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Forty-five years of observed soil moisture in the Ukraine: No summer desiccation (yet)

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[1] We present the longest data set of observed soil moisture available in the world, 45 yr of gravimetrically-observed plant available soil moisture for the top 1 m of soil, observed every 10 days for April–October for 141 stations from fields with either winter or spring cereals from the Ukraine for 1958–2002. We averaged the summer observations over the entire region to account for the observed scale of soil moisture variations, to enhance the portion of the variance that is related to meteorological forcing. The observations show a positive soil moisture trend for the entire period of observation, with the trend leveling off in the last two decades. Although models of global warming predict summer desiccation in a greenhouse-warmed world, there is no evidence for this in the observations yet, even though the region has been warming for the entire period. While the interannual variations of soil moisture simulated by both the European Centre for Medium-range Weather Prediction and the National Centers for Environmental Prediction/National Center for Atmospheric Research reanalyses are close to the observations, neither reanalysis simulates the observed upward trend. Climate model simulations for the period show the same general shape as the observations, but differ quite a bit from each other and from the observations. An observed downward trend in insolation may have produced a downward trend in evaporation and may have contributed to the upward soil moisture trend.

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1. Introduction

[2] Using actual in situ soil moisture observations [*Robock et al.*, 2000] is important for evaluating land surface models [e.g., *Robock et al.*, 2003], as ground truth for remote sensing [e.g., *Reichle et al.*, 2004; *Prigent et al.*, 2005], and studying the spatial and temporal scales of soil moisture variations [e.g., *Entin et al.*, 2000]. In this paper, we report on a new collection of such observations and use the data to study long-term trends.

[3] While producing accurate global soil moisture data sets will require a combination of remote sensing and data assimilation using accurate land surface models [*Mitchell et al.*, 2004], the closest we have come so far is the global reanalyses, which assimilate atmospheric observations and calculate soil moisture. Both the European Centre for Medium-range Weather Prediction (ERA40) [*Simmons and Gibson*, 2000] and the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (Reanalysis 1 (R-1)) [*Kalnay et al.*, 1996; *Kistler et al.*, 2001] reanalyses have produced soil moisture values for the entire globe. Details of the reanalysis soil moisture calculations are presented by *Li et al.* [2005] and summarized in the auxiliary material[1]. Here we evaluate these reanalyses in this one region, as an indication as to whether the reanalyses can be used for evaluating long-term climate change. The NCEP/Department of Energy Reanalysis 2 (R-2) [*Kanamitsu et al.*, 2002] fixed some errors in R-1 and used actual precipitation observations rather than model-generated precipitation, but only started in 1979, so we will not evaluate it here. *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. *Li et al.* [2005] have recently evaluated all three of these reanalyses with newly extended Chinese soil moisture observations, and found that while ERA40 did a fairly good job; both R-1 and R-2 had problems due to the very deep 190-cm second layer in their land surface scheme, which resulted in too long a time scale.

[4] Most global climate model simulations of the future, when forced with increasing greenhouse gases and anthropogenic aerosols, predict summer desiccation in the midlatitudes of the Northern Hemisphere [e.g., *Gregory et al.*, 1997; *Wetherald and Manabe*, 1999; *Cubasch et al.*, 2001]. This predicted soil moisture reduction, the product of increased evaporative demand with higher temperatures overwhelming any increased precipitation, is one of the gravest threats of global warming, potentially having large

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[1] Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2004GL021914.

impacts on our food supply. We use our extended data set here to evaluate these model simulations.

