The Impact of Natural and Anthropogenic Climate Variability on Tropical Cyclone Tracks

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THE IMPACT OF NATURAL AND ANTHROPOGENIC CLIMATE VARIABILITY ON TROPICAL CYCLONE TRACKS

By
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A DISSERTATION

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THE IMPACT OF NATURAL AND ANTHROPOGENIC CLIMATE VARIABILITY ON TROPICAL CYCLONE TRACKS

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To examine the impact of natural and anthropogenic climate variability on tropical cyclone (TC) tracks, a comprehensive analysis is conducted examining changes in TC tracks from changes in the large-scale steering flow and TC genesis for different climate scenarios. A Beta and Advection Model is used to create tracks under the different climate scenarios, which are then analyzed focusing on each contribution from changes in the large-scale steering flow and TC genesis separately and as a combined impact. Two experiments are conducted; the first examines potential changes in TC tracks due to anthropogenic climate change in the North Atlantic and Western North Pacific. The impacts of anthropogenic climate change on TC tracks are robust across models and potential future scenarios for changes in CO$_2$. For the North Atlantic and Western North Pacific, there is a statistically significant decrease in TC tracks that move straight, impacting the Gulf of Mexico and Western Caribbean, or the Philippines, and a statistically significant increase in TC tracks that recurve into the open ocean. These changes are predicted to be small for any given area, with a change of ~1-5 TCs per decade and are found to be primarily due to changes in the large-scale steering flow; however, small changes in TC genesis still contribute, especially in the North Atlantic.
The second experiment examines potential TC tracks during the Last Glacial Maximum. The Last Glacial Maximum had a substantially different climate from present day allowing for an analysis on the impact of climate variability with a larger magnitude of change. Through comparing model-simulated tracks in the Pre-industrial Control and the Last Glacial Maximum, a global decrease in TC tracks is found, except in the Central North and South Pacific. Unlike in the anthropogenic experiment, changes in TC genesis are the primary contributor to proposed differences in the TC tracks. Further analysis of the parameters that are used to calculate TC genesis show that unfavorable TC genesis conditions including cooler relative sea surface temperatures, drier mid-level moisture, and stronger vertical wind shear contribute to the decrease in TC genesis. In the regions where an increase in TC genesis is found, it is primarily a reduction in vertical wind shear and a warming of the relative sea surface temperatures that contribute.
Dedicated to my parents, brother, and godfather.
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The road to finish my Ph.D. has not been an easy one, but through a lot of love and support along the way, it is coming to a close as I begin the next chapter in my life. I look forward to the exciting things the future has to offer!

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CHAPTER 1

Introduction

1.1. An Overview

Tropical cyclones (TCs) signify a substantial socio-economic threat for coastlines world-wide (Southern 1979, Pielke and Landsea 1998, Raghavan and Rajesh 2003, Shultz et al. 2005, Pielke et al. 2008). As the climate changes in response to increased CO$_2$ in the atmosphere, the threat for coastlines, in part based on the policies employed to address climatic changes, will remain considerable, if not increase for certain regions (Pielke 2007). Many studies have identified environmental factors associated with both natural and anthropogenic climate variability which impact basin-wide TC activity (e.g., Gray et al. 1992, Landsea and Gray 1992, Jury 1993, Chan 2000, Maloney and Hartmann 2000, Emanuel 2007, Holland and Webster 2007, Kossin and Vimont 2007, Swanson 2007, Vecchi and Soden 2007, Vimont and Kossin 2007, Klotzbach and Gray 2008, Knutson et al. 2008, Chan 2009, Kim et al. 2011). However, less focus has been dedicated to the environmental factors, such as the large-scale steering flow and TC genesis, which influence the tracks of TCs and how these factors are related to climate variability on varying time scales (e.g. interannual to decadal).

To further understand the impacts of climate variability on TC tracks, natural and anthropogenic climate change scenarios are analyzed. Through the use of a Beta and Advection Model (BAM, see Section 1.2), the impact on TC tracks from changes in the large-scale steering flow and genesis are examined to provide valuable insight into the role of large-scale environmental factors on past, present, and future TC tracks and the resulting potential implications for coastlines.
For the North Atlantic and Western North Pacific, the potential risks from changes in TCs due to anthropogenic climate change can be considered among the highest due to large populations and property value along the coast. Thus, these two regions are the focus for studying the impacts of present day natural climate variability and potential future changes from anthropogenic climate change on TC tracks. However, a past climate, such as the Last Glacial Maximum, is also of interest in determining potential impacts from large variations in the climate system. Understanding how the climate responded to large changes in the past can provide clues into better prediction of climate responses to potential future changes.

1.2. Beta and Advection Model

The motion of a TC is determined by a combination of the large-scale steering flow and interactions between the steering flow and internal dynamics of the storm (e.g. the \( \beta \)-effect, Holland 1983, Dong and Neumann 1986, Carr and Elsberry 1990). The BAM is used to examine the relative importance of the large-scale steering flow and genesis location in observed and potential changes in TC tracks.

The first configuration of the BAM is used in Colbert and Soden (2012) to examine the impact of natural climate variability on TC tracks in the North Atlantic (see Section 1.3 for more details). The National Centers for Environmental Prediction – National Center for Atmospheric Research (NCEP-NCAR) reanalysis zonal \((u)\) and meridional \((v)\) winds (Kalnay et al. 1996) and a specified \( \beta \)-drift are used in the BAM. The mean steering flow is computed, as described later chapters, from the 850, 500, and 200 mb horizontal winds. To remove the effect of the storm circulation on the steering
flow, the TC vortex is removed from the $u$ and $v$ wind fields before computing the steering flow (see Appendix A in Colbert and Soden 2012).

A $\beta$-drift is imposed to include the effects of planetary vorticity advection by the storm’s circulation on storm movement. Marks (1992) experimented with an empirical $\beta$-drift with angles ranging from 295° to 315° and speeds of 1-3 m/s to impose a northwest deviation of the TC vortex from the environmental flow. In Colbert and Soden (2012), the speed of the $\beta$-drift is tuned to provide the best match between the observed and simulated mean track based on the 1950-2010 North Atlantic historical climatology. The BAM uses a constant angle of 315° and allows the $\beta$-drift speed to vary from 1.5 to 5 m/s depending on the TC’s current angle of trajectory. The advection model uses a second order Runge-Kutta time step which is integrated forward in time at one hour intervals for the full step. The $u$ and $v$ are calculated as an average value over a 7.5° by 7.5° box centered on the vortex location to reflect a realistic vortex size from the given reanalysis data for each half time step and full time step.

