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ERA-40 Project Report Series No. 20

Evaluation of reanalysis soil moisture simulations using updated Chinese soil moisture observations

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Abstract

Using 19 years of Chinese soil moisture data from 1981-1999, we evaluate soil moisture in three reanalysis outputs: ERA40, NCEP/NCAR reanalysis (R-1), and NCEP/DOE reanalysis 2 (R-2) over China. R-2 shows improved interannual variability and better seasonal patterns of soil moisture than R-1 as the result of incorporation of observed precipitation, but not for all stations. ERA40 produces a better mean value of soil moisture for most Chinese stations and good interannual variability. Limited observations in the spring indicate a spring soil moisture peak for most of the stations. ERA40 generally reproduced this event, while R-1 or R-2 generally did not capture this feature, either because the soil was already saturated or the deep soil layer is too thick and damps such a response. ERA40 and R-1 have a temporal time scale comparable to observations, but R-2 has a memory of nearly 5 months for the growing season, about twice the temporal scale of the observations. The cold season tends to prolong soil moisture memory by about 3 months for R-2 and 1 month for ERA40. The unrealistic long temporal scale of R-2 can be attributed to the deep layer of the land surface model, which is too thick and dominates the soil moisture variability. R-1 has the same land surface scheme as R-2, but shows a temporal scale close to observations, which actually is because of soil moisture nudging to a fixed climatology. This new long time series of observed soil moisture will prove valuable for other studies of climate change, remote sensing, and model evaluation.

1. Introduction

Our climate system is chaotic, such that a small perturbation in initial conditions may produce dramatically different weathern patterns after a finite amount of time (Lorenz 1963, 1993), and this property of the climate system makes a precise weather forecast beyond a few weeks nearly impossible. However, as pointed out by Lorenz, climate predictability is possible if based on forcing by slowly changing boundary conditions (climate predictability of the second kind). Over the ocean, the tropical atmosphere large-scale circulation and rainfall are mainly determined by the boundary conditions of sea surface temperatures and it is possible to predict large-scale circulation and rainfall over tropics provided ocean temperature can be predicted over this region (Shukla 1998). Over the continents, soil moisture is the most important component of meteorological memory, along with snow cover (Delworth and Manabe 1988, 1993). Especially in the extratropics, with its large seasonal changes, the soil plays a role analogous to that of the ocean (Shukla and Mintz, 1982). This idea has been validated by various studies. For example, Durre et al. (2000) found a memory of past precipitation existing in the interior of continents at least during summers. Eltahir (1998) proposed that this memory is provided by the land surface through a positive feedback between soil moisture and rainfall. GCM simulations also indicate soil moisture contributes to precipitation predictability (Dirmeyer, 2000), especially in transition zones between dry and humid climates (Koster et al. 2000, Koster et al. 2004).

Since soil moisture observations are limited both in time and space, model produced soil moisture often serves as an alternative in research work (Robock et al. 2000). Reanalyses are the most widely used substitutes, as they have the advantages of global coverage and long time series. Three most wide-known soil moisture reanalysis come from the European Centre for Medium Range Weather Forecasting (ECMWF) 40-year reanalysis (ERA40, Simmons and Gibson, 2000) and the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) (Reanalysis 1 (R-1), Kalnay et al. 1996, Kistler et al. 2001) and the follow-up NCEP/Department of Energy (Reanalysis 2 (R-2), Kanamitsu et al. 2002). These reanalysis products are widely used in model initializations and climatology research. However evaluations with *in situ* observations or model intercomparisons are indispensable for a better understanding of parameterization systems and improving reanalyses. Roads et al. (1999) compared surface water terms in R-1 to the NCEP global spectral model, and they found the variability of surface water in R-1 is less than that in the global spectral model, mainly due to the nudging term. Maurer et al. (2001) evaluated the surface water characteristics in R-1 and R-2 with model simulated surface fluxes, and they reported that evapotranspiration in R-2 shows less biases than R-1. However, these works are not based on observed fluxes. Recently, Dirmeyer et al. (2004) compared ERA40, R-1 and R-2 along with other 5 soil moisture products with observed soil moisture. They concluded that no single product was obviously superior in all climates, and that the mean annual cycle is generally better simulated than interannual variations.

In this paper, we take advantage of newly updated soil moisture observations from China to evaluate the t soil moisture simulations from ERA40, R-1 and R-2. In section 2, we describe our updated Chinese soil moisture, which is followed by a short review of soil moisture reanalysis products in section 3. In section 4, the soil moisture reanalysis is evaluated in terms of the seasonal cycle, interannual variability and temporal scale. Section 5 presents discussion and conclusions.

2. Updated Chinese Soil Moisture for 1981-1999

The Global Soil Moisture Data Bank archived a Chinese soil moisture data set for 43 stations for 1981-1991 (Robock et al. 2000). These data sets have been extensively used to investigate the scales of soil moisture variations (e.g., Entin et al. 2000, Liu et al. 2001) or for land surface model evaluation and have proved to be very helpful for model improvements (e.g., Entin et al. 1999). Recently we updated the Chinese soil moisture observations through 1999. Figure 1 shows the distributions of the stations, which are listed in Table 1. Soil moisture in China was measured 3 times each month on the 8th, 18th and 28th at 11 vertical layers – 5-cm layers from 0 cm down to 10 cm and 10-cm layers from 10 cm down to 1 m. The soil moisture is originally recorded as mass percentage by the gravimetric technique, and this has two major advantages: no auxiliary calibration is necessary and relatively small errors. The soil moisture then is converted to volumetric soil moisture:

$$\theta_v = \theta_m \frac{\rho_b}{\rho_w} \tag{1}$$

where ρ_b is the bulk density of soil, ρ_w is the density of water, θ_m is the mass percent of measured soil moisture and θ_v is volumetric soil moisture. For evaluation purposes, volumetric soil moisture usually is converted to total soil water by multiplying by the corresponding layer thickness or plant available soil moisture by subtracting the wilting level from the total. Figure 2 gives a sample plot of total soil moisture for

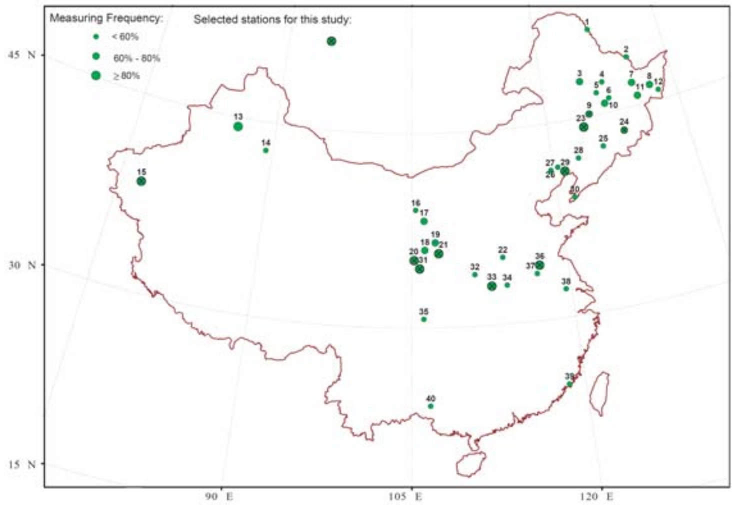


Figure 1: Soil moisture station map. The number is the station ID (see Table 1). The size of the circles indicates the data quality (frequency of available observations during the period April-October) and circles with an "X" are the stations chosen for comparison with the models

the top 10 cm, 50 cm and 1 m layers for station 9 (a northern station) and station 15 (a western station). Station 9 shows greater interannual variations than station 15 under the control of a different climate and both stations have a homogenous record over the 19 years.

