Project Title: Intraseasonal to Interannual Variability in the Intra-Americas Sea in Climate Models
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PIs: Eric D. Maloney (Colorado State University) and Shang-Ping Xie (Scripps Oceanographic Institute)
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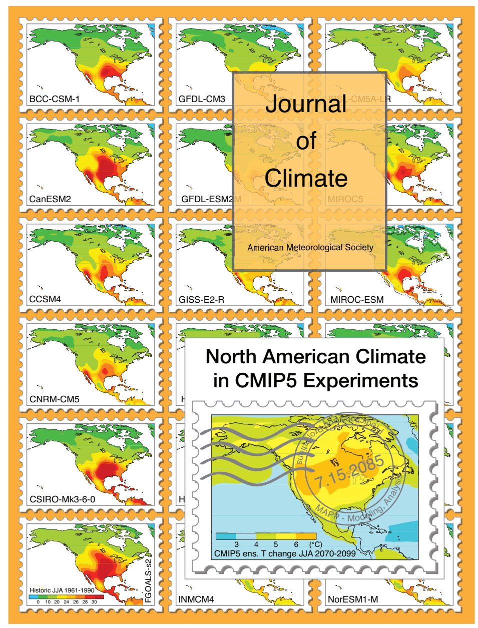
Results and Accomplishments

The following sections list some key accomplishments for all years of the study, with the 35 publications accumulated for the project listed in the publication list at the end of the document. Unfortunately, we cannot be entirely comprehensive given space constraints for all publications, and hence only list some of the highlights. Please contact me for more details if you are interested in anything that was missed.

NOAA MAPP CMIP5 Task Force

Eric Maloney was a co-chair, and Shang-Ping Xie a member, of the NOAA MAPP CMIP5 Task Force. The PI Maloney shepherded generation of a *Journal of Climate* special collection on North American Climate in CMIP5 Models (see figure), which includes the overview papers discussed in the report on Maloney et al. (2014a) below. Task force activities included thrusts related to 1) a comprehensive assessment of North American climate in CMIP5 models (see next section), 2) use of CMIP5 models to inform climate applications [see Sheffield et al. (2014) report in reference list below] and 3) process-oriented model diagnostics to inform model development and applications. Regarding point #3, the process-oriented diagnostics effort of the CMIP5 TF has laid the groundwork for a new task force called the NOAA MAPP Model Diagnostics Task Force that is currently being lead by the PI Maloney. The task force is developing a common software framework to allow rapid dissemination of process-oriented diagnostics into the evaluation packages of global climate and forecasting models. More discussion of this task will take place in the project report for a separate NOAA grant.



North American climate in CMIP5 experiments: Assessment of 21st Century projections. (Maloney et al. 2014a)

This is the third of a three part series of review papers led by the NOAA MAPP CMIP5 Task Force on CMIP5 models and North American climate. In Part 3 of this three-part study on North American climate in Coupled Model Intercomparison project (CMIP5) models, we examine projections of 21st century climate in the RCP8.5 emission experiments. This paper summarizes and synthesizes results from several coordinated studies by the authors. Aspects of North American climate change that are examined include changes in continental-scale temperature and the hydrologic cycle, extremes events, and storm tracks, as well as regional manifestations of these climate variables. We also examine changes in eastern north Pacific and north Atlantic tropical cyclone activity and North American intraseasonal to decadal variability (see also Jiang et al. 2013), including changes in teleconnections to other regions of the globe.

Projected changes are generally consistent with those previously published for CMIP3, although CMIP5 model projections differ importantly from those of CMIP3 in some aspects, including CMIP5 model agreement on increased central California precipitation. The paper also highlights uncertainties and limitations based on current results as priorities for further research. Although many projected changes in North American climate are consistent across CMIP5 models, substantial intermodel disagreement exists in other aspects. Areas of disagreement include projections of changes in snow water equivalent on a regional basis, summer Arctic sea ice extent, the magnitude and sign of regional precipitation changes, extreme heat events across the Northern U.S., and Atlantic and east Pacific tropical cyclone activity.