The BAM provides a tool for examining the relative importance of different factors (e.g. steering flow versus genesis location) in governing climatological changes in TC tracks, but is not meant for operational forecasting. Previous studies have used more complex algorithms to generate TC tracks. One uses a statistical downscaling method in which tracks are randomly produced based on the historical distributions and then fit to the large-scale circulation of a global climate model (Emanuel 2006, Emanuel et al. 2006). Another approach employs a statistical model in which the synthetic tracks are propagated using information from historical storm displacements (Hall and Jewson 2007, 2008).
1.3. North Atlantic Natural Climate Variability and TC Tracks

For the North Atlantic, the most direct impact on the large-scale steering flow is the North Atlantic Subtropical High (NASH) whose strength and location is influenced by a combination of local and remote factors (Chen et al. 2001, Rodwell and Hoskins 2001, Miyasaka and Nakamura 2005, Seager et al. 2003, Nigam and Chan 2009, Li et al. 2010, Kelly and Mapes 2011). A hypothesized relationship between the NASH and TC tracks is that when the NASH extends farther to the west and south, TCs remain at low latitudes, compared to when it contracts to the east and north, and TCs recurve into the western Atlantic (Namias 1955; Ballenzweig 1959; Elsner et al. 2000).

Remote and local climate oscillations can also contribute to changes in the large-scale circulation. Many studies have found a decrease in basin-wide TC activity and number of landfalling storms in the Atlantic during El Niño seasons (Gray 1984, Bove et al. 1998, Xie et al. 2005, Kossin et al. 2010).

A shift in landfalling hurricanes was also found based on the phase of the North Atlantic Oscillation (NAO). The positive NAO phase resulted in a higher threat of hurricane landfall for the East Coast of the US, whereas the negative NAO phase increased the landfall threat for the Gulf Coast of the US (when the NAO phase is determined based on the May-June average; Owens 2001, Elsner 2003). Furthermore, Kossin et al. (2010) found that during a negative May-June NAO phase the western portion of the NASH was generally weaker throughout the subsequent hurricane season, resulting in greater recurvature of TCs that formed north of the Main Development Region (MDR).
More locally to the tropical Atlantic, Kossin et al. (2010) also found an increase in TC activity and higher chance for landfalling storms associated with the positive Atlantic Meridional Mode (AMM) phase. Wang et al. (2011) examined the impact of the Atlantic Warm Pool, which is enhanced warming over the Gulf of Mexico, Caribbean Sea, and western tropical Atlantic, on TC tracks. During seasons with an eastward expansion of the Atlantic Warm Pool, they found a weakening of the NASH, anomalous deep layer easterlies along the East Coast of the US, and an eastward shift in genesis location all contributing to a decrease in the percentage ratio of US landfalling TCs.

In Colbert and Soden (2012), we examined the impact of changes in the large-scale circulation and genesis location due to natural climate variability on TC tracks. Focusing on storms that formed in the North Atlantic MDR, the best tracks from the Atlantic Hurricane Database (HURDAT; Jarvinen et al. 1984, McAdie et al. 2009) for 1950-2010 were categorized into three threat regions: straight-moving storms that threatened the Gulf of Mexico and Western Caribbean, recurving landfall storms that threatened the East Coast of the US, and recurving ocean storms that never threatened US land. To examine the large-scale steering flow for each track category, information on sea level pressure and zonal and meridional winds (850, 500, and 200 mb) from the NCEP-NCAR Reanalysis Data, with a 2.5° resolution, were used (Kalnay et al. 1996). As mentioned with the BAM in the previous section, the corresponding TC vortex was removed from the fields at 6 hourly increments for each TC in the study.

As expected, the climatological NASH was stronger with a more profound westward extension when storms track into the Western Caribbean and Gulf of Mexico compared to when they recurved into the Atlantic. Associated with this change was a
large anomalous anticyclonic circulation over a majority of the North Atlantic, which enhances the easterlies and steers storms towards the west. Interestingly, an anomalously low sea level pressure was also found when TCs were present throughout the basin even with the vortices removed from the reanalysis data.

To further investigate the influence of natural climate variability on TC tracks, three climate features were examined: the El Niño Southern Oscillation (ENSO), North Atlantic Oscillation (NAO), and Atlantic Meridional Mode (AMM). During El Niño years, a statistically significant reduction in the percentage of recurving landfall tracks and an increase in recurving ocean tracks was observed. When comparing El Niño seasons to La Niña seasons, Colbert and Soden (2012) found a weakening of the NASH and an anomalous cyclonic circulation across the mid-Atlantic during El Niño seasons contributing to the reduction in recurving landfall TCs observed. Additionally, a statistically significant difference in the average track for each ENSO phase is found, where the average El Niño track recurves more than the La Niña track. For the NAO, defined as the monthly averaged phase at the time of cyclogenesis, no change in observations between tracks and phase were found. For the AMM, a statistically significant difference in the average track between the positive and negative phase was found; however, no statistically significant change in the frequency of a given TC track category was found.

In order to further examine the observed track shifts due to climate variability, the BAM is used. The BAM did well with simulating the average track, especially for the three climate features examined. In addition, an experiment where the MDR is uniformly seeded, but all historical wind fields remain unaltered, was completed to
determine if the observed track differences were due to changes in the large-scale steering flow or shifts in MDR genesis locations.

Although differences between average genesis locations are expected and observed when comparing straight-moving, recurving landfall, and recurving ocean TC tracks, Colbert and Soden (2012) removed the genesis bias during the uniform seeding experiment to focus on the differences in the large-scale circulation. Interestingly, they found that straight-moving storms no longer threatened the Gulf Coast and Western Caribbean with their average track, but the difference between recurving landfall and recurving ocean average tracks was still consistent. This suggests that straight-moving TCs require a south and/or west genesis location in the MDR in order to become a threat to land, whereas the differences between recurving landfall and recurving ocean TCs are primarily due to changes in the large-scale steering flow.