Table 1 List of soil moisture stations. Stations with "§" on ID were selected in this study. "-" means that different types of vegetation were planted together and "/" means the vegetation changes from year to year. The elevation data with "" were extracted from a 1 km x 1 km digital elevation map of China (USGS, 2004). Soil types are based on a 1°×1° soil type map of China (FAO, 1970-78), thus providing only the dominant soil type for that particular grid box, which may not be representative of the actual station soil type.*

Station ID	**Name**	**Elevation (m)**	**Soil type**	**Vegetation**	**Record Period**
1	Huma	177	Silt clay	wheat/bean	1981-1999
2	Jiayin	90	Loam	wheat/bean	1981-1999
3	Fuyu	167	Loam	Not Available	1981-1999
4	Hailun	239	Loam	Not Available	1981-1999
5	Qinggang	205	Loam	wheat	1981-1999
6	Bayan	135	Loam	maize/bean	1981-1999
7	Jiamusi	81	Loam	cabbage-maize-bean	1981-1999
8	Baoqing	83	Loam	bean/wheat	1981-1999
§9	Fuyu2	*134	Loam	maize	1981-1999
10	Haerbin	*154	Silt clay	bean/maize	1981-1999
11	Boli	217	Clay loam	cabbage/beet	1981-1999
12	Hulin	100	Silt clay	wheat-bean	1981-1999
13	Wulanwusu	468	Sand	wheat	1981-1999
14	Tulufan	-49	Clay loam	cotton	1981-1999
§15	Shache	1231	Silt clay	wheat	1981-1999
16	Xilinguole	*1231	Clay loam	grass	1981-1999
17	Yongning	1117	Silt clay	wheat	1981-1999
18	Guyuan	1753	Silt clay	Not Available	1981-1999
19	Huanxian	*1302	Silt clay	wheat	1981-1999
§20	Tongwei	1768	Silt clay	Not Available	1981-1999
§21	Xifengzhen	1421	Silt clay	wheat	1981-1999
22	Xinxiang	79	Clay loam	wheat-maize	1981-1999
§23	Changling	189	Loam	Not Available	1981-1999
§24	Dunhua	524	Silt clay	maize/maize-bean	1981-1999
25	Hainong	*336	Silt clay	maize/millet	1981-1999
26	Chaoyang	169	Loam	Not Available	1981-1999
27	Jianping	*454	Loam	rice-maize-bean-potato	1981-1999
28	Xinmin	31	Loam	vegetables/bean/maize	1981-1999
§29	Jinzhou	*22	Silt clay	Not Available	1981-1999
30	Jinxian	27	Silt clay	maize/potato/bean/vegetables	1981-1999
§31	Tianshui	1083	Silt clay	wheat	1981-1999
32	Lushi	569	Silt clay	wheat-maize	1981-1999
§33	Nanyang	129	Sand	wheat-maize	1981-1999
34	Zhumadian	83	Loam	maize-wheat	1981-1999
35	Nanchong	309	Sand	Not Available	1981-1999
§36	Xuzhou	*46	Clay loam	wheat-potato-bean	1981-1999
37	Suxian	*30	Loam	wheat-bean/sesame	1981-1999
38	Zhenjiang	*15	Clay loam	vegetables-bean-wheat	1981-1999
39	Jinjiang	54	Loam	peanut-sweet potato	1981-1992
40	Baise	174	Clay loam	maize	1981-1999

We did quality control for the data sets in terms of the homogeneity and measuring frequency (the ratio of available observations to the entire period). The resulting 40 homogeneous stations are unevenly distributed and most of the stations are located in Northern or Central China, mainly in Yellow River basin and Song-Liao River basin (Figure 1). There are only three stations in less populated Western China and two stations in Southern China.

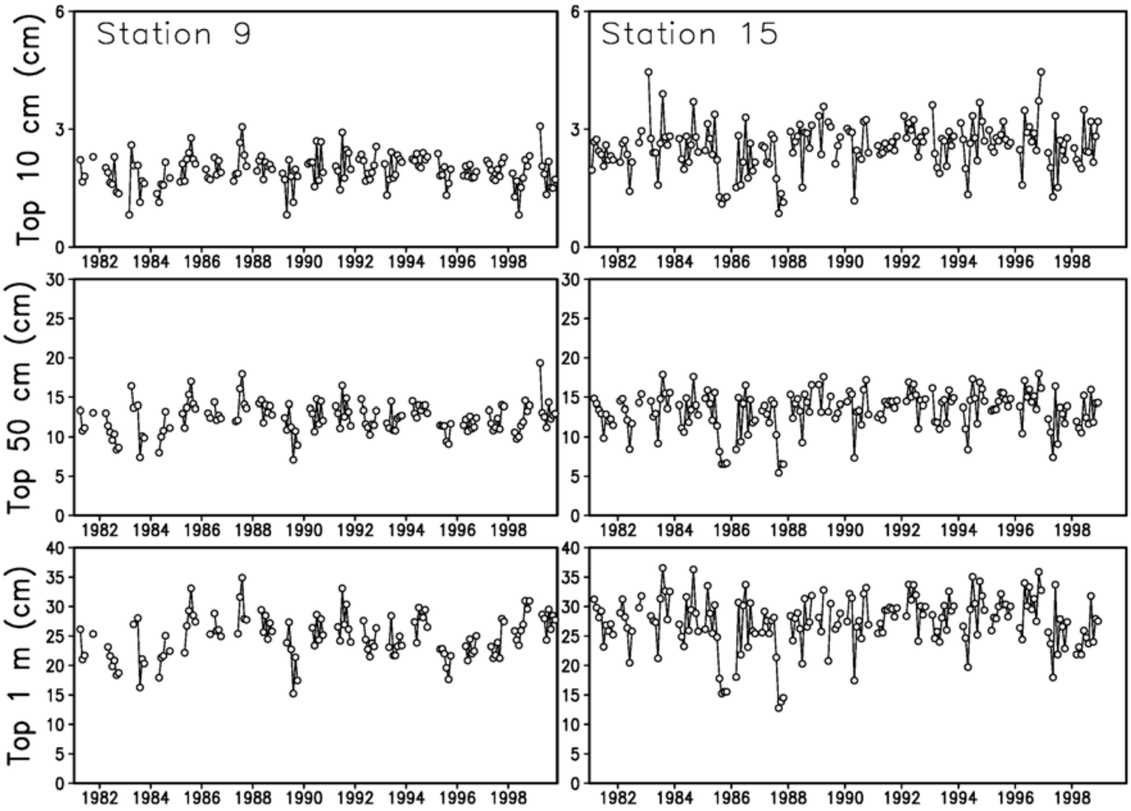


Figure 2: Total soil moisture (cm) at three levels: top 10 cm, top 50 cm and top 1 m for two representative stations, Station 9 from Northern China in the left column and Station 15 from Western China in the right column.

We also calculated the measuring frequency for the period from May to October, which generally covers the growing season, and we classified it into three categories: more than 80% of the time, between 60% and 80%, and less than 60%. There are 9 stations with measuring frequencies of more than 80% (Figure 1). Generally fewer measurements are available for Northern China due to the comparatively long frozen seasons when soil moisture is hard to measure. As for the top 10 cm, 28 out of 40 stations have a measuring frequency over 85%, which highlights the potential for remote sensing evaluations.

