CWRF Incorporation of a Conjunctive Surface-Subsurface Process Model to Improve Seasonal-Interannual Hydroclimate Forecasts

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1. Introduction

Accurate prediction of seasonal-interannual climate variation continues to be a key challenge for the modeling community, especially over the extratropical regions. One hypothesis is using the nested regional climate model (RCM) to better resolve the orographic effects from major mountains, moisture transport from low-level jets (LLJs), and water recycling through land and coastal ocean processes that contain certain memory. The present study focuses on the impact of incorporating a Conjunctive Surface-Subsurface Process model (CSSP; Liang et al. 2010b; Yuan and Liang 2010) into the Climate-Weather Research and Forecasting model (CWRF; Liang et al. 2005a-d, 2010a) on the seasonal-intreannual hydroclimate forecasts, based on the important role the land surface processes played over the midlatitude (Koster et al. 2004; Lorenz et al. 2010).

The CWRF has been developed on the basis of the Weather Research and Forecasting model (WRF, Skamarock et al. 2008) by incorporating numerous improvements that are crucial to climate scales, including interactions between land–atmosphere–ocean, convection–microphysics and cloud–aerosol–radiation, and system consistency throughout all process modules (Liang et al. 2010a). An essential aspect of the CWRF most relevant to the proposed research is its incorporation of a state-of-the-art Conjunctive Surface-Subsurface Process model (CSSP) in predicting soil temperature/moisture distributions, terrestrial hydrology variations, and land-atmosphere exchanges (Liang et al. 2010b). The CSSP is rooted in the Common Land Model (CoLM; Dai et al. 2003,2004) with a few updates from Community Land Model version 3.5 (CLM3.5; Oleson et al. 2008). The most prominent advances of the CSSP include an improved land surface albedo parameterization (Liang et al. 2005c), a scalable representation of subgrid topographic control on soil moisture (Choi et al. 2007), and an explicit treatment of surface-subsurface flow interaction (Choi 2006; Choi and Liang 2010), all of which are built upon realistic distributions of surface (soil and vegetation) characteristics (Liang et al. 2005a,b).

A comprehensive evaluation against observations at regional-local scales over the contiguous U.S. has demonstrated that the CSSP performance is overall superior to both the CoLM and CLM3.5 (Yuan and Liang 2010), including substantial improvements for surface heat fluxes, rooting zone soil moisture variations, soil temperature, extreme runoff and streamflow, snow pack and shallow water table depths. These advances will be very important for modeling the terrestrial hydrologic cycle and their feature changes identified with precipitation extremes. The coupled CWRF-CSSP, as driven by the global Climate Forecast System (CFS; Saha et al. 2006), shows high-quality downscaling skills in seasonal-interannual predictions for precipitation and terrestrial hydrology.

2. Offline Evaluation for Soil Moisture

Driven by the atmospheric conditions from the North American Regional Reanalysis (NARR; Mesinger et al. 2006), Yuan and Liang (2010) documented the CSSP performance on terrestrial hydrology over the contiguous U.S. Figure 1 compares soil moisture simulations with observations averaged over Illinois. For interannual variability, the CoLM roughly simulates the major wet and dry conditions occurred during 1984-2007. The CLM3.5 with new hydrologic parameterizations makes a significant improvement, having higher correlation coefficient (*CC*) and lower mean absolute error (*MAE*) than the CoLM. The CSSP presents a further improvement, with large *MAE* reductions (in mm) from the CLM3.5 (6.0, 21.6, 26.1) to (4.0, 13.3, 20.7) for the top 3 soil layers. The improvement is especially pronounced near the surface, where the CLM3.5 substantially underestimates the observed interannual variability.

