Just how important is model resolution for future projections of the North American Monsoon?

Jonathan D.D. Meyer: Department of Plants Soils and Climate, Utah State University (jonathan.meyer@aggiemail.usu.edu)
Jiming Jin: Department of Plants Soils and Climate & Department of Watershed Sciences, Utah State University

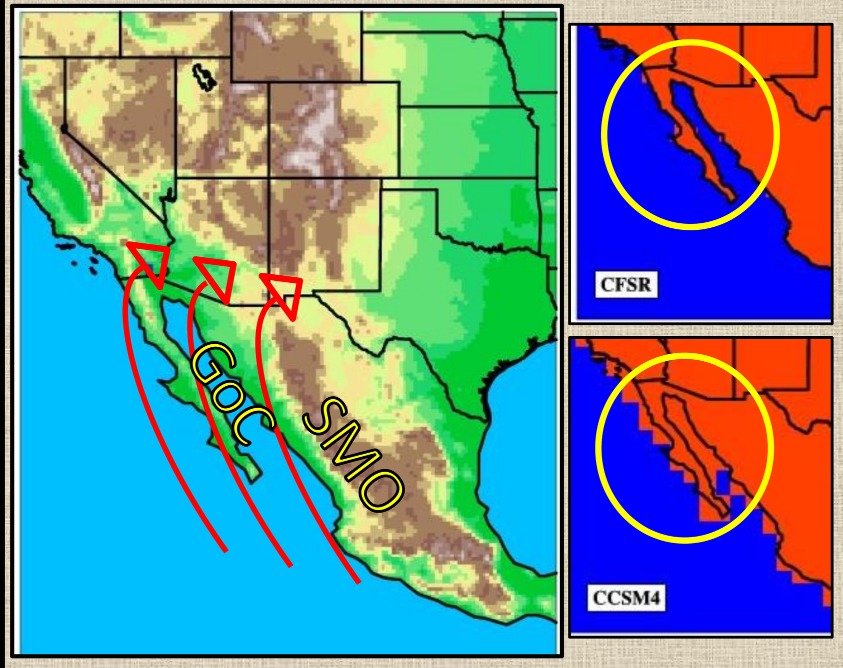
Introduction and Background

Unlike most global monsoons, the North American Monsoons (NAM) seasonal shift in moisture transport over southwestern North America depends more on mesoscale mechanisms than synoptic. The regional topography and land-sea orientation lead to a unique situation which enhances summer precipitation in the region.

Of particular importance is the interaction between the Gulf of California (GoC) and the Sierra Madre Occidental (SMO) mountain range. The GoC—which is characterized by a significant warming of sea-surface temperatures (SST) compared to the relatively cold SSTs found in the surrounding Pacific Ocean—contributes substantial amounts of low-level moisture. Mitchell et al., (2002) related the seasonal warming of GoC SSTs to the timing, amount, and regional extent of NAM rainfall. Their findings illustrate the dependence on the overall NAM system to the development of the warm GoC SSTs. As the SSTs increase, the along-axis orientation of the warm GoC and SMO allows a thermal-wind-driven inland sea-breeze during the day and a nocturnal low-level jet (LLJ). This diurnal cycle transports the low-level moisture northward and inland. Moisture transport helps destabilize the continental atmosphere, which leads to an environment that is more susceptible to convective triggering as well as enhanced convective intensity.

Here we present the limitations of coarse grid GCMs, which struggle to capture many of the mesoscale mechanisms important to resolving the NAM; particularly those associated with the GoC. Future projections of the NAM produced by GCMs have shown a general regional drying trend due to synoptic suppression of convection as the troposphere warms and a shift in the seasonality of NAM convection (Seth et al., 2013). Our aim in this study is to highlight the ability of unresolved mesoscale mechanisms to potentially overcome the mechanism leading to a drying NAM suggested by GCMs.