3. Soil moisture and nudging in reanalysis

Bengtsson and Shukla (1988) and Trenberth and Olson (1988) were pioneers who proposed the idea of reanalysis. Since then, several reanalysis projects have been conducted and three of the most well known global reanalyses are ERA40, R-1 and R-2. Recognizing the importance of soil moisture, these reanalyses archived model-calculated soil moisture at grid points. ERA40 produced soil moisture starting in 1957, and provided the values at a horizontal resolution of T159 (about 125 km) with global coverage. R-1 has soil moisture back to 1950 at a horizontal resolution of T62 (about 210 km) and recently R-2, an updated version of R-1, became available with the major advantages of reduced human errors and improved soil wetness (Kanamitsu et al, 2002), but it only started in 1979.

The soil moisture calculated by reanalyses depends on the land surface scheme used, the forcing (particularly precipitation and solar insolation), and the nudging employed. In terms of land surface, ERA40 uses a scheme called TESSEL (Tiled ECMWF Scheme for Surface Exchanges over Land, Van Der Hurk et al. 2000). The scheme has 4 prognostic layers for temperature and soil moisture with layer thicknesses of 7 cm, 21 cm, 72 cm and 189 cm going down from the top. There are some basic differences from the old scheme (Viterbo and Beljaars 1995, VB95) employed in ERA15, especially the treatment of snow and vegetation, an added prognostic snow layer on top of the soil, and reduced infiltration over frozen soils. Offline validation showed cold season processes are more realistic in TESSEL than in VB95. The uniform vegetation over land in VB95 was replaced by a 20-type vegetation map, with land surface parameters, such as root distribution and leaf area index, varying according to vegetation type. Van Der Hurk et al. (2000) pointed out that “model performance becomes increasingly dependent on a proper choice of vegetation dependent model parameters.”

R-1 and R-2 used the OSU LSM (Pan and Mahrt, 1987, Pan 1990) with two layer thicknesses of 10 cm and 190 cm separately. It was designed to model the essential characteristics of the land interactions with the atmosphere primarily for partitioning of net radiation into latent and sensible heat (Mahrt and Pan 1984). Vegetation types were from Simple Biosphere model (SiB) climatology (Dorman and Sellers 1989), while many parameters like soil properties (type, wilting point, critical point and porosity) and vegetation canopy cover were fixed globally.

Because model-generated precipitation and insolation are not perfect in reanalyses, soil moisture tends to drift to a too dry or too wet state. To prevent this, the soil moisture is nudged based on different criteria. For ERA40, soil moisture increments were provided by a linear combination of the screen level relative humidity and temperature increments each 6 hr (Douville et al. 2000, Mahfouf et al. 2000). This nudging technique is more reliable than the old nudging scheme in ERA15, which only assimilated specific humidity (Douville et al. 2000).

In R-1, soil moisture was nudged to the Mintz and Serafini (1992) climatology with a 60-day time scale. This nudging term is quite large (Maurer et al. 2001) so interannual variations are suppressed (Srinivasan et al. 2000, Kistler et al. 2001). Another concurrent problem is the nonclosure of the water budget. In R-2, soil moisture is constrained more elegantly in that the difference between model precipitation and observed pentad (5-day) precipitation is used to correct soil moisture (Kanamitsu et al. 2002). This provides an opportunity for us to detect possible model deficiencies previously obscured by the strong nudging in R-1.

4. Comparison of soil moisture observations with reanalyses

Srinivasan et al. (2000) used soil moisture observations for Illinois (Hollinger and Isard 1994) and central China (Robock et al. 2000) for 1981-1988 to evaluate R-1 and an earlier version of the ECMWF reanalysis (ERA-15, Gibson et al. 1997). They found that the reanalyses were able to capture some of the observed seasonal cycles, and the interannual variations in Illinois, but that the variations were damped out by the soil moisture nudging. Kanamitsu et al. (2002) compared R-2 to Illinois soil moisture, and found a better agreement than for R-1, in terms of mean, amplitude of seasonal cycle, and interannual variations. They cautioned about using R-2 for the first several years of the reanalysis due to spinup problems and because of problematic pentad precipitation (missing data were mistakenly reported as zero in the earlier period). We address the spinup issue later, showing that this anomalously long spinup period for R-2 is due to the too large moisture reservoir in the land surface model. This was also found by Robock et al. (1998) in some of the Atmospheric Modeling Intercomparison Project climate models based on the simplified simple biosphere model (Xue et al. 1991). Xue et al. (1996) and Robock et al. (1997) have shown that this long time scale is due to the slow exchange of soil moisture between the deep third layer and the upper 2 layers in these models.

To take full advantage of our long time records, we compared the reanalyses to 10 stations with relatively high measuring frequency (Figure 1), one station from Western China, four from Northern China and the other five from Central China. We used the values from the 28th of each month from each station and the corresponding daily value from the model grid point nearest the station. We used the original reduced Gaussian grid output from ERA40 to correct for ocean influences in the lower-resolution gridded data publicly available.

Missing data in observations is one of the major concerns when performing data analysis. Interpolation techniques can be used to fill data gaps but may introduce errors, which would make the quality of the analysis questionable. Thus we have not adjusted the missing data in the observations to avoid introducing artificial relationships. When we compare to reanalyses, we only use model output from the reanalyses for times when observations exist, and treat the other reanalysis output as missing, unless otherwise explicitly specified.

Since the land surface scheme in R-1 and R-2 only has two soil layers (0-10 cm and 10-200 cm), we used the following equation to scale the soil moisture to the top 1 m for R-1 and R-2 to compare with observations and ERA40,

$$W = 100\ (0.10 \times \theta_1 + 0.90 \times \theta_2) \tag{2}$$

where W represents the soil moisture (cm) in the top 1 m and θ_i is the fractional volumetric soil moisture for layer i. The fraction of each layer accounting for the contribution to the top 1 m was used as the weighing factor. Although other methods, such as extracting the unavailable soil moisture or simply summing up the soil moisture in the top 2 m and dividing by 2 would result in different amounts of soil moisture, they would tend to only shift the time series up or down along the vertical axes of the figures and the variations in time would not be very different.

As first explained by Vinnikov et al. (1996), the scale of soil moisture variations includes a very small scale related to local soil, root, and topographic features and a much larger scale driven by the atmosphere. The atmospheric-driven spatial scale of soil moisture, which represents most of the variance, is about 500 km (Entin et al. 2000; Liu et al. 2001). As the resolution of ERA40 is about 215 x 275 km^2 over China, and that of R-1 and R-2 is about 160 x 210 km^2, the mismatch of scale between point observations and reanalysis grid will not present a problem.

4.1 Time series and correlations

Figure 3 shows comparisons of observed soil moisture for three stations with the three reanalyses. Generally, R-1 has very large amplitude of seasonal variation but very small interannual variability, the only exception being for Station 15, which has nearly constant soil moisture and small amplitudes of variation for both R-1 and ERA40. At the same time the amplitude of variations in R-2 is also comparable to observations, but R-2 underestimates the soil moisture most of the time for 8 out of our 10 stations, and such systematic biases do not exist in ERA40 or R-1. Other soil moisture indices, such as plant-available soil moisture, may not necessarily give the same result. However our results are in agreement with the analysis of Dirmeyer et al. (2004), who used a soil wetness index for Illinois (see their Figure 14).

