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Solar dimming and CO_2 effects on soil moisture trends

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[1] Summer soil moisture increased significantly from 1958 to the mid 1990s in Ukraine and Russia. This trend cannot be explained by changes in precipitation and temperature alone. To investigate the possible contribution from solar dimming and upward CO_2 trends, we conducted experiments with a sophisticated land surface model. We demonstrate, by imposing a downward trend in incoming shortwave radiation forcing to mimic the observed dimming, that the observed soil moisture pattern can be well reproduced. On the other hand, the effects of upward CO_2 trends were relatively small for the study period. Our results suggest tropospheric air pollution plays an important role in land water storage at the regional scale, and needs to be addressed accurately to study the effects of global warming on water resources. **Citation:** Robock, A., and H. Li (2006), Solar dimming and CO_2 effects on soil moisture trends, *Geophys. Res. Lett.*, *33*, L20708, doi:10.1029/2006GL027585.

1. Introduction

[2] Understanding soil moisture variation is crucial to modeling and understanding climate changes due to its long meteorological memory [*Vinnikov et al.*, 1996], active role in land-atmosphere interactions [*Koster et al.*, 2004], and contribution to atmospheric predictability [*Dirmeyer*, 2000]. Potential soil moisture changes from global warming, especially desiccation in growing seasons, are a grave threat to food security on which human society relies. Numerical models have been utilized to explore how water storage will change with global warming. Many models predict a decline of soil moisture over the midlatitudes of the Northern Hemisphere [*Manabe and Wetherald*, 1987; *Gregory et al.*, 1997]. These analyses highlight possible climatic consequences, with an emphasis on the radiative effects of increased CO_2.

[3] Many plant species tend to reduce stomatal openings with increasing atmospheric CO_2. The concurrent higher canopy resistance reduces water loss through plant transpiration and thus may have profound impacts on the hydrological cycle [e.g., *Henderson-Sellers et al.*, 1995; *Sellers et al.*, 1996]. A recent study suggests such CO_2 effects are to a large extent responsible for continental runoff increases for the 20th century [*Gedney et al.*, 2006].

[4] On the other hand, as the driving forces for land surface hydrology, precipitation and net radiation impose a first order control on evaporation and runoff at annual or longer timescales [*Koster et al.*, 2001]. In terms of soil moisture, more realistic simulations can be obtained by assimilating observed precipitation into climate models [*Kanamitsu et al.*, 2002; *Li et al.*, 2005]. In short-term field experiments, an artificial increase in downward heat flux has been shown to cause a significant reduction in summer soil moisture [*Harte et al.*, 1995]. Both ground-based observations [*Abakumova et al.*, 1996; *Gilgen et al.*, 1998; *Stanhill and Cohen*, 2001; *Liepert*, 2002; *Wild et al.*, 2005] and satellite measurements [*Pinker et al.*, 2005] reveal a widespread reduction of solar irradiance from 1950s to 1990s and a gradual recovery [*Wild et al.*, 2005; *Pinker et al.*, 2005] afterwards, known as the "global dimming" phenomenon. Increasing atmospheric aerosol loading from rapid industrialization is believed to be the culprit. Aerosols can affect solar irradiance reaching the Earth's surface through scattering and absorbing radiation (direct aerosol effect), and modifying cloud properties (indirect aerosol effects). The net effect of the mechanisms is a reduction in downward surface solar radiation [*Ramanathan et al.*, 2001]. In the context of the hydrological cycle, the reported decline of shortwave radiation over such a long period may potentially increase water storage over land by damping evaporative demand from the atmosphere [*Liepert et al.*, 2004; *Wild et al.*, 2004]. Recent studies [*Robock et al.*, 2005] (also H. Li et al., Evaluation of Intergovernmental Panel on Climate Change Fourth Assessment soil moisture simulations for the second half of the twentieth century, submitted to *Journal of Geophysical Research,* 2006) (hereinafter referred to as Li et al., submitted manuscript, 2006) show no summer desiccation based on analysis of over 40 yr of gravimetrically-measured soil moisture observations for Ukraine and Russia during a period when surface air temperature rose. Rather, observations for Ukraine and Russia show an upward soil moisture trend. While *Robock et al.* [2005] suggested that solar dimming may have been responsible, this has not been tested before with a theoretical model. The reported upward summer soil moisture trends for many Former Soviet Union stations are consistent with the decrease of pan evaporation around the same period for the same region [*Peterson et al.*, 1995], as pan evaporation can be thought as a direct measurement of the atmospheric evaporative demand.

