North America Hydroclimate Variability in CMIP5 model climate simulations and projections: are simulations improving and projections converging?

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2. Results and Accomplishments

The goals of the current proposal chime with those from the National Climate Assessment which look to assess the evolution in the historical simulations and climate projections from CMIP3 to CMIP5 projects. This coincidence, together with the needs of the MAPP's CMIP5 Task Force, spurred an unanticipated gathering and analysis of historical simulations of the 20th century climate in a large number of models, namely, 14 for the CMIP3 models, and 17 for the CMIP5 models (Sheffield et al. 2014a, b, c). Assessment of the models has been focused on two aspects of the simulations over North America: climatology (Sheffield et al. 2014b, c), and spatiotemporal characterization of the Atlantic Multidecadal Oscillation (AMO) and its hydroclimate impact (Kavvada et al. 2013, Kavvada 2014, Nigam et al. 2011, Ruiz-Barradas and Nigam 2013, Ruiz-Barradas et al. 2013, 2014, Sheffield et al. 2014a).

Assessment of the regional climatology imposes some challenges for the models as seen by their multi-model ensemble (MME) means of CMIP3 and CMIP5 model simulations. Regions that needed improvement in the CMIP3 models are still practically the same in the CMIP5 models. The CMIP5 MME mean shows no improvements over the corresponding mean of CMIP3 models of mean winter and summer precipitation (P) over North America (Fig. 1; Sheffield et al. 2014b, c). Differences with observations show that the winter MME mean P is larger than observations practically over the whole of North America except over the East South Central region of the US and Central America and southern Mexico where P is less than observed. The general structure of the CMIP3 and CMIP5 MME means of summer P are similar to each other and to the observed summer P, however differences are apparent over the Mountain, West North Central and South Atlantic states of the US and over the high plains of Mexico.

The MME mean of CMIP5 models shows no improvement over the corresponding mean of CMIP3 models of winter-to-spring and summer-to-fall seas surface temperature (SST) in the adjacent oceans of North America (Fig. 2; Sheffield et al. 2014b, c). The Western Hemisphere Warm Pool (WHWP), where SST is equal or larger than 28.5°C (thick black line on maps), usually is absent from December to February, and appears in the Pacific from March to May, while it is present in the Caribbean and Gulf of Mexico, or Intra-Americas sea, from June to November. High P along the Mexican coasts, Central America, the Caribbean Islands and the central-eastern US is associated with tropical SST in excess of 27°C during the warm half of the year; a decrease in the regional precipitation south of the equator is also evident in this warm half of the year. The structure of the CMIP3 and CMIP5 MME means agree with each other and with the general structure of the observed winter-to-spring SST, except that they do not show the high SST in the eastern Pacific and Intra-Americas sea around Central America, or the weak cold tongue in the equatorial eastern Pacific off the coasts of Ecuador and Peru. The errors are characterized by warm biases along the coastal waters on the Atlantic side of the northeastern US, California and the Pacific side of northwestern Mexico, and off the coasts of Ecuador and Peru, a problem that may be related to the models' poor ability to simulate stratus clouds and transport by Ekman currents; cold biases are extensive over both oceans. The structures of the CMIP3 and CMIP5 MME means also agree with each other and with the general structure of the observed summer-to-fall SST, except that the SST in the Atlantic Warm Pool (AWP) region is cooler than observed. The CMIP3 and CMIP5 MME mean errors highlight similar areas of cold/warm bias to those in the winter-to-spring part of the year except that the cooling bias over the Pacific side of Central America is no longer present in the CMIP5 MME mean in this half of the year.

Decadal variability in the Atlantic Ocean is still poorly understood so it is not properly incorporated in state-of-the-art climate models. Decadal variability associated with the Atlantic Multidecadal Oscillation, including its spatiotemporal structure in both atmosphere and ocean and its hydroclimate impact over North America, have not improved consistently through the models (Ruiz-Barradas et al. 2013). Detailed analyses of a subset of CMIP5 models indicate that a reasonable oceanic structure of the simulated AMO does not guarantee a reasonable simulation of the atmospheric features including the hydroclimate impact over North America (Kavvada et al 2013). It is thought that a better understanding of decadal variability in the North Atlantic can be obtained from subsurface temperatures (Kavvada 2014, Ruiz-Barradas et al. 2014).