Table 1. Linear Trends for Summer (JJA) Soil Moisture (*W*), Precipitation (*P*), and Air Temperature (*T*) Over the Ukraine (see Figure 2)

Period:	1958–1979	1980–2002	1958–2002
W – winter cereals (cm/10 yr)	0.91	−0.22	0.72
W – spring cereals (cm/10 yr)	0.89	−0.32	0.64
P (mm/10 yr)	4.36	−5.52	−0.31
T (°C/10 yr)	−0.45	0.78	0.15

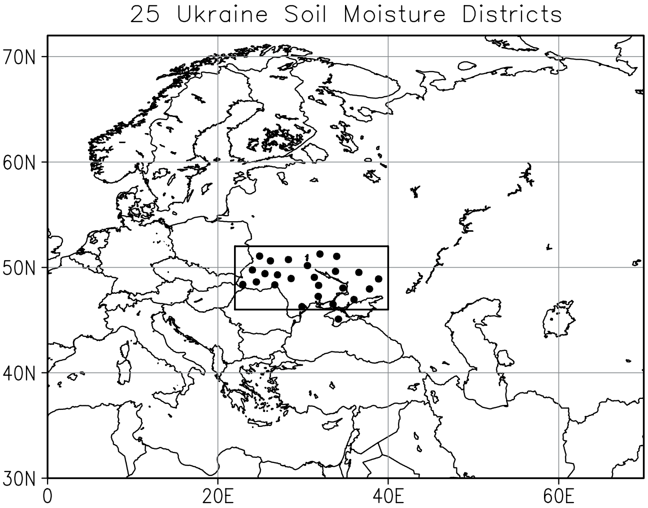

Figure 1. Location of 25 soil moisture districts with 45 yr of soil moisture observations, for the period 1958–2002. Each district has on average six soil moisture stations. Also show is the 22–40°E, 46–52°N box used for averaging the observations and model simulations shown in Figures 2–4. See Ancillary Material in HTML for color and high-resolution versions of this Figure.

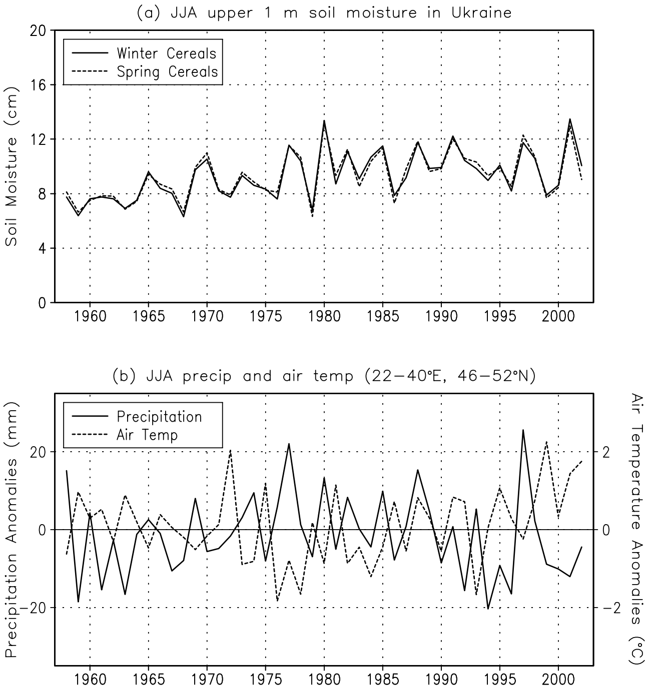

Figure 2. a) Summer (June, July, August) plant-available soil moisture in the top 1 m of soil, averaged separately for fields with winter cereals and spring cereals for the region 22–40°E, 46–52°N in the Ukraine (Figure 1). b) Summer precipitation and temperature anomalies (with respect to the mean for 1971–2000), averaged for the same stations. See Ancillary Material in HTML for color and high-resolution versions of this Figure.

2. Observations

[5] We have recently been able to enhance and update the RUSWET-AGRO data set described by *Robock et al.* [2000] with data from the Ukraine for 141 stations (Figure A1) with observations through the end of 2002. The data are district-average plant-available soil moisture for the upper 20 cm and 1 m layers at agricultural fields with winter and spring cereal crops (given separately) for 25 administrative districts of the Ukraine (Figure 1 and Table A1). The measurements of an average of about three stations for each crop type were used for each district with equal weights. The data have temporal resolution of 10 days (3 measurements per month) during the growing period, from April 8 to October 28. These data are the product of a system for soil moisture monitoring at agricultural fields established by the former Soviet Union and continued today. This 45-yr data set of observed soil moisture is the longest one of which we are aware.

