

**Evaluation of the Tropical Storm Track Across the Intra-Americas Sea in IPCC AR5
Models and the Mechanisms of Change in a Warmer Climate**

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Final Report (8/1/2010 – 7/31/2014)

1. Results and Accomplishments

Our NOAA/MAPP project entitled "Evaluation of the Tropical Storm Track Across the Intra-Americas Sea in IPCC AR5 Models and the Mechanisms of Change in a Warmer Climate" with PI Yolande Serra (GC#10-398) investigates characteristics of the tropical storm track in the Intra-Americas Sea (IAS) in a warmer climate by comparing CMIP5 historical to RCP4.5 and RCP8.5 simulations. We additionally investigate the representation of the North American monsoon (NAM) in historical and projected simulations, focusing on northwest Mexico and Arizona. Limited investigation has also been done to determine the value added of dynamically downscaling a well performing climate model to a resolution that better captures the terrain, particularly in the monsoon region, in order to better capture regional precipitation for the historical and future climate projections.

Representation of the Tropical Storm Track in the IAS in CMIP5 Model Historical Simulations

This aspect of the study was focused on assessing the representation of easterly or tropical depression (TD) wave activity across the IAS in CMIP5 models for the May-November 1979-2005 time period when these disturbances are most active. This activity was assessed in two ways: 1) through tracking of 6-hourly low-level vorticity centers following the method of Hodges (1995) and demonstrated in the East Pacific using reanalyses by Serra et al. (2010); and 2) through application of a wavenumber-frequency filter to daily outgoing longwave radiation (OLR) selecting for the TD-band (Wheeler and Kiladis 1999) as presented in Serra et al. (2008;

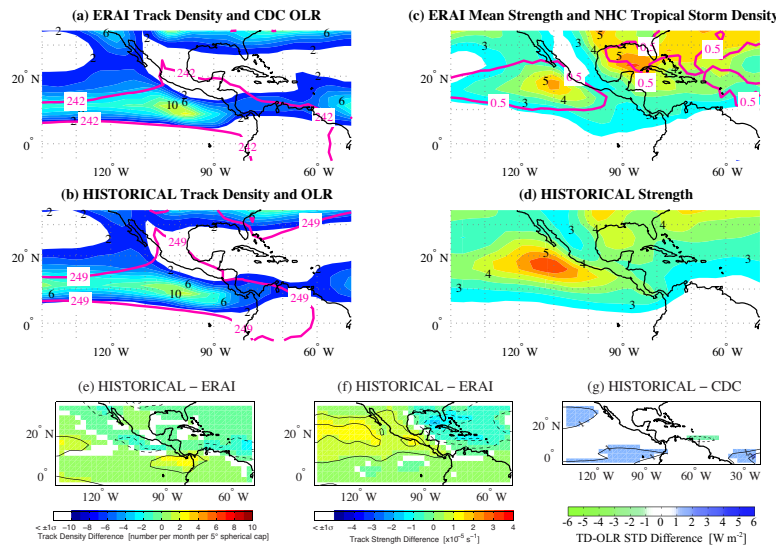


Figure 1. Track density at 850 hPa (filled contours) and OLR (contour line) based on data from (a) ERAI and NOAA CDC and (b) the MME for the May-November 1979-2005 period. The 25th percentile OLR contour is shown in each figure. Track mean strength at 850 hPa (filled contours) based on data from (a) ERAI and (b) the MME for the same period. The NHC Best Track tropical storm density 0.5 counts per day contour is also shown in (c) for reference. Biases in (e) track density, (f) mean strength and (g) TD-filtered OLR standard deviation also for the historical period. Only differences that exceed one standard deviation of the mean for the CMIP5 models are shown in color in (e)-(g).

2010). We selected nine (9) CMIP5 models for the track and OLR analyses (BCC: BCC-CSM1.1, CAN: CanESM2, CCS: CCSM4, CNR: CNRM-CM5, HGE: HadGEM2-ES, GFM: GFDL-ESM2M, MI5: MIROC5, MPI: MPI-ESM-LR, and MRI: MRI-CGCM3), using one ensemble member from each model and no more than one model from a given modeling center, which maximizes the independence of our model subset for our multi-model ensemble (MME) statistics. In addition we selected modeling centers from several countries, also increasing the independence of the analysis. This work is part of a publication to be submitted to the Journal of Climate in the upcoming weeks (Serra and Geil 2014). Early results of this work are also part of the CMIP5 Task Force joint paper published in the Journal of Climate CMIP5 special issue (Sheffield et al.

2013b) and have been presented at five professional meetings since 2010.