Models misrepresent the observed temporal features of the AMO (Ruiz-Barradas and Nigam 2013). A short sample of the models was analyzed in detail by using all ensembles available of the models CCSM3, GFDL-CM2.1, UKMO-HadCM3, and ECHAM5/MPI-OM from the CMIP3 project, and the models CCSM4, GFDL-CM3, UKMO-HadGEM2-ES, and MPI-ESM-LR from the CMIP5 project. The mature stage of the warm phase of the AMO, as well as its evolution before and after reaching this stage, have evolved from the CMIP3 to the CMIP5 versions but not consistently through the models. While the characteristic period of the AMO (smoothed with a binomial filter applied fifty times) is underestimated by the three of the models, the e-folding time of the autocorrelations shows that all models underestimate the 44-year value from observations by almost 50%. Variability of the AMO in the 10-20/70-80 year ranges is overestimated/underestimated in the models and the variability in the10-20 year range increases in three of the models from the CMIP3 to the CMIP5 versions (Fig. 3; Ruiz-Barradas et al 2013). Mean subsurface regressed positive salinity anomalies associated with the positive phase of the AMO in the second half of the 20^{th} century are largely focused along the Labrador

Sea and to the south of Greenland in observations, but the CMIP5 models seem to be unable to capture them properly (even though they have some positive anomalies in the midlatitudes); the GFDL-CM3 model is the most successful in capturing the spatial variability of the SSTA-associated, salinity field (Kavvada et al 2013).

Spatial variability and correlation of the AMO regressed precipitation and SST anomalies in summer and fall indicate that models are not up to the task of simulating the AMO impact on the hydroclimate over the neighboring continents, especially because anomalous moisture fluxes from the Atlantic are behind the anomalous precipitation and some of these models fail to capture the low-level circulation driving them (e.g., Nigam et al. 2011, Kavvada et al. 2013, Ruiz-Barradas and Nigam 2013). This is in spite that the spatial variability and correlations in the SST anomalies improve from CMIP3 to CMIP5 versions in two of the models. The multi-model mean from a sample of 14 models indicates there are not improvements in the structure of the SST anomalies of the AMO or associated regional precipitation anomalies in summer and fall from CMIP3 to CMIP5 (Fig. 4; Ruiz-Barradas et al 2013).