The uniform seeding experiment also yielded interesting results with the observed differences in tracks due to natural climate variability. The divergence in average track between El Niño and La Niña seasons is reproduced regardless of the initialized genesis location, suggesting that the changes in the large-scale steering flow are attributable to the observed differences in average track. Thus during El Niño seasons, in addition to a reduction of TC activity (Xie et al. 2005), the storms that form are more likely to recurve into the open ocean than threaten the East Coast of the US. In contrast, the observed difference in average track between the two phases of the AMM disappeared in the uniform seeding experiment, which further supports a systematic change in genesis location across the MDR between AMM phases (Kossin and Vimont 2007). This result differs slightly from Wang et al. (2011), which is most likely due to differences in the
definitions of the two modes of climate variability being examined (the AMM and the Atlantic Warm Pool). Consistent with observations, there is no difference in the average track of each NAO phase when the influence of genesis location is removed. Colbert and Soden (2012)’s results complimented and extended previous studies on the influence of natural climate variability on TC tracks for the North Atlantic, most notably Kossin et al. (2010).
CHAPTER 2
The Impact of Climate Change on North Atlantic
Tropical Cyclone Tracks

2.1. Background
The impact of rising CO$_2$ on tropical cyclones (TCs) is an area of great interest. Previous studies have focused on the effects of anthropogenic climate change on TC frequency and intensity (Landsea et al. 2006, Bengtsson et al. 2007, Elsner et al. 2008, Gualdi et al. 2008, Knutson et al. 2008, Garner et al. 2009, Knutson et al. 2010, Yu et al. 2010, Zhao and Held 2010). For example, a recent assessment projects a reduction of global TC frequency of 6-34% and an increase in TC intensity of 2-11% by the end of the 21st Century (Knutson et al. 2010).

The potential impact of anthropogenic climate change on TC tracks has received less attention. Vecchi and Soden (2007) noted an eastward shift in climate model simulations of the Genesis Potential Index (GPI; Emanuel and Nolan 2004) over the North Atlantic main development region (MDR) in response to increased CO$_2$. This eastward shift in genesis location was identified as a potential cause for the decrease in southeastern U.S. landfalling TCs and increase in northeastern U.S. landfalling TCs in high resolution model simulations by Murakami and Wang (2010; hereafter referred to as MW10). Moreover, when the impact of evolving observing networks on historical record is taken into consideration, an eastward shift in the location of North Atlantic TC tracks since the late-19th century appears in the observed record (Vecchi and Knutson 2008, 2011), qualitatively similar to the projections for an eastward shift. In addition, Wu and
Wang (2004) used a high resolution GCM to suggest changes in TC tracks due to rising CO₂ could result from shifts in both the large-scale steering flow and genesis location.

We use a Beta and Advection Model (BAM) in conjunction with reanalysis wind fields and climate model simulations to examine the impact of changes in the large-scale steering flow and genesis location on TC tracks. This approach permits us to consider potential changes in steering flow and genesis location from a large multi-model ensemble mean rather than just an individual model. It also allows us to isolate the impact of changes in the large-scale steering flow from that due to changes in genesis location, thus providing insight into their relative importance. Based upon these projections, we find a statistically significant decrease in straight-moving (westward) storm tracks and an increase in recurving (open ocean) tracks. This shift is shown to primarily result from changes in the large-scale steering flow rather than from changes in genesis location.

2.2. Methodology

The BAM uses a deep layer steering flow that is computed from the horizontal wind fields \( \mathbf{V} \) at 850, 500 and 200 mb defined as:

\[
<V> = 0.25*V_{850 \text{ mb}} + 0.5*V_{500 \text{ mb}} + 0.25*V_{200 \text{ mb}}.
\]

and empirically determined β-drift (see Colbert and Soden (2012; hereafter referred to as CS12) for details). The Atlantic hurricane database (HURDAT; Jarvinen et al. 1984, McAdie et al. 2009) is used to obtain the locations of the 256 TCs that formed in the MDR – defined as the area south of 20°N and west of 65°W – between 1950 and 2010 (CS12). Following CS12, control simulations (CTRL) are performed by initializing each TC at its historical genesis location and, using the BAM model, advected for the actual lifetime of that TC using the corresponding steering flow obtained from the
National Centers for Environmental Prediction – National Center for Atmospheric Research (NCEP-NCAR) reanalysis (Kalnay et al. 1996). For the A1b radiative forcing scenario simulation (atmospheric CO$_2$ stabilization at 720 ppm by 2100; A1b), the model projected changes in steering flow and genesis location are accounted for as described below.

To examine the impact of increasing greenhouse gases on the TC steering flow, monthly zonal ($u$) and meridional ($v$) wind anomalies for 850, 500, and 200 mb are computed for each of the 17 Coupled Model Intercomparison Project version 3 (CMIP3) models (Table 1). The anomalies are calculated as the difference between the 20-year averages at the beginning and end of the 21st century ([2081-2100] - [2001-2020]). The monthly anomalies for each model are added to the corresponding NCEP-NCAR reanalysis winds, where they are linearly interpolated in time to match the 6-hourly reanalysis fields. The BAM model is then run for all 256 TCs as in the CTRL simulation, but with the modified wind fields for each of the CMIP3 models. The resultant TC tracks, as well as the wind anomalies used to obtain the tracks, are averaged to obtain a multi-model ensemble mean.

To examine the influence of changes in genesis location on TC tracks, we use the GPI calculations for the same 17 CMIP3 models from Vecchi and Soden (2007) which are based on the formulation of Emanuel and Nolan (2004). The seasonal (June-November) average GPI is calculated for the first twenty years (2001-2020; CTRL) and last twenty years (2081-2100; A1b) of the A1b scenario. The difference in GPI ([2081-2100]-[2001-2020]) is computed for each model and then averaged to form the ensemble mean change. For both the CTRL and A1b simulations, the storm count in each grid box
of a given TC is weighted by the GPI of the genesis location for that storm. Although
each model has its own biases, the simulated GPI at the beginning and end of the 21st
century is well sampled using observed genesis locations since the GPI and observed
genesis distribution patterns have similar spatial distributions. Thus, we assume that
there is not a significant contribution from areas where TC genesis did not historically
occur. While changes in TC intensity may indirectly be accounted for through the use of
the GPI, the BAM simulations performed for this study use the same deep layer steering
levels for all storms. Although a relationship between storm intensity and steering level
has been observed (Dong and Neumann, 1986; Velden 1993), no attempt is made to
account for such behavior in this study.

2.3. Results

Figures 2.1a-b compare the regional distribution of observed and BAM-simulated TC
counts for the period 1950-2010. While the BAM captures the overall distribution of
storm density, the simulated tracks tend to have a larger spread relative to the
observations resulting in smaller maxima in the tropical and mid-latitude central Atlantic.
While an accurate representation of the climatological distribution of TC tracks is one
test of the model, for the purposes of this study it is more important that the model
capture changes in TC tracks due to a change in genesis location or steering flow. To
evaluate this, CS12 examined the model’s ability to simulate the response of TC tracks to
naturally-driven variations in climate. They showed that the model successfully
reproduced the observed shift in tracks associated with the El Niño Southern Oscillation
(ENSO) and the Atlantic Meridional Mode (AMM), and the absence of any significant
change in tracks associated with the North Atlantic Oscillation (NAO). This lends credibility to the model’s ability to simulate changes in TC tracks due to anthropogenic climate change.