We examined the relationship of the spatial distribution of CMIP5 model means and biases in 850 – 200 hPa vertical wind shear (WSH), sea surface temperature (SST) and mid level moisture (q700) to the spatial distribution of track density and mean strength in order to identify the important physical mechanisms determining the distribution of TD wave activity across the IAS. We also investigated the role of the genesis potential index (GPI) (Emanuel and Nolan 2004; Camargo et al. 2007) on TD track density and mean strength. GPI is a non-linear function of low-level relative vorticity, q700, SST and WSH, where increases in all but WSH cause increases in GPI. We use GPI here to understand the combined role of the environmental fields in determining wave activity over the region. Significant results from this aspect of our study can be summarized as follows:

- The MME track density is in good agreement with ERAI (Fig. 1e), though there is quite a bit of variability among individual models (Serra and Geil 2014). Good agreement is also seen in the MME TD filtered OLR where TD tracks have the highest density (Fig. 1g), but again large variability is seen among individual models. On the other hand, MME mean strength is overestimated in the tropical eastern Pacific and underestimated in the Gulf of Mexico and West Atlantic (Fig. 1f), with general consistency among the individual models.
- The spatial distribution of track density and mean strength is highly correlated with GPI in both the reanalyses and CMIP5 models for both the historical and future periods (Table 1), suggesting that GPI is also a good indicator of TD wave activity.
- Biases in CMIP5 track density are attributed primarily to biases in both SST and q700, while biases in CMIP5 mean strength are primarily attributed to biases in SST, with biases in q700 having a secondary role (Table 1).

CMIP5 Model RCP 4.5 and RCP 8.5 Projections for the Tropical Storm Track

For this part of our study we examined model projections for the RCP 4.5 and RCP 8.5 warming scenarios focusing on the 2070-2099 time period. These results are reported in the Serra and Geil (2014) manuscript, with early results summarized in the CMIP5 Task Force joint paper (Maloney et al. 2014) and at four professional meetings since 2010. Here, we summarize the significance of this work.

- The MME track density and TD-filtered OLR variance are projected to shift southward in the future period, consistent with CMIP3 results for the A1B warming scenario (Bengtsson et al. 2006), while the MME mean track strength is projected to weaken over the West Atlantic

Table 1. Spatial point correlations (0°-22.5°N, 125°W-50°W), >95% significant correlations shown in bold. For HISTORICAL column Δ indicates bias in MME with respect to ERAI WSH, q700 or GPI or Hadley ISST, while Δ for RCP 8.5 column indicates difference between 2070-2099 and 1979-2005 MME means.

	ERAI / HadISST	HISTORICAL	RCP8.5
TDEN, MSTR	0.30	0.42	0.26
TDEN, GPI	0.66	0.70	0.66
MSTR, GPI	0.40	0.78	0.73
Δ TDEN, Δ MSTR		0.16	0.28
Δ TDEN, Δ SST		0.49	-0.14
Δ MSTR, Δ SST		0.73	0.29
Δ TDEN, Δ WSH		-0.24	-0.45
Δ MSTR, Δ WSH		0.05	-0.38
Δ TDEN, Δ q700		0.48	0.41
Δ MSTR, Δ q700		0.35	0.63
Δ TDEN, Δ GPI		0.29	0.66
Δ MSTR, Δ GPI		-0.18	0.34

(Fig. 2). These results are similar for the RCP 4.5 and RCP 8.5, but become more pronounced with more warming.

- A southward shift is also seen in the mean OLR over the IAS, suggesting an overall southward shift of the ITCZ across the region (Fig. 2).
- The MME WSH differences between the historical and RCP 8.5 projections indicate higher wind shear across the IAS. As suggested by Vecchi and Soden (2007), the increased wind shear over the region is correlated with a reduction in the strength of the MME Pacific Walker Index (PWI), linking the projected changes in the IAS WSH to the projected weakening of the global tropical circulations.
- The southward shift in the MME track density is significantly correlated with changes in the spatial distribution of GPI (Table 1). The projected southward enhancement in the GPI is associated with both the increase in WSH over the Caribbean and far eastern tropical Pacific, as well as increased q700 south of the enhanced WSH zone.

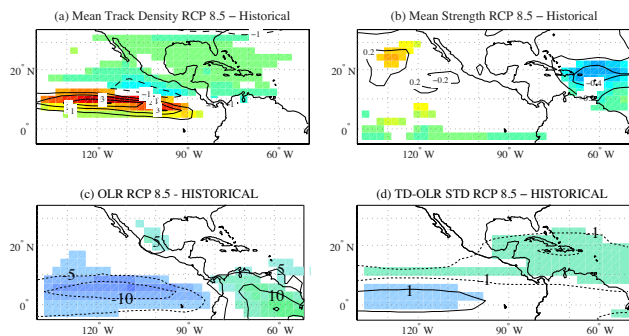


Figure 2. MME RCP 8.5 minus historical period (a) track density, (b) mean strength, (c) OLR and (d) TD-OLR standard deviations.