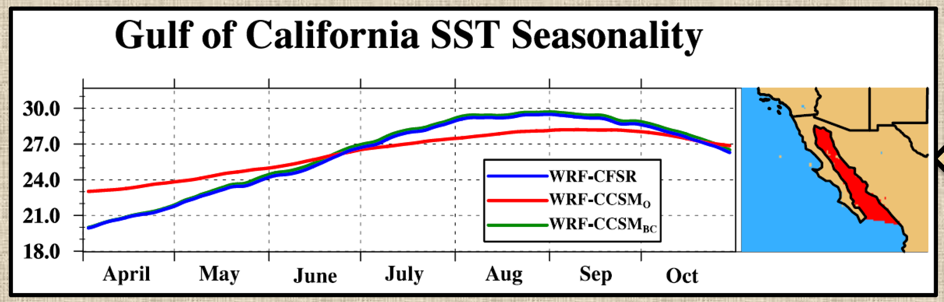
Methods & NAM Domain



Here, we compare the ability of ½-degree CFS reanalysis and 1.25x0.93 degree CCSM4 output to resolve several key NAM mesoscale mechanisms. A 20-km WRF domain was used to investigate the sensitivity of the NAM when surface features are better resolved. A 32-year (1979-2010) historical climatology was simulated along with a future period spanning 2068-2099. Simulations were initialized Apr. 1st, and ended Nov 1st.

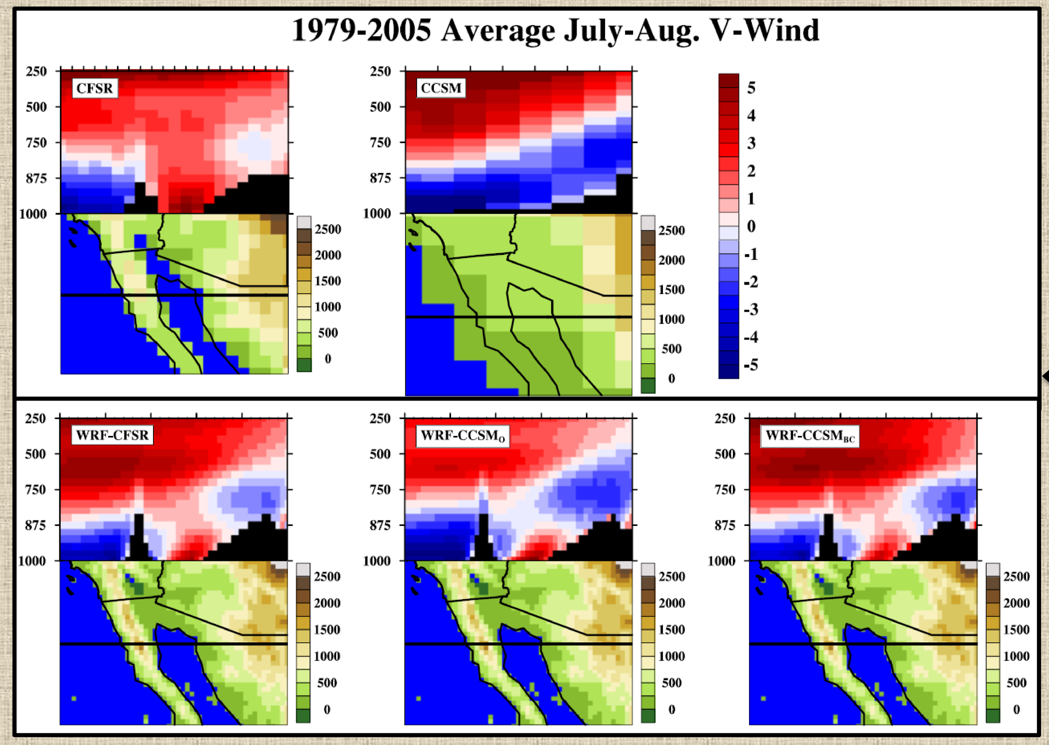
Furthermore, with our historical analysis highlighting the limitation when downscaling CCSM4 data, we use CFSR as a baseline to perform bias-correction to remove the long-term biases in the 6-hrly CCSM4 boundary conditions. Our hope is through improved surface features and reduced biases in CCSM4 data, our future projections of the NAM contain less uncertainty and are more reliable than conventional GCM studies.

