Quantifying the Strength of Soil Moisture-Precipitation Coupling and its Sensitivity to Surface Water Budget Changes

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1. Introduction

Over regions of strong soil moisture-precipitation coupling, precipitation prediction at the seasonal and sub-seasonal time scale can benefit from knowledge of soil moisture, a slowly varying boundary condition for the atmosphere. Identifying the regions of strong coupling therefore quantifying the strength of soil moisture-precipitation coupling is therefore of critical importance. However, the recent Global Land-Atmosphere Coupling Experiments (GLACE) project indicated a high degree of model dependence in quantifying the strength of coupling (Koster et al., 2004). In order to understand the model dependence and to ultimately reduce such model dependence, it is important (1) to understand how certain model parameters and parameterization changes influence the strength of coupling and (2) to identify an index for the strength of coupling that responds to model parameter/parameterization changes in an understandable way.

In this paper we compare two different indices quantifying the soil moisture-precipitation coupling strength, the GLACE index ($\Delta\Omega$) and an alternative index we propose ($\Delta\Phi$), and examine how they response to a modification in the vegetation canopy interception parameterization that leads to significant surface water budget changes using the coupled CAM3-CLM3 model.

2. Models

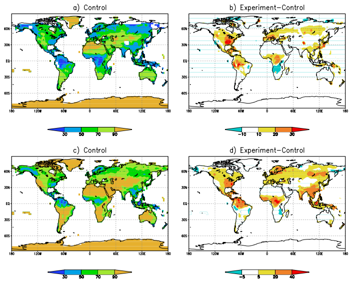
We make use of two different versions of the CAM3-CLM3 model: the Control model (the default) and the Experiment model that includes a new canopy interception scheme in CLM3 (Wang et al., 2005). This difference in canopy hydrology parameterization leads to substantial difference in surface water budgets (Figure 1): A larger fraction of precipitation infiltrates into soil (thus has a larger potential to influence soil moisture) in the Experiment model than in the Control, and a larger fraction of evapotranspiration (the direct pathway through which soil moisture influences precipitation) comes from (therefore can be potentially controlled by) soil moisture.

In both models, the oceanic boundary conditions are prescribed with the climatological monthly-varying sea surface temperature and sea ice coverage. Among the three dynamics schemes available in CAM (Eulerian spectral, semi-Lagrangian dynamics and Finite Volume [FV] dynamics), we choose the Eulerian spectral dynamical core with a T42 horizontal resolution and a total of 26 levels in the vertical direction.

Figure 1:

(Upper panels) Percentage of precipitation infiltrating into soil (JJA average);

(Lower panels) Percentage of evapotranspiration from soil



3. Methodology

Here we follow the GLACE approach (Koster et al. 2004) in experimental design, and focus on JJA season only. First of all, a 16-year model integration is carried out to derive 16 initial conditions for June 1 that will be used to initialize four 16-member ensemble simulations: Control_W & Control_S using the Control model and Experiment_W & Experiment_S using the Experiment model. In each “W” ensemble, the sixteen simulations (W1-W16) differ in their initial conditions, and soil moisture values in every time step from one member (e.g., W1) were saved in a data file; in each “S” ensemble (S1-S16), the model predicted soil moisture values in all sixteen member simulations are overwritten according to the same data file saved from the corresponding “W1” member simulation. Note that in the official GLACE “S” ensembles, soil moisture is overwritten in the deep root zone only; while in our “S” ensembles here, soil moisture is overwritten in all soil layers.

Since different members of a same “S” ensemble share the same slow-varying soil moisture, their precipitation time series are expected to have a higher degree of similarity and a lower degree of spreading than those of the corresponding “W” ensemble. This difference reflects the impact of soil moisture-precipitation coupling, and thus provides an objective measure for the coupling strength.

