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Evaluation of hydrologic components of community land model 4 and bias identification

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ABSTRACT

Runoff and soil moisture are two key components of the global hydrologic cycle that should be validated at local to global scales in Earth System Models (ESMs) used for climate projection. We have evaluated the runoff and surface soil moisture output by the Community Climate System Model (CCSM) along with 8 other models from the Coupled Model Intercomparison Project (CMIP5) repository using satellite soil moisture observations and stream gauge corrected runoff products. A series of Community Land Model (CLM) runs forced by reanalysis and coupled model outputs was also performed to identify atmospheric drivers of biases and uncertainties in the CCSM. Results indicate that surface soil moisture simulations tend to be positively biased in high latitude areas by most selected CMIP5 models except CCSM, FGOALS, and BCC, which share similar land surface model code. With the exception of GISS, runoff simulations by all selected CMIP5 models were overestimated in mountain ranges and in most of the Arctic region. In general, positive biases in CCSM soil moisture and runoff due to precipitation input error were offset by negative biases induced by temperature input error. Excluding the impact from atmosphere modeling, the global mean of seasonal surface moisture oscillation was out of phase compared to observations in many years during 1985–2004. The CLM also underestimated runoff in the Amazon, central Africa, and south Asia, where soils all have high clay content. We hypothesize that lack of a macropore flow mechanism is partially responsible for this underestimation. However, runoff was overestimated in the areas covered by volcanic ash soils (i.e., Andisols), which might be associated with poor soil porosity representation in CLM. Our results indicate that CCSM predictability of hydrology could be improved by addressing the compensating errors associated with precipitation and temperature and updating the CLM soil representation.

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1. Introduction

The Community Land Model (CLM) serves as the land model for the Community Climate System Model (CCSM) (Collins et al., 2006) and includes land biogeophysics, hydrology, and biogeochemistry. Hydrology comprises key processes that link and integrate atmosphere, ocean, vegetation, and human systems. Increasing greenhouse gas concentrations and potential global warming may affect water cycle dynamics, which in turn provide feedbacks to the atmosphere and land surface. As a tool for predicting future states of ecosystems and climate, land surface model development requires rigorous calibration and validation against observations.

The growing demand for assessing the potential impacts of projected climate change on human systems (Field et al., 2014) highlights the importance of understanding surface hydrological responses within fully coupled Earth System Models (ESMs), in addition to evaluating the accuracy of standalone land surface models. While the IPCC AR5 has implemented a new framework for assessing these impacts (Field et al., 2014) a recent study with the newly developed integrated Earth System Model (iESM), which directly couples the Global Change Assessment Model (GCAM) with the Community Earth System Model (CESM) (Collins et al., 2014), has quantified the unintended consequences of not implementing complete consistency among land use and land cover components of the economic Integrated Assessment Models (IAMs) and the biophysical ESMs (Di Vittorio et al., 2014). The next steps for assessing climate impacts include implementing and examining feedbacks between ESM water supply and IAM water demand and management. In the context of the iESM, closer examination of the

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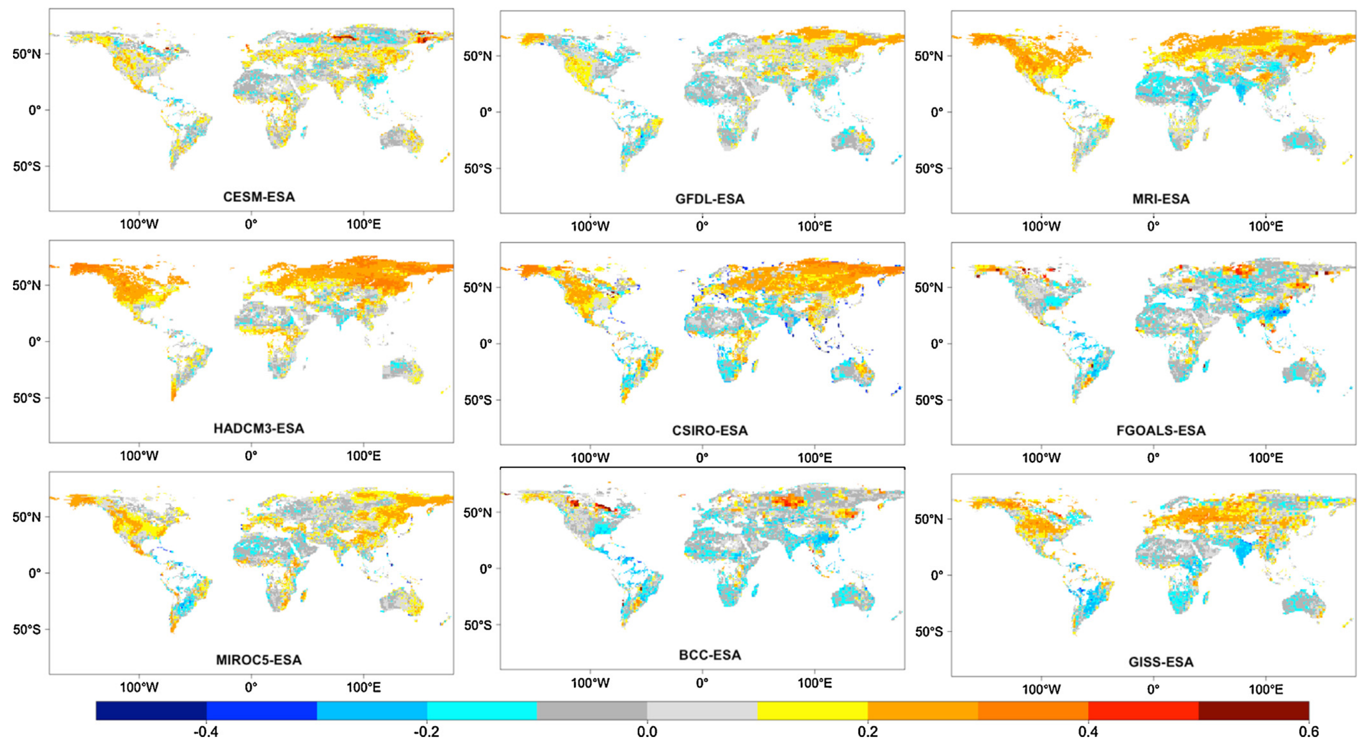