Historical NAM Evaluation



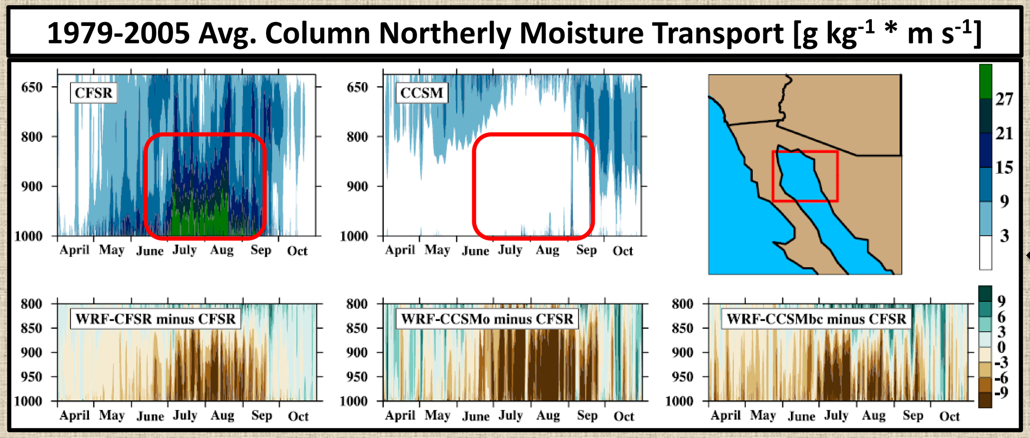
The seasonal cycle of GoC warming plays a large role in NAM mechanisms. After interpolating to the 20km WRF domain the high-fidelity OISST in the CFSR dataset shows the CCSM4 SSTs misses the timing and magnitude of the GoC warming. With no GoC present in the CCSM4, the WRF domain is forced to rely on the surrounding Pacific SSTs for interpolations. After bias-correction, the seasonal cycle matches the CFSR observation-based SSTs.

By the end of the 21st century, a consistent one degree of warming is depicted in the CCSM4 GoC SSTs. Our corrected CCSM SST's exhibit early- and late-season warming around one degree, while the mature phase (Jul-Aug) shows ~two degrees of warming. Surface moisture flux is a non-linear function of temperature, meaning the difference between the future original and bias-corrected GoC SSTs can yield large differences in low-level moisture.



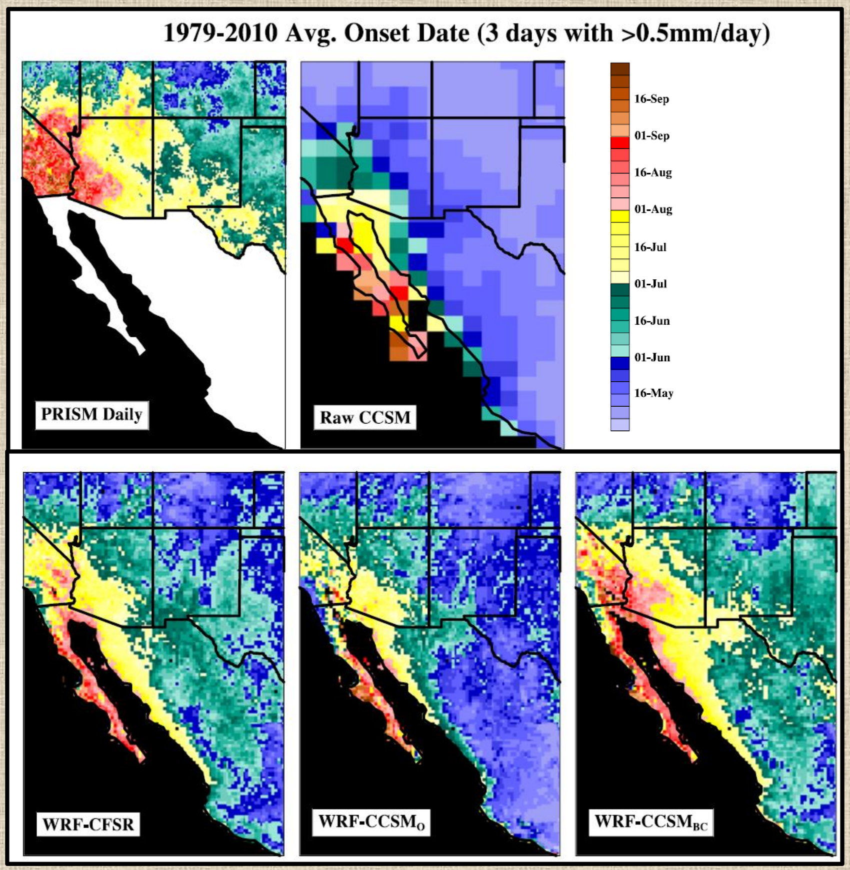
The response to the warming GoC SSTs is a southerly LLJ. Historically, the CFSR depicts a local maxima in V-winds during the greatest SSTs (July-Aug) directly above the surface of the GoC. Without the GoC SST's resolved in the CCSM4, a complete lack of a climatological LLJ is present, leaving the synoptic northerly winds to dominate the lower-levels. The 20-km WRF domain reproduced the LLJ, although the depth of the local maxima is lesser than CFSR. With cooler GoC SSTs, the downscaled CCSM simulations produced the weakest and most localized LLJ.