[6] This new long soil moisture data set is now available at no cost at the Global Soil Moisture Data Bank, http://climate.envsci.rutgers.edu/soil_moisture/. The India, Mongolia, and China [*Li et al.*, 2005] data have just been updated and within the next year we have made arrangements to also update observations from Russia.

[7] The summer soil moisture observations for the top 1 m are shown in Figure 2a, separately for the fields with winter wheat and those with spring cereals (barley and maize), averaged for the entire region. We present averages because the scale of soil moisture variations for the midlatitudes is several hundred km [*Entin et al.*, 2000]. Thus we are studying the part of the soil moisture variations that is driven by climatic forcing, while minimizing the noise from local, small-scale features.

[8] That the two curves in Figure 2a are so close to each other, even though taken from completely independent measurements, gives us confidence that they are representative of actual soil moisture in this region. While these are

Table 2. Correlations of Soil Moisture, Precipitation, And Air Temperature Over the Ukraine, for Time Series Shown in Figure 2[a]

Period:	1958–1979	1980–2002	1958–2002
Corr [ΔW, *P*]	0.50 (0.46)	0.39 (0.38)	0.35 (0.44)
Corr [*W*, *P*]	0.58 (0.53)	0.56 (0.55)	0.48 (0.57)
Corr [*W*, *T*]	−0.50 (−0.42)	−0.25 (0.21)	−0.22 (−0.38)
Corr [*P*, *T*]	−0.58 (−0.53)	−0.37 (−0.24)	−0.46 (−0.46)
5% sig. level	0.42	0.41	0.29
1% sig. level	0.53	0.52	0.38

[a] ΔW is the change of soil moisture from spring (MAM) to summer (JJA), *W* is summer soil moisture, *P* is summer precipitation, and *T* is summer air temperature. Values in parenthesis are after removing the linear trend.

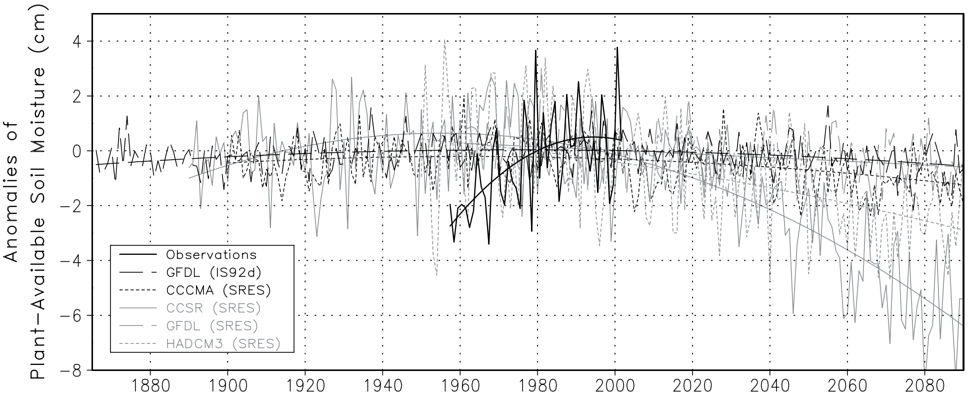

Figure 3. Anomalies of top 1-m plant available summer soil moisture for the region 22–40°E, 46–52°N in the Ukraine (Figure 1), showing results from five climate model simulations (Table 3) compared to the average of the winter and summer wheat observations. While the smoothed curves generally have the same shape, the observed trends have been much larger. See Ancillary Material in HTML for color and high-resolution versions of this Figure.

agricultural fields, they are not irrigated, and the observations are taken for the purpose of monitoring natural soil moisture in the region, so we expect them to be representative.

