Title: Quantification and reduction of uncertainties in projections of climate impacts on drought and agriculture for North America

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Final Report

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Introduction

Agricultural productivity is highly dependent on climate variability and is thus susceptible to future changes including temperature extremes and drought. The latter is expected to increase in frequency regionally over this century. However, the uncertainty in projections of drought and its impacts on agriculture is high due to emission scenarios, climate model differences, uncertainty in initial/boundary conditions, and translation to regional scales. Climate models are unanimous in projecting future warming but differ in the magnitude and even sign of regional precipitation changes. They also differ in terms of extremes of temperature, precipitation and other meteorology. When projecting future impacts on crop productivity, these uncertainties are compounded because current crop models often use simplified treatments of climate response and do not include comprehensive treatments of water availability. Therefore, projections of regional climate change, variability and its impacts on water availability and agriculture are highly uncertain and reduction of uncertainties requires attention to all levels in the climate-water-agriculture continuum.

Rationale: Given the uncertainties in future agricultural production and the complex relationships between climate, hydrology and crop development, there is pressing need to make improved estimates of future changes in climate change and crop yields. *We propose to evaluate the uncertainties in estimates of future changes in climate, water availability and agricultural production, and make improved estimates by incorporating state of the art knowledge of the relationships between climate, hydrology and agriculture into modeling and downscaling.* This has ramifications for disaster preparedness and mitigation, policy making and the political response to climate change, and intersects with fundamental science questions about climate change, extremes and hydrologic cycle intensification. It is central to the mission of the Climate Program Office's MAPP program to "enhance the Nation's capability to predict variability and changes of the Earth's System" and directly addresses its priorities to evaluate and reduce uncertainties in climate projections. This work will leverage from the PIs' experience and ongoing activities in large-scale climate analysis and hydrologic modeling, particularly in changes in drought historically and under future climates, and agricultural modeling and relationships between climate and crop productivity.

Results and Accomplishments

<u>*Task 1. Quantify the relationships between hydroclimate variables and the implications for water, drought and agriculture.*</u>

Proposed work: We will look at relations between soil moisture, temperature and other hydrologic variables in the context of drought and agriculture, leveraging from previous work by the PIs on drought occurrence, hydrologic anomaly propagation, land-atmosphere interactions and agriculture-climate relationships. This will draw from the suite of hydroclimate datasets (reanalysis, remote sensing, observational, off-line land surface modeling) described in section 4.3.1. Key metrics that will be explored include precipitation-temperature-soil moisture relationships, factors influencing evaporation, the persistence of soil moisture, and the occurrence and severity of drought.

Results:

Uncertainty in large-scale drought variability

We analyzed the NLDAS2 multiple land surface model (LSM) database (Xia et al., 2012) in terms of drought to understand the uncertainties in hydrological response derived from different LSMs (Sheffield et al., 2012a) that analyzed. Figure 1 shows a set of drought statistics from the four NLDAS2 models. The models are forced by the same meteorological dataset but show very different magnitudes and spatial variability of the statistics. We have previously shown this to be related to differences in the model definition of soil layers and depths and the parameters (Wang et al., 2011), as well as coupling between soil moisture and other hydrological components such as evapotranspiration and runoff (Sheffield et al., 2012b). We extended this analysis to other types of datasets including state-of-the-art reanalysis datasets, and evaluations over the US (Figure 2) indicate reasonable consistency with the NLDAS2 multimodel mean at large scales, although the datasets tend to diverge in recent years and on finer spatial scales, which is related to changes in observing systems that enter the reanalysis datasets.

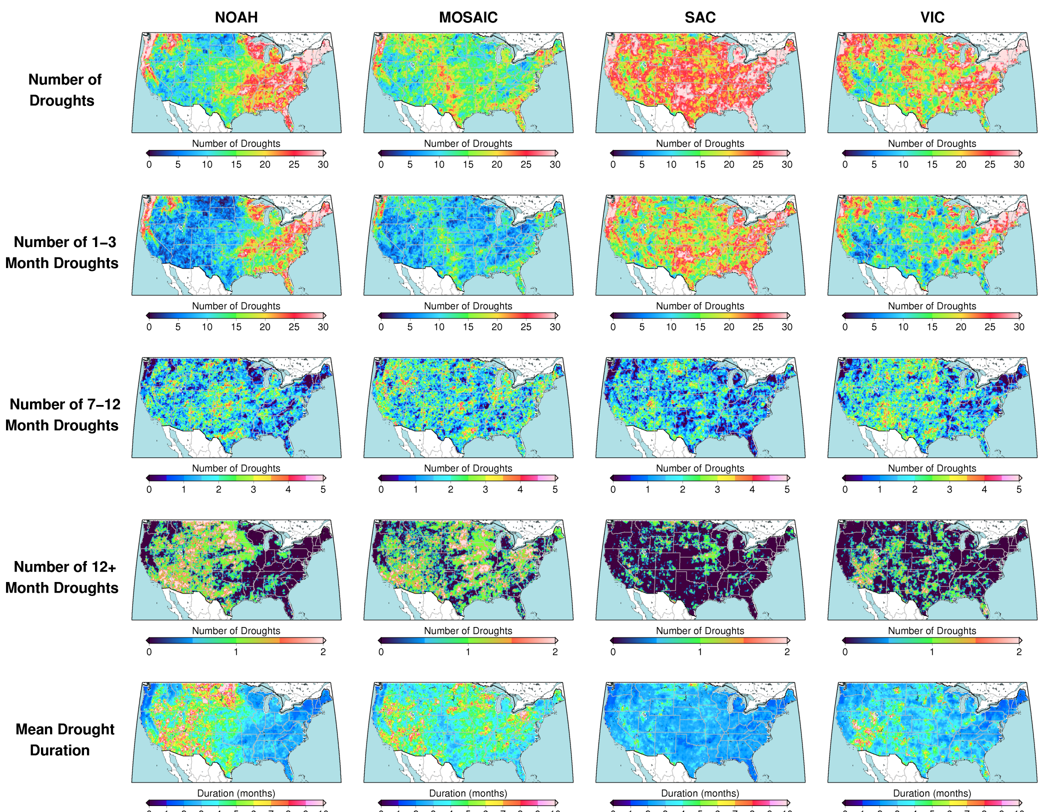


Figure 1. Multi-model comparison of drought statistics for 1979-2008 from the NLDAS2 LSMs. All models are forced by the same meteorological dataset.

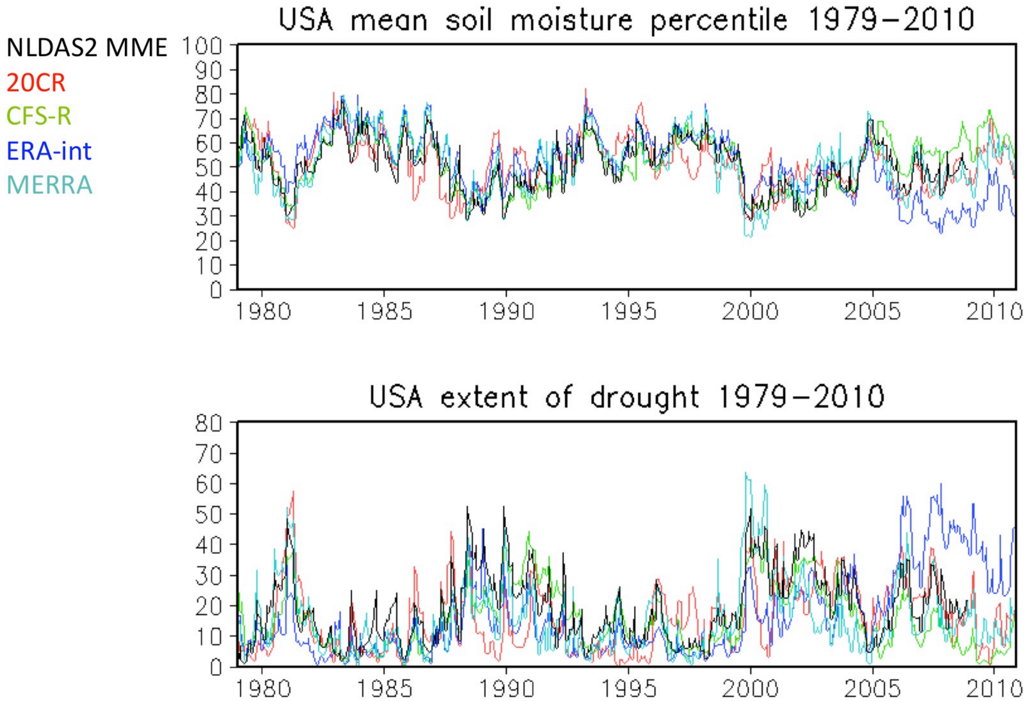


Figure 2. Time series of US averaged soil moisture percentile and area in drought for 1979-2010 from the NLDAS2 multi-model ensemble mean and the four state-of-the-art reanalysis datasets.