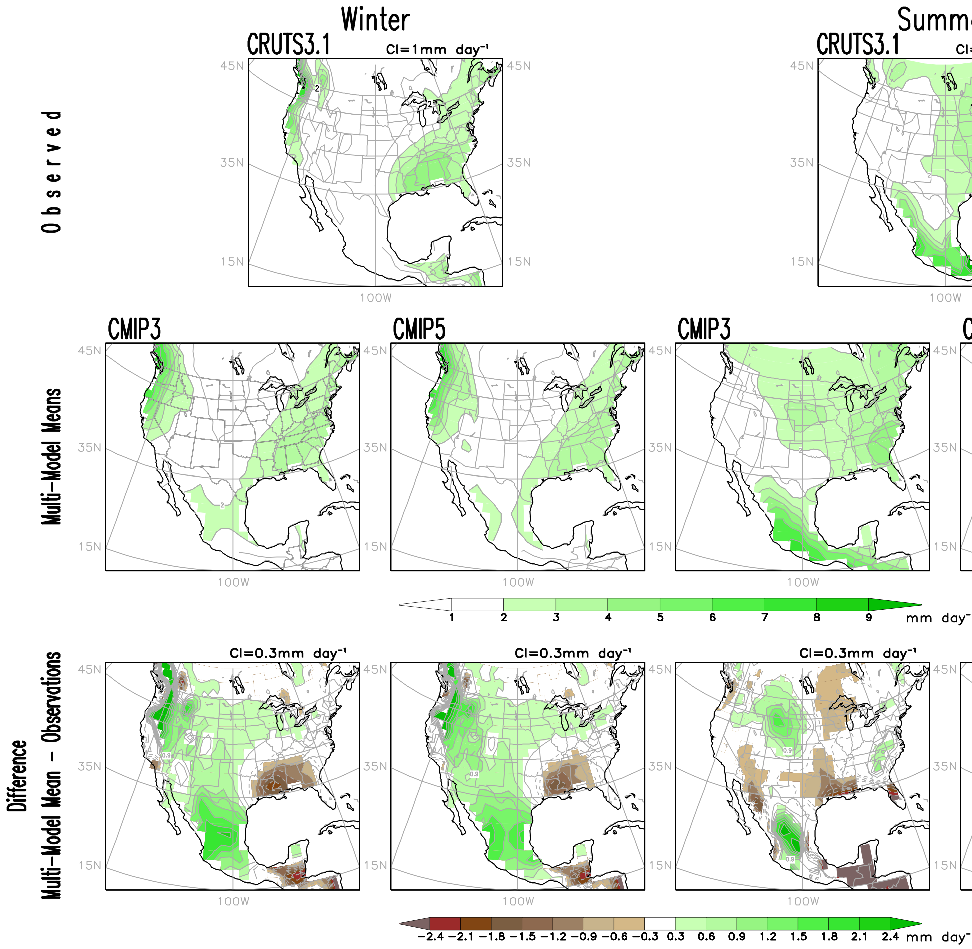

Figure 1 Mean winter and summer climatological precipitation for the period 1971-1999. Observations (upper row, from CRUTS3.1), CMIP3 and CMIP5 multi-model means (middle row) and difference of multi-model mean minus observations (lower row). Green/brown shading denotes positive/negative differences in precipitation (lower row) statistically significant at the 95% level; contour interval is 1mm day^{-1} for the mean values and 0.3 mm day^{-1} for the differences. Fields have been interpolated to a common 1.5°×1.5° grid.