Following CS12, the tracks are classified into three categories: straight-moving (SM), recurving landfall (RCL), and recurving ocean (RCO) as defined in Figure 2.1c (see also CS12). SM TCs threaten the Caribbean and Gulf of Mexico, RCL TCs threaten the East Coast of the US, and RCO TCs recurve into the ocean without threatening the US coast. TCs that dissipate before reaching one of the defined boundaries are also included as described in CS12.

The CMIP3 projected changes in both genesis location and the large-scale steering flow lead to modest, but statistically significant, shifts in tracks. For the CTRL and A1b simulations, the tracks are reclassified into SM, RCL, and RCO TC tracks. The warming climate is associated with a statistically significant reduction of SM TCs (5.5%) and a statistically significant increase of RCO TCs (5.5%; Fig 2.2c). Using a two-tailed binomial test (see CS12), the changes in SM and RCO are determined to be significant at the 91% and 92% level, respectively. The changes are also robust with 15 of the 17 models projecting a decrease in SM TCs and 12 of the 17 models projecting an increase in RCO TCs. However, no changes in RCL TC track frequency are found.

To investigate the spatial distribution of the shift in track frequency, the distribution of storm counts for both the CTRL and A1b simulations are plotted in Figures 2.2a and 2.2b, respectively. The difference in storm counts between the CTRL and A1b simulation (A1b-CTRL; Fig. 2.2d) shows substantial regional variability. There is a spatially coherent reduction in TCs by 1-1.5 per decade over the southern Gulf of
Mexico, Caribbean, and Central America which is primarily responsible for the reduction in SM TCs. Conversely, there is an increase in storm counts throughout the mid-Atlantic of approximately 1-1.5 TCs per decade which is responsible for the increase in RCO TCs. Although there is no change in RCL track frequency, the distribution suggests a slight increase along the US southeast and northeast coasts and decrease in the ocean adjacent to the coastline. This finding suggests recurrvature occurs more frequently such that a portion of SM TCs become RCL TCs, and a portion of RCL TCs become RCO TCs.

To interpret the causes of these shifts in tracks, we examine the changes in the GPI and large-scale steering flow. As noted in Vecchi and Soden (2007), the 17-model ensemble mean difference ([2081-2100]-[2001-2020]) shows an eastward shift in genesis location in the MDR (Fig. 2.3a). Although a majority of the models (12 of 17) agree on an increase over the eastern MDR, the magnitude of this shift varies substantially from model to model.

Figure 2.3b depicts the composite of the deep layer steering flow used in the BAM simulations for all 256 storms for the NCEP-NCAR reanalysis wind fields. Figure 2.3c shows a similar composite of the A1b wind anomalies ([2081-2100]-[2001-2020]) for the 17 model ensemble mean (black arrows), where the blue arrows indicate anomalies in which 12 or more of the 17 models agree on the sign of the change in zonal wind. The most prominent feature is the westerly wind anomaly across the southern Gulf of Mexico and Caribbean which extend into the Atlantic. This wind anomaly weakens the easterlies and encourages recurrvature of TCs away from the Caribbean and Southern Gulf of Mexico which is consistent with the projected increase in RCO tracks and decrease in SM tracks.
To determine whether changes in genesis location or large-scale steering flow are the primary cause of the projected changes in TC tracks, we use the BAM to isolate their individual contributions.

2.3.a. Genesis

To isolate the impact of changes in genesis location, we compare the results obtained by weighting the tracks simulated from the NCEP winds (Fig. 2.1b) by the CTRL GPI and A1b GPI. Differences between the CTRL and A1b GPI climate result in very small and statistically insignificant changes (at the 90% level) in the frequency of track types. There is a slight increase in RCO TCs and decreases in SM and RCL TCs in 12 of the 17 models, consistent with the eastward shift in GPI. However, the ensemble mean changes are small relative to the simulations which consider both GPI and large-scale steering flow (Fig. 2.4c).

Figures 2.4a and 2.4b illustrate the track distributions for the CTRL and A1b GPI simulations, respectively. The projected distribution for the A1b GPI simulation is very similar to the distribution for the CTRL GPI simulation. The differences between the CTRL and A1b GPI weighted NCEP tracks are very small with a slight enhancement in the eastern MDR and a slight reduction in the western MDR (A1b-CTRL; Fig. 2.4d). This is consistent with the projected changes in the frequency of track types, but they are not statistically significant.

2.3.b. Large-scale Steering Flow

To isolate the impact of changes in the large-scale steering flow, the CTRL TC count is compared to the A1b TC count (as in Figure 2.2), but excluding the respective GPI weighting for both simulations (Fig 2.5a,b). Changes between the two simulations result
in an increase in RCO TCs (4.7%) and a decrease in SM TCs (3.9%) and RCL TCs (0.8%) by the end of the 21st century (Fig. 2.5c). The increase in RCO TCs and decrease in SM TCs are not significant at the 90% level. Both of the changes are robust with 15 of 17 models projecting a decrease in SM TCs and 14 of 17 models projecting an increase in RCO TCs when the changes in the large-scale steering flow are isolated. These shifts are consistent with a weakening of the subtropical easterlies, which allows for more TCs to recurve.

The difference between the CTRL and A1b simulation is shown in Figure 2.5d. There is an increase in tracks over the central North Atlantic of approximately 1-1.5 TCs per decade and a decrease in tracks of approximately 1-1.5 TCs per decade over the Caribbean, southern Gulf of Mexico, and Central America. As with the GPI, the spatial changes correspond to the projected increase in RCO TCs and decrease in SM TCs track frequency.

This analysis suggests that changes in the large-scale steering flow are the primary contributor to the projected shifts in TC track frequency and distribution. However, the decrease in SM TCs and increase in RCO TCs are smaller when only the large-scale steering flow is considered, than when both the large-scale steering flow and GPI for the end of the 21st century are combined. This suggests that while the eastward shift in genesis location in the MDR is small, it complements the changes in large-scale steering flow and contributes to the overall projected changes in TC tracks.
2.4. Summary and Discussion

We examined the impact of projected increases in CO$_2$ on North Atlantic TC tracks. Simulated changes in the large-scale steering flow and genesis location suggest a statistically significant decrease of 5.5% of SM TCs and an increase of 5.5% of RCO TCs. These shifts in track frequency result in a reduction of storm counts over the southern Gulf of Mexico, Caribbean, and Central America of approximately 1-1.5 TCs per decade and an increase in storm counts across the Mid-Atlantic of approximately 1-1.5 TCs per decade. Changes in the large-scale steering flow, which result from a weakening of the subtropical easterlies, steer TCs away from the Gulf and Caribbean region contributing to a decrease in SM TCs. However, the decrease in SM TCs is not statistically significant without also accounting for the eastward shift of genesis location in the MDR. This result suggests that changes in both the large-scale steering flow and genesis location are important factors for TC tracks in the North Atlantic, with the steering flow being the primary contributor.