Land-atmosphere coupling in observations and constrained models. Land-atmosphere coupling is a key aspect of drought development but also a key uncertainty in coupled models, shaping relationships between soil moisture, temperature and precipitation through turbulent fluxes. We focused on analyzing land-atmosphere coupling in observations and off-line models, and used these results to evaluate climate models. We obtained observations from the Soil Climate Analysis Network (SCAN), which consists of 174 stations over the United States (Figure 3), including air temperature, precipitation, soil moisture and temperature for 5 layers. 85 sites were chosen according to two criteria: 1) At least 2 years of data is available for the period of 2002-2009; 2) All data during 2010-2012 is available. Quality control, including automatic removal of outliers and manual checking was carried out for soil moisture for January 2002 to September 2009 by Liu et al (2011). Similar procedures were applied 2010-2012 data by 1) detecting step changes, 2) removing data when soil temperature is below 0ºC and 3) removing unreasonable soil moisture values such as random oscillations.

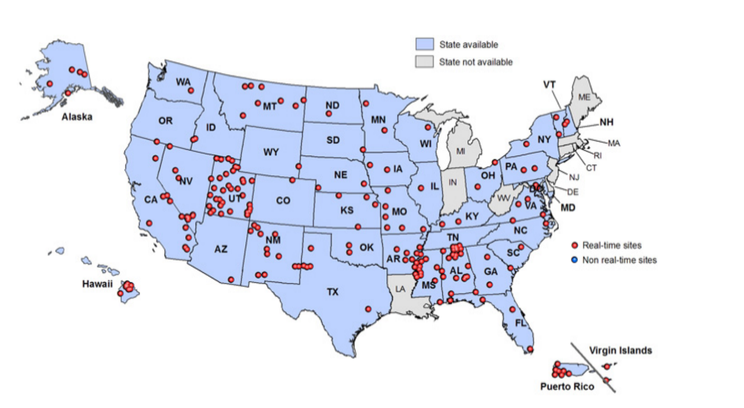


Figure 3. Soil Climate Analysis Network (SCAN) sites.

Land-atmosphere coupling was considered in terms of relationships between precipitation/temperature and soil moisture. We hypothesized that 1) precipitation and soil moisture are positively correlated under wet conditions; and that 2) temperature and soil moisture are negatively related under dry conditions when evapotranspiration starts to decline because of moisture limitation. Using the SCAN data we found that monthly precipitation and soil moisture are strongly positively correlated, with correlation highest for upper layers as expected. On a daily scale, we also quantified the lagged correlation between precipitation and soil moisture change, and a lag of 1 day gives the highest correlation, and is positive for all soil layers except the lowest layer at 100cm. Temperature-soil moisture relationships were also examined on different temporal scales for the summer months (JJA). In general, a negative correlation between air temperature and soil moisture exists at monthly and daily scale, but these relationships are noisy, especially at the daily scale. We also examined the relationship with the number of hot days (NHD) in JJA as an index of hot conditions. NHD is defined as the number of days that have air temperature exceeding the 90th percentile. NHD and monthly SM are negatively correlated for most sites and all soil layers with correlations generally insignificant in the east, increasing westwards and reaching a maximum in the western US (Figure 4). This is consistent with hot spots of land-atmosphere coupling shown by models (Seneviratne et al., 2006) and seasonal precipitation and temperature data (Mueller and Seneviratne, 2012).

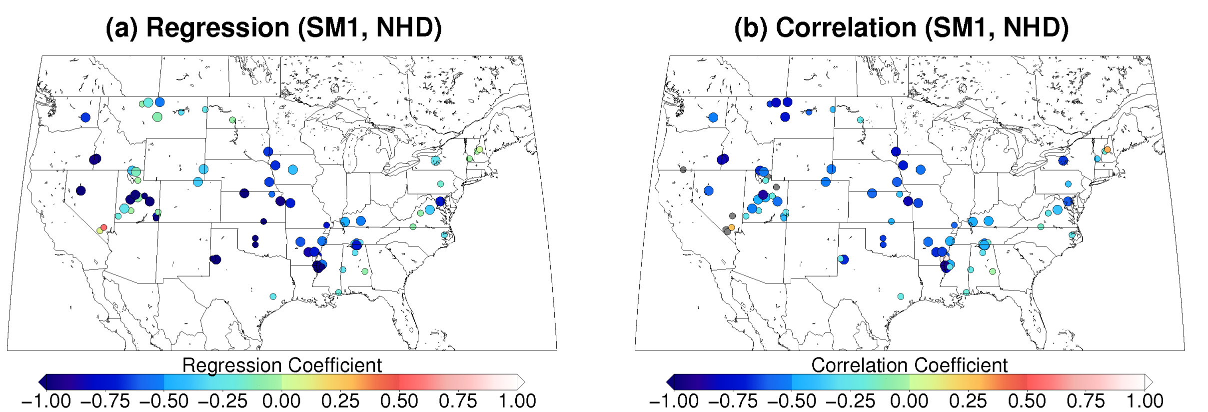


Figure 4. Coupling between JJA soil moisture (SM – shown for the top layer) and number of hot days (NHD) for ~80 SCAN sites. (a) Linear regression coefficients between SM and NHD. (b) Correlation coefficients between SM and NHD. Statistical significance is indicated by larger symbols.

We hypothesized that low soil moisture contributes to the development and maintenance of heat waves through reduced evapotranspiration, and explored the contribution of local heating from dry soil conditions versus temperature advection using a simple metric of advection based on the

NLDAS-2 dataset. Figure 5 shows an example of the correlation between the NLDAS-2 temperature advection and air temperature changes as estimated either from NLDAS-2 or from the local SCAN observations, for 12 sites in the central U.S. that show strong coupling between soil moisture and temperature. The NLDAS-2 results indicate that up to 25% of the variance can be explained by temperature advection for the hottest days suggesting that soil moisture feedbacks may be contributing to hot days, at least within the NLDAS-2 dataset. The NLDAS-2 versus SCAN results show low or negative correlation suggesting that inconsistencies between the NLDAS-2 and SCAN data (due to biases, scale mismatches, etc) obscure any potential relationships. This work is being written up as Xu and Sheffield, (2015).