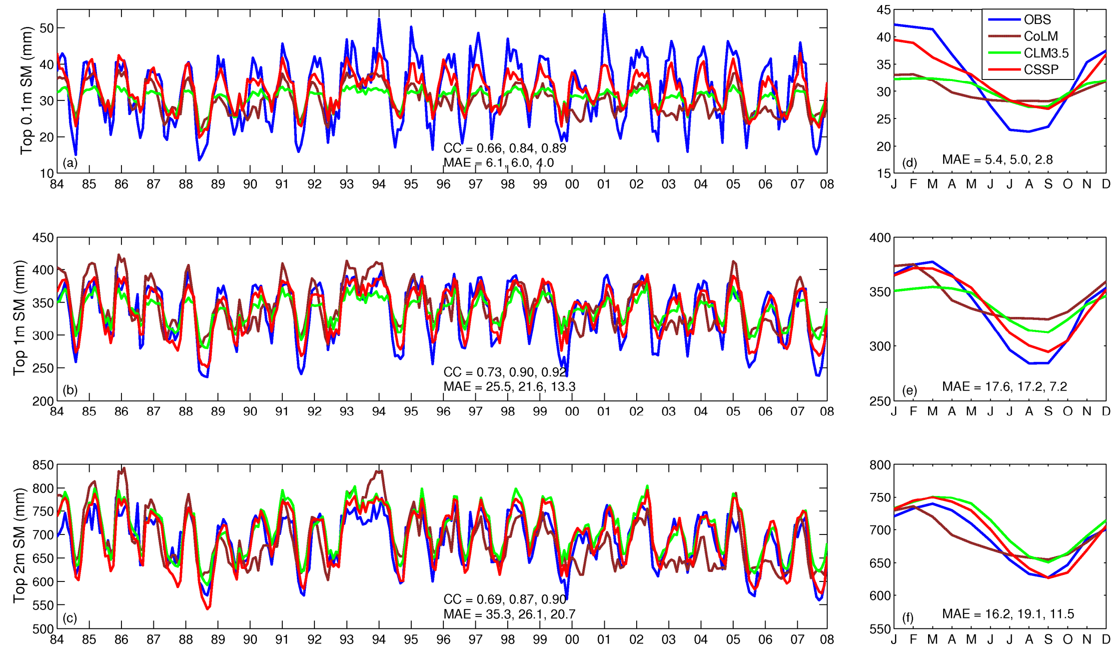

Figure 1. Simulated soil moisture (mm) averaged over Illinois by CoLM, CLM3.5 and CSSP in comparison with observations for top 0.1m, top 1m and top 2m soil. *CC* is the correlation coefficient, and *MAE* is the mean absolute error.

Similar improvements are also reflected in the Illinois soil moisture annual cycle (Figs. 1d-e), where the CSSP best reproduces observations while the CoLM remains the poorest performer for all top (0.1m, 1m, 2m) layers. This is particularly obvious in *MAE* (mm), for which the CSSP yields (2.8, 7.2, 11.5) that are much smaller than even the CLM3.5 (5.0, 17.2, 19.1). The large *MAE* values are identified with low rooting zone soil moisture variability, which was acknowledged by Oleson et al. (2008) as one of the major deficiencies remaining in the CLM3.5. The model skill in depicting the annual cycle amplitude can be measured by the ratio of standard deviation simulated over observed. For the rooting zone layers, the CSSP produces the highest ratios (0.58, 0.83), as compared with the CoLM (0.44, 0.79) and CLM3.5 (0.29, 0.48). Thus the CSSP generates not only the most realistic phase but also the best amplitude of the soil moisture annual cycle, systematically throughout the root zone.

3. CWRF Downscaling Seasonal Climate Prediction

After validating the CSSP standalone, we use it online with the CWRF to downscale the CFS seasonal forecasts for wintertime. The initial experiments are composed of five members over a period of 27 years (from 1982 to 2008) for the forecast period Dec. 1-Apr. 30, with initial dates at Nov. 29-Dec. 3. The lateral boundary conditions are updated every 3 hours. The study domain centeres at (37.5˚N, 95.5˚W), covers the whole continental U.S. with a 30-km grid spacing. The buffer zones are located across 14 grids along 4 domain edges, where varying LBCs are specified through a dynamic relaxation technique (Liang et al. 2001).

Figure 2 shows the frequency distributions of root mean square errors (*RMSE*) for the interannual variations of seasonal mean precipitation predicted by the CFS and CWRF, which depicts that the CWRF reduces the errors obviously in general. The peaks of *RMSE* in different leading month forecasts are larger than 1 mm/day for the CFS, while around 0.5 mm/day for the CWRF. The geographic distribution of bias and *RMSE* (Fig. 3) indicates that the CWRF reduces the errors significantly over middle to high latitude and the North American monsoon (NAM) regions, especially over North Rockies and Great Lake regions where the CFS has large wet bias and low predictability. Like many other GCMs (Liang et al. 2004), the CFS has a dry bias over the Gulf States during DJF; while the CWRF alleviates the dry bias to some extent, which is an interesting issue that needs further investigation. On average, the CWRF reduces the *RMSE* for DJFMA mean precipitation from 1982 to 2008 by 0.3 mm/day.

