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Seasonal Prediction with CCSM: Impact of Atmosphere and Land Surface Initialization

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1. Background

As shown by Shukla and Mintz (1982) and many subsequent studies (*e.g.*, Delworth and Manabe 1988; Atlas *et al.*, 1993), the presence or absence of water at the land surface can have a profound effect on the seasonal climate. Koster *et al.* (2004) showed that that effect can vary considerably over the planet, with its most pronounced impacts occurring in the semi-arid transitional zones that often lie between humid regions and deserts. They also showed that the various coupled land-atmosphere models used to gauge this effect disagree considerably on its magnitude. These results have also been borne out in several subsequent studies, which indicate that the presence or absence of moisture in the soil enhances the predictability at intraseasonal and longer time scales (*e.g.*, Wang and Kumar, 1998; Fennessy and Shukla, 1999; Yang *et al.* 2004).

As part of a project is to explore the efficacy of using the Community Climate System Model (CCSM), in conjunction with the NOAA Climate Forecast System (CFS), to provide a multi-model ensemble of climate predictions that are superior to predictions made with either model alone, we have developed methods to initialize the land and atmosphere model components of the CCSM and CCSM with observed states. Using that process, along with the ocean initial state produced at the University of Miami, we produced a set of one-year re-forecasts. In parallel to this effort, we produced similar re-forecasts for which only the Parallel Ocean Program (POP), the ocean model component of CCSM, was initialized.

2. Experimental setup

Model: The model used in this study is the CCSM3 (Collins *et al.*, 2006), which is a coupled ice-oceanatmosphere- land climate model with state-of-the-art formulations of dynamics and subgrid-scale physical parameterizations. The atmosphere is Community Atmospheric Model (CAM3, Eulerian dynamical core) at T85 (~150 km) horizontal resolution with 26 vertical levels. Experiments have been conducted with both the CAM3.0 and CAM3.5 versions of the subgrid-scale physical parameterizations, referred to as the CCSM3.0 and CCSM3.5 experiments, respectively. The ocean model is the standard version of POP with 1º resolution, stretched to 1/3º near the equator.

Re-forecast Experiments: Retrospective forecasts cover the period 1981-2000 (1982–1998) with initial states in January (July). One set of runs was made with observed initial states for the global ocean (OCN-only; Kirtman and Min, 2009), and one set of runs was made with full initialization of the global atmosphere, ocean, and land surface (ATM-OCN-LND). Ensembles of 4 (10) and 6 (10) hindcasts were run in the OCN-only (ATM-OCN-LND) experiments for the January and July cases, respectively.

Ocean Initialization: In all experiments, the ocean initialization uses the GFDL ocean data assimilation system, based on the MOM3 global ocean model with a variational optimal interpolation scheme. The GFDL ocean initial states were interpolated (horizontally and vertically) to the POP grid using a bi-linear interpolation scheme. (Climatological data from long simulations of CCSM3 were used poleward of 65°N and 75°S.) The ocean initial state is identical for each ensemble member.

Atmosphere and Land Initialization: In the OCN-only experiments, the atmospheric and land surface initial states were taken from an extended atmosphere/land-only (CAM3) simulation with observed, prescribed SST. The atmospheric ensemble members were obtained by resetting the model calendar back one week and integrating the model forward one week with prescribed observed SST. In this way, it is possible to

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generate initial conditions that are synoptically independent (separated by one week) but have the same initial date. Thus all ensemble members were initialized at the same model clock time (1 Jan or 1 July) with independent atmospheric initial conditions.

In the ATM-OCN-LND experiments, land and atmosphere were initialized for each of the 10 days preceding the date of each ocean initial state - 22-31 December for the 1 January ocean states, and 22-30 June for the 1 July ocean dates. The atmosphere was initialized by interpolating from daily reanalysis data. The land surface was initialized from daily Global Soil Wetness Project analyses (GSWP-2; 1986- 1995) and daily ERA40 (1982-1985 and 1996-1998). The observed anomalies were superimposed on a climatology for the Common Land Model (CLM), which is a component of the CCSM. The snow depth was initialized from ERA40, and the sea-ice was initialized to climatological monthly conditions based on a long simulation of CCSM3.0.