CMIP5 Model Historical, RCP 4.5 and RCP 8.5 Projections for the North American Monsoon

This aspect of our study focused on the representation of the core NAM region (24°N-29°N, 105°W-109°W) in 21 CMIP5 models during the historical period using both monthly and daily precipitation (Geil et al. 2013, Sheffield et al. 2013a). Of the 21 CMIP5 models examined, we isolated nine that we considered the best performing in terms of capturing the large-scale circulations

and seasonal cycle in NAM rainfall to examine the projections of these quantities in the future period. Some of these results are reported in the CMIP5 Task Force joint paper (Maloney et al. 2014) and in the Task Force NOAA Technical Report (Sheffield et al. 2014), with the full results to be submitted to the Journal of Climate early next year (Serra et al. 2014). Significant results from this aspect of our project are summarized below.

- CMIP5 models overestimate the peak monsoon rainfall in the core NAM region. In addition, while the majority of models capture the onset of the monsoon, with notable improvements over CMIP3 models, they fail to terminate the monsoon, contributing to the models' overestimates of precipitation in the fall and winter.
- CMIP5 models underestimate peak monsoon season rainfall over Arizona, at the northern edge of the core monsoon region, but overestimate it in the fall and winter months. These results suggest that during the peak season, the monsoon is not carried as far north in the models as in observations, while late season moisture supply is overestimated throughout the region (Geil et al. 2013).
- The overestimation of rainfall in the latter part of the year is attributed at least in part to the models' tendency to overestimate the low-level moisture flux convergence into the NAM region. This excess moisture convergence is consistent with errors in model low-level geopotential height patterns, where models with the best spatial correlations in 850-hPa geopotential heights with reanalyses also indicate more accurate moisture flux convergence

in the latter part of the season and better termination of the NAM than models with poor spatial correlations with reanalyses (Geil et al. 2013).

- Seven out of the nine best performing models project that conditions for the NAM will be drier in the future under the RCP 8.5 warming scenario, with a multi-model mean difference of -15.4%. Using a larger set of 16 models, the change in annual mean rainfall is -22.2%. The projected change for rainfall totals over Arizona is similar, but with even more variability among individual models (Maloney et al. 2014, Serra et al. 2014).
- We found no significant change in the onset or retreat dates for the core monsoon region for the RCP 8.5 scenario (Sheffield et al. 2014, Serra et al. 2014).

Dynamical Downscaling HadGEM2-ES: Historical and Future Periods

A limited study was undertaken to investigate the value of downscaling a well performing CMIP5 model over the IAS/NAM domain in terms of improving precipitation biases in the historical period. We were additionally interested in comparing projected NAM rainfall annual totals and seasonal cycle to the coarse model projections. HadGEM2-ES was chosen for this aspect of the study as it was a better performing model by the criteria used in Geil et al. (2013) and their 6-hourly data was available near the start of this study. Downscaling was done using the Weather Research and Forecasting model with a single domain at 32 km resolution. Simulations were done for the historical and future periods for the RCP 4.5 warming scenario (RCP 8.5 6-hourly model data was not available at the time of our downscaling effort). Our preliminary analyses were presented at the 2012 AMS Meeting and in a MAPP Webinar in 2013. These results will be used to leverage future support to downscale additional CMIP5 models and include simulations under the RCP 8.5 warming scenario. A summary of our results using the HadGEM2-ES model is as follows:

- The downscaled simulations reduce coarse model overestimates of peak monsoon rainfall in the core NAM region, however overestimates of fall precipitation show little improvement over the coarse model suggesting biases in the large-scale forcing (Fig. 3a).

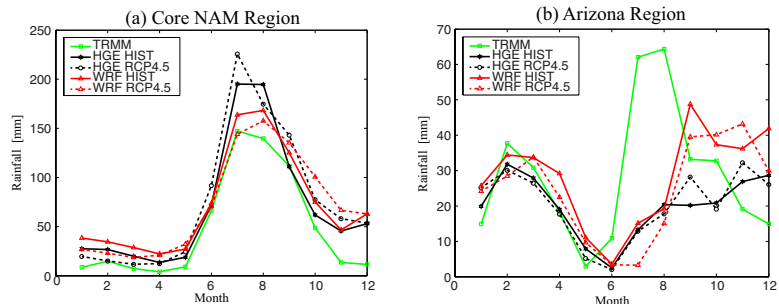


Figure 3. Seasonal cycle in rainfall for the historical and future periods for (a) the core NAM region and (b) the Arizona region, for the HadGEM2-ES (HGE) and downscaled HGE (WRF).