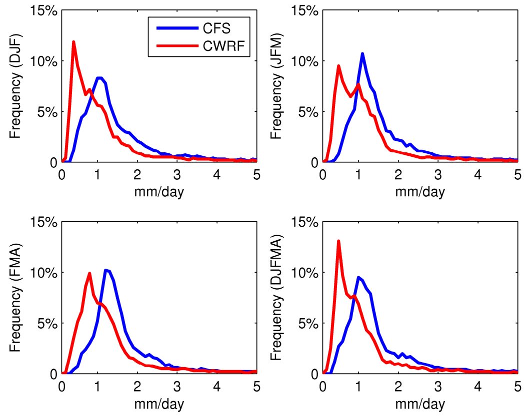

Figure 2. Frequency distribution of root mean square errors (*RMSE*, mm/day) for the interannual variations of the seasonal mean precipitation over land predicted by the CFS and CWRF based on 5 ensemble members during wintertime of 1982-2008. Seasonal precipitation is binned at an interval of 0.1 mm/day.

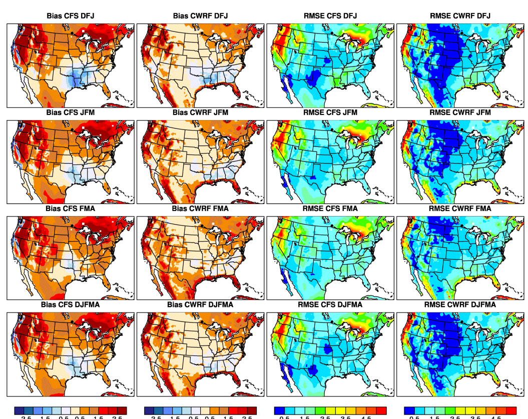

Figure 3. Geographic distributions of the bias and *RMSE* (mm/day) of seasonal precipitation for the CFS and CWRF.

Figure 4 presents spatial distributions of observed and forecasted number of rain days and 95th percentile daily precipitation during boreal winter (JFM) averaged over 1983-2008. Similar to the bias pattern (Fig. 3), the CFS overestimates the number of wet days greatly along the northern tier of the domain; while the CWRF downscaling results demonstrate more accurate amount and sufficient geographic details, especially over the western and central U.S., and the NAM region. Over the major mountain regions (e.g., the North Rockies, Appalachian and Sierra-Madre-Occidental), the improvement are mainly due to the fine resolution of orographic precipitation; over the central U.S., the reasonable bowen ratio (see Fig. 5 for surface heat fluxes) and its related land-atmosphere interaction play an important role; while over the Great Lake region, the enhancement are dependent on the incorporation of some new surface processes including a 11-layer lake model, a 5-layer snow model and a subsurface frozen soil parameterization. Figure 4 also shows that though the patterns of 95th percentile daily rainfall are similar between the CFS and CWRF, the latter better resolves the extreme precipitation over the northern California (>40 mm/day) and Gulf States (>30 mm/day).

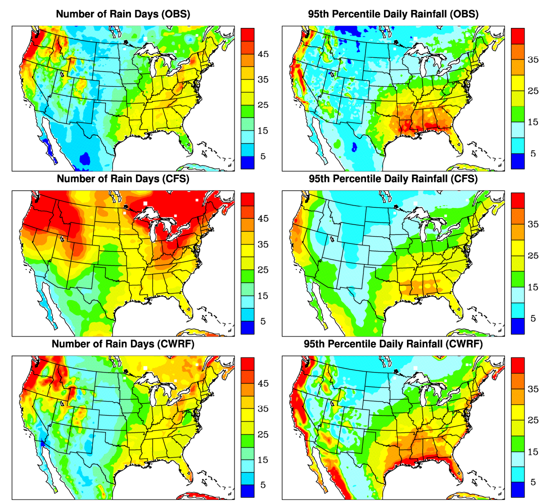

Figure 4. Average number of rain days (>1 mm) and 95th percentile daily rainfall (mm/day) for boreal winter (JFM) during 1983-2008 from observation, CFS and CWRF.

