Soil Moisture and Snow Cover: Active or Passive Elements of Climate?

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Abstract

Ensembles of predictability studies have been constructed using the NCAR CCM3 in which the relative roles of initial surface and atmospheric conditions over the central and western U.S. were compared in determining the subsequent evolution of soil moisture and of snow cover. Sensitivity studies were also made with exaggerated soil moisture and snow cover anomalies in order to determine the physical processes that may be important. Results with realistic soil moisture anomalies indicate that internal climate variability is the strongest factor, with the initial atmospheric state of lesser importance. The initial state of soil moisture is not important, a result that held whether simulations were started in late winter or late spring. Model runs with exaggerated soil moisture reductions (near-desert conditions) showed a much larger effect, with warmer surface temperatures, reduced precipitation, and lower surface pressures; the latter indicating a response of the atmospheric circulation. These results suggest the possibility of a threshold effect in soil moisture, whereby an anomaly must be of a sufficient size before it can have a significant impact on the atmospheric circulation and hence climate. Results from simulations with realistic snow cover anomalies indicate that the time of year can be crucial. When introduced in late winter, these anomalies strongly affected the subsequent evolution of snow cover. When introduced in early winter little or no effect is seen. Runs with exaggerated initial snow cover indicate that the high reflectivity of snow is the most important process by which snow cover can impact climate, through lower surface temperatures and increased surface pressures. In early winter, the amount of solar radiation is very small and so this albedo effect is inconsequential while in late winter, with the sun higher in the sky and period of daylight longer, the effect is much stronger. Subsequent accumulation of snow through the winter also helps to mask the original anomalies.

Keywords: climate; soil moisture; snow; drought; climate predictability

1. INTRODUCTION

The extent to which soil moisture and snow cover actively interact with the atmosphere leads to the possibility of a degree of predictability in precipitation at seasonal to interannual time scales. Enabling this potential predictability requires (i) understanding the physical mechanisms involved in this interaction, especially the way that soil moisture and snow cover can affect the atmospheric state and hence precipitation; (ii) evaluating the importance of these mechanisms relative to all the others (e.g., tropical sea surface temperature anomalies) that can also affect precipitation; and (iii) evaluating the time scales over which soil moisture and snow cover are most likely to have a predictable effect on precipitation.

Namias [1959, 1988, 1991] suggested that reduced soil moisture during late winter and/or spring over a mid-continental region (such as the central United States) could help induce and amplify a warm, dry summer over the same region, in part by reduction of the local evaporative contribution, but also by modifying the large-scale atmospheric circulation through the so-called ‘thermal mountain’ effect [*Stern and Malkus,* 1953].

We ask the following questions: Does the current state of soil moisture have any predictive power in determining the subsequent evolution of the soil moisture? Does the initial state of the atmosphere? As will be shown, the study also raised an important additional question: do thresholds exist in which a soil moisture anomaly must be sufficiently large before it can exert a strong influence?

The effect of atmosphere–snow interactions on the climate of mid-latitude continents, including the western U.S., has long been a topic of speculation and study, but remains poorly understood (e.g., *Clark and Serreze*, 2000). Previous work makes it clear that snow cover can act as a climatic forcing mechanism, some degree of seasonal climate predictability may be inherent in snow cover. That is, knowing the initial state of the snow cover may enable some prediction skill in forecasting the subsequent evolution of snow cover and hence its impact on the atmosphere.

The most basic question to answer here is whether the initial state of the snow cover is positively or negatively correlated with the subsequent snow cover. In other words, does a large initial snow cover (in extent and volume) tend to perpetuate itself, or rather to instead induce feedbacks that limit its eventual size? Or is there no strong correlation at all, which implies that atmospheric variability is more important than the initial state of the atmosphere?