Future comparisons between the historical and future CCSM4 output show a strengthening of the CCSM4 V-winds, but the dominant northerly winds remain in place without any GoC. Comparison between the historic and future downscaled simulations highlights the importance of GoC SSTs to modulate these localized V-winds. Compared to the increases in future GoC SSTs shown above, the greater warming contained in the bias-corrected GoC results in a much stronger increase to the northerly winds. Compared to the already stronger historical winds in the bias-corrected simulation shown to the left, the future changes become that much more impressive



CFSR historical northerly moisture transport through the head of the GoC shows a strong increase in the low-level moisture coinciding with NAM onset (late June-early July). Without the GoC, the CCSM4 contain no climatological northerly moisture transport signal. When downscaling, each WRF climatology contains a dry bias during the NAM that we speculate comes from both the higher resolution WRF landmask allowing more land coverage, as well as the fact that CFSR specific humidity is a model derived product, and prone to biases. An important comparison is the downscaling of the original CCSM dataset, which contains the largest dry biases. As shown above, the GoC in the downscaled original CCSM has the coolest SSTs, and thus has the lowest evaporative potential. Once again, we note that even when surface features are improved through downscaling, the lack of the GoC in the original CCSM4 model inhibits accurate modeling of the GoC mechanisms.

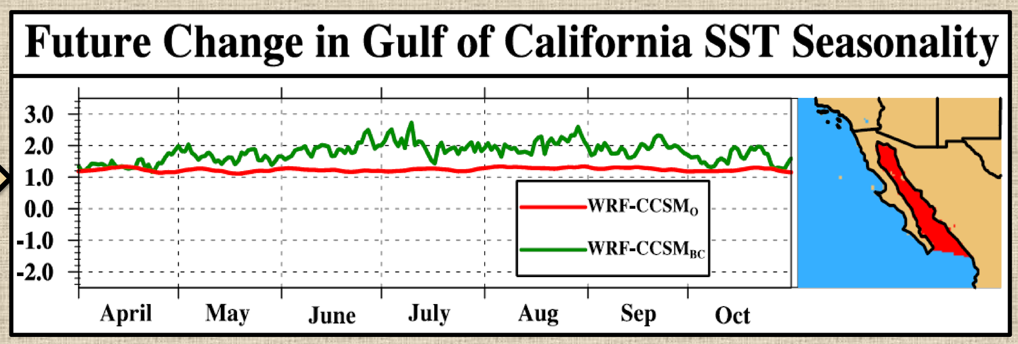
Future differences shown to the right indicate little significant changes in the CCSM4 moisture transport, especially during the onset and mature phase of the NAM. When downscaling, the original CCSM4 produces a modest general increase over the lower levels, while the bias-corrected CCSM climatology indicates a strong increase in northerly moisture transport through the head of the GoC. With stronger southerly winds, and elevated moisture in the low levels due to the warming GoC SSTs, the downstream region will contain a more convective favorable environment.

