on continental river runoff [*Gedney et al.*, 2006]. These results are encouraging and underlining the nature that global climate models should better integrate the biological, chemical, and physical components of the Earth system [*Karl and Trenberth*, 2003].

[23] To our knowledge, no soil moisture evaluation using observations has been done in the previous IPCC reports. We attempt to provide quantitative evidence for the forth-

coming IPCC AR4 about the observed and model simulated soil moisture patterns. We hope our analysis will assist modelers to identify model deficiencies and further improve model performances. With better parameterization systems implemented in the next generation models, we expect to see more realistic soil moisture products.

[24] **Acknowledgments.** We thank the international modeling groups for providing their data for analysis, the Program for Climate Model Diagnosis and Intercomparison for collecting and archiving the model data, the JSC/CLIVAR Working Group on Coupled Modelling and their Coupled Model Intercomparison Project and Climate Simulation Panel for organizing the model data analysis activity, and the IPCC WG1 TSU for technical support. We thank Nina Speranskaya for updating the Russian data and Masahiro Hosaka (MRI), Seita Emori (NIES/FRCGC), Teruyuki Nishimura (FRCGC) and Toru Nozawa (NIES) for providing top 1 m soil moisture model output to us, and Chris Milly and one other reviewer for valuable comments. We are grateful to the Max Planck Institute for Meteorology (Johann Feichter, Philipp Stier) for making the ECHAM5 HAM simulations available. This work is supported by NOAA grant NA03-OAR-4310057. Work at ETH is supported by the National Center for Competence in Climate Research.

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