Figure 5 compares the predicted average surface heat fluxes with the NARR data during the boreal winter. The CFS simulates much less sensible heat than the NARR, while the CWRF downscaling reduces the underestimation significantly. The CWRF generates less latent heat flux than the CFS, and results in better simulations over the northern and western regions, where the precipitation prediction is better than the CFS (Fig. 3). Corresponding to the dry bias over the Gulf States (Fig. 3), the CWRF produces less latent heat than the NARR; while whether insufficient precipitation leads to low latent heat or vice versa is an unknown issue. However, the CFS presents different evapotranspiration (ET)-precipitation relationship over the same region: it has dry bias for precipitation and wet bias for ET. In other word, the CWRF provides more reasonable precipitation efficiency (Yuan et al. 2008) than the CFS over the Gulf States. As compared with Global

Runoff Data Center (GRDC) data, the CWRF generates more detail geographic characteristics than the CFS (Fig. 5). In particular, the CWRF correctly predicts the boreal winter runoff over the northwestern and eastern U.S., which is totally missed by the CFS. Over the Rocky Mountain region, the CWRF produces larger runoff than the CFS and GRDC. Besides the influence of positive precipitation bias (Fig. 3), this enhancement may likely result from its incorporation of the effects of subgrid topographic control and shallow bedrock constraint on surface and subsurface water movements. The differences, however, may well be within observational uncertainties due to the scarcity and poor quality of the actual data driving the GRDC analysis, including discharge, precipitation, and temperature, in the mountainous region. As discussed above, the CFS has wet bias for precipitation over the North Rockies and southeastern Canada (Fig. 3), but the simulated snow water equivalent (SWC) is still less than the Canadian Meteorology Center (CMC) analysis data (Fig. 5). In contrast, the CWRF provides much better SWC, which indicates the advantage of snow module in RCM.

4. Summary

The 30-year continuous offline integration and the 27 cold season online downscaling forecasts indicate that the CWRF incorporation of the CSSP shows substantial improvements for precipitation characteristics, surface heat fluxes, rooting zone soil moisture variations, extreme runoff and snow pack. To further improve the seasonal hydroclimate predictions, future efforts will be devoted to the refinement of land surface initial conditions (e.g., soil moisture, snow and groundwater) which contain certain memory, and the optimized ensemble forecast (Liang et al. 2007) based on multiple physical options in CWRF.

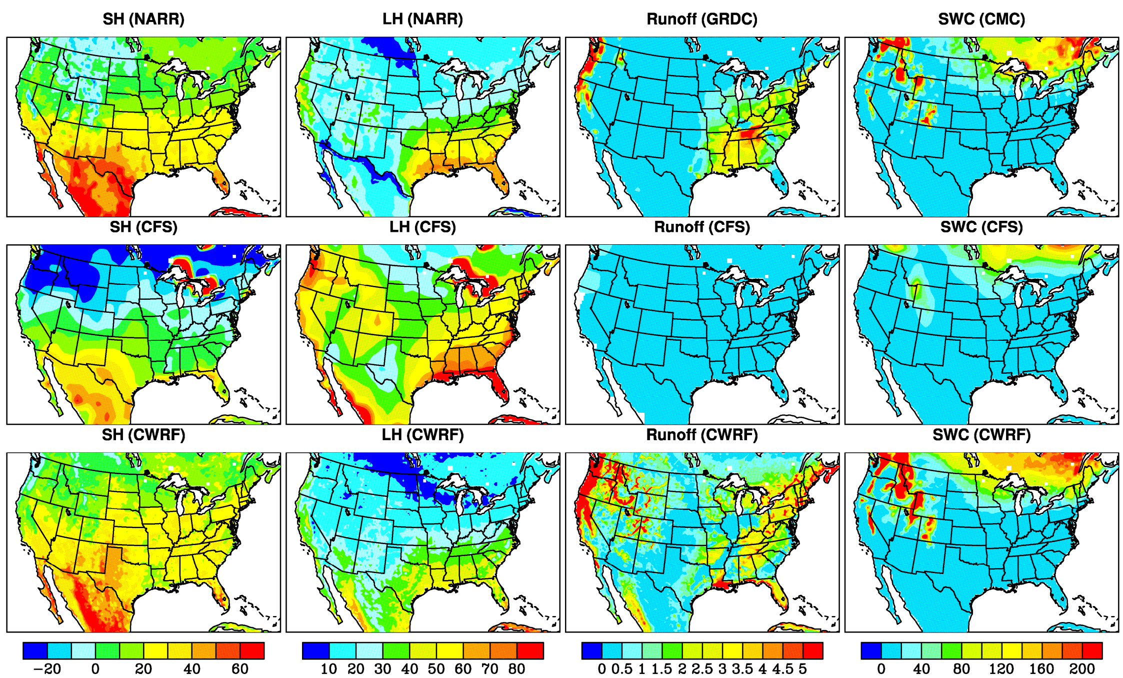

Figure 5. JFM mean results for sensible heat (SH, W/m^2), latent heat (LH, W/m^2), total runoff (mm/day) and snow water equivalent (SWC, mm) from reanalysis (NARR, GRDC and CMC), CFS and CWRF.

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