2. Experiment Design

[5] To understand the relative contribution of solar dimming and physiological effects of CO_2 on the observed soil moisture pattern for Ukraine and Russia (Figure 1), we conducted a series of off-line sensitivity experiments with a modified version of the Community Land Model (CLM3.0) [*Oleson et al.*, 2004]. A unique advantage of off-line experiments is that the model can be forced with realistic precipitation and temperature, so the sensitivity of soil moisture can be better sorted out. We set the land cover type to "agricultural" for all grid points in the study

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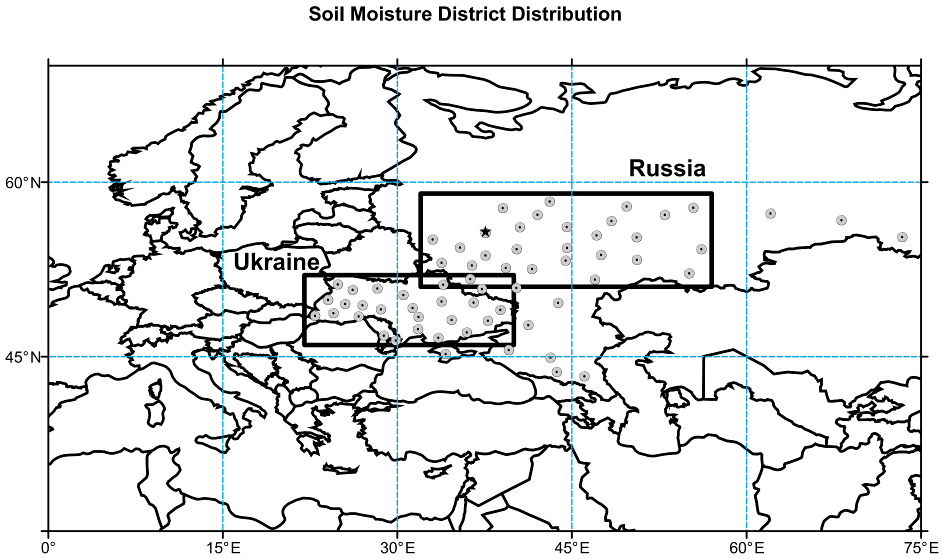

Figure 1. Soil moisture district distribution. Each district (circle with a solid dot in center) is an average of 3–6 stations. Rectangles represent the modeling domain for Ukraine (22°–40°E, 46°–52°N) and Russia (32°–57°E, 51°–59°N). The observed soil moisture for Ukraine spans 1958–2002 and 1958–1998 for Russia. The measurements are taken gravimetrically two to three times per month during growing seasons for the top 0–20 cm and 0–100 cm. The black star shows the location of the solar radiation station at Moscow.

regions, so we could compare the results to observations, which were made in agricultural fields. We made improvements to the land surface hydrology of CLM 3.0, mainly interception, frozen soil, and runoff, following the work of *Niu et al.* [2005] and *Niu and Yang* [2006], which leads to more realistic runoff and soil moisture. We further reformulated the β factor (soil moisture control on photosynthesis) similar to other studies [*Cox et al.*, 1999; *Daly et al.*, 2004] as $A = \beta \times A_p$, where A is photosynthesis, A_p is the potential photosynthesis calculated by a leaf-photosynthesis module that is not constrained by water stress and is dependent on CO_2 concentration, and β is the soil moisture availability weighted by root distribution:

$$W_i = \begin{cases} 0 & , \quad \psi_i < \psi_w \\ \dfrac{\psi_i - \psi_w}{\psi_c - \psi_w}, & \psi_w \le \psi_i < \psi_c \\ 1 & , \quad \psi_i \ge \psi_c \end{cases}, \qquad (1)$$
$$\beta = \sum r_i \times W_i$$

where r is the root percentage, ψ is the matric potential, i represents soil layer, and subscripts w and c represent wilting point and critical point (specified as 70% of field capacity here).

[6] We drive the land model using recently-created forcing data sets [*Qian et al.*, 2006], based on National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis outputs [*Kalnay et al.*, 1996] but adjusted by observations. The reanalysis values of surface air temperature and precipitation were adjusted so the monthly means matched observations. Downward solar radiation was adjusted based on variations and trends from cloud observations, and then for the mean seasonal cycle of observed radiation, but not for observed trends in radiation. The adjustment implicitly incorporates changes in cloud lifetime but not the indirect aerosol effect that involves changes in radiative properties of clouds. Possible vegetation structural changes due to CO_2 increases (through land cover change) [e.g., *Levis et al.*, 2000; *Eastman et al.*, 2001] are not considered here since the study regions are primarily agricultural zones that remain quite consistent over the years.