The first and second parts of the three part series of papers described at the top of this section are Sheffield et al. (2013 a,b), which provide an assessment of the ability of CMIP5 models to simulate current North American climate and related processes.

Remote versus Local Control of East Pacific Intraseasonal Variability (Rydbeck et al. 2013)
This work is documented in the M.S. thesis of Adam Rydbeck and a paper published in *J. Climate*. During boreal summer, interactions between intraseasonal variability in the Eastern Hemisphere and the east Pacific are often described as a local amplification of the eastward propagating MJO due to rapid eastward communication by dry Kelvin waves. However, the precise mechanism by and degree to which intraseasonal variability in the Eastern Hemisphere interacts with the east Pacific are not well understood. To quantify the relationship between intraseasonal events in the Eastern Hemisphere and the east Pacific, sensitivity tests in two separate models are used (NCAR CAM and the International Pacific Research Center Regional Atmosphere Model [IRAM]). The models use different schemes to isolate the east Pacific from outside intraseasonal signals. When isolated from dry Kelvin waves originating in association with the MJO, the CAM model produces similar east Pacific intraseasonal variability to observations. Although Kelvin waves do not appear necessary to the initiation and maintenance of east Pacific intraseasonal events in the CAM, the waves are a possible phase locking mechanism between hemispheres. When the east Pacific is isolated from remote intraseasonal signals in the IRAM, east Pacific intraseasonal events are weak and noisy. However, the IRAM contains an important bias in the climatological low-level winds that alters the relationship between low-level winds and latent heat flux anomalies that may suppress east Pacific intraseasonal variability.

Sensitivity of MJO activity to the pattern of climate warming (Maloney and Xie 2013).
This work is published in the AGU journal *JAMES.* An aquaplanet general circulation model is used to assess the sensitivity of intraseasonal variability to the pattern of SST warming. Three warming patterns are used. Projected SST warming at the end of the 21st Century from the GFDL CM2.1 model is one pattern, and zonally symmetric and globally uniform versions of this warming perturbation that have the same global mean SST change are the other two. It is shown that the change in intraseasonal variability is acutely sensitive to the pattern of SST warming, with significant decreases in MJO-timescale precipitation and wind variability for a zonally symmetric warming, and significant increases in MJO precipitation amplitude for a globally uniform warming. The amplitude of the wind variability change does not scale directly with precipitation, but is instead mediated by increased tropical dry static stability associated with SST warming. The

patterned SST simulations have a zonal mean SST warming that maximizes on the equator, and fosters increases in equatorial SST-driven boundary layer convergence and tropics-relative SST that support increased convection. Mean precipitation is decreased and gross moist stability is increased in the off-equatorial Eastern Hemisphere near 10^{o}S in the patterned warming simulations, where the strongest MJO-related intraseasonal precipitation variability is preferred in both the model and observations. It is argued that futures changes in MJO activity may be acutely sensitive to the pattern of SST warming, which shows significant differences among CMIP models.

Tropical Atlantic Biases (Richter et al. 2012)
Most coupled general circulation models (GCMs) perform poorly in the tropical Atlantic in terms of climatological seasonal cycle and interannual variability. The reasons for this poor performance are investigated in a suite of sensitivity experiments with the Geophysical Fluid Dynamics Laboratory (GFDL) coupled GCM. The experiments show that a significant portion of the equatorial SST biases in the model is due to weaker than observed equatorial easterlies during boreal spring. Due to these weak easterlies, the tilt of the equatorial thermocline is reduced, with shoaling in the west and deepening in the east. The erroneously deep thermocline in the east prevents cold tongue formation in the following season despite vigorous upwelling, inhibiting the Bjerknes feedback. The surface wind errors are due, in part, to deficient precipitation over equatorial South America and excessive precipitation over equatorial Africa, which already exist in the uncoupled atmospheric GCM. Additional tests indicate that the precipitation biases are highly sensitive to land surface conditions such as albedo and soil moisture. Thus, improving the representation of land surface processes offers a way of improving model performance in the tropical Atlantic.