3. Results

Using the results of both sets of re-forecasts (OCN-only and ATM-OCN-LND), we performed an analysis with an eye to gauging the benefits of initializing CCSM3.0 with the observed atmospheric, land and ocean states in comparison to initializing with only the observed ocean state. We expect that a large part of the monthly to seasonal predictability in the atmosphere and land as simulated by the CCSM will be forced by temperature anomalies at the ocean surface. The working hypothesis is that a major factor in any enhanced predictability in the ATM-OCN-LND re-forecasts will be driven by long-term, large-scale anomalies of soil moisture. Therefore, we have focused on the predictability of the land surface and near surface variables.

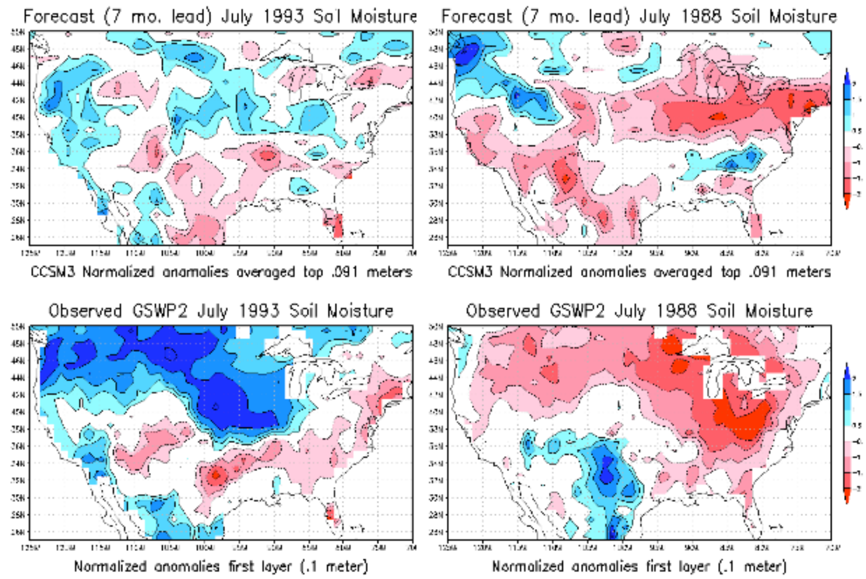

Fig. 1 (Top row) Forecasts at 7-month lead time of the monthly mean soil moisture anomaly in the top 9 cm of soil in the contiguous U.S. (Bottom row) Analyzed values of soil moisture in the top 10 cm, based on the Global Soil Wetness Program (GSWP) analysis. In both rows, the left panels are for July 1993 and the right panels are for July 1988. All anomalies are normalized by their respective standard deviations, based on 18 years of data, at each grid point.

As an example of what can be gained by initializing the land surface, Fig. 1 shows the soil moisture anomalies at 7-month lead time for forecasts initialized in January 1993, an extreme flood year, and January 1988, an extreme drought year. In 1993, the upper Mississippi valley was well above normal soil moisture with positive anomalies to the northwest and anomalously dry conditions to the south and east. During the 1988 drought, the center of the dry anomaly was in the northeastern U.S., with dry conditions extending to the west through the upper Mississippi valley and the high plains of the northwest. Wetter than normal conditions were present in the semi-arid and desert region of west Texas and the southwest. The predicted pattern of anomalies, and to a lesser extent the predicted intensity, closely resemble the observed pattern in both cases, except the wet anomaly in the southwest.