[7] The control experiment directly uses the forcing data from *Qian et al.* [2006]. To mimic the dimming, we conducted additional experiments that impose linear trends on the shortwave radiation field. *Abakumova et al.* [1996] found a linear trend of decreasing total insolation of about −0.5%/yr for the period 1960–1987 in the region of the Ukrainian and Russian boxes (Figure 1), with some stations having a trend of −0.6 to −0.7%/yr, and trends for direct radiation averaging −0.6 to −0.7%/yr, with some stations up to −1.4%/yr. To investigate this dimming, we performed experiments with −0.5%/yr and −1.0%/yr changes in insolation for the period 1961–1980, and call the experiments −0.5% EXP and −1% EXP respectively. For the −0.5% EXP, we use the following equation to mimic the dimming effect for 1961–1980:

$$SW^{(s,t)}_{-0.5\%} = \left(1 - \frac{year - 1960}{200}\right)\% \times SW^{(s,t)}_{control}, \qquad (2)$$

where $SW^{(s,t)}$ is shortwave radiation at every grid point and every time step. For each year from 1961–1980, a cumulative 0.5%/year is subtracted from the corresponding radiation field of the control forcings. After 1980, a constant 10% is subtracted from the control forcing. The −1% EXP is similar to that of −0.5% EXP except that the denominator in equation (2) is changed to 100 so that a cumulative 1%/year rate is subtracted for 1961–1980 and a constant 20% is maintained afterwards, i.e., a much stronger dimming scenario. The spin-up is done by repeatedly forcing the model with the forcing data for 1955 until there is no trend,

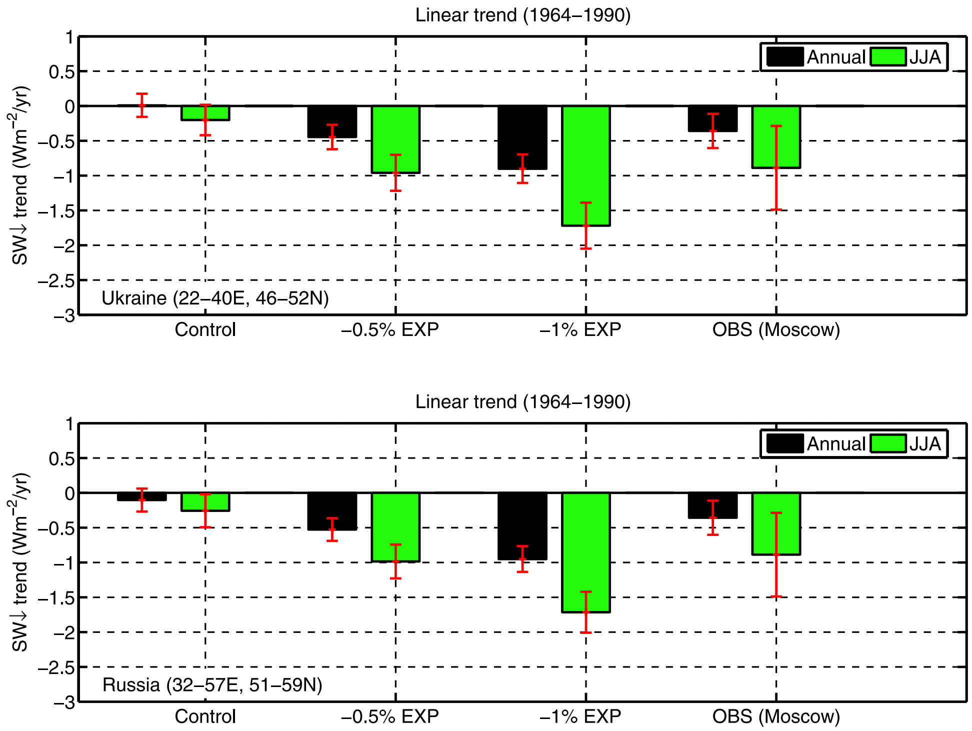

Figure 2. Estimated linear trends for shortwave radiation for Ukraine (top panel) and Russia (bottom panel). Error bar represents the 95% confidence interval for the estimated trends based on linear regression. There is no significant decrease for the control or NCEP/NCAR reanalysis for either region. Also shown are the trends estimated from nearby station-based observations (Moscow).

and then the model is run over the 1955–2002 period with a 1° × 1° resolution for the land surface.