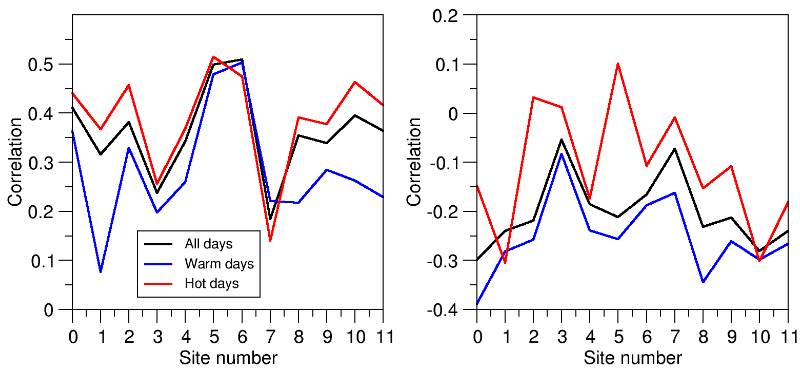


Figure 5. Correlation between (left) NLDAS-2 temperature advection and change in NLDAS-2 temperature and (right) NLDAS-2 temperature advection and change in SCAN temperature for 12 sites in the central U.S. for all days, warm days, and hot days (> 25°C).

Task 2. Evaluate sensitivities of hydrologic and crop models to changes in climate and drought

Proposed work: It is expected that differences in climate trends, climate variability, land-atmosphere coupling and hydrologic persistence will lead to differences in key metrics of water and agriculture. This will be inferred from a set of experiments in which the hydrologic and crop models are driven by our existing observational meteorological dataset as well as synthetic experiments whereby plausible changes in climate mean, variability and drought persistence are imposed on the models. Statistical and process-based crop models will be run in their standard mode to evaluate the influence of historical climate variability and trends. Comparison of the statistical and process- based approaches will reveal if one approach is more or less sensitive to variations in temperature, precipitation, and/or soil moisture in the current model configuration.

Completed work: Princeton was the lead on looking at sensitivities of hydrological models to changes in climate. We set up a multiple land surface model framework, which provides alternative models to the VIC model to help understand the sensitivities. We set up global simulations for two other models: CLM V3.5 and Noah V2.8 and upgraded CLM to V4 and Noah to V3.5, which are the latest versions. CLM and Noah were run for the global domain but were analyzed over the U.S. following similar procedures for our multi-model drought analysis for China (Wang et al., 2011). Figure 6 shows an example of the differences in modeled available water (precipitation – evapotranspiration) for multiple land surface models and for multiple precipitation forcing datasets. In drying regions the uncertainties in trends are dominated by precipitation uncertainty, but uncertainties are decreasing. In wetting regions, uncertainties are about equal between model and precipitation uncertainty and uncertainties are increasing. This is, in part, due to increasing differences in precipitation datasets as the number of gauges declines.

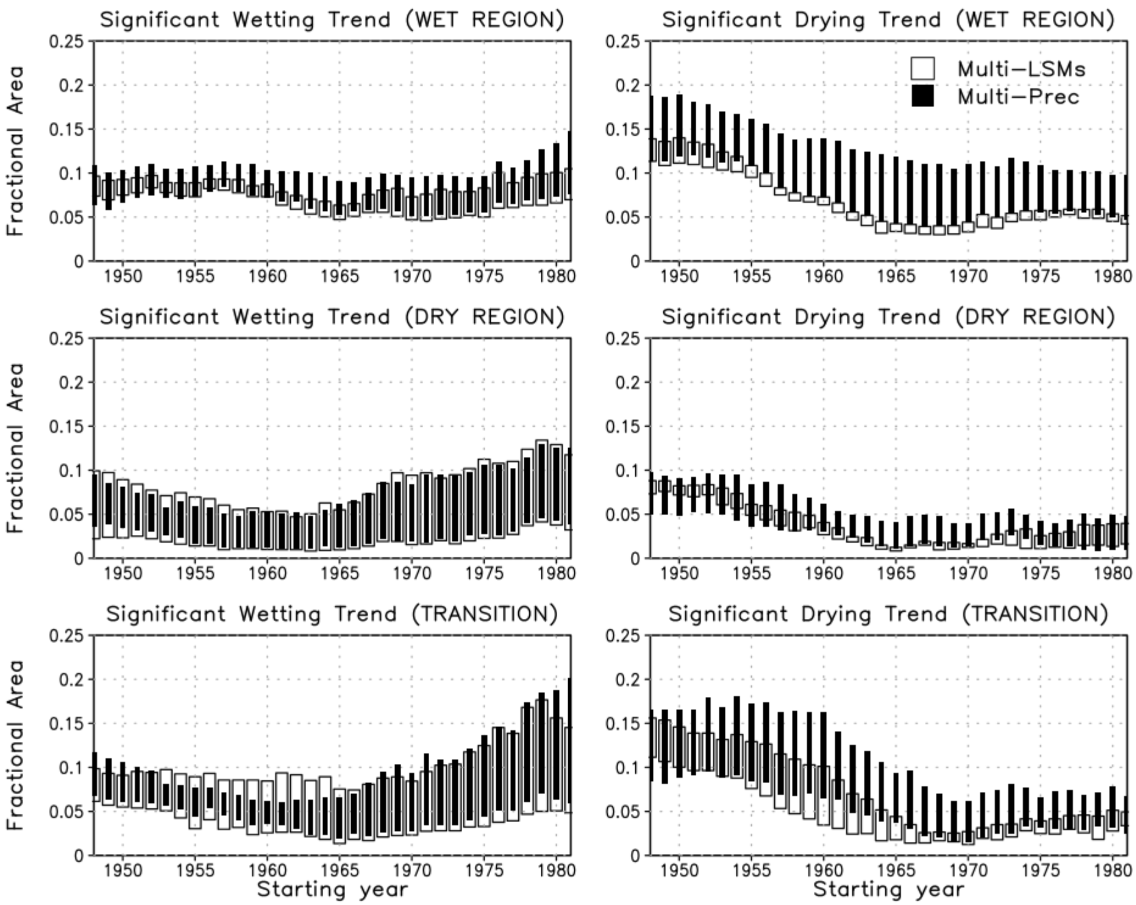


Figure 6. Uncertainty in the area of significant trends in P-E for multiple land surface models (open bars) and multiple precipitation forcing datasets (closed bars) for different regions. The trends are calculated for 30-year moving windows.

To augment the work on crop models, we developed a simple crop model based on standard FAO methods using crop coefficients and stress factors for heat and water. Results for historic and future climate projections of agricultural productivity were presented by Sheffield et al. (2011) for sub-Saharan Africa.

<u>*Task 3. Evaluate current climate models in how they replicate these observed relationships*</u>

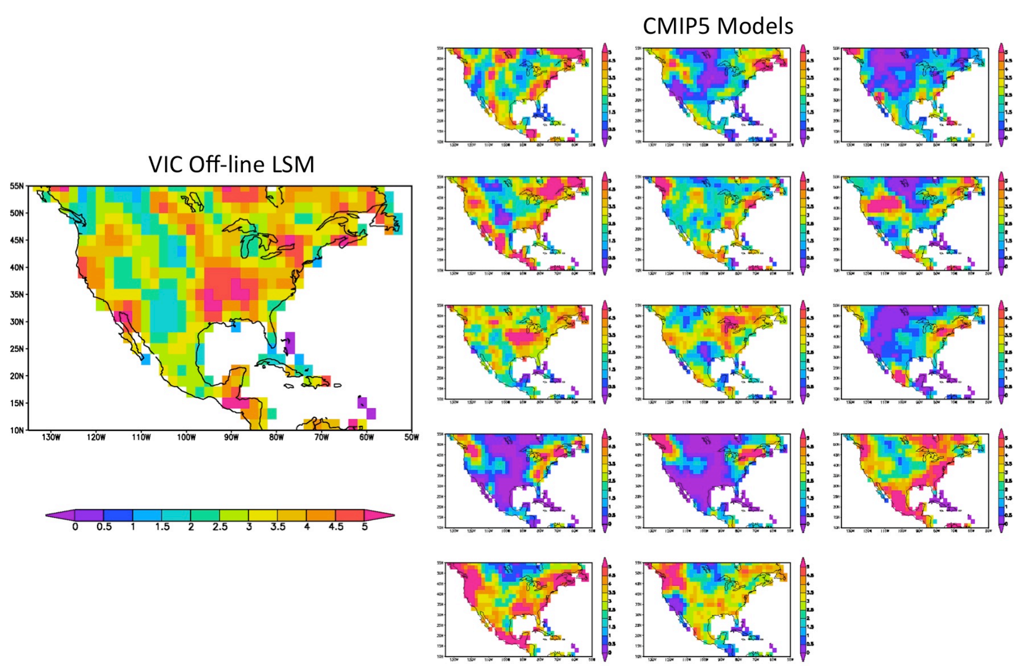
Proposed work: We will evaluate the CMIP5 20th century simulations at a variety of time and space scales for regions across North America, but with focus on agricultural regions. A set of impact relevant metrics will be examined, including the representation of drought and its drivers, relationships between temperature and soil moisture, and so on. The impact of identified biases will be further evaluated by forcing the hydrologic and crop models with raw climate model output (without downscaling or bias correction). Cluster analysis will be used to identify similar models that will aid in the reduction of uncertainties in later tasks.