More broadly, Fig. 2 shows the correlation of observed and first month forecast of soil moisture in the top 3 layers of the CLM, for both ATM-OCN-LND and OCN-only forecasts, and for both experiments, from the end of December and the end of June ICs. The observations are taken from the ERA-40, and represent the first layer of the TESSEL soil model, which has a depth of 7 cm. We used this same data to initialize CLM for 1981-1985 and 1996-1999. A different land surface data set from the GSWP-2, was used for 1986-1995. The forecasts with initialized soil moisture anomalies produce a much better forecast of soil moisture anomalies in the first month. This is especially impressive, considering that these top three layers represent a total depth of only 9 cm. These maps also highlight an obvious benefit from initializing with observed snow depth. Those areas with persistent winter snow cover (and presumably frozen soil underneath) will tend to preserve their initial soil moisture anomalies. Similar correlation maps for the mid-layer (9-29 cm) CLM soil moisture (not shown) show the same results for month one, with generally higher positive correlation.

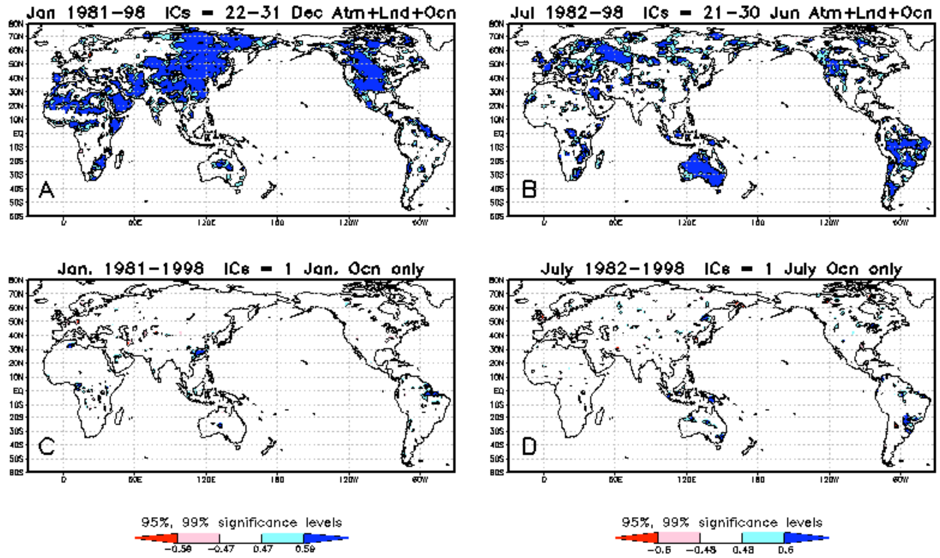

Fig. 2 A) Correlation of January monthly soil moisture in the top 9 cm from the CCSM3.5 Atm+Lnd+Ocn forecast initialized end of December versus January ERA-40 soil moisture in the top 7 cm; for Jan. 1981-1998. B) As in Fig. 2A, but for CCSM3.5 Atm+Lnd+Ocn forecast initialized end of June versus July ERA-40 soil moisture; for July 1982-1998. C) As in Fig. 2A, but for the CCSM3.5 Ocn only forecast initialized 1 January. D) As in Fig. 2A, but for the CCSM3.5 Ocn only forecast initialized 1 July. Shading indicates correlations significant at 95% and 99% levels.

Similar, though less impressive results, are present in the forecasts of the first season (JAS, JFM) soil moisture (not shown). Longer range forecasts are adversely affected by the tendency of the simulated soil moisture in CLM3.0 to dry out over time. We hope that improvements in the CLM3.5 will reduce these systematic errors.