These results agree with MW10, in that both studies find a tendency for an eastward shift of North Atlantic tropical storm tracks. However, the dominant mechanism here differs from that of MW10, who suggested that the primary contributor to a shift in tracks was an eastward shift in genesis location. MW10 found a decrease in TCs over the Caribbean, Gulf of Mexico, and southeastern US and an increase in recurving tracks, including an increase over the northeastern U.S. The results of this study support an increase in recurving TCs and decrease in straight-moving TCs; but, statistically significant changes for the eastern U.S. are not found. However, a slight increase in the track distribution along the U.S. northeastern coast and decrease offshore suggests that a
portion of SM TCs become RCL TCs, and a portion of RCL TCs become RCO TCs. Differences in the methodology of the two studies may create this discrepancy in the results. MW10 use one high resolution model to simulate changes in TC frequency, genesis, and track, which may have limited TC simulation abilities in the MDR. We use a 17 model ensemble mean and decompose the results into changes in tracks due to genesis location and changes in large-scale steering flow, but assume no change in TC frequency. In addition, we use the historical genesis distribution to initialize the BAM, whereas MW10 use model estimated genesis.

This study focused on the tropical North Atlantic only, where the observational record is the most reliable and where the BAM has proven to be an effective tool for studying change in TC tracks associated with natural variations in climate. We note that the more substantial changes in large-scale steering flow and genesis location may occur in other ocean basins (e.g., the Western North Pacific) and a similar analysis is planned for future work that includes an analysis with CMIP5 models.
Figure 2.1: The mean track distribution over 61 seasons for all MDR forming TCs in a) observations from 1950-2010 (OBS) and b) BAM simulated tracks with corresponding NCEP-NCAR reanalysis wind fields (CTRL). All grid boxes are 5°x5°. c) From CS12, the track boundaries for classifying TC tracks. The straight-moving (SM, green) TCs threatened the Gulf Coast and western Caribbean. The recurving landfall (RCL, red) TCs threatened the east coast of the US. The recurving ocean (RCO, blue) TCs never threatened the US. All TCs had to form in the Main Development Region (MDR, gray).
Figure 2.2: The mean track distribution over 61 seasons for all MDR forming TCs in a) BAM simulated tracks (CTRL tracks) weighted by the 20-year, 17 model ensemble mean GPI at the beginning of the 21st century (2001-2020, CTRL GPI) and b) BAM simulated tracks with the 17 model ensemble mean anomalous winds from each respective model added to the historical wind fields (A1b tracks) weighted by the 20-year, 17 model ensemble mean GPI at the end of the 21st century (2081-2100, A1b GPI). c) The percent change in track frequency between the CTRL and A1b simulations for SM, RCL and RCO TCs (A1b-CTRL). The number in parentheses is the number of TCs that changed over 61 seasons for each respective track classification. d) The track density difference of A1b-CTRL. The contour levels are 0.2, 0.15, 0.1, 0.05, and 0.02 where blue is negative and red is positive, and 0.1 is equivalent to 1 TC per decade. All grid boxes are 5°x5°.
Figure 2.3: a) The 17 model ensemble mean difference ([2081-2100]-[2001-2020]) in GPI. The shaded contour levels are 0.1, 0.2, 0.3, 0.4, and 0.5 where blue is negative and red is positive. The black contours are the 17 model ensemble mean control (2001-2020) GPI. Hash tags are where 12 or more of the 17 models agree on the sign of change. b) The black arrows are the corresponding NCEP-NCAR reanalysis deep layer steering flow averaged over all MDR forming TCs for their duration from 1950-2010 (scaled at 5 m/s). c) The anomalous deep layer steering flow difference ([2081-2100]-[2001-2020]) averaged over all MDR forming TCs for their duration (black/blue arrows; scaled at 1.5 m/s). The blue arrows are where 12 or more of the 17 models agree on the zonal sign of change.
Figure 2.4: Same as in Figure 2.2, except the changes in genesis location are isolated to show the NCEP wind tracks that are weighted by the a) CTRL GPI and b) A1b GPI, and the differences.
Figure 2.5: Same as in Figure 2.2, except the changes in the large-scale steering flow are isolated to show the a) CTRL tracks (NCEP winds) and b) A1b tracks (NCEP and anomalous winds) and the differences.
CHAPTER 3

The Impact of Climate Variability on Western North Pacific Tropical Cyclone Tracks

3.1. Background

The Western North Pacific (WNP) has the largest frequency of, and often most intense, tropical cyclones (TCs) that occur globally (Yumoto and Matsuura 2001, Ho et al. 2004). Natural climate variability can influence the frequency, intensity, and tracks of TCs in the WNP (e.g. Chan 2008). Furthermore, anthropogenic climate change may result in additional impacts for TC tracks through changes in the large-scale steering flow and genesis location (Wu and Wang 2004, Murakami et al. 2011, Yokoi et al. 2012).

One of the major sources for interannual TC variability in the WNP is the El Niño Southern Oscillation (ENSO). A well-documented influence of ENSO in the WNP is a southeastward displacement in the mean genesis location for TC development during El Niño seasons (Sobel and Maloney 2000, Wang and Chan 2002, Chia and Ropelewski 2002, Camargo et al. 2007). The shift in genesis location increases storm duration, leading to more intense storms, especially during strong El Niño events (Camargo and Sobel 2005).

Previous studies have also noted a shift in TC tracks during ENSO, where storms tend to recurve more during El Niño events and less during La Niña events, resulting in more landfall threats during La Niña (Chan 2000, Elsner and Liu 2003, Wu et al. 2004, Yonekura and Hall 2011). When El Niño events are subdivided into Central Pacific Warming and Eastern Pacific Warming events, TCs are found more likely to recurve
during Eastern Pacific Warming events, resulting in less TC landfalls (Kim et al. 2011, Wang and Wang 2013).

In addition to the impacts from ENSO, the Pacific Decadal Oscillation (PDO) and Asian monsoon can modulate TC activity. The PDO is found to influence the decadal variability in TC intensity and tracks through changes in the large-scale circulation (Chan 2008, Liu and Chan 2008). Previous studies have shown the importance of the Asian monsoon for tropical cyclogenesis and TC activity in the WNP through the frequency of TC genesis within the monsoon trough (Chen et al. 2004, Chen et al. 2006, Wu et al. 2012, Molinari and Vollaro 2013). Strong monsoon rainfall years over India relate to a greater frequency of monsoon lows and more instability within the monsoon trough (Sikka 1980).