We focus on these soil moisture and snow cover questions, and therefore have constructed ensembles of predictability studies using the NCAR CCM3 in which we compared the relative roles of initial surface and atmospheric conditions over the central and western U.S. GAPP region in determining the subsequent evolution of soil moisture and snow cover. We have also made sensitivity studies with exaggerated soil moisture and snow cover anomalies in order to determine the physical processes and linkages with the atmosphere that may be important accounting for this predictability. The use of a global climate model is required so that we can assess the adjustment of the atmosphere and the surface state to imposed initial anomalies. Use of a reanalysis dataset, or a regional climate model forced at the lateral boundaries by a reanalysis, would always drive the solution back towards a predetermined state and not allow for full interaction between the surface and atmosphere

2 MODEL AND EXPERIMENTS

2.1 The NCAR CCM3

The climate model used for this study is the National Center for Atmospheric Research (NCAR) Climate System Model (CSM) [*Boville and Gent*, 1998]. The CSM includes atmospheric, oceanic, land surface, and sea ice components, see *Kiehl et al.* 1998 for a detailed description). The standard horizontal resolution of the model is T42, or an equivalent gridpoint resolution of 2.8° latitude by 2.8° longitude and the vertical is resolved by 18 layers. The standard land surface option for CSM (and hence CCM3) is the Land Surface Model (LSM) [*Bonan,* 1998]. Soil and vegetation type and characteristics are prescribed and vary monthly. Soil temperatures and soil moisture are calculated using a 6-layer soil energy and moisture model. The LSM incorporates components of the improved snow hydrology of *Marshall and Oglesby* [1994]. *Hack et al.* [1998] summarize important characteristics of the model-generated climate.

The LSM snow climatology has been assessed by *Yang et al.* [1997]. They find the LSM snow model replicates reasonably well the melt rates of snow cover in the spring but does more poorly during the accumulation season. This is partly due to a warm bias over snow cover found in the LSM. Although the LSM underestimates peak snow accumulation, it overestimates total snow mass over North America and Eurasia when compared with estimates from the Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR). Assessment of the model performance of soil moisture is more problematical due to the lack of suitable observations, though *Oglesby et al.* [2001] found broad model-observation agreement for a few mid-latitude continental sites.

A baseline simulation model simulation used in this study is a 45-year CCM3 run with monthly SST for each year specified according to observations supplied by NCEP for the years 1950-1998 (henceforth called CCM3/SST). Results from the CCM3/SST run can be directly compared to atmospheric observations on a year-to-year basis, with the caveat that the SST forcing is the only forcing that relates model years to actual calendar years (see *Oglesby et al*., 2001 for a more thorough discussion and description of this run). A number of anomaly runs were made as described in the next section.

2.2 Model Simulations

The regions of interest are different between the soil moisture and snow cover portions of the study. For soil moisture, we focus on the central U.S. 'GCIP' region as described by *Oglesby et al.* [2001]. For snow, we focus on the western 1/3rd of the U.S. Time series results are for averages over the entire regions in each case.

2.2.1 Soil Moisture Experiments

We made two sets of soil moisture 'predictability experiments'. We used soil moisture averaged over June and March for the central U.S. region to determine years with the largest and smallest amount of soil moisture as simulated by CCM3 in the 45-year baseline run. One set of simulations had initial soil moisture taken from the dry year but the initial atmospheric state from the wet year; the other set simply reversed this. Simulations were started either on June 1 or March 1. In order to evaluate model variability, each set contained five simulations, each of which had small, random perturbations to the initial conditions.

We also made a series of experiments with greatly exaggerated, 'desert-like' reductions in soil moisture, again starting from either June 1 or March 1. The purpose of these runs is to explore physical mechanisms involved in soil moisture-atmosphere interactions.

2.2.2 Snow Cover Experiments

We also made two sets of snow 'predictability experiments'; as with the soil moisture runs, each set contained five simulations. One set was based on years that had relatively high or low January, February, and March snow anomalies over the western U.S. and that clearly demonstrated these anomalies on February 1, while the other set was based on snow cover for November, December and January as well as December 1. In both cases, snow cover was obtained from the baseline model run.

We also made two simulations in which an extreme anomaly of 1 meter snow water equivalent (SWE) is imposed over the western U.S. domain only. One simulation starts on February 1; the other on December 1.

3. RESULTS

3.1 Soil Moisture

Fig 1a shows the case with dry initial soil moisture but the initial state of the atmosphere taken from a year with normal levels of soil moisture; Fig 1b shows the case with initial soil moisture from the normal year but initial atmosphere from a year with dry soil. Shown are the mean and +/- one standard deviation for the sets of five experiments, plus reference curves for the evolution of soil moisture in the dry and normal years in the baseline simulation. Clearly, in both cases the envelope of the experiments quickly goes to the opposing state; indeed the envelope encompasses both dry and normal states. Thus we conclude that neither the initial state of the soil moisture or the initial state of the atmosphere dominates; most important is variability in the model.