Completed work:

Evaluation of CMIP5 Climate Models for U.S. Hydroclimate

We downloaded and processed a suite of model outputs from the CMIP5 database for daily and monthly precipitation and temperature and for monthly hydroclimate variables (evapotranspiration, runoff, soil moisture and snow). The CMIP5 data were analyzed in terms of how well individual models represent observed (estimated from off-line LSMs) drought variability and relationships between hydroclimate variables. Figure 7 compares the CMIP5 models with the VIC LSM in terms of drought frequency and shows large spread among the models. A handful of models show similar spatial variation in the drought statistics to the VIC model, albeit given the uncertainty in observational estimates from off-line models. Several models severely underestimate the frequency of short-term drought, which is related to underestimation of precipitation mean and variability. Figure 8 summarizes the evaluations for different regions in the US and puts this in the context of evaluations for global regions and compared to CMIP3 models. The CMIP3 and CMIP5 results are generally similar, with slightly less spread in the CMIP5 models.

20C Evaluations: Frequency of Short-Term (4-6 month) Drought



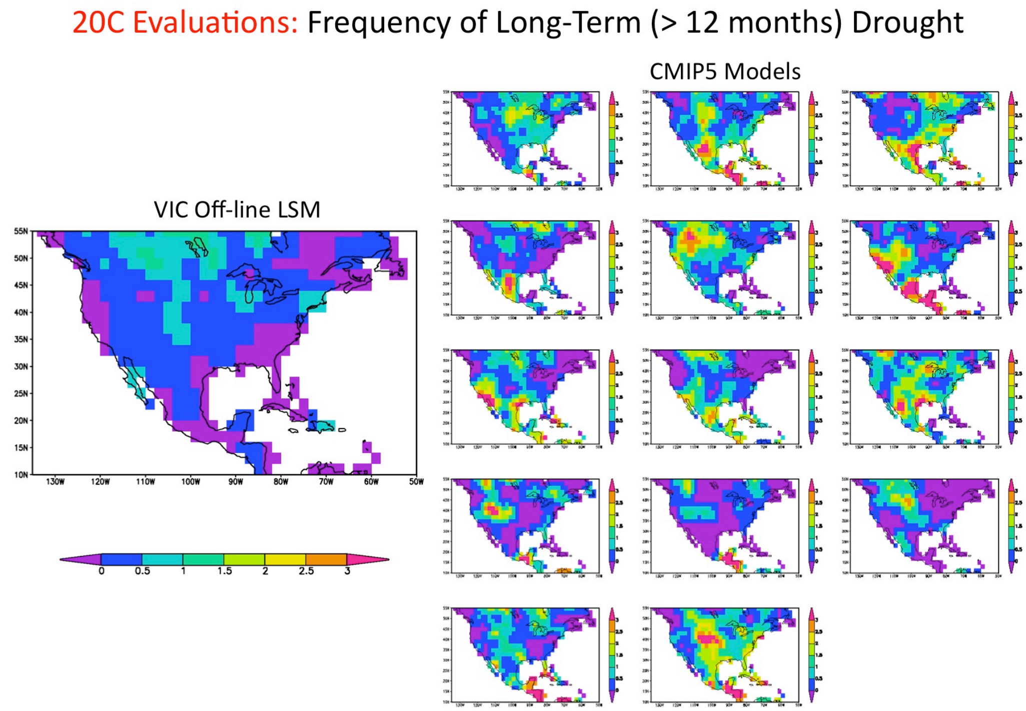


Figure 7. Comparison of drought frequency for (top) short (4-6 month) and (bottom) long-term (> 12 months) drought between CMIP5 models and the VIC LSM.

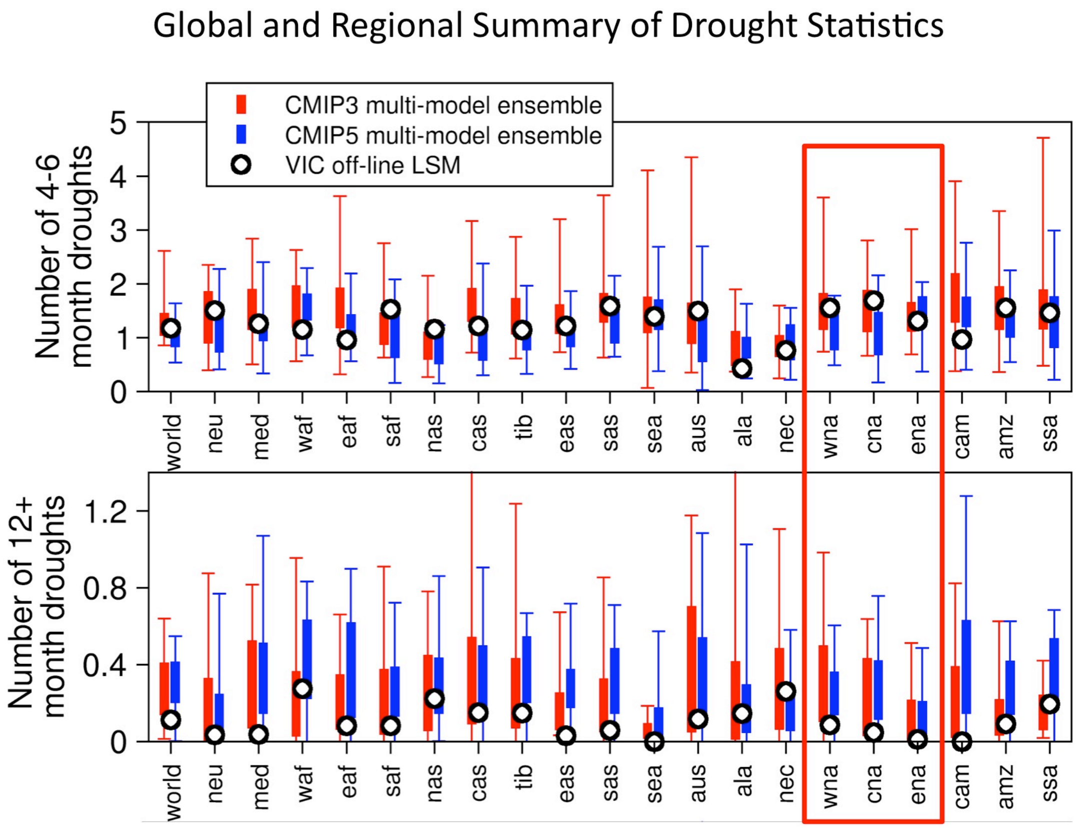


Figure 8. Global and regional drought statistics for CMIP3 and CMIP5 models compared to the VIC LSM. US regions (western NA, central NA and eastern NA) are highlighted.