In addition to natural climate variability, the impact of anthropogenic climate change on TC activity is an area of great interest. Many studies have focused on potential changes in TC frequency and intensity (e.g. Oouchi et al. 2006, Stowasser et al. 2007, Knutson et al. 2010, Murakami et al. 2012), with a recent assessment projecting a global reduction of 6-34% in TC frequency and increase of 2-11% in TC intensity (Knutson et al. 2010).

Additional studies have begun considering the potential impact of anthropogenic climate change on TC tracks. Wu and Wang (2004) identified the two main contributors to TC track changes in the WNP as variations in the large-scale steering flow and genesis location. They project a shift to northeastern recurving TCs by the mid-century. Murakami et al. (2011) and Yokoi et al. (2012) found similar results with an increase in recurving storms and decrease in straight-moving (westward) storms. They found a
projected reduction in TC frequency in the region, but attribute the increase in central WNP TC tracks to an eastward shift of genesis and secondly due to changes in the large-scale steering flow that are more favorable for recurvature.

We follow the methodologies established in Colbert and Soden (2012, hereafter CS12) and Colbert et al. (2013, hereafter CSVK13) to examine the natural and anthropogenic impact of climate variability on TC tracks in the WNP. First we establish a control climatology based on observations in Section 3.2, followed by analyses of the impact of natural (Section 3.3) and anthropogenic (Section 3.4) climate variability on TC tracks using a Beta and Advection Model (BAM) driven by reanalysis and coupled ocean-atmosphere model simulations. Lastly, we discuss and summarize results in Section 3.5.

3.2. Control Climatology

3.2.a. TC track classification

To establish an observational TC track climatology, the International Best Track Archive for Climate Stewardship (IBTrACS) database is used (Knapp et al. 2010). This database averages best track position observations for every 6-hr from multiple agencies in the WNP (see Knapp et al. 2010 for more details). We limit our study region to tracks that form in the Main Development Region (MDR), defined as 135°E to 180°E and 5°N to 20°N (Fig. 3.1), for the period 1976-2010. The year 1976 is chosen as it corresponds to the beginning of using satellites to identify TCs, and thus a more accurate record. As in CS12, the focus on MDR forming TCs is chosen to best examine the influence of the large-scale steering flow on TC tracks; however, we recognize that numerous TCs form
outside our region of interest (i.e. South China Sea), and exclude these due to their proximity to land (Fig. 3.1a).

To examine the impact of climate variability and establish a base climatology for comparison, we divide TC tracks into three categories: straight-moving (SM), recurving landfall (RCL), and recurving ocean (RCO). SM tracks threaten the Philippines and southern China. RCL tracks threaten Taiwan, northern China, Korea, and Japan, and RCO tracks recurve into the open ocean without threatening land. Each is classified based on the track category boundary that it passes through first (Fig. 3.1b). A similar track classification was used in Elsner and Liu (2003). For storms that dissipate before reaching any of the track category boundaries, they are classified based on their dissipation location. For storms that dissipated west of 145°E and south of 20°N, they are classified as SM. Storms that dissipate west of 135°E and north of 20°N or west of 145°E and north of 25°N are classified as RCL. Lastly, storms that dissipate east of 145°E and north of 20°N are classified as RCO. If a given TC is still not grouped in a track category classification, then the mean angle of trajectory computed over the lifetime of the storm is used to extrapolate the storm into one of the track category boundaries. For the 428 TCs included in the study, this categorization yields 149 SM TCs, 185 RCL TCs, and 94 RCO TCs. This track classification will be used throughout the study to analyze TC track frequency and its dependence upon different modes of climate variability.

Figure 3.1b shows the average 10-day TC track for each of the three categories. The shaded cone represents ±1 standard error in the longitude and latitude associated
with the tracks. Overall, the classification system successfully produces three distinct track types based on the predefined regions of threat.

To determine the probability of obtaining a given track type based on genesis location, we examine the spatial distribution of genesis for the three track categories (Fig. 3.2). Similar to the North Atlantic (CS12), SM TCs are more likely to form farther south in the MDR than any other track type, whereas RCO TCs are more likely to form in the north and east MDR. RCL TCs were much less likely to form in the eastern MDR, with a majority forming in a diagonal region from the south central to northwest MDR. All of these distributions are expected as the farther north and east a TC forms, the less time it will take for the β-drift to direct the TC out of the easterlies and recurve the TC. The farther west the TC forms, the closer the storm is in proximity to land, and thus more likely to threaten it.

3.2.b. Characterization of the large-scale steering environment

Using the best track position estimate from IBTrACs, the 6-hourly TC vortex is located and removed from the corresponding sea level pressure (SLP) and horizontal wind fields (850, 500, and 200 mb) in the National Center for Environmental Prediction – National Center of Atmospheric Research (NCEP-NCAR) reanalysis data (Kalnay et al. 1996) as done in CS12 (see Appendix in CS12 for more details). These modified SLP and horizontal wind fields are used to calculate composites that show the dominant large-scale steering flow for each track category. For the wind, a deep-layer steering flow $V$ is computed from the horizontal wind fields at 850, 500, and 200 mb, defined as $V = 0.25V_{850mb} + 0.5V_{500mb} + 0.25V_{200mb}$. To compute the SLP and wind field composites,
the average is taken of every corresponding 6-hr field when a TC is present for a given track category.

Figure 3.3 depicts the average SLP and deep-layer steering flow for the three track categories. As expected, the center of the anticyclonic circulation in the deep layer steering flow travels from 120°E (SM) to 150°E (RCO) corresponding to a weakening in the western extension of the Western North Pacific Subtropical High. There is large variability over land between the three track categories that could be related to seasonal differences in the timing of the TCs. To remove any potential for seasonal bias in the results, an anomaly field is calculated for the SLP and deep-layer steering flow for each time when a TC is present. To calculate the anomaly field, first a climatological field is computed as the 35-year climatological mean at each time for SLP and the deep layer steering flow regardless of a TC being present. Then the climatological field is subtracted from the original SLP and deep layer steering flow fields for every time a TC is present. The average anomalous SLP and deep-layer steering flow for the three track categories is then composited and shown in Figure 3.4. Similar to the North Atlantic (CS12), for each track category there is an area of anomalous low pressure along the path that the TCs follow (e.g. over the Philippines and South China Sea for SM TCs). The anomalous lower SLP, with anomalous higher SLP to the north or northeast, corresponds to anomalous anticyclonic circulation that shifts eastward with track type as in Figure 3.3.