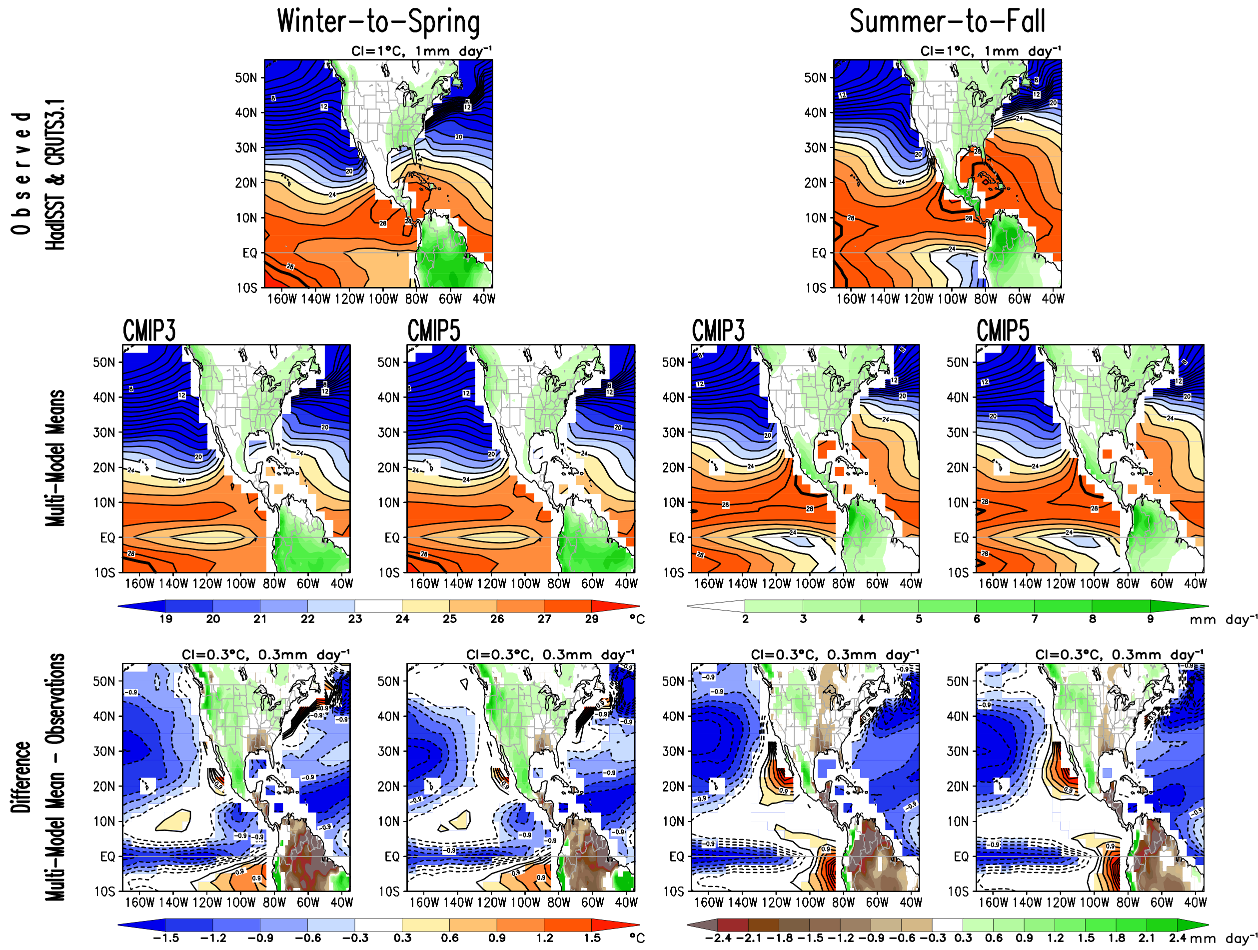

Figure 2 Mean winter-to-spring and summer-to-fall climatological sea surface temperature and precipitation for the period 1971-1999. Observations (upper row from HadISST and CRUTS3.1), CMIP3 and CMIP5 multi-model means (middle row) and difference of multi-model mean minus observations (lower row). Red/blue shading denotes positive/negative differences in temperature while green/brown shading denotes positive/negative differences in precipitation (lower row) statistically significant at the 95% level; contour interval is 1°C (1 mm day^{-1}) for mean values for temperature (precipitation) and 0.3 mm day^{-1} (0.3°C) for the differences. The thick black line is the 28.5°C isotherm which is used as a marker for the Western Hemisphere Warm Pool. Temperature (precipitation) fields have been interpolated to a common 5°×2.5° (1.5°×1.5°) grid.