4. Definition of the two Different Indices for Coupling Strength: ΔΩ vs. ΔΦ

The intra-ensemble similarity index Ω and the GLACE coupling strength index $\Delta\Omega$ (Koster et al., 2004):

$$\Omega_P = \frac{16\sigma_{\bar{P}}^2 - \sigma_P^2}{15\sigma_P^2}$$

$$\Delta\Omega_P = \Omega_P^S - \Omega_P^W$$

Mathematically, the two indices emphasize different aspects of land-atmosphere coupling. Over regions of strong soil moisture-precipitation coupling, knowledge of soil moisture will both improve the predictability of precipitation mean (i.e., reduce the spreading of different ensemble members around the mean) and improve the predictability of precipitation temporal variability (i.e., increase the temporal coherency of different ensemble members). $\Delta\Omega$ emphasizes the impact of coupling on the predictability of precipitation temporal variability/trend, while $\Delta\Phi$ emphasizes the impact of coupling on the predictability of precipitation mean, as visualized in Figure 2 using an idealized example.

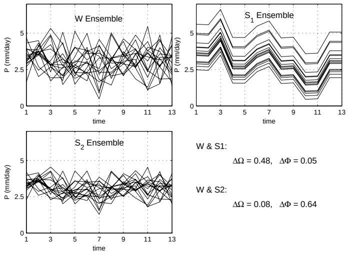


Figure 2: Precipitation time series from a W ensemble and two idealized S ensembles, each emphasizing a different aspect of soil moisture-precipitation coupling captured by the two coupling strength indices.

The intra-ensemble relative variance Φ and the alternative coupling strength index $\Delta\Phi$ (Wang et al., 2006):

$$\Phi_P = \frac{1}{n}\sum_{j=1}^{n}\left\{\frac{1}{\overline{P}_j^2} * \left(\frac{1}{16}\sum_{i=1}^{16}(P_{ij} - \overline{P}_j)^2\right)\right\}$$

$$\Delta\Phi_P = \frac{\Phi_P^W - \Phi_P^S}{\Phi_P^W}$$

Based on results from CAM3-CLM3, the two indices show similar dependence on the precipitation climatology (mean & standard deviation) (results not shown), but differ significantly in their dependence on the relative importance of atmospheric internal variability (measured by the ratio of precipitation variance due to internal variability to temporal variability, σ_i^2/σ_t^2) (Figure 3). In particular, $\Delta\Omega$ has a well defined upper limit that decreases with the increase of σ_i^2/σ_t^2. When the atmospheric internal variability is large, the $\Delta\Omega$ index is always small. On the contrary, $\Delta\Phi$ shows little dependence on the importance of atmospheric internal variability.

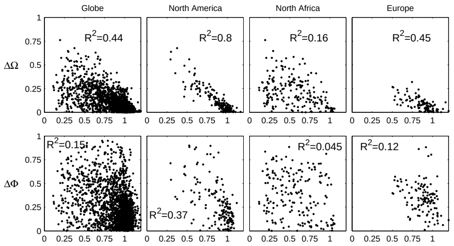


Figure 3: Scattering plot of the two coupling strength indices (y-axis) versus the ratio of precipitation internal variability to temporal variability σi2/σt2 (x-axis), over the globe, in North America, North Africa, and west Europe.

5. Results from CAM3-CLM3

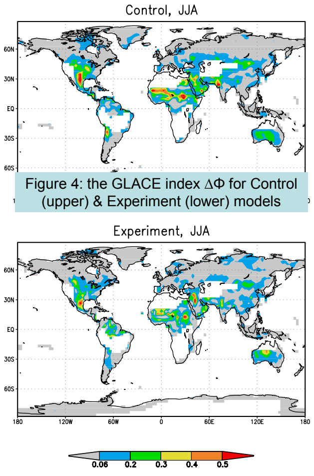


Figure 4: the GLACE index ΔΦ for Control (upper) & Experiment (lower) models

ΔΦ vs. ΔΩ:

Similarity: Both indices identify central North America and West Africa as regions of strong coupling in both the Control and Experiment models.

Difference: ΔΦ index identifies Europe as a region of medium (in Control) to strong (in Experiment) coupling, while ΔΩ indicate a fairly weak coupling in Europe.