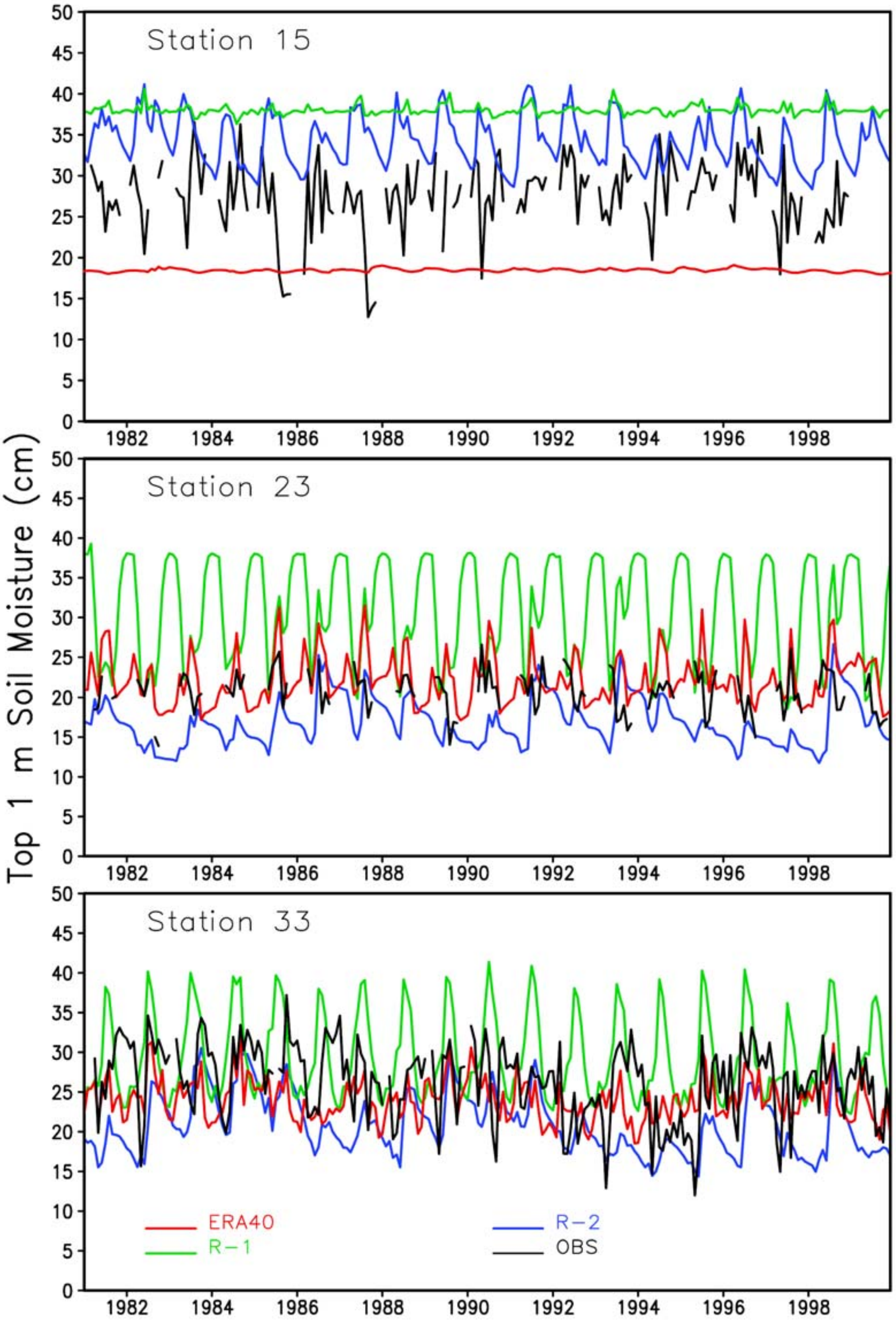


Figure 3: Total top 1 m soil moisture for Station 15 (Western China), Station 23 (Northern China) and Station 33 (Central China). R-1 has very little interannual variability. For Station 15, the amplitude of the interannual variability is too small for R-1 and ERA40.

We have also calculated the correlation coefficients of monthly soil moisture (28th day of each month) between models and observations (Figure 4). Generally, R-2 had a higher correlation than R-1 (7 out of 10 stations). The correlation of ERA40 is smaller, but still comparable to that of R-2. For station 23, both R-1 and R-2 had negative correlations. Removal of the seasonal cycle generally improved the correlations for ERA40 and R-1 but not for R-2, discussed next.

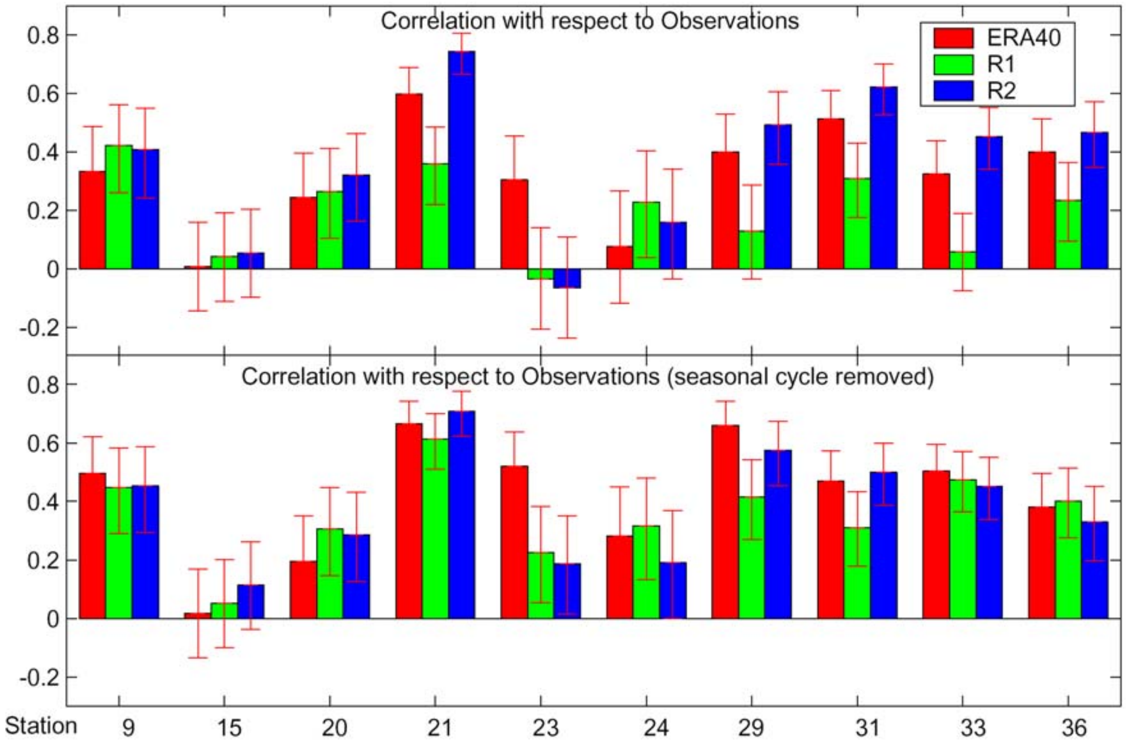


Figure 4: Correlation of monthly (day 28 of each month) soil moisture observations for 10 stations indicated in Figure 1 with reanalyses. Top panel includes the seasonal cycle and bottom panel has the mean seasonal cycle removed. The black error bars indicate the 95% significance level for the correlation coefficients. Remarkably, in general the correlations are higher with the seasonal cycle removed, except for R-2.