- No improvement to the phase of the seasonal cycle was observed over Arizona, where both the coarse model and the downscaled simulations fail to capture the peak monsoon rainfall in July and August and overestimate rainfall in the latter half of the year (Fig. 3b). This supports the results of Geil et al. (2013) that the biases are due to large-scale forcing errors.
- The HadGEM2-ES future projections of changes to total annual rainfall are +8% in the core NAM region and +2% in the Arizona region. This is in contrast to the 16-model mean of -22.2% in the core NAM region. The downscaled simulations project -1% and -18%, respectively, for the core NAM and Arizona regions. Thus, the downscaled simulations bring the HadGEM2-ES projected change for the core NAM region closer to the MME projections indicating some value added with the downscaled simulations.

2. Highlights of Accomplishments

- This study has shown that the CMIP5 models capture the spatial distribution of TD wave activity across the IAS, but slightly underestimate their number density, overestimate their strength in the eastern Pacific and underestimate their strength in the Gulf of Mexico and West Atlantic. Biases in track density are attributed primarily to biases in both SST and q_{700} , while biases in mean strength are primarily attributed to biases in SST alone.
- This is the first study to show that GPI is not only a good indicator of tropical cyclone activity, but also a good indicator of TD wave activity in both reanalyses and CMIP5 models, contributing to our understanding of CMIP5 model controls on tropical convective activity on synoptic time scales, the smallest scales resolved by the models.
- The projected southward shift in track density and, to a lesser extent, the weakening of track mean strength in the future period are significantly correlated with changes in the spatial distribution of GPI. Enhanced WSH over the IAS, associated with a weakening of large-scale tropical circulations, and enhanced q_{700} south of the enhanced shear zone dominate the changes in GPI in the future period affecting TD wave activity.
- CMIP5 models overestimate the peak monsoon rainfall in the core NAM region but underestimate it over Arizona, suggesting that the monsoon does not reach as far north in the models as in observations. In addition, while the majority of models capture the onset of the monsoon in the core NAM region, with notable improvements over CMIP3 models, they fail to terminate the monsoon, contributing to the models' overestimates of precipitation in the fall and winter over the region.
- The overestimation of rainfall in the latter part of the year is attributed to errors in model large-scale fields, where models with the best spatial correlations in 850-hPa geopotential heights with reanalyses also indicate more accurate moisture flux convergence in the latter part of the season and better termination of the NAM than models with poor spatial correlations with reanalyses.
- The majority of models project that the conditions for the NAM will be drier in the future under the RCP 8.5 warming scenario. The projected change for rainfall totals over Arizona is similar, but with even more variability among individual models.
- We found no significant change in the onset or retreat dates for the core monsoon region for the RCP 8.5 scenario in daily data.

3. Publications from the Project to Date

- Geil, K. L., Y. Serra, and X. Zeng 2013: Assessment of CMIP5 model simulation of the North American Monsoon System. *J. Climate*, **26**(22), 8787–8801. doi: 10.1175/JCLI-D-13-00044.1.
- Serra, Y., and K. L. Geil, 2014: Historical and Projected Intra-Americas Sea TD-Wave Activity in Select IPCC AR5 Models. *J. Climate*, in progress.
- Serra, Y., K. L. Geil, and X. Zeng, 2014: Assessment of CMIP5 Model Simulation of the North American Monsoon System: Future Projections. *J. Climate*, in progress.

Joint CMIP5 Task Force Papers

- Maloney, E., et al., 2014: North American Climate in CMIP5 Experiments: Part III: Assessment of 21st Century Projections. *J. Climate*, **27**, 2230–2270. doi: 10.1175/JCLI-D-13-00273.1.
- Sheffield, J., 2013a: North American Climate in CMIP5 Experiments. Part I: Evaluation of Historical Simulations of Continental and Regional Climatology. *J. Climate*, **26**(23), 9209–9245. doi: 10.1175/JCLI-D-12-00592.1.
- Sheffield, J., et al., 2013b: North American Climate in CMIP5 Experiments. Part II: Evaluation of Historical Simulations of Intra-Seasonal to Decadal Variability. *J. Climate*, **26**(23), 9247–9290. doi: 10.1175/JCLI-D-12-00593.1.

NOAA Technical Report

- Sheffield, J., et al., 2014: Regional Climate Processes and Projections in CMIP3 and CMIP5 for N. America: Differences, Attribution and Outstanding Issues. NOAA Technical Report, 61pp, submitted.

Review Article with contributions from this work:

- Serra, Yolande L., Xianan Jiang, Baijun Tian, Jorge Amador-Astua, Eric D. Maloney and George N. Kiladis, 2014: Tropical Intraseasonal Modes of the Atmosphere. *Annu. Rev. Environ. Resour.*, **39**:189–215. doi: 10.1146/annurev-environ-020413-134219.

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