Note: In Figures 4 and 5, areas are shaded gray where the coupling strength is statistically insignificant; land areas without shading are places of extreme seasonal aridity (with JJA rainfall less than 0.25 mm/day).

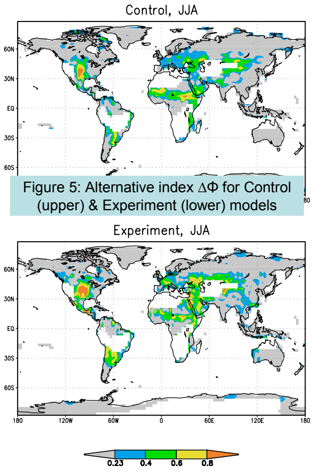
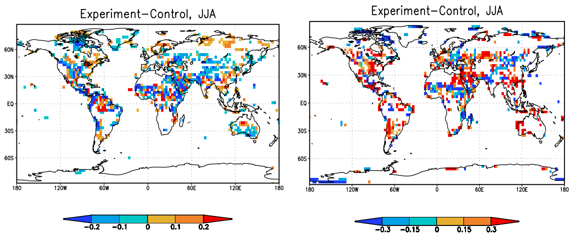


Figure 5: Alternative index ΔΦ for Control (upper) & Experiment (lower) models

Figure 6: Coupling strength differences between Experiment & Control models based the GLACE index ΔΩ (left) and the alternative index ΔΦ (right). Only statistically significant results are shown.



From the Control model to the Experiment model, the GLACE index $\Delta\Omega$ decreases in more areas than it increases, while the alternative index $\Delta\Phi$ increases in more areas than it decreases.

The direct pathway for soil moisture-precipitation coupling involves three links: 1) precipitation influences soil moisture; 2) soil moisture controls evapotranspiration; 3) evapotranspiration influences precipitation. Due to the surface water budget differences between Control and Experiment models shown in Figure 1, the first two links are strengthened in the Experiment model. If the third link is no limiting the soil moisture-precipitation coupling, we would expect the coupling to be stronger in the Experiment model than in the Control model.

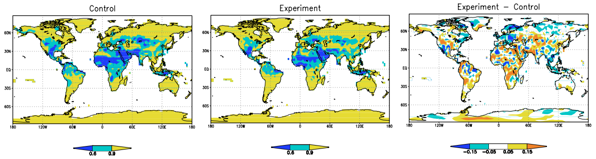


Figure 7: The ratio of precipitation variance σ_i^2/σ_t^2, estimated for the Control model, Experiment model, and the differences between the two.

Among the regions of strong coupling identified by the alternative index $\Delta\Phi$, West Europe is the only region where the σ_i^2/σ_t^2 ratio is very high (Fig. 7). Due to the relationship shown in Figure 3, this high variance ratio guarantees a low value of the GLACE index $\Delta\Omega$ in West Europe. Over most of the globe, the σi2/σt2 ratio increases from Control to Experiment (Fig. 7), setting the stage for a decrease of the GLACE index $\Delta\Omega$. These partly contribute to the differences between the two indices in quantifying the strength of coupling and in how they respond to moodel parameetrization changes.

6. Summary

An alternative index is proposed to quantify the strength of soil moisture-precipitation coupling. The proposed alternative emphasizes the predictability of mean precipitation, while the GLACE index emphasizes the predictability of precipitation temporal variability and trend.

In CAM3-CLM3, the newly proposed index identifies Europe as a major region of modest-to-strong coupling in addition to what the GLACE index suggests. In response to a model parameterization change that presumably favors a stronger soil moisture-precipitation coupling, the proposed index shows more increase while the GLACE index shows more decrease.

The strong dependence of the GLACE index on the σ_i^2/σ_t^2 Ratio is a potentially important cause for the differences between the two indices.

References:
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Wang DG, Wang GL, and Anagnostou EN, 2005: Use of satellite-based precipitation observation in improving the parameterization of canopy hydrological processes in land surface models. *Journal of Hydrometeorology*, 6, 745-763
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