4.2 Seasonal Cycle

Figure 5 gives the seasonal cycles of soil moisture for our three representative stations. Station 15 has nearly constant soil moisture estimates for both R-1 and ERA40, which do not reproduce the observed seasonal cycle. For ERA40, the value is virtually constant at the wilting point, while for R-1 it is constant at the saturation value. In both cases, the seasonal cycle of precipitation and evapotranspiration are so much out of balance that soil moisture cannot change as observed. For most stations, R-2 has a good climatology and patterns of seasonal variation similar to observations, but underestimates the mean soil moisture amount. This is in contrast with R-1, which has quite a strong seasonal variation, because it is nudged to the Mintz and Serafini (1992) climatology, as also pointed out by Kanamitsu et al. (2002). In terms of monthly average values, ERA40 is closest to observations. For the non-western stations, all models produce the soil moisture peak correctly around late summer due to the arrival of the summer monsoon precipitation.

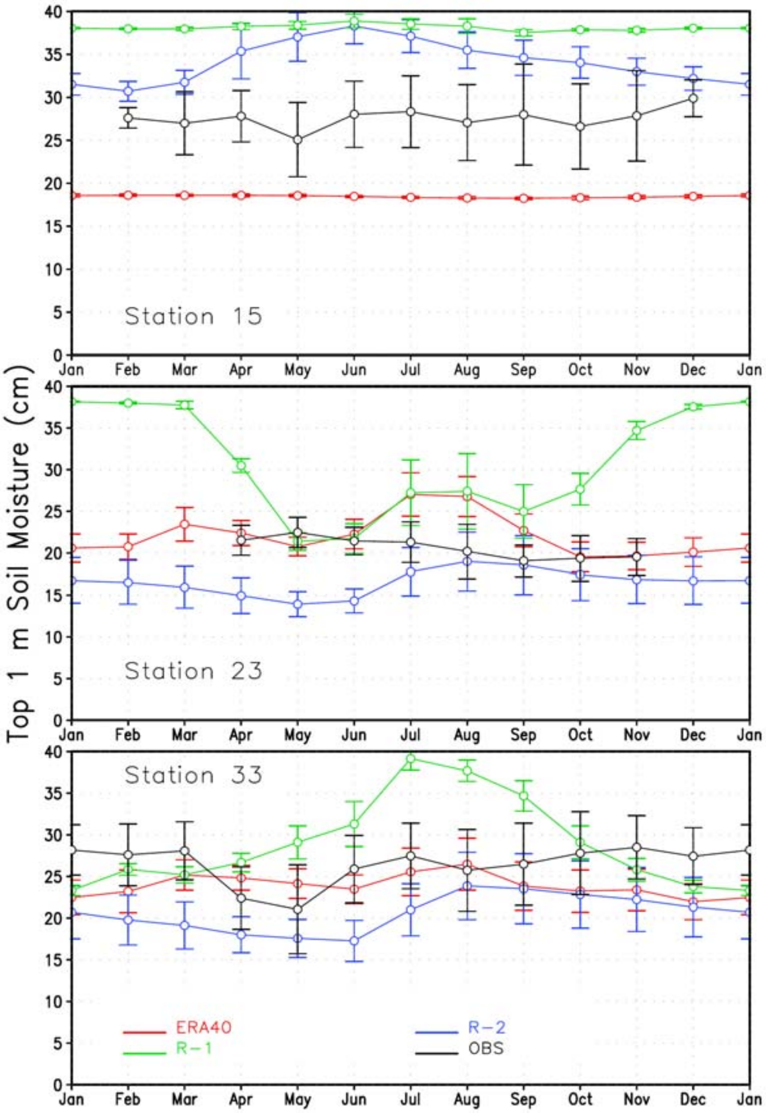


Figure 5: Seasonal cycle of top 1 m total soil moisture for three stations (see Figure 1) and reanalyses. The error bars are ±1 standard deviations from the means.

4.3 Spring Snow Melt

Melting snow is an important source of moisture for northern and western agricultural regions since it can recharge the soil and produce runoff. Whether the melting snow will recharge the soil or run off as streamflow depends on the soil conditions. In the case of saturated soil, there is no extra space for water to infiltrate (Robock et al. 1998, 2003), and thus it is very likely the melting snow produces spring runoff. Generally, ERA40 has a small soil moisture peak in early spring due to snow melting recharging, while such a soil moisture peak is basically missing in R-1, especially for northern China where the soil is pretty wet in winter. Although the soil in R-2 is not as wet as in R-1, the spring soil moisture peak is still missing or too weak. Our speculation is that this may be attributed to the physical configuration of R-1 and R-2, since the deep layer in R-1 and R-2 is too thick (190 cm) and the water holding capacity is unrealistically too large. Although missing observations in the cold season inhibit a deeper investigation for spring snow melting events, limited observations from stations in central China in cold seasons confirm the existence of a soil moisture peak in early spring. This may be similar to the observations in Russia (Robock et al. 1998) where the water table intrudes into the top 1 m, a phenomenon which is not included in the R-1 and R-2 reanalysis land surface schemes.

4.4 Monthly and Interannual Variability

Figure 6 shows the monthly and interannual variations of soil moisture for selected stations and the reanalyses, and Figure 7 shows the soil moisture anomalies. R-1 shows a rather small interannual variation, especially during winter. Since snow melting is mainly responsible for soil moisture changes in cold season, and a unit error for snow melt in R-1 wets the ground excessively (Kanamitsu, personal communication), this is especially evident for Northern stations. R-2 shows a larger interannual and seasonal variations than R-1 although the soil generally is too dry. Drier soil in R-2 may partly be attributed to warmer soil and 2-m air temperature as well as to a better albedo algorithm than R-1 (Kanamitsu et al. 2002). The variability of ERA40 is closest to the observations. Models generally did a pretty good job of reproducing the anomalous wet and dry years, such as the wet years of 1984 at Station 33 and the dry year of 1982 at Station 23 (Figure 7). In a test of how closely the interannual variability of reanalyses matches the observations, we calculated the anomaly correlation between the models and observations for the summer months (JJA). Generally ERA40 has the best interannual variability with respect to observations (Figure 8).

In Figure 7 it is quite obvious that the soil moisture does not change in the winter for R-2. This means that the time scale of soil moisture anomaly in R-2 is comparatively large. Delworth and Manabe (1988) developed a theory that soil moisture variations can be approximated as a first-order Markov process,

$$r(t) = e^{-\frac{t}{T}} \tag{3}$$

where r is the autocorrelation, t is the time lag, and T is the time scale. This theory has been extensively used to investigate the scales of soil moisture variations using observations (Vinnikov et al. 1996, 1999a, 1999b). Using this theory, Entin et al. (2000) calculated the temporal scale of Chinese soil moisture to be 1.6-2.4 months, which increases from south to north.