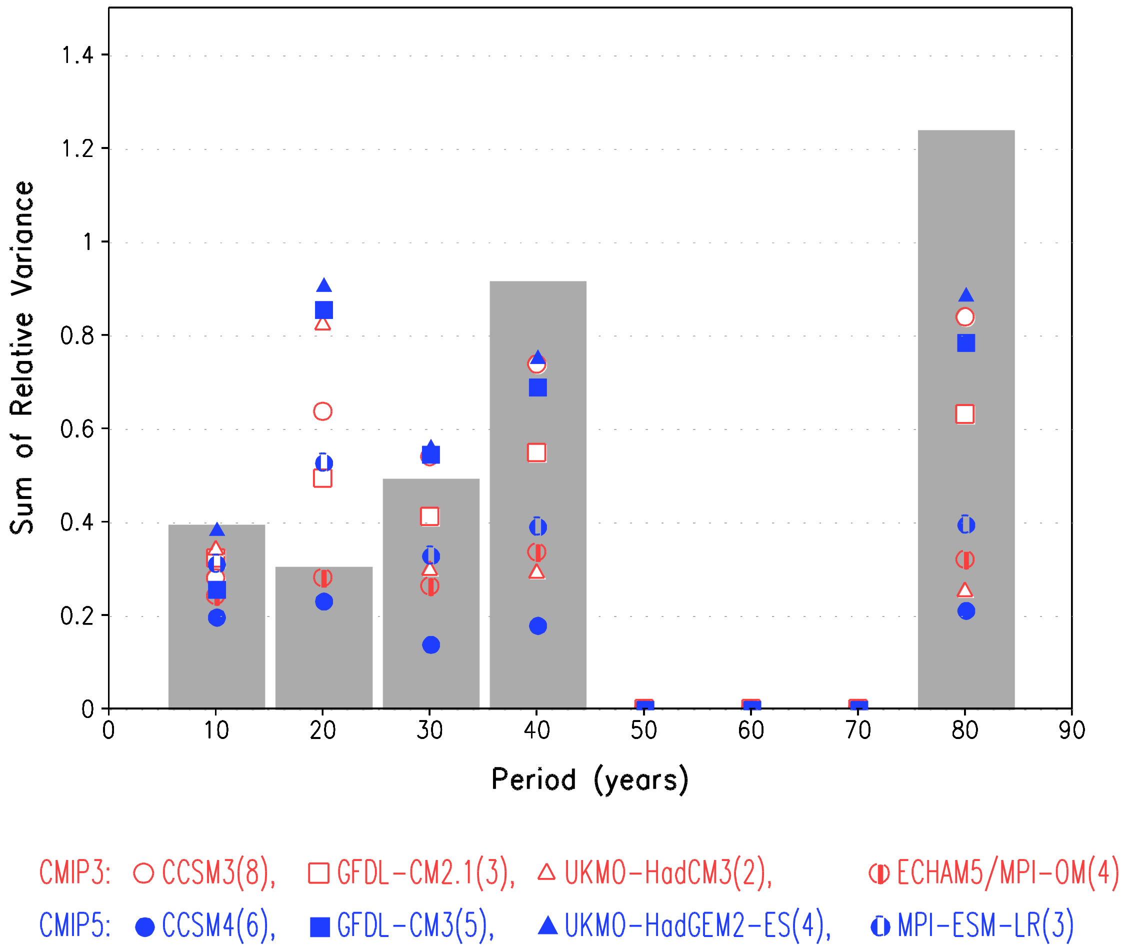

Figure 3. Histogram of mean spectral analysis peaks from spectral analyses of smoothed AMO indices for the period 1900-1999. The y-axis denotes the sum of relative variance in the following ranges 2.5-10 years, 11-20 years, 21-30 years, 31-40 years, and 71-80 years. Spectral peaks from the AMO index from observations are shown with the gray bars; the corresponding peaks for the CMIP5 models are shown by the symbols in blue, and those for the CMIP3 models are in red; see legend to identify particular models. The number in parenthesis denotes the number of ensembles used for each model. Spectral analyses were calculated for each ensemble member, and then a mean spectrum was obtained by averaging the spectrum of the ensembles for each model.

