Solar dimming and CO\textsubscript{2} effects on soil moisture trends

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Abstract. 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 CO₂ 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 CO₂ 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.
1. Introduction

Understanding soil moisture variations 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 mid-latitudes 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 CO2.

Many plant species tend to reduce stomatal openings with increasing atmospheric CO2. 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 CO2 effects are to a large extent responsible for the continental runoff increases for the 20th century [Gedney et al., 2006].

On the other hand, as the driving forces for hydrological cycle, 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]. 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 [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 afterwards,
known as the “from dimming to brightening” 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 of atmosphere. Recent studies [Robock et al., 2005; Li et al., 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

To understand the relative contribution of solar dimming and physiological effects of CO$_2$ on the observed soil moisture pattern for Ukraine and Russia (Fig. 1), we conducted a series 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 made improvements to the land surface hydrology, mainly interception,
frozen soil and runoff, of CLM 3.0 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 $\beta$ 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 $\beta$ is the soil moisture availability weighted by root distribution:

$$W_i = \begin{cases} 0, & \psi_i < \psi_w \\ \frac{\psi_i - \psi_w}{\psi_c - \psi_w}, & \psi_w \leq \psi_i < \psi_c \\ 1, & \psi_i \geq \psi_c \end{cases}$$

where $\beta = \sum r_i \times W_i$

(1)

where $r$ is the root percentage, $\psi$ 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).

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 adjusted precipitation and temperature fields are quite close to observations, but there is no solar dimming in either the original reanalysis or the adjusted forcing, which only adjusts for cloud amount and mean radiation [Qian et al., 2006]. 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.
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. For simplicity, we call the experiments with two different degrees of imposed trends –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:

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

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 to reflect possible transitions since then. The –1% EXP is similar to that of –0.5% EXP except that the denominator in Eq. (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, and then the model is run over the 1955-2002 period with a 1°×1° resolution for the land surface.

Figure 2 shows that the imposed forcing trends are quite similar for Ukraine and Russia, about –0.5 Wm\(^{-2}\)/year 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 than that of Moscow, which, while the best available, is at one point and may have local urban influences.

In addition, to see how CO₂ increases may have impacted soil moisture, two parallel experiments, one with constant CO₂ and another with transient CO₂ increases, were conducted for each case described above. For the constant CO₂ experiments, CO₂ concentrations are fixed at the 1960 level of the observations from Mauna Loa Observatory [Keeling et al., 2005]. For the transient CO₂ experiments, prior to 1961, CO₂ concentration is fixed at the 1960 level. From 1961, the time-dependent CO₂ 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., 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, over 80% of the roots are in the top 1 m).

3. Results

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 response in soil moisture can be attributed to the adjustment for
evapotranspiration which serves as the crucial linkage between atmosphere and land surface for energy and water exchange. When energy availability becomes limited, evapotranspiration decreases to balance energy reduction. The simulated evapotranspiration in summer for Ukraine on average decreases about 5% and 11% for the –0.5% EXP and –1% EXP runs respectively for the period of 1961-2000 compared to the control. The numbers are 6% and 12% for Russia.

In terms of soil moisture, the –1% EXP essentially reproduces the observed pattern, especially for Ukraine, showing an increase from 1961-1980 and then leveling off. There is a general increase for soil moisture observations 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 elevated CO₂ caused very small soil moisture increases in contrast with the constant CO₂ scenario. This is no surprise since in the elevated CO₂ cases, evapotranspiration decreased by only about 0.1%. The lines for the transient CO₂ runs are essentially identical to those for the constant CO₂ runs in Fig. 3. Over a decadal scale, therefore, 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), CO₂ effects are likely to cause a much larger sensitivity.

Recent studies [Robock et al., 2005; Li et al., 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 despite global warming. 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 relative small CO$_2$ effects as indicated from our study on decadal scales, increasing CO$_2$ may be one of the most important modifiers to water cycle for the past century and the effects may become more conspicuous if CO$_2$ and concentrations keep soaring up. 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.

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 at the one available station. A better agreement awaits testing this hypothesis with better data sets and better models.

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References


Figure 1. Soil moisture district distribution. Each district (green circle with a solid dot in center) is an average of 3-6 stations. Red 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.
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).
Figure 3. JJA plant available soil moisture for 1958-2002. The model simulated soil moisture is adjusted to the mean of 1958-1960 observations. Top panel is for Ukraine box in Fig. 1 and bottom panel is for Russia box. Solid lines are simulations with constant CO₂ and dashed lines (barely visible) are simulations with time-dependent CO₂ increase. The effects of solar dimming are remarkable while the effects of increasing CO₂ on soil moisture are negligible.