Here we adapt the same theory and assume that the soil moisture variation is stationary. We removed the seasonal cycle and calculated the temporal scale for all the 10 stations. Two groups of calculations are carried out. One considers the missing values in observations by taking out the corresponding data in reanalyses, thus making the results comparable. To investigate the possible influence of the cold season on temporal scale (because missing values in observations are generally in winter), we did another set of calculations for the full data sets for the reanalyses. Figure 9 shows the temporal autocorrelation results and Table 2 gives the numeric values. The slopes of the lines in Figure 9 correspond to the temporal scales.

ERA40 shows the highest variability between stations. The soil moisture increments were set to be zero when the air temperature is below freezing or the snow covers the ground in ERA40 (ECMWF 2003), so this should increase the temporal scale (about 1 month in general, see Table 2) for the northern stations.

Station 15 exhibits a much lower autocorrelation than the other stations in R-1 and R-2, which must be related to the parameters for the land surface model at that point. The calculated temporal scale for R-1 shows the largest similarity between stations and between full data and only data that correspond to the observations. This must be the effect of relaxing the values to the Mintz and Serafini climatology. R-2 has a temporal scale longer than 6 months for all nonwestern stations. The mean temporal scale of R-1 and ERA40 is comparable to observations, which is consistent with the results of Entin et al. (2000), while R-2 has an unrealistically long mean time scale of about 8 months. Thus these calculations support that the deep layer in

R-2 is too thick and dominates the overall variability of soil moisture (Roads et al. 1999). This could further impact the evaporation and precipitation.

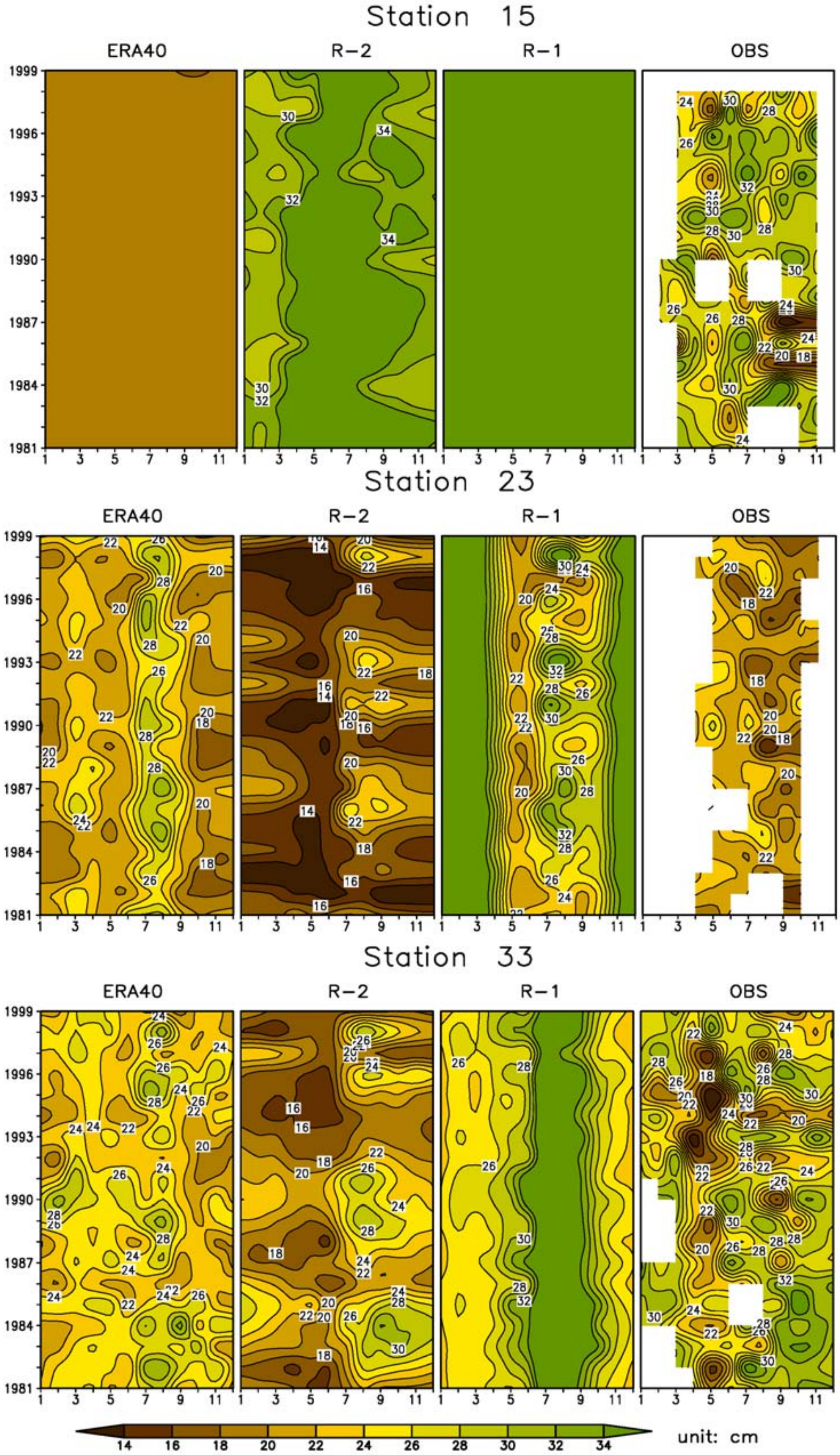


Figure 6: Month-year plots of top 1 m total available soil moisture evolution for three stations and reanalyses.