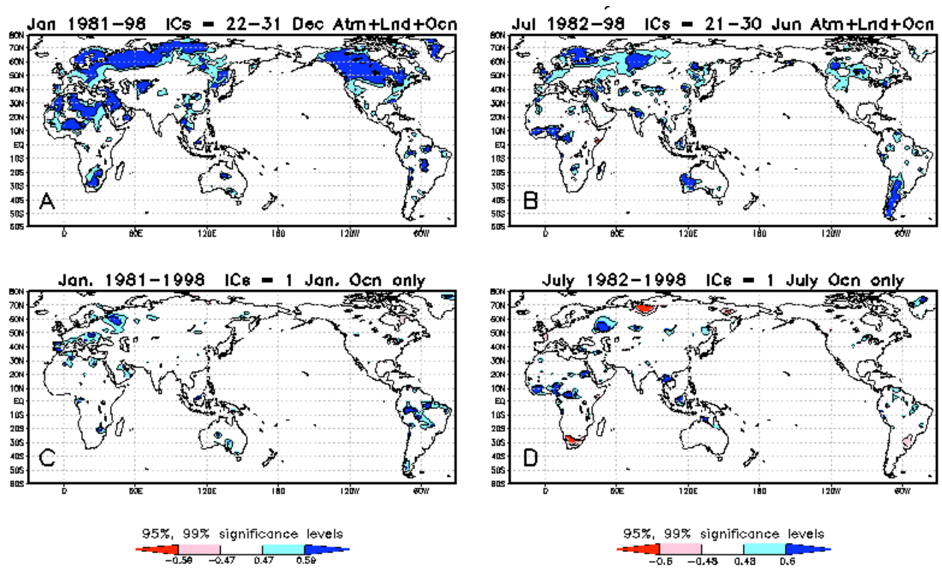

Fig. 3 A) Correlation of January monthly 2 meter temperature over land from the CCSM3.5 Atm+Lnd+Ocn forecast initialized end of December versus CAMS observed surface temperature, for Jan. 1981-1998. B) As in Fig. 3A, but for the CCSM3.5 Atm+Lnd+Ocn forecast initialized end of June; for July 1982-1998. C) As in Fig. 3A, but for the CCSM3.5 Ocn only forecast initialized 1 January. D) As in Fig. 3B, but for the CCSM3.5 Ocn only forecast initialized 1 July. Shading indicates correlations significant at 95% and 99% levels.

Figure 3 shows the correlation of the 2-meter temperature for the first month of the re-forecasts with observed surface temperature as represented by the CAMS dataset (Ropelewski *et al.*, 1985). Temperatures over the ocean have been masked out in order to focus on the land; since the two forecasts begin with the same ocean initial state, the correlations are close to identical. The simulation of the land surface temperature is clearly superior for the ATM-OCN-LND case, especially for the forecasts from 1 January ICs. In general, those areas in Fig. 2 with a good forecast of soil moisture tend also to have a good forecast of surface temperature. Figure 3 again suggests that there may be some benefit derived from the initialization of the snow depth. The correlation over snow-covered areas is generally good (*e.g.*, note southern South America in Fig. 3b.) Also note the significant correlation over northwest Europe, where the correlation of forecast and observed soil moisture was not significant.