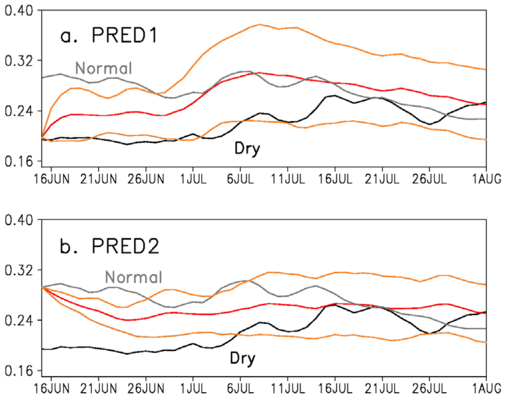

Figure 1. (a) PRED1 (dry initial soil and normal initial atmosphere) and (b) PRED2 (normal initial soil and dry initial atmosphere) ensemble average soil moisture (volumetric fraction) compared to the dry (1974) and normal (1998) soil moisture years. Color lines represent the mean (red) and standard deviation about the mean (orange) of the PRED ensembles.

Previous work (*Oglesby and Erickson,* 1989; *Oglesby,* 1991) had suggested that large soil moisture anomalies could have a major impact. The results presented here suggest that for smaller, realistic anomalies this impact could not be detected. What happens if we impose a large soil moisture reduction on the model? Fig. 2 shows surface temperature, precipitation, and sea level pressure for the exaggerated anomaly run started on June 1, averaged over the following

August. Very large changes are seen, with surface temperatures warming, precipitation decreasing, and sea level pressure decreasing. The latter indicates a response of the atmospheric circulation. These changes are robust and long-lasting; after one year (the following May) the changes are still substantial. Clearly, the size of the initial soil moisture anomaly is the most crucial factor.

3.2 Snow Cover

Fig. 3 shows that for runs starting on February 1 the initial prescription of snow cover maintains itself for up to several months. Unlike with soil moisture, the initial state of the atmosphere is far less important. Furthermore, the response to the initial snow anomaly also overwhelms model variability. Fig. 4, on the other hand, shows a very different story for runs starting on Dec 1. Now the results are much more like those for soil moisture; no clear response to either the initial snow or atmospheric conditions is seen; model variability dominates.

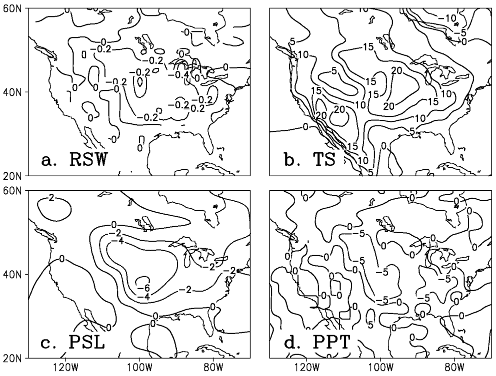

Figure 2. Dry soil moisture experiment minus CCM3 control anomalies of (a) soil moisture (RSW, volumetric fraction), (b) surface temperature (TS, °C), (c) sea level pressure (PSL, mb) and (d) precipitation (PPT, mm/day) averaged for the month of August, following a June 1 start date.

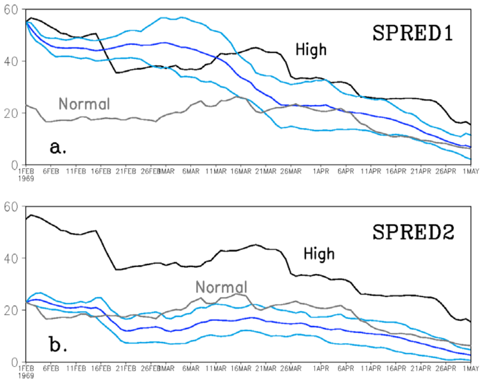

Figure 3. Time series of (a) SPRED1 (high initial snow cover, normal snow atmosphere) and (b) SPRED2 (normal initial snow cover, high snow atmosphere) ensemble average snow cover depths (mm, water equivalent) compared to the control high snow year (1967) and normal snow year (1971). Color lines represent the mean (darker blue) and standard deviation about the mean (lighter blue) of the SPRED ensembles.