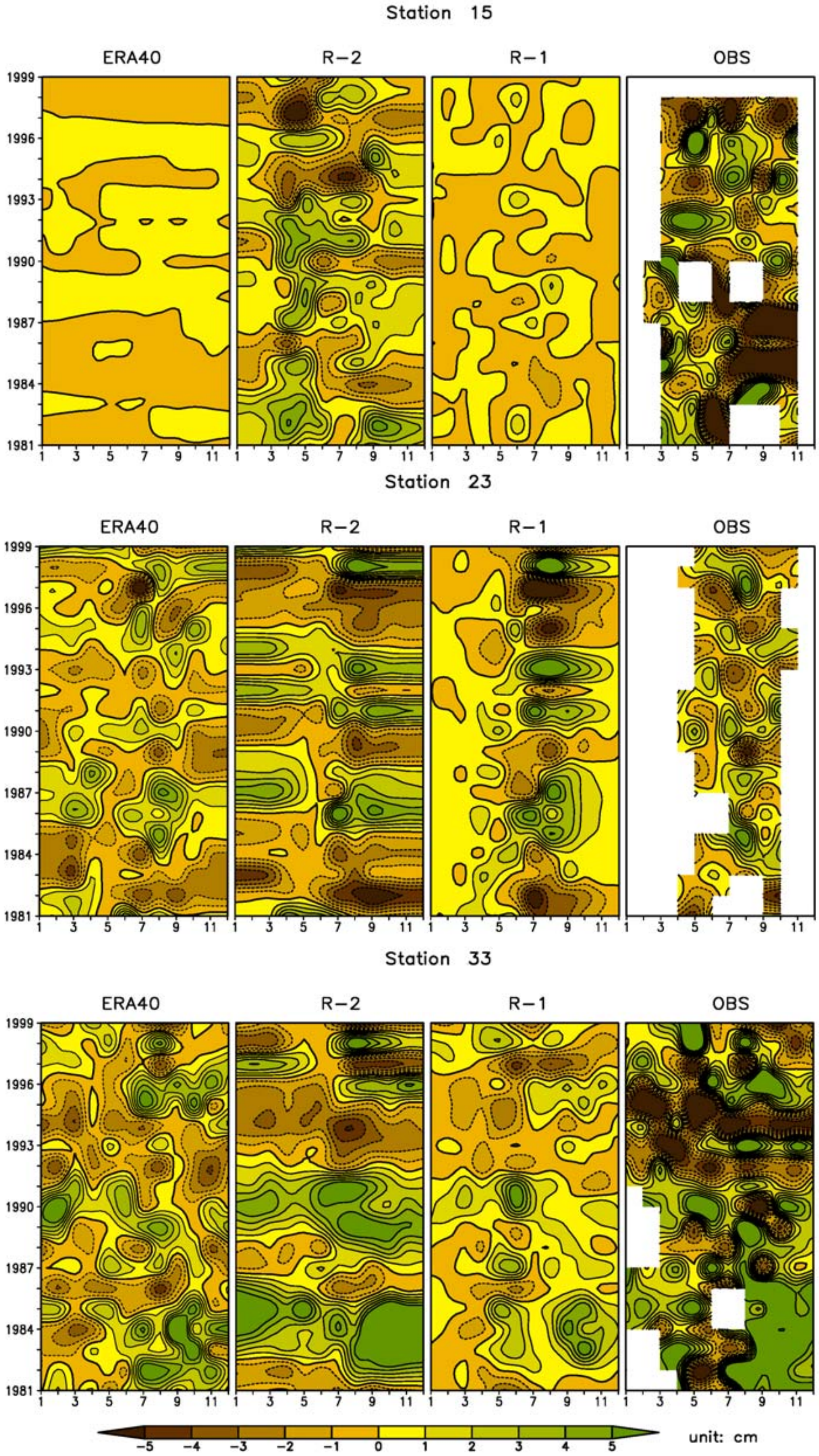
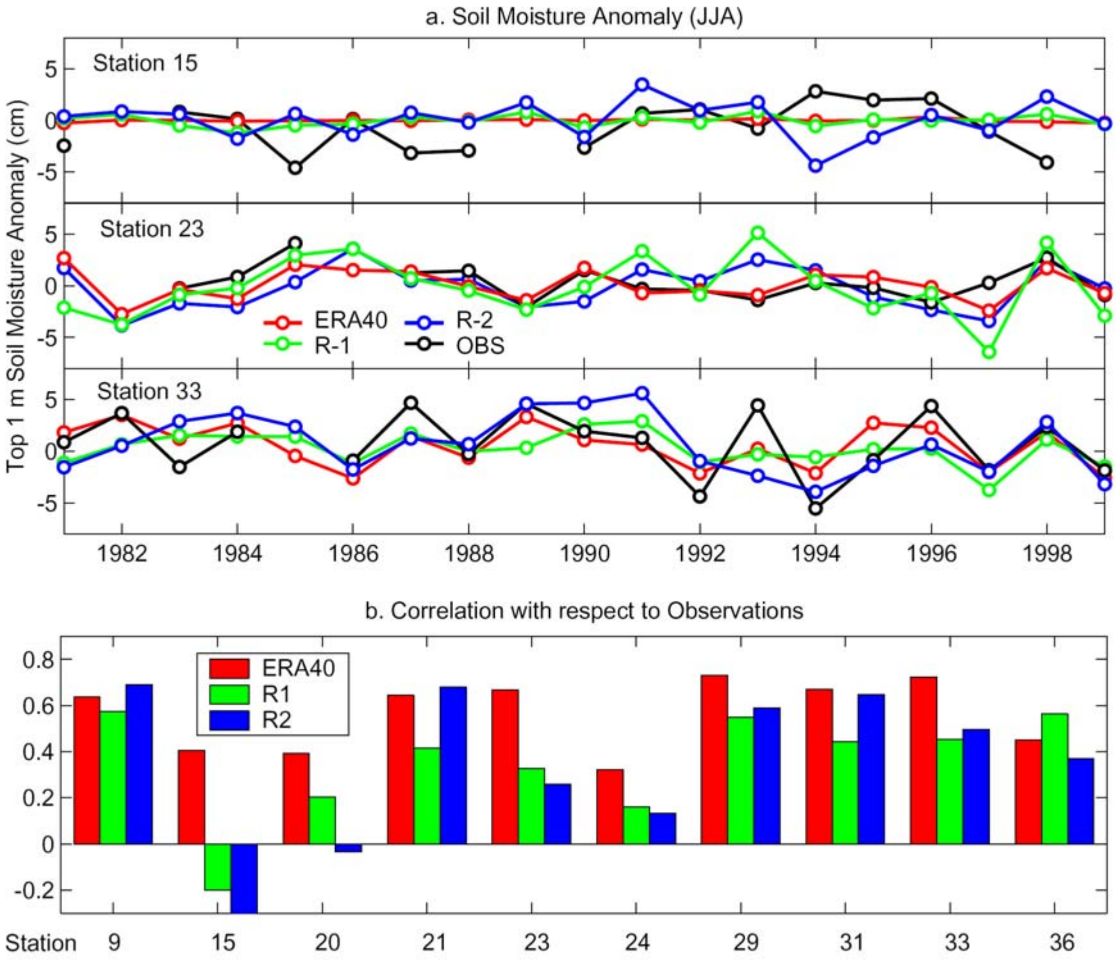


Figure 7: Same as Figure 6, but for anomalies with respect to the mean for 1990-1998. Thick line is 0, and contour interval is 1 cm.


a. Soil Moisture Anomaly (JJA)

b. Correlation with respect to Observations

Figure 8 Soil moisture summer interannual variability. (a) Top 1 m soil moisture anomaly for Station 15 (Western China), Station 23 (Northern China) and Station 33 (Central China). Anomaly was calculated as the mean value for summer months (JJA) in every year based on climatology of 1990-1998. (b) Soil moisture anomaly correlation between models and observations for JJA. ERA40 generally exhibits the best interannual variability as compared to observations among three models.