[8] Figure 2 shows that the imposed forcing trends are quite similar for Ukraine and Russia, about -0.5 Wm^{-2}/yr decline for the -0.5% EXP and about twice that for the -1% EXP for the annual means. Larger decreases are found for summer (JJA), which can be explained by higher radiation during summer (the same percent decrease means a much larger magnitude). We use the surface radiation observations from Moscow as the reference, the closest long-term radiation station available, where observations are documented for the period of 1964 to the mid-1990s [*Gilgen and Ohmura*, 1999]. The imposed trends for the -0.5% EXP are comparable to those of observations at Moscow, although the latter exhibits stronger interannual variability. The magnitude of real solar dimming over these two regions might be larger or lower [*Abakumova et al.*, 1996] than that of Moscow, which, while the best available, is at one point and may have local urban influences.

[9] In addition, to see how CO_2 increases may have impacted soil moisture, two parallel experiments, one with constant CO_2 and another with transient CO_2 increases, were conducted for each case described above. For the constant CO_2 experiments, CO_2 concentrations are fixed at the 1960 level of the observations from Mauna Loa Observatory (C. D. Keeling and D. P. Whorf, Scripps Institute of Oceanography, data set available at http://cdiac.ornl.gov/ftp/trends/co2/maunaloa.co2). For the transient CO_2 experiments, prior to 1961, CO_2 concentration is fixed at the 1960 level. From 1961, the time-dependent CO_2 evolution follows the monthly mean values of Mauna Loa. We evaluate the model simulations with the longest available observational data sets of soil moisture, from the Ukraine (1958–2004 [*Robock et al.*, 2005]) and Russia (1958–1998 (Li et al., submitted manuscript, 2006)), freely available from the Global Soil Moisture Data Bank [*Robock et al.*, 2000]. We focus on the summer soil moisture since it is closely related to plant growth. We analyze soil moisture from the top 0–1 m where most of plant roots reside. (For the model, 96% of the roots are in the top 1 m.)

3. Results

[10] Figure 3 shows the simulated and observed soil moisture in summer. To account for the differences between observations (plant-available soil moisture, i.e., with wilting levels subtracted) and model simulations (total soil moisture), we adjust each model simulation to the mean of observations for 1958–1960. The observed soil moisture for Ukraine exhibits an increase from 1958 to the early 1980s and then starts to level off afterwards. So does the soil moisture in the control but with much smaller magnitude. Imposed dimming brings additional soil moisture increase compared to the control. The stronger the dimming, the higher the increase in soil moisture. Such a response in soil moisture is a response to evapotranspiration, which serves as the crucial linkage between atmosphere and land surface for energy and water exchange. The simulated evapotranspiration in summer for Ukraine on average decreases about 5% and 16% for the -0.5% EXP and -1% EXP runs respectively for the period of 1981–2000