The differences between the models and with observational estimates are partly due to differences in model persistence in soil moisture (Figure 9). Persistence is calculated as the average number of months that soil moisture is below or above the median and is generally higher in the Western US where climate variability is low and tends to persist in one state (wet or dry) for many months to years, and low in the eastern US where climate variability is high and droughts are broken quickly after a few months at most. Some models are able to capture the east-west gradient quite well. Many other models place the location of highest persistence in the central US.

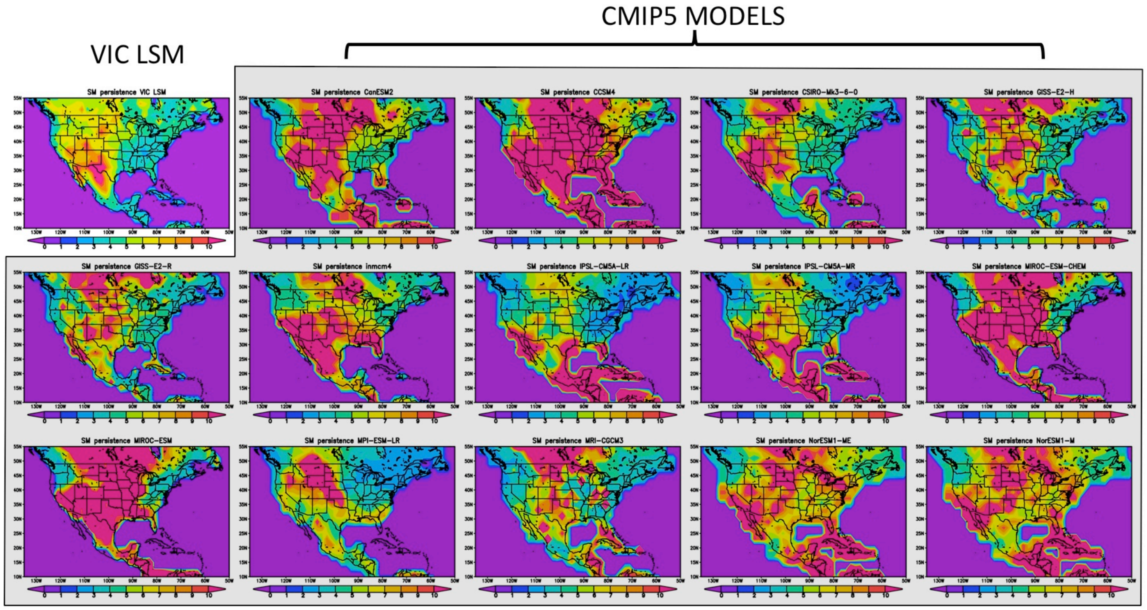


Figure 9. Persistence in soil moisture anomalies from VIC and selected CMIP5 models.

Figure 10 shows the mean seasonal cycle of water budget components averaged over US regions. Compared to the VIC LSM, soil moisture tends to wet too early in CMIP5 models and has a larger dynamic range. The latter may be related to deeper soils, more precipitation, and more evapotranspiration in the climate models. Precipitation is too high in the west in the CMIP5 models and evapotranspiration is generally too high, regardless of the modeled precipitation. Runoff is too low and the spring melt peaks too early.

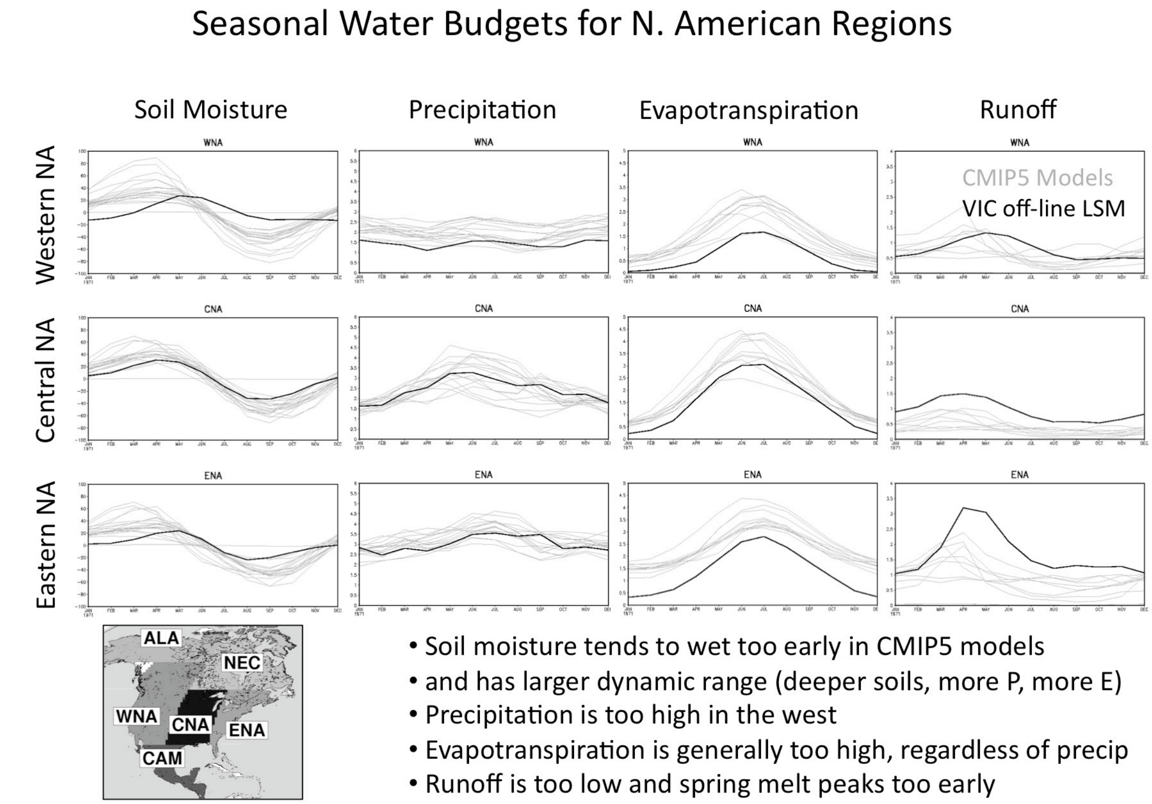


Figure 10. Mean seasonal regional water budgets for the VIC LSM and the set of CMIP5 models.

We also looked at correlations between hydroclimate variables (Figure 11). In winter time, precipitation is well correlated with runoff over the southern 2/3 of the US in the VIC LSM and correlation rapidly drops off into Canada because of snow accumulation. The models do reasonably well at replicating this. The correlation between precipitation and evaporation is very low in VIC with some sublimation across the northern plains and Canadian prairies. However, the models show various patterns of higher correlation especially over the western mountain and eastern Canada. The correlations with soil moisture are consistent across models and with VIC. In the summer time, runoff is highly correlated with precipitation over much of the region. But the models vary in how they match this. Evaporation is highly correlated with precipitation in the drier southwest. The models mostly pick this up but some models have too strong coupling and too spatially extensive. For soil moisture, VIC shows high correlation in the east where there is plenty of water for evaporation. There are a wide variety of correlation patterns for soil moisture in the models, but they all pick up the higher correlations in the east.