[9] The observed precipitation and temperature data that we used are from the version 2 datasets of the Global Historical Climatology Network [*Peterson and Vose*, 1997]. The precipitation and temperature for the same region are shown in Figure 2b. They are negatively correlated (Table 2), as cloudy periods are associated with both higher precipitation and lower temperatures. Interannual variations of soil moisture are clearly driven by precipitation. The correlation between soil moisture and precipitation shown in Figures 2a and 2b is 0.48 (0.57 if the trend is removed) for the entire period of 45 years. (To account for the effect of interannual variations in winter storage, we calculated the correlation between precipitation and the change from spring (MAM) to summer (JJA) soil moisture, and found that it is also positive; see Table 2.)

[10] An alternative way to interpret the soil moisture trends is that soil moisture has a large upward trend for the first half of the record, but is relatively constant for the second half. Tables 1 and 2 show the linear trends and correlations for the soil moisture, precipitation, and temperature curves in Figure 2 if they are separated into two halves, 1958–1979, and 1980–2002. The strong upward trend of soil moisture in the first period is matched by a strong upward trend in precipitation, but the precipitation has an even stronger downward trend in the second half of the period, while the soil moisture has only a weak trend. Again, the interannual variability is driven by precipitation in both periods, but if temperature is a surrogate for evapotranspiration, then the negative correlations between temperature and soil moisture are also consistent.

[11] Even though for the entire period there is a small upward trend in temperature and a downward trend in summer precipitation, the soil moisture still has an upward trend for both winter and summer cereals (Table 1), possibly driven by a downward trend in evaporation. *Liepert et al.* [2004] recently demonstrated with a climate model calculation that the observed decrease in solar insolation for the past several decades, attributed to increased aerosol pollution of the troposphere with direct and indirect effects on shortwave radiation, would reduce evaporation and produce simultaneous upward trends in surface air temperature and soil moisture. Our new observations are consistent with this idea. In fact, *Peterson et al.* [1995] showed observations of observed pan evaporation trends for the European part of the former Soviet Union, and the time series looks like an almost perfect inverse of our soil moisture time series (Figure 2a), with a strong downward trend from 1950 to 1980 and very little trend after that. While pan evaporation is not a perfect analog of actual evapotranspiration, this may help explain past soil moisture changes but predictions of future aerosol loading would be necessary to predict this component of a future soil moisture trend.

3. Summer Desiccation?

[12] *Robock et al.* [2000] presented observations from a neighboring region in Russia and showed that there was an upward trend of summer soil moisture through 1995, but it appears that the trend has been leveling off during the past 20 yr (Figure 2a). Whether this is an indication that in the future soil moisture will start to decrease in this region will have to await future observations, but such a shape to summer soil moisture is what most climate models simulate for a greenhouse-warmed world.

[13] In Figure 3 we compare our observations of summer soil moisture variations for the Ukraine with simulations

Table 3. General Circulation Models Used in Figure 3[a]

Model Version	Modeling Group	Scenario	Reference
CCCma	Canadian Center for Climate Modelling and Analysis, Victoria, Canada	SRES-A2	*Boer et al.* [1992]
CCSR/NIES	Center for Climate System Research, Tokyo, Japan	SRES-A2	*Emori et al.* [1999]
GFDL_R30	NOAA Geophysical Fluid Dynamics Laboratory, Princeton, New Jersey	IS92d, SRES-A2	*Delworth et al.* [2002]
HADCM3	Hadley Centre for Climate Prediction and Research, Bracknell, UK	SRES-A2	*Cox et al.* [1999]

[a] All were run with observed equivalent CO_2 and tropospheric aerosols for the past and with the specified future-forcing scenario.