Figure 3.5 compares the anomalous SLP and deep-layer steering flow for each track category. Figure 3.5a (SM-RCO) indicates that SM storms experience enhanced SLP across the central WNP and corresponding anomalous southward flow that favors a southward track for the storm. These are part of an anomalous anticyclonic circulation
that steers TCs towards the Philippines and prevents recurvature into the open ocean. Similarly, Figure 3.5b (SM-RCL) indicates that SM storms are associated with enhanced SLP across Taiwan and Southern Japan relative to RCL storms. A weaker, but still present anomalous anticyclonic circulation develops that steers TCs away from the coastlines of Taiwan, China, and Japan and towards the Philippines. Lastly, Figure 3.5c (RCL-RCO) indicates that RCL storms experience enhanced SLP centered near 150°E with weakened SLP over Taiwan and Eastern China. This is associated with an anomalous anticyclonic circulation centered at 130°E that steers TCs towards Taiwan and China, and away from recurving into the open ocean.

3.2.c. Beta and Advection Model

In order to analyze the relative influence of natural and anthropogenic climate variability on TC track changes due to changes in the large-scale steering flow and genesis location, the BAM from CS12 is developed for the climatology of WNP TC tracks for the period 1976-2010. The BAM uses the deep-layer steering flow computed from the corresponding 6-hourly NCEP-NCAR reanalysis and an empirically fitted β-drift, which adds a necessary NW deviation from the steering flow to have TCs recurve. There are two parameters that can be adjusted for the β-drift component: the β speed and the β angle. A range of values of the maximum β speed and β angle was tested. To determine the best fit, half of the tracks were randomly chosen and the sum of the distance error between the observed tracks and simulated tracks was calculated. This was repeated with the other half of the tracks, and the parameters with the lowest error were chosen. The best fit was found for a β speed that varied between 1.5 m/s and 2.75 m/s based on the TC’s current angle of trajectory, as in CS12, and a β angle held constant at 310°.
Additional sensitivity analyses that altered the proportions of the deep-layer steering flow between the upper level and lower level winds resulted in no significant improvement in the simulated track errors.

Figure 3.6 shows the resulting storm density plot for the observed TC tracks (Fig. 3.6a) compared to the BAM simulated TC tracks (CTRL tracks, Fig. 3.6b). Each track is initialized at the historical genesis location and run for the historical storm lifetime for all 428 TCs included in the study. The storm density is calculated as the total number of TCs that travel through a 5°x5° grid box over the 35 year period. A given TC is counted only once per grid box, then divided by the total number of seasons. The BAM simulated storm density has a greater variability and spread with biases to the southwest and northeast of the observed distribution.

To evaluate the fit of the BAM we compare the average tracks for each of the three categories for observations and the CTRL simulations (Fig. 3.7a). It is clear that the error in the BAM simulated tracks increases substantially after about 7 days, with SM and RCL tracks recurving more sharply than in observations. However, the decrease in model skill after 7 days is due in part to less TCs being present (i.e. many storms have dissipated), reducing the amount of tracks to average between and producing a larger error. The model does successfully capture three distinct track categories.

One advantage of the BAM is the ability to separate the influences of the large-scale steering flow from genesis location. This is performed by uniformly seeding the MDR, rather than using the observed genesis location. Thus we initialize a TC at the same historical time as observed, but simulate tracks separately at every 2.5° grid box in the MDR. We then average the tracks based on their original TC track classification.
Figure 3.7b shows the resulting average of the uniformly-seeded tracks. When the effects of genesis location are removed, SM TCs follow a similar track to RCL TCs, suggesting that the more southern genesis location of SM TCs is very important in their westward tracks. However, the RCL and RCO average tracks are very different from each other, suggesting that differences in the large-scale steering flow are an important factor in their track differences. These results are similar to those found in the North Atlantic (CS12).

3.3. Natural Climate Variability

For natural climate variability, we examine the influence of ENSO, PDO, and the All-India Monsoon Rainfall (IMR) on TC tracks. Analyzing natural climate variability provides both insight into the relative sensitivity of the region to climate variations and a basis for testing the ability of the BAM to capture observed climate variability. The TCs in the study, or a given season, are categorized according to the phase of the climate anomaly. Their corresponding SLP fields and average tracks are then calculated. Following CS12, a two-tailed binomial test is conducted on the TC track frequencies to determine statistical significance and a standard error analysis (with a temporal autocorrelation taken into account) is conducted on the SLP fields.

3.3.a. El Niño Southern Oscillation

For ENSO, we classify a given season from 1976-2010 as either El Niño, La Niña, or neutral based on the Climate Prediction Center’s oceanic Niño index classification (Climate Prediction Center 2011). This index classifies an El Niño event if there are five consecutive months in which the 3-month running mean Niño-3.4 index is greater than 0.5°C, or less than -0.5°C for a La Niña event. A given season is classified based on the
phase during the November, December, January 3-month mean, where November and December are from the same year as the season being classified. This resulted in 12 El Niño, 8 La Niña, and 15 neutral seasons. There is a slight increase in TC frequency in the MDR during El Niño seasons with an average of 13.8 storms per season, and a decrease in TCs during La Niña seasons with an average of 8.75 storms per season, when compared to the average TC frequency for the entire dataset which is 12.2 storms per season. The relative increase and decrease in TC frequency in the MDR is most likely related to the documented southeastward shift in TC genesis during El Niño, rather than representing a basin-wide signal, which shows a slight decrease in TC frequency during El Niño (Yonekura and Hall 2011).

Figure 3.8a shows the TC track frequencies during the three phases of ENSO. Although there is slight variations between the phases, with neutral being very similar to the observed total frequency distribution, none of the shifts are statistically significant. However there is a noticeable shift towards recurving TCs during El Niño seasons and increase in land threatening TCs (SM and RCL) during La Niña seasons. These shifts are expected based on results from previous studies (i.e. Wu et al. 2004). Figure 3.8b and 3.8c are discussed in later sub-sections.

Figure 3.9a shows the difference in SLP and deep-layer steering flow anomalies between El Niño and La Niña seasons. The averages are calculated as was done with the control climatology (see Section 3.2.b), but for all TCs in a given ENSO classification rather than by track category. During El Niño, there is an anomalous reduction in the SLP along the northern half of the MDR and an anomalous increase in SLP along the coastline. This corresponds to an anomalous steering flow that favors recurvature by
steering TCs away from the coastline and towards the open ocean. As expected, the averaged tracks show an El Niño track that is farther east than the La Niña track and a southeastward shift in the mean genesis location during El Niño.

In order to examine the importance of the shift in genesis location on the average TC tracks, the BAM is used. Similar to the analysis with the control climatology, both the fit of the model and the uniform seeding experiment are conducted. Figure 3.10a show the fit of the model to observations. As before, the model successfully captures the average track until around 7 days. The uniform seeding experiment results in a large difference between the two tracks during El Niño and La Niña suggesting that there is a strong difference in the steering flow that is contributing to the changes in tracks, not just the southeast shift in genesis (Fig. 3.10b), which adds support to findings in Chan (2000).