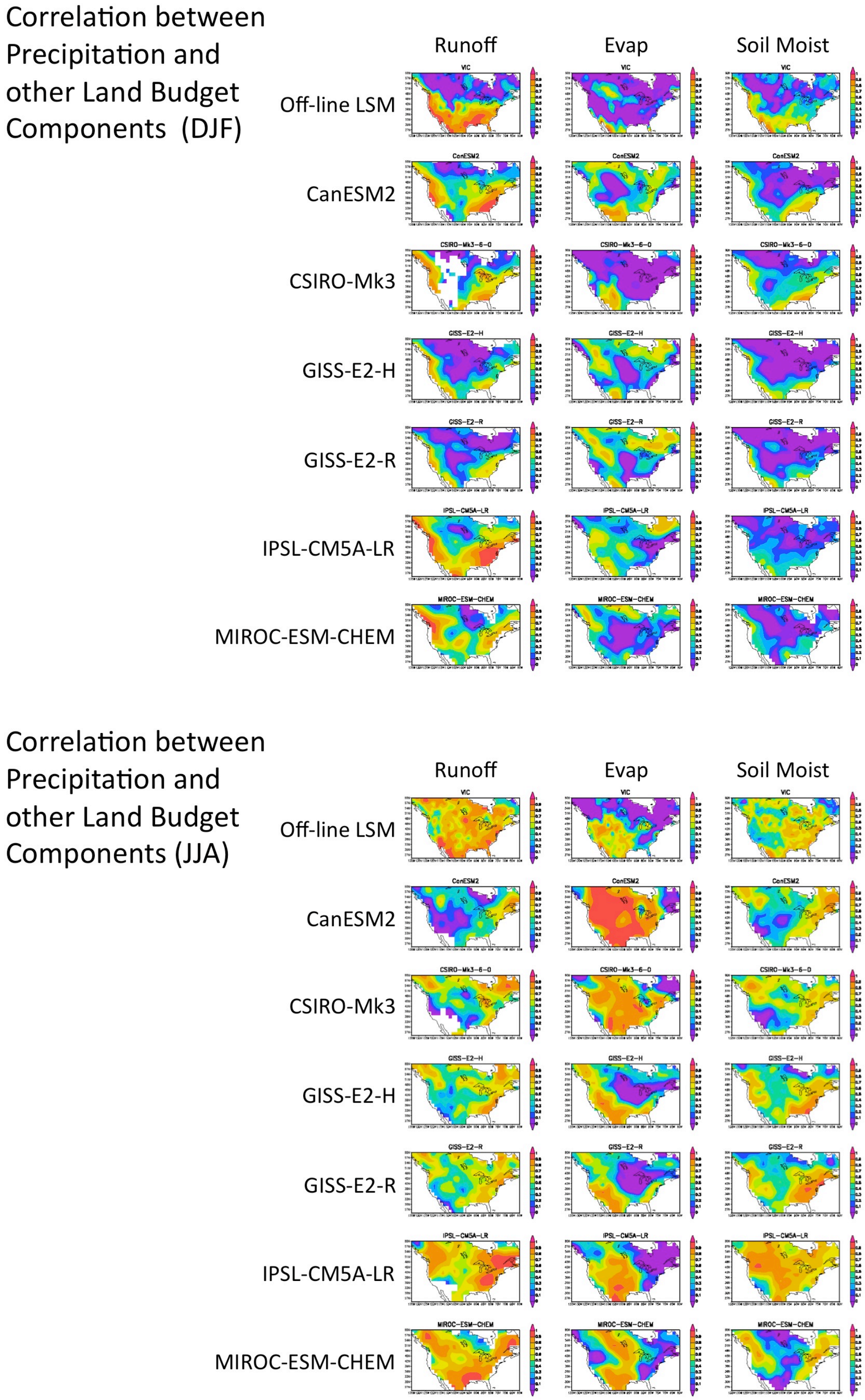


Figure 11. Correlation between precipitation and runoff, evapotranspiration and soil moisture in winter (top) and summer (bottom) for the VIC LSM and selected CMIP5 models.

Part of this analysis contributed to three multi-author papers on evaluation of N. American climate simulations in CMIP5 models (Sheffield et al., 2013a,b; Maloney et al., 2013), including the evaluation of terrestrial water budgets against NLDAS-2 data and of extreme temperatures against the HadGHCND observational dataset.

Following on from the synthesis analysis of CMIP5 model simulations for N. America, we have led the development of a Highlights and Outstanding Questions document that details significant differences between CMIP3 and CMIP5 for N. America. These differences were driven by queries from the staff of the National Climate Assessment to put the latest NCA, which is based on CMIP3 results, in the context of the latest CMIP5 results. The document highlights many aspects of N. American climate for which the CMIP5 simulations have not improved significantly since CMIP3 but other aspects for which the future projections have become more robust in terms of agreement among models. A key difference may the treatment of aerosols, which appears to be related to shifts in projected changes, such as for the line between wetting and drying which is further south in CMIP5 simulations. The document was delivered to NOAA as a technical report (Sheffield et al., 2014).

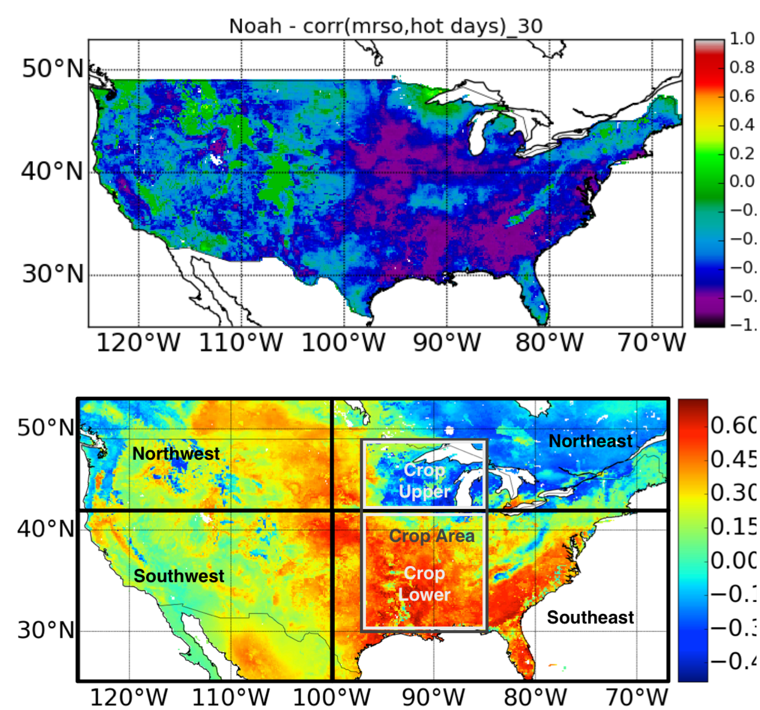


Figure 12. (top) Correlation between soil moisture and number of hot days from the Noah NLDAS-2 LSM. (bottom) Land atmospheric coupling metric and the sub-regions. Data shown are the average values of the NLDAS-2 Noah and VIC land surface models for JJA, 1979-2005.

Evaluation of CMIP5 Climate Models for Land-Atmosphere Coupling

We also extended the work on analysis of land-atmosphere coupling by evaluating land surface models and coupled climate models in the same context. We evaluated land surface models from the NLDAS-2 dataset against the SCAN coupling results to test whether they reproduced the sign and spatial distribution of coupling between soil moisture and temperature (Figure 12). We developed metrics of land-atmosphere coupling based on correlations between summertime mean soil moisture and evapotranspiration (ET) and normalized by the mean ET and bounded by -1 (strong atmospheric control - no coupling) and 1 (strong soil moisture control – coupling present). Figure 12 also shows the coupling metric calculated from averaging two land surface model datasets from the NLDAS-2 database, with distinct regions of low and high coupling in the southeast/Midwest and northeast, respectively, and transitional regions in the West. We also focused on two regions with intensive agricultural in the Midwest that are characterized by low and high coupling.

Task 4. Estimate uncertainties in future projections of climate, drought and agriculture

Proposed work: This task will determine the uncertainties using the cascade of models to ascertain the propagation of uncertainties through all levels of the climate-hydrology-agriculture continuum. We will strategically sample the cascade of different model permutations (taking into account low probability but high impact models) to provide an estimate of the full uncertainty that is obtainable from such a framework. We will decompose the uncertainties in projections into that attributable to scenario, model, and internal variance and apply this to relevant variables (such as temperature, precipitation, drought occurrence, crop yield) at various time and space scales.