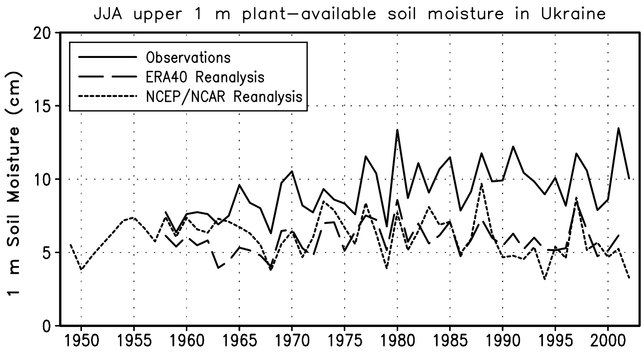

Figure 4. Top 1 m plant available summer soil moisture for the region 22–40°E, 46–52°N in the Ukraine (Figure 1), showing the simulations from the R-1 and ERA40 reanalyses compared to the average of the winter and summer wheat observations. While both models capture the interannual variations, for the most part, neither simulates the observed upward trend. See Ancillary Material in HTML for color and high-resolution versions of this Figure.

from several general circulation models (Table 3) of the atmosphere and ocean forced by observed anthropogenic greenhouse gases and aerosols for the past and global warming scenarios for the future. Figure 3 shows the simulated summer (JJA) soil moisture anomalies from four SRES A2 and one IS92d scenario runs [*Nakicenovic and Swart*, 2000]. This forcing was essentially business as usual, with increasing greenhouse gases and sulfate aerosols, but none of the models were forced with black carbon aerosols, which may have contributed somewhat to the global dimming effects [*Liepert et al.*, 2004]. All of the runs clearly show a weak upward soil moisture trend in the Ukraine before 1960 and a strong downward trend after 1960. The GFDL-R30 and CCCma model runs simulate less summer desiccation than the HADCM3 and CCSR/NIES models simulate more. However, none of simulations is well matched with the observations. This is not unexpected, as there should be a random component to interannual precipitation variations, especially for a region as small as the one studied here.

4. Reanalysis Evaluation

[14] Calculations of soil moisture by the R-1 and ERA40 reanalyses for the Ukraine are shown in Figure 4 compared to the observations. While both models capture the interannual variations for the most part, neither simulates the observed upward trend. In fact it appears that both models have a downward soil moisture trend for the past 20 yr. While we cannot analyze the complete water budget for this region with observations, we can with the reanalyses. In both cases, interannual variations of evaporation and runoff are very small and the interannual variations of soil moisture are almost entirely driven by precipitation.

[15] The interannual variations of surface air temperature for both models are almost identical to observations. The interannual precipitation variations of ERA40 closely track the observations, but those of R-1 are about twice the amplitude of the observations (see Figure A2). Nevertheless, the amplitude of the ERA40 soil moisture variations is about half of the observations, and that of R-1 is about the same as the observations.

[16] We suggest that both the lack of a trend and the damped interannual variations of reanalysis soil moisture are a result of soil moisture nudging applied to the simulated soil moisture to prevent the reanalyses from drifting to too dry or wet soil and to compensate for errors in precipitation and insolation. R-1 nudges soil moisture to the *Mintz and Serafini* [1992] climatology, and ERA40 adjusts soil moisture due to surface air humidity differences from observations. While ERA40, with its improved land surface model and smaller nudging as compared to ERA15, has the potential to produce long-term trends, apparently the nudging overwhelms the small actual trend.

5. Conclusion

[17] The new 45-year data set of Ukrainian soil moisture has proven useful for evaluation of climate model simulations, as illustrated here. We expect it and other data sets in the Global Soil Moisture Data Bank will continue to also be useful for evaluation of land surface models, as ground truth for remote sensing, and for studying climate change.

[18] **Acknowledgments.** NCEP/NCAR Reanalysis data were obtained from the NOAA Climate Diagnostics Center web site at http://www.cdc.noaa.gov/. We thank Pedro Viterbo for the ERA40 output. The climate model output came from the GFDL and IPCC Data Distribution Centre web sites. We also would like to thank the reviewers for helpful comments. Supported by NOAA grant NA03-OAR-4310057 and NASA grant NNG04GF18G to AR and by NOAA grant NA17EC1483 to KV.

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