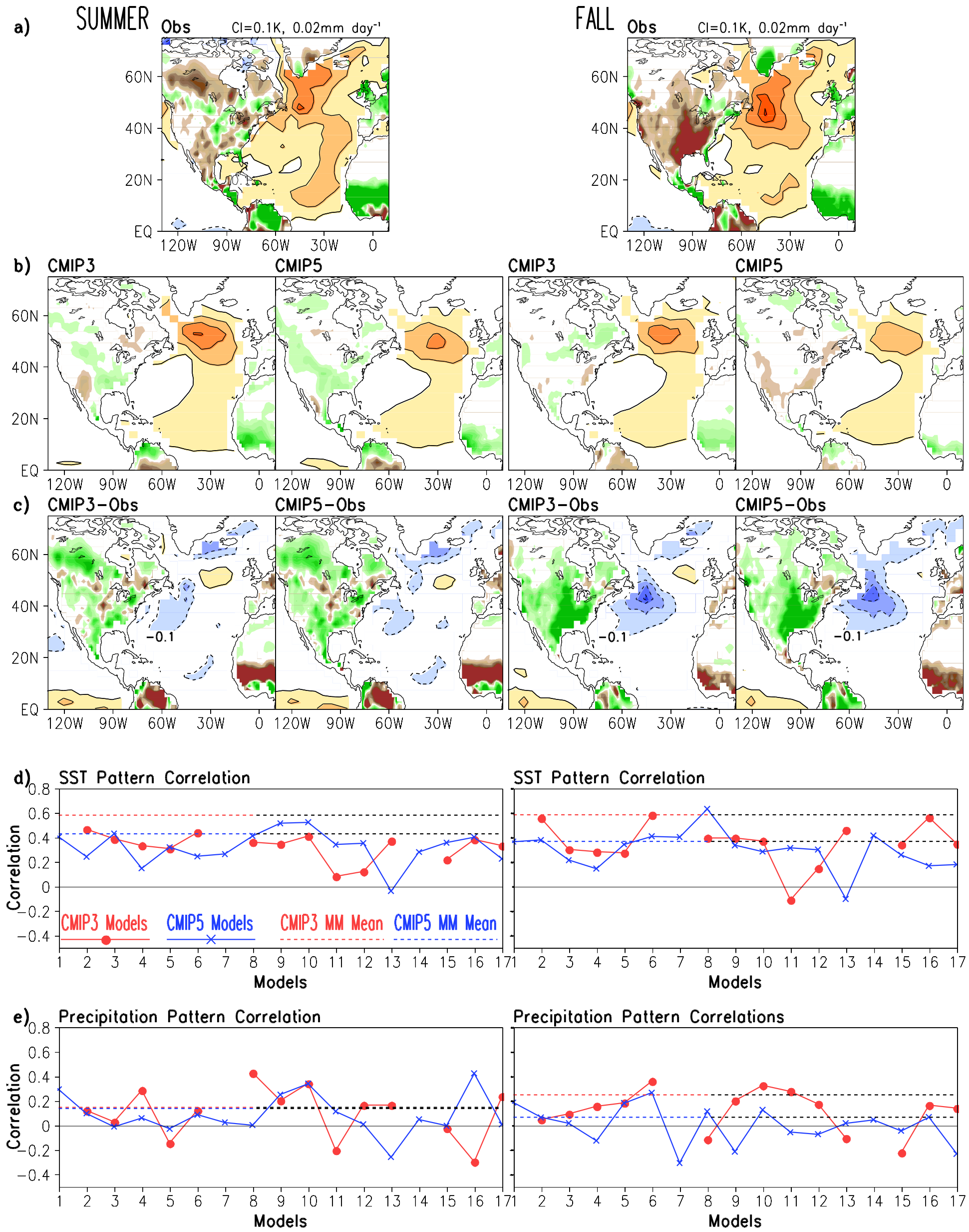

Figure 4. Observed and multi-model mean SST and precipitation regressions on smoothed AMO indices and spatial pattern correlations in summer and fall for the period 1901-1999. a) regressions from observations in summer (left) and fall (right), b) mean multi-model regressions from CMIP3 and CMIP5 models in summer (left panels) and fall (right panels), c) difference between multi-model mean regressions and observations in summer (left panels), and fall (right panels). d) diagrams for spatial correlations between regressed SST anomalies over the domain (130°W-10°E, 0°-75°N) from CMIP3 and CMIP5 models with the corresponding from observations in summer (left) and fall (right). e) diagrams for spatial correlations between regressed continental precipitation anomalies over the domain (130°-60°W, 0°-60°N) from CMIP3 and CMIP5 models with the corresponding from observations in summer (left) and fall (right). Yellow-to-red/blue shading denotes positive/negative SST anomalies plotted with a 0.1K contour interval, and brown/green shading denotes positive/negative precipitation anomalies with a 0.02 mm day^{-1} interval in panels a-c). Lines in red/blue denote CMIP3/CMIP5 model correlations in panels d) and e); continuous lines with marks are for the individual models while the dashed lines are correlations for the multi-model means. Spatial correlations for the regressed SST anomalies from the CMIP5/CMIP3 multi-model means are 0.43/0.58 in summer and 0.36/0.58 in fall, and spatial correlations for the regressed precipitation anomalies from the CMIP5/CMIP3 multi-model means are 0.13/0.14 in summer and 0.06/0.25 in fall.

3. Highlights of Accomplishments

- Climatological precipitation over North America and sea surface temperatures around it have not improved from CMIP3 to CMIP5 historical simulations.

- A notable feature of all models in summer precipitation is that all tend to put a maximum over central US which is not present in observations.
- Changes in winter and summer precipitation from the first half to the second half of the 20^{th} century are not captured by the models.
- Models show the general observed change in SSTs from cold to warm around the WHWP region from the December-May half to the June-November half. However the eastern Pacific cold tongue is farther to the west than observations indicate.