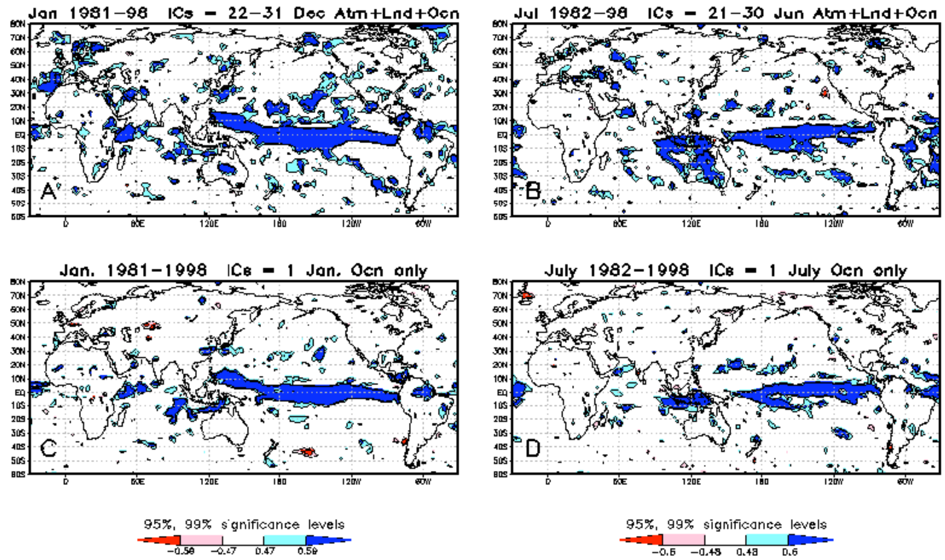

Fig. 4 A) Correlation of January monthly precipitation from the CCSM3.5 Atm+Lnd+Ocn forecast initialized end of December versus CMAP observed precipitation, for Jan. 1981-1998. B) As in Fig. 4A, but for the CCSM3.5 Atm+Lnd+Ocn forecast initialized end of June; for July 1982-1998. C) As in Fig. 4A, but for the CCSM3.5 Ocn only forecast initialized 1 January. D) As in Fig. 4B, but for the CCSM3.5 Ocn only forecast initialized 1 July. Shading indicates correlations significant at 95% and 99% levels.

Figure 4 shows the first month forecast of total precipitation versus observation as represented by CMAP (Xie and Arkin, 1997). There is little evidence that the ATM-OCN-LND initialization has provided much improvement in the forecast of precipitation over land, with the possible exceptions of Brazil and Australia in the end-of-June forecasts. Curiously, there is evidence of an improvement in the simulation of precipitation over the oceans, particularly in the extra-tropics in winter. If this improvement were to have arisen from the difference in initialization, it would seem more likely to be due to the atmospheric initialization, which might impart some skill to the first month's forecast. It might also be just an artifact of the smaller sample in the OCN-only forecasts, which had only four and six members for the 1 January cases and 1 July cases, respectively. We will investigate further.

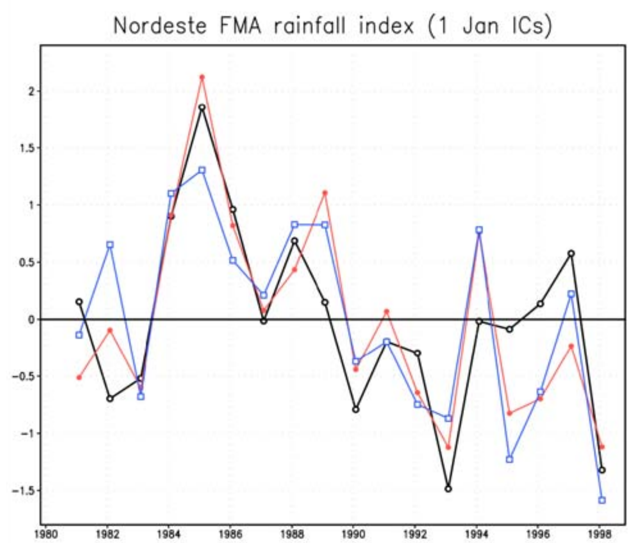

Fig. 5 Time series indices of an index of February – April rainfall over the Nordeste region of Brazil for the OCN-only forecasts (blue curve), the ATM-OCN-LND forecasts (red curve), in comparison with the same index computed from the CMAP precipitation analysis (black curve).

We studied specific instances of the ability of our forecast system to simulate climate and predictability of seasonal anomalies. For example, indices of FMA rainfall over the Nordeste region of Brazil for both the ATM-OCN-LND and OCN-only forecast precipitation (Fig. 5) provide a good approximation of the variability of an identical index constructed from observed rainfall. We also note that the climatology of the monsoon rainfall over India is well simulated by both sets of forecasts (not shown); although both of the forecasts do a poor job of reproducing the interannual variability.

4. Future work - CCSM3.5

We have updated and improved our initialization methods for CCSM3.5, and have begun producing retrospective forecasts.

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