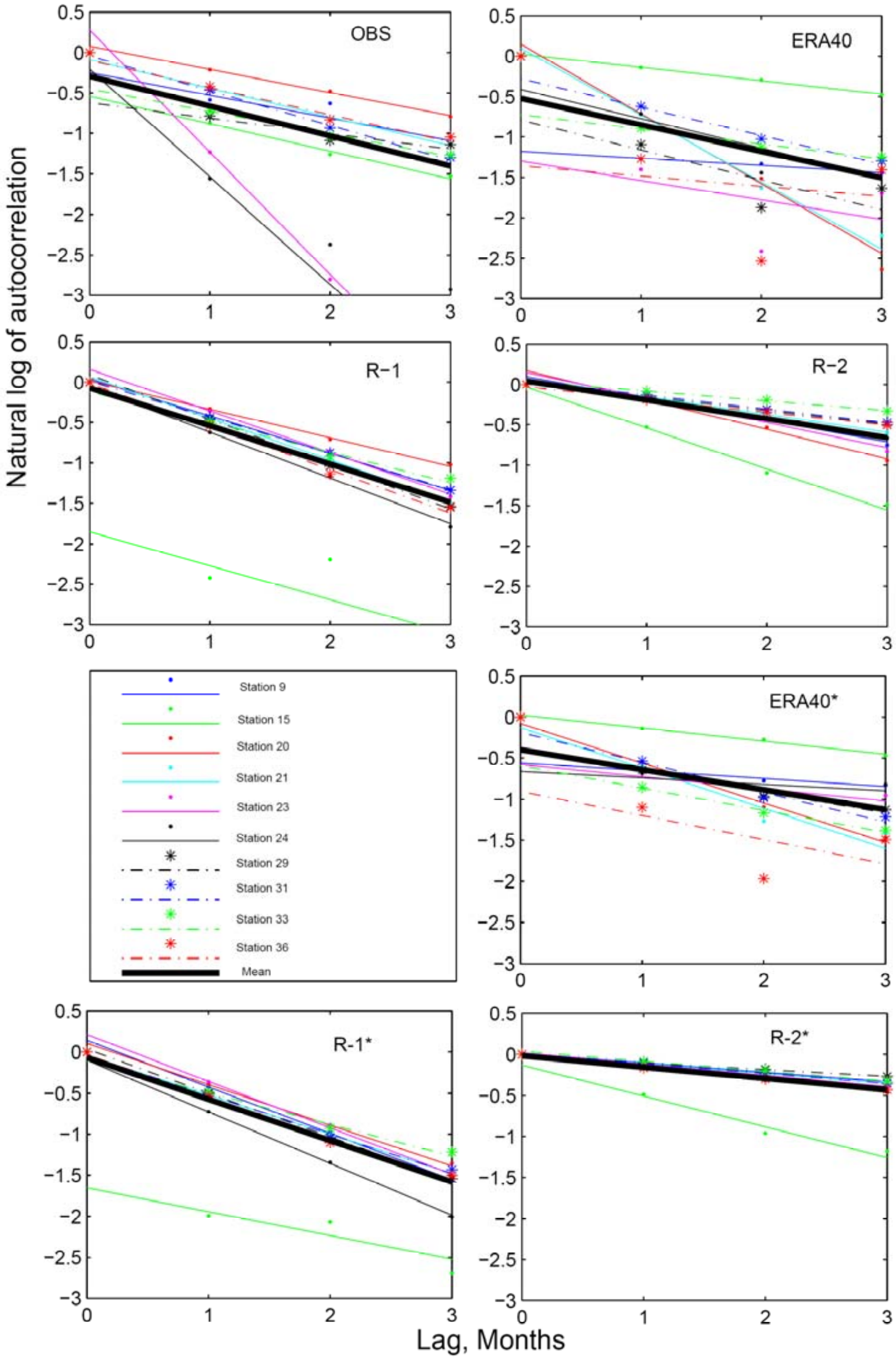


Figure 9 Temporal autocorrelations of observations and reanalyses for all 10 stations indicated in Figure 1, plotted as natural logarithm of the correlation coefficients. The slope of the best fit line gives the temporal scale. Top 4 panels are results when taking out the corresponding data from reanalyses if there have missing values in observations. Bottom 3 panels are calculations based on full data sets in reanalyses. The thick lines in black show the arithmetic average for all 10 stations.

*Table 2: Temporal scale of soil moisture variation (months) for observations and each reanalysis for each station, and the mean values. Calculations for reanalyses were done only for the times when data existed for the observations, and for the complete time series (rows with * and in italics). Also shown in parenthesis is 1 standard deviation from the mean.*

	West	North				Center					
Station	15	9	23	24	29	20	21	31	33	36	Mean
OBS	2.9	3.6	0.7	0.8	5.2	3.5	2.8	2.3	3.6	3.0	2.8 (± 1.4)
ERA40	6.1	11.5	4.2	2.7	2.7	1.2	1.2	2.8	5.5	8.0	4.6 (± 3.3)
*ERA40**	*6.3*	*10.5*	*6.9*	*12.9*	*4.0*	*2.1*	*2.0*	*2.8*	*3.7*	*3.4*	*5.4 (± 3.7)*
R-1	4.4	2.2	2.1	2.0	1.8	2.9	1.6	2.0	2.8	2.1	2.4 (± 0.8)
*R-1**	*6.1*	*1.8*	*1.9*	*1.8*	*1.8*	*1.8*	*1.8*	*1.8*	*2.6*	*2.0*	*2.3 (± 1.3)*
R-2	2.0	4.0	3.2	4.0	6.5	2.9	4.6	6.0	8.4	6.7	4.8 (± 2.0)
*R-2**	*2.8*	*8.9*	*7.2*	*6.2*	*13.6*	*7.1*	*8.0*	*8.0*	*8.4*	*7.9*	*7.8 (± 2.7)*

Since R-1 uses the same land surface scheme as R-2, this brings up the question of why its temporal scale is so much smaller. This is to a large extent because R-1 nudges soil moisture to the Mintz and Serafini (1992) climatology with a 60-day time scale while nudging in R-2 is based on observed precipitation. However this advantage of R-2 is compromised by its use of a model with a very large soil moisture reservoir, which produces an unrealistically large time scale. To most clearly separate nudging effects from other influences, since other improvements in R-2 also contribute to soil moisture simulations, would require additional experiments that keep all other physics exactly the same but with different nudging schemes.

5. Conclusions

An updated Chinese soil moisture data set has proven valuable to evaluate reanalysis simulations of soil moisture. This new data set is available without restriction at the Global Soil Moisture Data Bank (http://climate.envsci.rutgers.edu/soil_moisture).

Using 19 years soil moisture observations from a monsoon-dominated region; we evaluated three prominent soil moisture reanalysis data sets: ERA40, R-1 and its updated counterpart R-2. Kanamitsu et al. (2002) in their studies found improved soil moisture fields from R-2 when validating with Illinois soil moisture observations (Hollinger and Isard, 1994). Our analysis supports their conclusions with soil moisture observations from a different climate, where R-2 also exhibits the highest correlation with observations among the three soil moisture reanalyses. But this is a result of R-2 having a good mean climate. A reanalysis product with good mean state but poor year-to-year variations may not be a good choice for use in climate modeling. ERA40 is also generally highly correlated with observations after removing seasonal cycle, and produces less bias and a time scale closer to observations. Although Kanamitsu et al. (2002) argued that direct comparison between observed soil moisture and model simulations could be misleading, negative R-2 biases exist when comparing the Illinois soil moisture observations with R-2 even after removing the unavailable soil moisture (see Figure 1 of Kanamitsu et al. 2003). Whether these results are universal would require further investigation for different regions. In terms of interannual variability, ERA40 is the best among the three reanalyses products.

The temporal scale of soil moisture anomalies in ERA40 (disregarding stations 9 and 23) and R-1 are comparable to that of observations, but the scale of R-2 is extraordinarily long, about 2 times of that of observations in growing season, and cold season tends to prolong soil moisture memory around 1 month in

ERA40 and 3 months for R-2. This prolonged memory may further propagate into evaporation and precipitation. Our suspicion is that R-2 has a too thick deep layer which has a dominant influence on the soil moisture variability of the whole soil column. Clearly it is responsible for the long spinup problems found by Kanamitsu et al. (2002). An improved land surface scheme is capable of resulting in a much better precipitation prediction (e.g., Betts et al. 1996, Beljaars et al. 1996), which will be beneficial to weather forecasting. We expect that improved land surface models in future reanalyses combined with actual precipitation forcing will produce an excellent soil moisture product. The new regional reanalysis (Mitchell et al 2004), which uses a descendant of OSU LSM – the Noah model (Chen et al. 1996, Chen et al. 1997, Ek et al. 2003), which performed well in North American Land Data Assimilation System experiments (Robock et al. 2003) and which assimilates actual precipitation observations, has the potential to produce such excellent soil moisture simulations.

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