- Moisture flux and associated convergence play a prominent role in the generation of precipitation anomalies over the Great Plains at pentad scales. This finding complements the PIs previous findings regarding the role of moisture fluxes at larger scales.

- Decadal variability and trends in the North Atlantic Ocean seem to be better captured by the subsurface temperature than by the sea surface temperature.

- The Atlantic Multidecadal Oscillation has played a prominent role in the generation of extreme hydroclimate events over the Great Plains, even more than previously realized. The AMO, in particular, contributed the most in two of some reconstructed episodes: the spring of the Dust Bowl drought, and the fall of the 1980s pluvial.

- The warm phase of the AMO has larger SST anomalies in fall than in summer in observations, and so the associated precipitation anomalies over North America have a larger and more extensive deficit of precipitation in fall than in summer.
- There is an uneven progress in simulating the AMO spatiotemporal features in the atmosphere and the ocean and its hydroclimate impact from CMIP3 to CMIP5 models.
- Sea surface temperature anomalies of the AMO in fall are larger than those in summer in observations but not in CMIP3 or CMIP5 models. Associated observed drying over central US is not well captured by the models.
- Summer and fall maximum SST anomalies of the AMO are smaller in CMIP5 models than in CMIP3 models. Spatial correlations with observed anomalies have decreased from CMIP3 to CMIP5 models.
- Summer precipitation anomalies associated with the warm phase of the AMO are similarly wet in CMIP3 and CMIP5 models, and similarly dry in fall; models underestimate the observed drying over North America in both seasons. Spatial correlation over North America remains the same in summer but has decreased in fall from CMIP3 to CMIP5 models.

4. Publications from the Project

Kavvada A., *A. Ruiz-Barradas,* and S. Nigam 2013: AMO's Structure and Climate Footprint in Observations and IPCC AR5 Climate Simulations. *Climate Dynamics*, **41**,1345-1364.

Kavvada A., 2014: Atlantic Multidecadal Variability: Surface and Subsurface Thermohaline Structure and Hydroclimate Impacts. Ph.D. Thesis. University of Maryland. 152 pp.

Nigam, S., B. Guan, and A. Ruiz-Barradas, 2011: Key Role of the Atlantic Multidecadal Oscillation in 20th Century Drought and Wet Periods over the Great Plains. *Geophys. Res. Lett.*, 38, L16713, doi:10.1029/2011GL048650.

Ruiz-Barradas A., and S. Nigam 2013: Atmosphere-Land-surface Interactions over the Southern Great Plains: Characterization from Pentad Analysis of DOE-ARM Field Observations and NARR Reanalysis. *J. Climate*, **26**, 875-886.

Ruiz-Barradas A., S. Nigam, and A. Kavvada 2013: The Atlantic Multidecadal Oscillation in 20th Century Climate Simulations: Uneven Progress from CMIP3 to CMIP5. *Climate Dynamics*, **41**, 3301-3315.

Ruiz-Barradas, A., S. Nigam and A Kavvada, 2014: AMO's subsurface temperature and salinity structure in observations and CMIP5 climate simulations: Notable discrepancies. *Climate Dynamics,* in preparation.

Sheffield, J., et al. (including S. Nigam and A. Ruiz-Barradas), 2014a: North American Climate in CMIP5 Experiments. Part II: Evaluation of 20th Century Intra-Seasonal to Decadal Variability. *J. Climate,* ***26****, 9247-9290*.

Sheffield, J., et al. (including S. Nigam and A. Ruiz-Barradas), 2014b: North American Climate in CMIP5 Experiments. Part I: Evaluation of 20th Century Continental and Regional Climatology. *J. Climate*, **26**, 9209-9245.

Sheffield, J., et al. (including A. Ruiz-Barradas), 2014c: Regional Climate Processes and Projections in CMIP3 and CMIP5 for N. America: Differences, Attribution and Outstanding Issues. *NOAA Technical Report on CMIP3/CMIP5 for N. America*, in preparation.

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