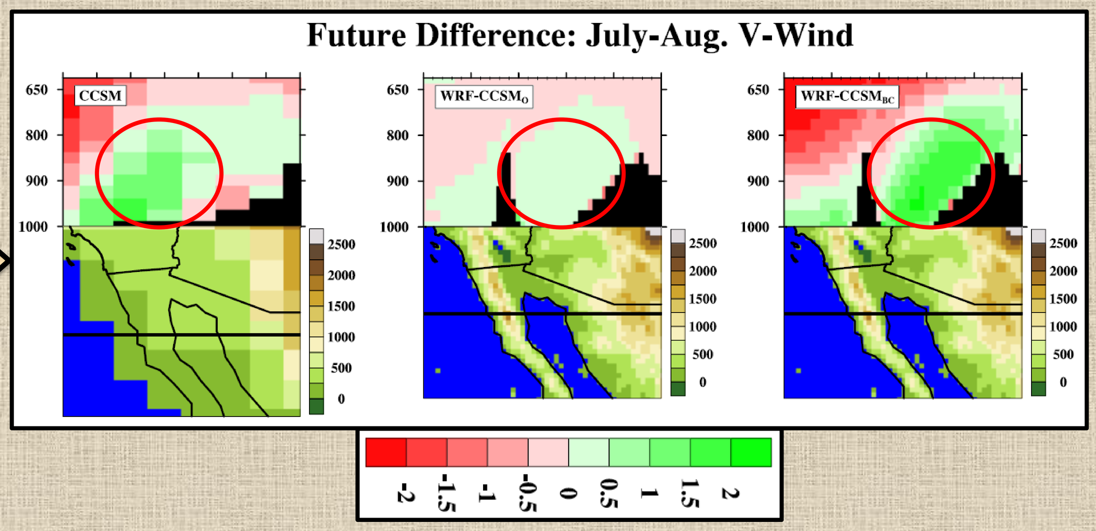


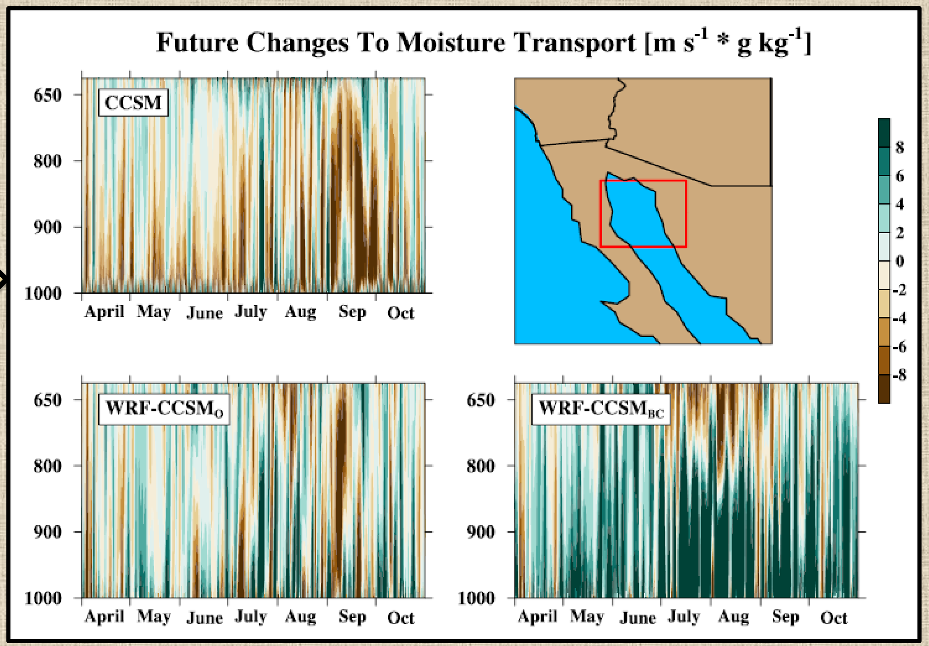
Monsoon onset—which we define as the first consecutive three day period with at least 0.5mm or rain—has been linked to the warming of GoC SSTs. Both CCSM4 and the WRF-CCSM$_O$ exhibit an average onset which is far too early over both Mexico and the southwestern U.S. This pattern agrees with the warmer early season GoC SSTs shown above. After bias correction, the average onset date becomes much closer to observations, although generally around a week too late in northwestern Mexico and the southwestern U.S.

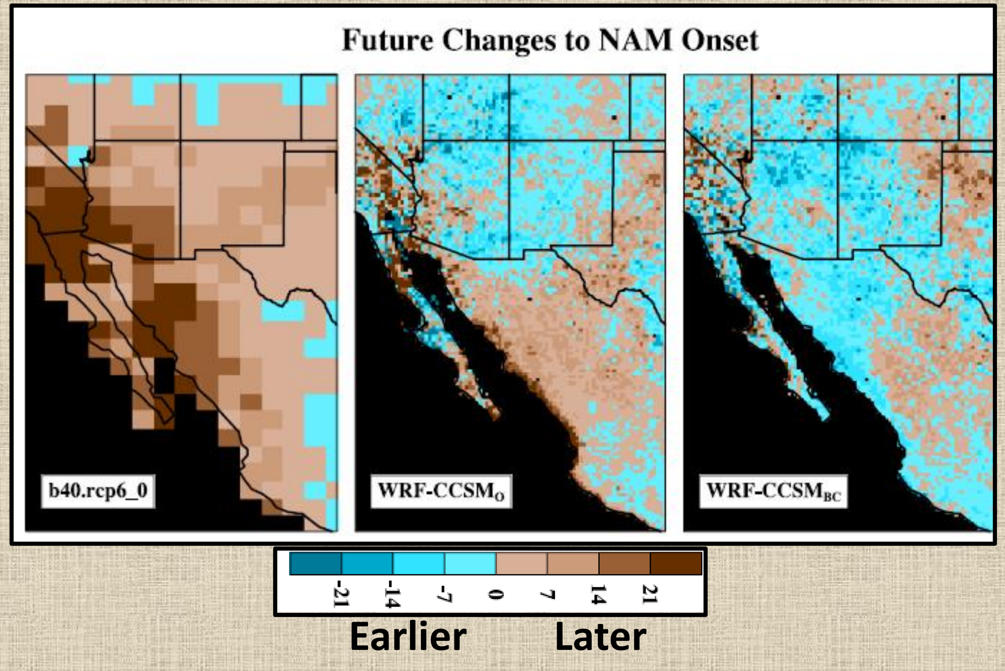
By the end of the 21st century, the CCSM4 rcp6_0 scenario projects onset dates that are generally one to two weeks later than the historical CCSM4, which aligns with findings by Seth et al., (2013). When downscaled with WRF, the rcp6_0 produces onset dates that are again delayed in western Mexico, but over the southwestern U.S., the onset dates are reversed, with one to two week earlier onset. After bias correction, onset dates are one to two weeks earlier across the majority of the NAM domain. Earlier onset dates would coincide with the warmer GoC SSTs within the bias-corrected CCSM dataset, which would produce earlier conditions favorable for convective triggering.