Completed work: We analyzed the CMIP5 models in terms of 20th century evaluations and their future projections of drought. The results for the CMIP5 database indicate that soil moisture is projected to decline globally, similar to the CMIP3 data, but with slightly more uncertainty across models by the end of the 21st century. Figure 13 shows global average time series of multi-model CMIP5 and CMIP3 20th and 21st century long-term projections for soil moisture and a set of drought characteristics. The shading represents the distribution across models. A few CMIP5 models project increases in soil moisture in high latitudes. Soil moisture generally dries for all models and there is a commensurate increase in all aspects of drought, such as increased drought frequency and areal extent. Drought tends to increase everywhere despite higher annual precipitation in some places (notably higher latitudes), because the seasonality of changes in climate and how it interacts with the surface hydrology is important.

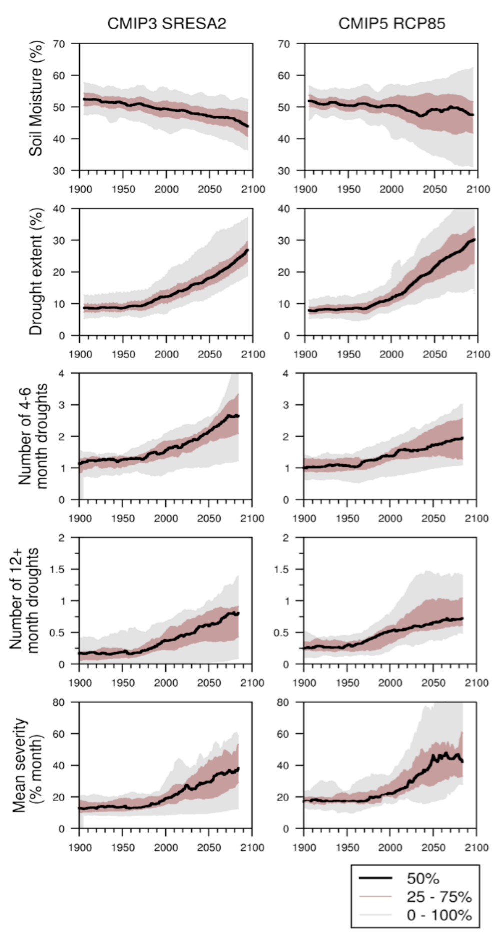


Figure 13. Projected changes in soil moisture and drought from the CMIP3 and CMIP5 climate models.

We analyzed these results for the U.S. as a contribution to a paper on climate extremes on CMIP models (Wuebbles et al., 2014) (Figure 14). There is consensus among the models for future summer soil moisture decreases throughout the U.S. and for winter soil moisture decreases in most of the

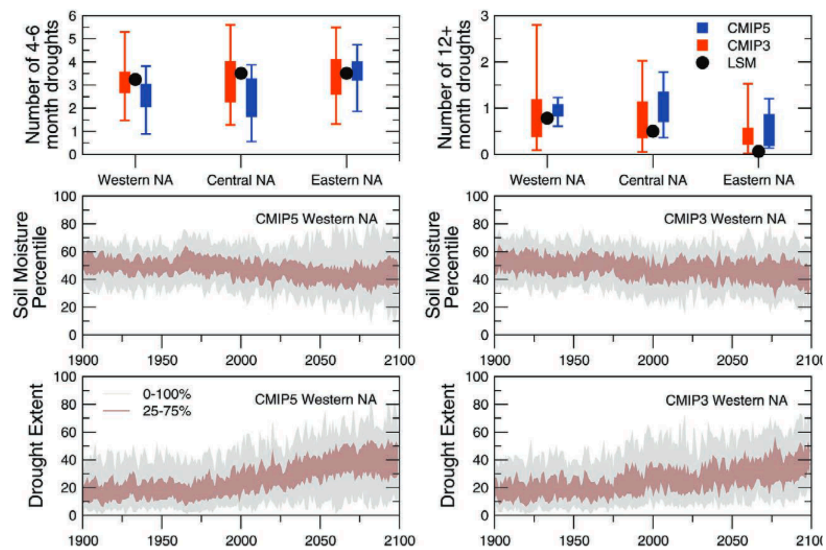


Figure 14. (top) Evaluation of CMIP5 and CMIP3 models against offline land surface model (LSM) estimates of observed regional drought frequency (number of droughts per 30 yr) for (left) droughts that last for 4–6 months and (right) droughts that last for more than 12 months. (middle) Distribution of projected changes in soil moisture percentile from (left) CMIP5 and (right) CMIP3 models for western North America. (bottom) Distribution of projected changes in drought extent from (left) CMIP5 (higher RCP8.5 scenario) and (right) CMIP3 (mid–high SRES A2 scenario) models for western North America. Drought is defined as soil moisture below the 20th percentile.

CONUS. Comparisons of CMIP3 and CMIP5 twentieth-century simulations against the off line hydrological modeling estimates indicate that the models on average capture the regional variation in drought frequency, although there

are large intermodel variations and a tendency to overestimate longer-term drought frequency (Fig. 14). The latter is related to differences in modeled variability at interannual to decadal time scales and differing land surface representations

Diagnosis of CMIP Model Projections

We evaluated the CMIP5 coupled models in their ability to represent the spatial distribution of surface climate and coupling and how this relates to future projections of soil moisture, drought and heat waves. In the historical period, models with lower precipitation have stronger soil moisture coupling in transitional regions (i.e. where there is relatively high evapotranspiration and it is controlled by soil moisture) that does not change much in the future. Those models that start with atmospheric control experience a decrease as the regime shifts closer towards becoming controlled by soil moisture.

These drier models also start with higher mean near surface air temperatures and higher inter-annual variability in temperature, whose distribution shifts farther to the right (higher increases in the mean), but the standard deviation is not substantially largely affected. These higher changes in temperature also translate in higher increases in the number of hot days as defined by a percentile threshold. This implies that shift in the inter-seasonal mean is responsible for changes in the distribution of intra-seasonal near-surface air temperatures. Figure 15 below shows an example of these kinds of relationships for the case of the Southeast. The top-left panel shows the results of a linear regression between the mean precipitation values during the historical period and the projected changes in mean precipitation (normalized by the changes in the mean monthly near-surface air temperature). Although the CMIP5 ensemble mean (i.e. large blue circle) is close to the NLDAS-2 ensemble mean (i.e. large green triangle), there is a wide spread showing both positive and negative biases in mean precipitation. This bias also relates to the future projections where drier models become drier and wetter models wetter. The top right panel also relates the bias to changes in drought frequency, where models that start drier project more frequent droughts. The bottom left panel shows a weak relationship between mean precipitation and mean near-surface air temperature during the historical period, where drier models are also hotter than the others. This relationship also translates to the models' future projections, where the drier/hotter models project more severe heat waves than the wetter/cooler models. This work is being written up as Herrera-Estrada and Sheffield (2015).