Process-oriented diagnosis of east Pacific intraseasonal variability (Maloney et al. 2014b).
June-October east Pacific warm pool intraseasonal variability is assessed in eight atmospheric general circulation simulations. Complex empirical orthogonal function analysis is used to document the leading mode of 30-90 day precipitation variability in the models and Tropical Rainfall Measuring Mission observations. The models exhibit a large spread in amplitude of the leading mode about the observed amplitude. Little relationship is demonstrated between amplitude of the leading mode and ability to simulate the observed propagation characteristics. Several process-oriented diagnostics are explored that attempt to distinguish why some models produce a better representation of intraseasonal variability than others. A diagnostic based on the difference in 500-850 hPa averaged relative humidity between the top 5% and the top 10% of precipitation events exhibits a significant correlation with leading mode amplitude. Diagnostics based on the vertically-integrated moist static energy budget also demonstrate success at discriminating models with strong and weak variability. In particular, the vertical component of gross moist stability (GMS) exhibits a correlation with amplitude of -0.9, suggesting that models in which convection and associated divergent circulations are less efficient at discharging moisture from the column are more able to sustain strong intraseasonal variability. The horizontal component of GMS exhibits a significant positive correlation with amplitude. Consequences of these successful diagnostics for the dynamics of east Pacific intraseasonal variability are discussed.

Cause of the pause of global temperature rise (Kosaka and Xie 2013)
Despite the continued increase in atmospheric greenhouse gas concentrations, the annual-mean global temperature had not risen in the twenty-first century as of the time of this writing,

challenging the prevailing view that anthropogenic forcing causes climate warming. Various mechanisms have been proposed for this hiatus in global warming, but their relative importance has not been quantified, hampering observational estimates of climate sensitivity. Here we show that accounting for recent cooling in the eastern equatorial Pacific reconciles climate simulations and observations. We present a novel method of uncovering mechanisms for global temperature change by prescribing, in addition to radiative forcing, the observed history of sea surface temperature over the central to eastern tropical Pacific in a climate model. Although the surface temperature prescription is limited to only 8.2% of the global surface, our model reproduces the annual-mean global temperature remarkably well with correlation coefficient $r = 0.97$ for 1970–2012 (which includes the current hiatus and a period of accelerated global warming). Moreover, our simulation captures major seasonal and regional characteristics of the hiatus, including the intensified Walker circulation, the winter cooling in northwestern North America and the prolonged drought in the southern USA.

Climate model evaluation of the ITCZ and Cold Tongue Bias (Li and Xie 2014)
Errors of coupled general circulation models (CGCMs) limit their utility for climate prediction and projection. Origins of and feedback for tropical biases are investigated in the historical climate simulations from the Coupled Model Intercomparison Project phase 5 (CMIP5), together with the available Atmospheric Model Intercomparison Project (AMIP) simulations. The excessive equatorial Pacific cold tongue and double intertropical convergence zone (ITCZ) stand out as the most prominent errors of the current generation of CGCMs. The comparison of CMIP-AMIP pairs enables us to identify whether a given type of errors originates from atmospheric models. The equatorial Pacific cold tongue bias is associated with deficient precipitation and surface easterly wind bias in the western half of the basin in CGCMs, but these errors are absent in atmosphere-only models, indicating that the errors arise from the interaction with the ocean via Bjerknes feedback. For the double ITCZ problem, excessive precipitation south of the equator correlates well with excessive downward solar radiation in the Southern Hemisphere midlatitudes, an error traced back to atmospheric model simulations of cloud during austral spring and summer. This extratropical forcing of the ITCZ displacements is mediated by tropical ocean-atmosphere interaction, and is consistent with recent studies of ocean-atmospheric energy transport balance.