Fig 5 shows results averaged over March for the exaggerated snow anomaly run started on Feb 1, which helps identify the physical mechanisms responsible for the large sensitivity to initial snow at this time of year. Notably, surface temperatures are much cooler, which in turn leads to increased surface pressures (and a response of the atmospheric circulation). Both the high reflectivity and the high emmisivity of snow could lead to this response; the fact that in the realistic anomaly runs it occurs more strongly in February than in December suggests that the reflectivity effect dominates. In December the sun is simply too low in the sky to provide much short wave radiation for the snow to reflect.

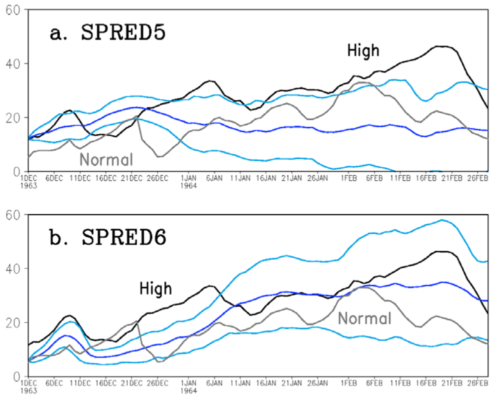

Figure 4. Time series of (a) SPRED5 (high initial snow cover, normal snow atmosphere) and (b) SPRED6 (normal initial snow cover, high snow

atmosphere) ensemble average snow cover depths (mm, water equivalent) compared to the control high snow year (1963) and normal snow year (1985). Color lines represent the mean (darker blue) and standard deviation about the mean (lighter blue) of the SPRED ensembles.

4. DISCUSSION AND CONCLUSIONS

The key overall results of this study are (1) the size of the soil moisture anomaly is most important, and (2) most important for a snow anomaly to have a significant effect is the timing.

The most striking feature of the soil moisture results is the strong dichotomy in the response of the atmosphere between the runs with an exaggerated anomaly and those with realistic anomalies. The obvious conclusion is that the size of the soil moisture anomaly is crucial. Too small, and little discernable effect is seen on the atmosphere, which instead is dominated by natural variability and, to a smaller extent, remote effects (as reflected in the initial state of the atmosphere). Further analyses suggest that the state of the soil moisture at depth plays a major role in modulating surface anomalies and hence atmospheric interactions. Drying or moistening the near-surface layers has little effect; drying or moistening the deep soil layers can have a profound, long-lasting effect that may be crucial for drought on decadal or longer time-scales.

With snow cover, the size of the anomaly is less important than the timing. Anomalous snow cover early in the winter season has little effect, whether the anomaly is large or small. The sun is too low in the sky for the albedo (reflectivity) effect to be important; also subsequent snow accumulation during the rest of the winter helps ameliorate the initial anomaly. Later in the season, a snow anomaly can have a much larger effect; the response of the atmosphere is similar regardless of whether the anomaly is a realistic one obtained from year to year variations in a model simulation, or an exaggerated one that might be more applicable to simulations of glacial inception.

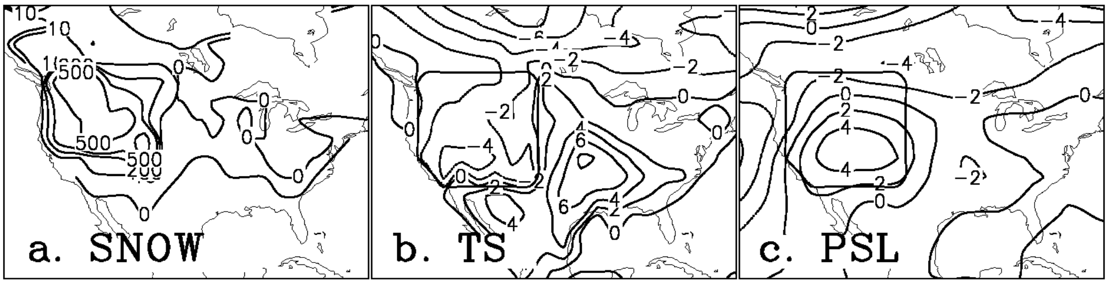

Figure 5. ANOM-FEB minus CCM3/SST (low snow year of 1969) anomalies of (a) snow cover depth (mm, snow water equivalent), (b) surface temperature (TS, °C), and (c) sea level pressure (PSL, mb) averaged for the month of April, following a Feb. 1 start date.

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