Future NAM Difference

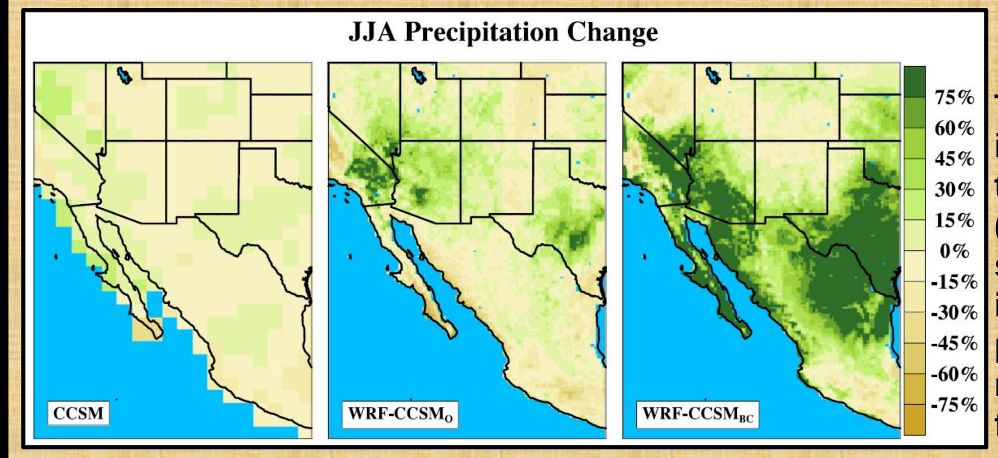








Discussion



The goal of this study was two-fold; improving mechanisms of the NAM through dynamical downscaling (which increased the accuracy of surface features) as well as improving confidence in future projections to NAM changes by reducing biases in the CCSM4 forcing data.

- CCSM4, which fails to capture the mesoscale mechanisms such as the LLJ and strong low-level moisture transport shows a general drying trend across the NAM domain by the end of the 21st century. Recent studies explain this drying by a shift in seasonality and growing synoptic-scale suppression of convection during the early months of the NAM.
- Due to the biases inherent to CCSM4, simply downscaling with WRF shows a similar drying across the Mexican NAM domain. However, despite the incorrect seasonality and too cold GoC SSTs, the higher resolution WRF domain captures the general feedbacks from GoC mechanisms and projects increasing NAM rainfall over the southwest U.S. (where GoC moisture is typically advected). This result infers the importance of the GoC on the NAM system and highlights the importance of higher model resolutions when simulating the NAM.
- Downscaling the bias-corrected CCSM dataset—which contains a much more accurate season cycle of the NAM environment—yields an overwhelming positive trend across the NAM domain. We suspect the ability of sensible and latent heat supplied by the GoC—which warms by an average of 2°C during the mature phase of the NAM—is able to overcome the synoptic suppression of convection by destabilizing the lower atmosphere. Furthermore, with a more accurate seasonal cycle, the bias-corrected dataset contains onset dates that are much closer to historical observations, and that are projected to advance by the end of the 21st century, leaving a longer period for NAM rainfall to accumulate.

References & Acknowledgement

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