Interdecadal variations in the rate of global warming (Kosaka and Xie 2016)
Global mean surface temperature change over the past 120 years resembles a rising staircase: the overall warming trend was interrupted by the mid-twentieth-century big hiatus and the warming slowdown since about 1998. The Interdecadal Pacific Oscillation has been implicated in modulations of global mean surface temperatures, but which part of the mode drives the variability in warming rates is unclear. Here we present a successful simulation of the global warming staircase since 1900 with a global ocean–atmosphere coupled model where tropical Pacific sea surface temperatures are forced to follow the observed evolution. Without prescribed tropical Pacific variability, the same model, on average, produces a continual warming trend that accelerates after the 1960s. We identify four events where the tropical Pacific decadal cooling markedly slowed down the warming trend. Matching the observed spatial and seasonal fingerprints we identify the tropical Pacific as a key pacemaker of the warming staircase, with radiative forcing driving the overall warming trend. Specifically, tropical Pacific variability amplifies the first warming epoch of the 1910s–1940s and determines the timing when the big

hiatus starts and ends. Our method of removing internal variability from the observed record revealed that anthropogenic warming has already reached 1.2^{o}C, much larger than previously thought.

In Situ Initiation of East Pacific Easterly Waves in a Regional Model (Rydbeck et al. 2016)

The in situ generation of easterly waves (EWs) in the east Pacific (EPAC) is investigated using the Weather Research and Forecasting Model (WRF). The model's sensitivity to the suppression of EW forcing by locally generated convective disturbances is examined. Specifically, local forcing of EWs is removed by reducing the terrain height in portions of Central and South America to suppress robust sources of diurnal convective variability, most notably in the Panama Bight. The regions of high terrain are associated with mesoscale convective systems that routinely initiate in the early morning and propagate westward into the EPAC warm pool. When such mesoscale convective systems are suppressed in the model, EW variance is significantly reduced. This result suggests that EPAC EWs can be generated locally in association with higher frequency convective disturbances, and these disturbances are determined to be an important source of EPAC EW variability. However, EPAC EW variability is not completely eliminated in such sensitivity experiments, indicating the importance for other sources of EW forcing, namely EWs propagating into the EPAC from west Africa.

A mechanism is proposed to explain the in situ generation of EPAC EWs. Serial mid-level diurnal vorticity and divergence anomalies generated in association with deep convection and originating in the Panama Bight underpin the local generation, intensification, and spatial scale selection of EW vorticity through vertical vorticity stretching. Diurnal vorticity anomalies in the Panama Bight are able to initiate disturbances capable of growing into robust EWs by a mechanism of upscale vorticity organization. This paper is in press in *J. Atmos. Sci*.

Highlights of Accomplishments

- We have helped lead NOAA MAPP CMIP5 Task Force activities. This leadership has included the science and organization of a *Journal of Climate* special collection and the process-oriented model diagnostics effort of the TF.
- A comprehensive assessment of the ability of CMIP5 models to accurately simulate North American climate, as well as model projections of future climate, was conducted in a comprehensive 3-part series of papers (Sheffield et al. 2013a,b; Maloney et al. 2014), as well as specialized science papers (e.g. Jiang et al. 2013; Li and Xie 2014)
- We developed several successful process-oriented model diagnostics that can distinguish models with good and poor intraseasonal variability, and applied these diagnostics to several versions of the GFDL AM2 and AM3, and the NCAR CAM and SP-CAM. This analysis included both the tropical Americas and the broader tropics.
- We have diagnosed reasons for CMIP5 model bias in the ITCZ and cold tongue regions of the Pacific, helping to inform model development
- We showed that changes in future Madden-Julian oscillation activity are acutely sensitive to the pattern of SST warming, making CFMIP-type experiments with uniform warming unrealistic for assessing the impact of climate changes (Maloney and Xie 2013).
- We have attributed the recent global warming hiatus and other hiatus periods to variability associated with the east Pacific coupled system

- We have demonstrated using observations and a regional model that east Pacific easterly waves that spawn hurricanes and tropical storms are locally generated without the need for Atlantic influence

Publications From the Project

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PIs Contact Information

Eric D. Maloney (lead PI)
Department of Atmospheric Science
Cooperative Institute for Research in the Atmosphere (CIRA)
Colorado State University
1371 Campus Delivery
Fort Collins, CO 80523-1371
Phone: (970) 491-3368
Fax: (970) 491-8449
emaloney@atmos.colostate.edu

Shang-Ping Xie (co-PI)
Scripps Institution of Oceanography
UC San Diego
9500 Gilman Drive # 0206
La Jolla CA, 92093-0206
Phone: 858-822-0053
Fax: 858-822-0302