Fig. 1. Absolute surface soil moisture difference indicates CCSM4's soil moisture exceeds ESA CCI SM observation by up 0.05–0.20 (vol vol^{-1}) in the Rocky Mountains, central Europe, central Africa, south of Himalayas, most of China, and west Australia. CCSM4 underestimated surface soil moisture by up to 0.20 in high latitude areas. Most other CMIP5 models had positive biases in high latitude areas and United States except FGOALS and BCC.

surface hydrology of the fully coupled CCSM/CESM will enable development of a more consistent framework for incorporating human-earth water cycle feedbacks into projections of water availability and use.

Runoff is an important component of the hydrological cycle, but runoff trend detection at the global scale is a difficult task. Even the sign of the trends are uncertain, as recent estimates of global runoff trends in the twentieth century from various modeling studies are both positive (Gedney et al., 2006; Labat et al., 2004; Piao et al., 2007) and negative (Dai et al., 2009; Shi et al., 2011). Positive trends may be a result of increased continental precipitation, stomatal closure due to rising CO_2 concentration, land use changes, or decline of land ice content (Alkama et al., 2013). Decreasing trends in global runoff could be a consequence of climate forcing changes with minor effects from nitrogen deposition and land use change (Shi et al., 2011). These uncertainties in runoff simulations are largely due to different model implementations of atmosphere-plant-soil system interactions and the range in responses from these parameterizations to model-specific climate forcings.

Soil moisture has been demonstrated to affect regional climate via evaporation and evaporative cooling (Seneviratne et al., 2013). For example, atmospheric circulation over the land surface is largely affected by soil moisture during summer (Owe et al., 2008). In particular, surface soil moisture controls partitioning between sensible and latent heat, and affects partitioning between overland flow and infiltration (Hou et al., 2012). However, surface soil moisture is among the most complex hydrologic variables to simulate as it interacts with the atmosphere, plant canopy and roots, and vadose zone. This complexity is likely evidenced by studies showing that peak variability in soil moisture occurs at the surface (Decker and Zeng, 2009).

Our evaluation procedures comply with the benchmarking framework proposed by Luo et al. (2012). We focus on runoff and soil moisture because observation-based, gridded, global datasets have recently become available for these two key hydrologic variables (Fekete and Vorosmarty, 2002; Liu et al., 2012). Other variables such as river discharge and soil water storage of CLM4 (Lawrence et al., 2011) and earlier versions (3-3.5) were reported to match observations of major basins globally, although the accuracy of timing for simulated hydrologic quantities varied among rivers and areas (Lawrence et al., 2011; Oleson et al., 2008; Qian et al., 2006). However, CLM4 hydrologic simulations have not been fully assessed at the level of a global grid. Thus, we define a set of metrics including absolute and normalized biases, temporal correlation, and seasonal dynamics to identify model strengths and deficiencies at the grid level. Using these metrics, we identify the contributions of uncertainty from both the atmosphere and the land components of the earth system model to soil moisture and runoff. Based on our evaluation, we propose improvements to the land model hydrology. Our results not only meet evaluation objectives that are coincident with CMIP5 goals (Taylor et al., 2012), they also provide insights toward coupling ESM and IAM water cycles to examine human-earth feedbacks affecting water supply, demand, and management.

2. Datasets and methods

The study was designed as two parts to answer following questions:

1. How well do the fully coupled models, particularly CCSM/CLM, represent the surface soil moisture and runoff? What atmospheric forcings have the greatest influence on these two variables?

The hydrologic simulations of the CMIP5 models are largely dependent on the forcings of various atmosphere models, but the ensemble comparison may still help to reveal areas where hydrology is frequently underrepresented by the earth system models and areas where observations/satellite products have biases.

2. What are the contributions of these dominant forcings to hydrologic biases? How do these biases relate to biases gener-