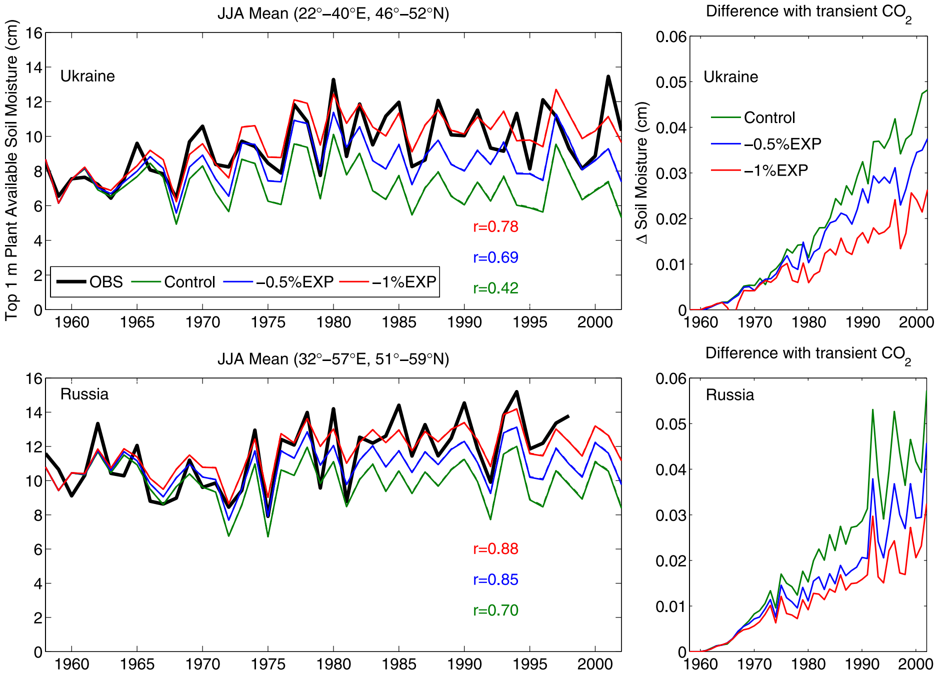

Figure 3. Observed and simulated JJA plant available soil moisture for 1958–2002. The model simulated soil moisture is adjusted to the mean of 1958–1960 observations. Top panels are for Ukraine box in Figure 1 and bottom panels are for Russia box. (left) Solid lines are simulations with constant CO_2 and dashed lines (barely visible) are simulations with time-dependent CO_2 increase. Also shown are the correlation coefficients between simulations and observations for the time period of the observations. (right) Soil moisture increases due to elevated CO_2, plotted as the differences between the dashed and solid lines on an expanded vertical axis. The effects of solar dimming are large while the effects of increasing CO_2 on soil moisture are negligible in this model.

compared to the control. The numbers are 9% and 20% for Russia.

[11] As can be seen in Figure 3, the drier region of Ukraine has a slightly larger sensitivity to changes of insolation than Russia, even though the absolute changes in radiation are about the same (Figure 2). This is because of subtle differences in the interconnected changes of all the terms in the water budget, including runoff and drainage, connected to different specifications of the seasonal cycle of the leaf area index in the two regions in CLM. In the control run for Russia, the combined runoff and drainage is almost twice as large as in Ukraine, and in the dimming experiments increases more than in the Ukraine, providing a larger compensation for the decreased evapotranspiration.

[12] In terms of soil moisture, the −1% EXP essentially reproduces the observed pattern for both regions, showing an increase from 1961–1980 and then leveling off for the Ukraine, and a general increase in soil moisture for Russia during the entire period. Although model simulations exhibit weaker interannual variations, the simulated soil moisture with dimming included follows that of observations better, especially for the −1% EXP. The correlation coefficients in Figure 3, while not an ideal statistical measure, also support the finding that the −1% EXP produces the best simulations.

[13] The elevated CO_2 caused very small soil moisture increases in contrast with the constant CO_2 scenario. This is no surprise since in the elevated CO_2 cases, evapotranspiration decreased by only about 0.1%. The lines for the transient CO_2 runs are essentially identical to those for the constant CO_2 runs on the left side of Figure 3. Over a decadal scale, therefore, this model shows that carbon fertilization may have limited influence on regional soil moisture changes. Such effects, however, are not negligible for the past century [*Gedney et al.*, 2006]. Also, model-simulated plant transpiration accounts for only about 30% of the total evapotranspiration for these two regions. Over regions where evapotranspiration is composed of primarily transpiration (e.g., Amazon rainforest), CO_2 effects are likely to cause a much larger sensitivity.

[14] Recent studies [*Robock et al.*, 2005; Li et al., submitted manuscript, 2006] show that reanalysis systems and the latest Intergovernmental Panel on Climate Change Fourth Assessment Report models cannot capture the magnitude of the observed soil moisture increase for Ukraine and Russia. In addition to precipitation and temperature, our analysis suggests that solar dimming played a significant role on regional soil moisture variations. Over aerosol emission source regions, the aerosol effects are expected to continue to play a major role unless effective pollution controls are in effect. In agreement with our results, *Liepert et al.* [2004] argued that reduced surface solar radiation from increasing anthropogenic aerosols would be able to reduce evaporation to the extent that it can slow down water cycling (locally) despite global warming. Thus, the observed intensification of the hydrological cycle over extratropical land is more likely attributable to increased moisture advection from the oceans than to increased local moisture release through evaporation [*Wild et al.*, 2004]. To capture the hydrological cycle and its components more realistically, we need better parameterization systems to characterize

aerosol effects in climate models. In spite of the relatively small CO_2 effects as indicated from our study on decadal scales, increasing CO_2 may be one of the most important modifiers of the water cycle for the past century and the effects may become more conspicuous if CO_2 and concentrations continue to increase. To that end, these human-induced external forcings have to be better understood to reduce uncertainties in future predictions and for better water availability assessments.

[15] The results here use a current state-of-the-art land surface model, but should be repeated with other models to test for model dependency on the specifications of evapotranspiration, hydrology, and CO_2 effects. Our best agreement between model results and solar dimming are with a dimming slightly larger than that observed. A better agreement awaits testing this hypothesis with better data sets and better models.

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