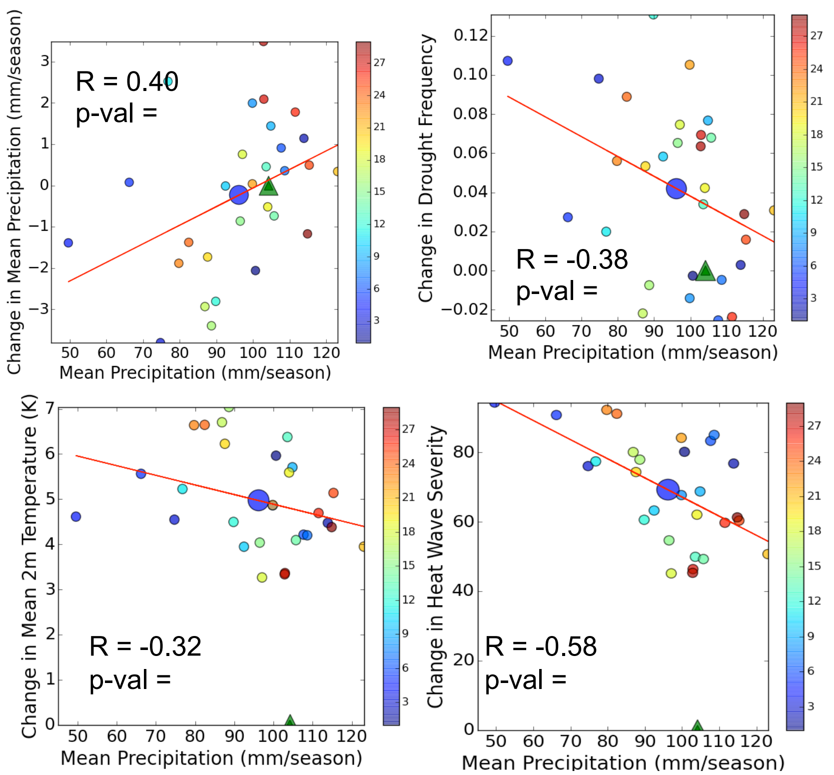


Figure 15. Relationships between CMIP5 representation of historic mean summertime precipitation and future projected changes in mean precipitation, drought frequency, air temperature and heat wave severity for the Southeast region.

<u>Task 5. Implement a set of methods to reduce uncertainties in future projections.</u>

Proposed work: Carry out statistical downscaling of climate model projections that impose bias correction at various levels of details of relevance to impacts. For example, current statistical downscaling techniques are often based on changes in monthly temperature and precipitation, yet changes at finer time scales and to other variables, may be equally large and may have comparable importance for impacts. For example, changes in diurnal temperature range, frequency of extreme precipitation events and surface radiation can all have profound impacts on hydrology, drought and agriculture, but are almost never included in downscaling.

Completed Work: We upgraded and implemented our bias correction/statistical downscaling scheme (Li et al., 2010) on the CMIP5 database of model output. This scheme improves on previous methods that use quantile matching to bias correct climate model data by also taking into account the change in the distribution between the model historic and future periods, which has important implications for changes at the tails of the monthly distributions of climate variables. The scheme was implemented on 16 CMIP5 climate models at 1.0-degree, 3-hourly, globally for 1901-2100 for the RCP4.5 and RCP8.5 future climate scenarios. Over 15Tb of corrected and downscaled data have been produced.

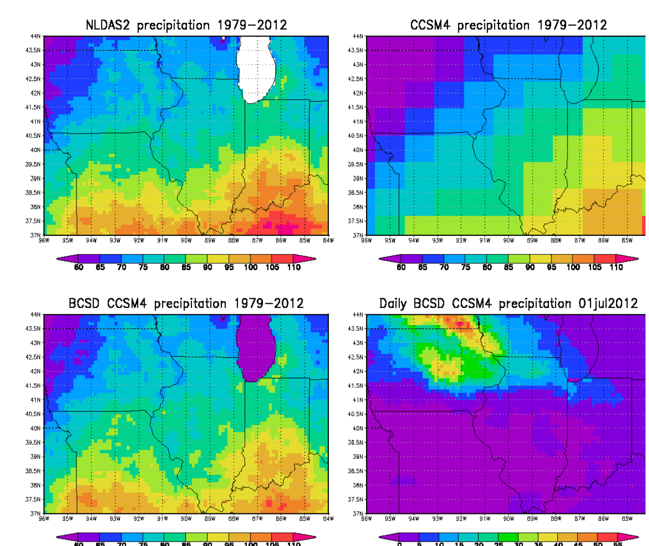


Figure 16. Example of the bias-correction and statistical downscaling (BCSD) for the CCSM4 climate model. (a) NLDAS2 observational monthly mean precipitation. (b) CCSM4 simulated monthly mean precipitation. (c) BCSD CCSM4 monthly mean precipitation. (d) Example of BCSD CCSM4 daily precipitation

We set up the bias-correction and downscaling procedures for high-resolution climate grids for the U.S. at 1/8th-degree and daily resolution. This was applied to 16 CMIP5 climate models to produce daily precipitation, temperature and wind speed for 1901-2100 for the "historical" and RCP85 scenarios. This data was used to force the VIC model for the central U.S. and the soil moisture output contributed to an analysis of yield sensitivities to future climate and CO2 change Urban et al., 2014). Figure 3 shows an example for the central U.S. of the original and bias-corrected/statistically downscaled precipitation data for the CCSM4 climate model.

Reducing uncertainties in future projections

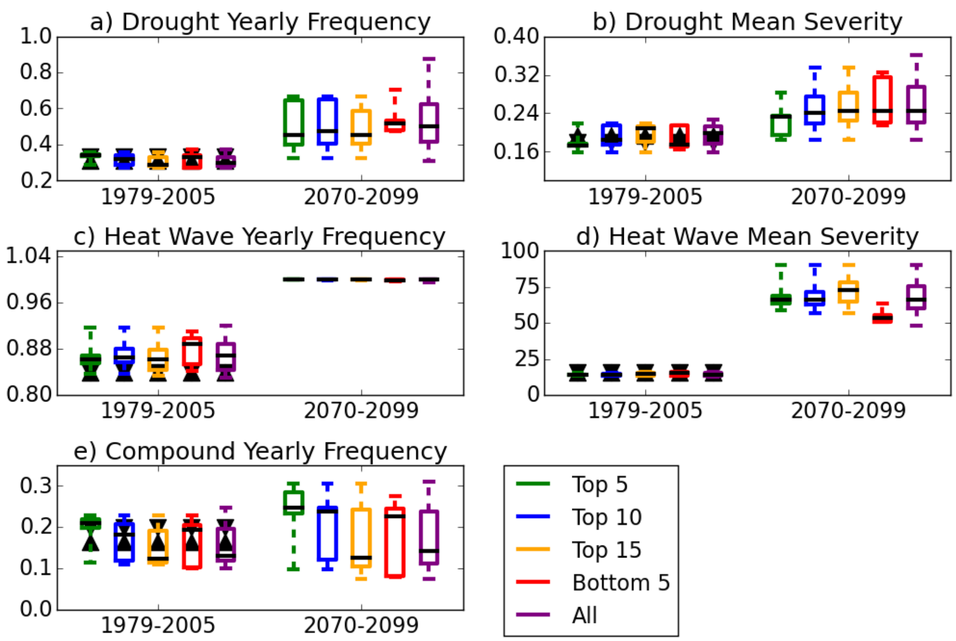


Figure 17. Boxplots of the characteristics of extreme events for each model averaged across the entire region. The models were ranked based on the mean of the relative errors in mean MAM precipitation, mean JJA precipitation, and the coupling metric. The top 5, 10, 15 and the bottom 5 models were used to recreate the boxplot to compare with the one where all of the models are considered.

On the basis of the CMIP5 model evaluations of historic simulations and the relationship with future projections, we analyzed sub-ensembles of models that showed better or worse performance for a set of land hydrology and land-atmospheric metrics. Figure 17 shows an example of how uncertainty in projections of extremes (drought, heatwaves and compound events) varies with selected sub-ensembles. In general, the top 5 models tend to exhibit reduced uncertainty in the projections, but there are exceptions such as for drought frequency. Part of the reason for this is that models are not universally better for all regions. These results have been analyzed relative to the sampling uncertainty for sub-ensembles to understand whether selected sub-ensembles can be identified by chance. This work forms the last part of Herrera-Estrada and Sheffield (2015).

4. Publications from the Project

Duffy, P. B., E. Maloney, and J. Sheffield, 2014: Global climate model simulations of North America. in Climate change in North America, G. Ohring (Ed.), Springer, pp 167-200

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