3.3.b. Pacific Decadal Oscillation

For the PDO, TCs are classified as positive or negative phase based on the phase of the PDO index during the corresponding month of genesis for the given TC. The PDO index is calculated as the leading PC of the monthly sea surface temperature (SST) anomalies poleward of 20°N in the North Pacific with the monthly mean global average SST anomalies removed (Mantua et al. 1997). This classification results in 293 storms during the positive phase and 135 storms during the negative phase.

As with ENSO, the difference in TC track frequencies between the two phases resulted in no statistically significant changes (Fig. 3.8b). However there are slight increases in RCO TCs and decreases in RCL TCs during the negative phase.

Figure 3.9b, as with ENSO, shows the difference in the anomalous SLP and deep-layer steering flow between the positive and negative phase of the PDO. The SLP
changes are north and east of the MDR, thus limiting their influence in the TC tracks included in this study. However there is an anomalous anticyclonic circulation above the eastern MDR during the positive phase that could slightly enhance the easterlies steering TCs closer to the coastline. As shown with the average tracks and genesis locations, the two tracks are very similar but out of phase in timing with the negative phase leading the positive phase TC tracks. This is most likely due to a slight northwest shift in average genesis location during the negative phase.

As analyzed with ENSO, the BAM is used to determine the importance of changes in genesis location versus steering flow. Figure 3.10c, shows the BAM simulated average tracks versus observed. Once again, the model does well until 5-7 days. However, it successfully captures a similar track path, just slightly more recurved to the east. Not surprisingly, the uniform seeding experiment shows nearly identical tracks (Fig. 3.10d). This suggests that it is the slight change in genesis during PDO that is the cause for the difference in observed tracks, rather than changes in the large-scale steering flow.

3.3.c. All-India Monsoon Rainfall

For IMR, a TC season is classified as positive or negative based on the phase of the All-India Monsoon Rainfall index (Parthasarathy et al. 1995). The index is calculated by taking the climatological average of the June, July, August, and September total rainfall for 1976-2010 and then plotting the values for each season minus the climatological average. If the season has more rain than the climatological average, it is classified as positive; conversely for the negative phase. This results in 21 positive seasons and 14
negative seasons. However, there was no detectable change in the average TC frequency based on IMR phase.

As with ENSO and PDO, the TC track frequencies between the two phases resulted in no statistically significant changes (Fig. 3.8c). However, there is a slight increase in RCL TCs during the negative phase.

Figure 3.9c shows the difference in the anomalous SLP and deep-layer steering flow for the positive and negative phase of IMR. There is a slight increase in SLP between 130°E and 140°E that extends north from the MDR. Unlike with the PDO, this location for a change in SLP appears to cause a more westward track during the positive phase; however, a majority of the SLP changes are outside the region of interest for TC tracks. The anomalous deep-layer steering flow shows weak northerlies near the increased anomalous SLP, which would also promote a more westward track during the positive phase. The average tracks are very similar except for a slight displacement in their timing until after 6 days, when the negative phase averaged track begins to recurve more sharply.

As with ENSO and PDO, the BAM is used to test the influence of genesis location on observed track differences. Figure 3.10e shows that the BAM successfully captures the average observed track for 6 days, before recurving too sharply. However, as with PDO, the model is able to reproduce a similar difference in the two tracks, just displaced slightly to the east. For the uniform seeding experiment, the two tracks show a slight difference during the two phases after 6 days, similar to what is seen in observations. This suggests that the difference in the large-scale steering flow discussed
above contributes to the difference in observed tracks, rather than solely the slight difference in genesis location.

3.4. Anthropogenic Climate Change

To study the impact of anthropogenic climate change on TC tracks, we adapt the methodology established in CSVK13 with a few extensions. Using the BAM and control simulations described in Section 3.2.c, the BAM simulated tracks in Figure 3.6b are the control simulations (CTRL tracks) for this portion of the study. We use two different scenario simulations and datasets to evaluate the impact of future increases in CO$_2$. As in CSVK13, we use the A1b radiative forcing scenario simulation (atmospheric CO$_2$ stabilization at 720ppm by 2100; A1b) for 17 Coupled Model Intercomparison Project Phase 3 (CMIP3) models (Table 1). Additionally, we use the 1% to doubling of CO$_2$ scenario simulation (CO$_2$ is initialized at pre-industrial levels then increases at a rate of 1% per year until a doubling of the CO$_2$ is reached, then stabilizes; 1pct2x) for 26 Coupled Model Intercomparison Project Phase 5 (CMIP5) models (Table 2, Taylor et al. 2012). Results from the A1b experiment will be referred to as CMIP3 and results from the 1pct2x experiment will be referred to as CMIP5 in discussions and figures. The model projected changes in the large-scale steering flow and genesis location are accounted for following CSVK13 and described below.

To examine the impact of anthropogenic climate changes in the large-scale steering flow, the monthly horizontal wind anomalies for the deep-layer steering flow (compromised of the 850, 500, and 200 mb levels) are computed for each of the models. For the CMIP3 experiment, the anomalies are calculated as the difference between the
20-year average at the beginning and end of the 21st century ([2081-2100] – [2001-2020]). Similarly for the CMIP5 experiment, the anomalies are calculated as the difference between the 20-year average the beginning and end of 140 years of the simulation ([121-140] - [1-20]). These anomalies are added to the corresponding NCEP-NCAR reanalysis wind fields and linearly interpolated to match the 6-hourly time resolution. The BAM model is then run for all 428 TCs as done in the CTRL simulation with the modified winds for each model (CC tracks). The multi-model ensemble mean is then calculated for each experiment (CMIP3 and CMIP5) through averaging the CC tracks and anomalous wind fields.

To examine the impact of anthropogenic climate change on genesis location, two versions of a Genesis Potential Index are used. We use the Emanuel and Nolan (2004) GPI (referred to as GPI-EN), which is defined as:

\[ 10^5 \eta^{3/2} \left( \frac{\mathcal{H}}{50} \right)^3 \left( \frac{V_{pot}}{70} \right)^3 (1 + 0.1 V_{shear})^{-2} \]

where \( \eta \) is the 850 mb absolute vorticity in s\(^{-1}\), \( \mathcal{H} \) is the 700 mb relative humidity in percent, \( V_{pot} \) is the maximum potential intensity (MPI, Emanuel 1995) in m s\(^{-1}\), and \( V_{shear} \) is the magnitude of the vertical wind shear between 850 mb and 200 mb in m s\(^{-1}\). However, although still widely used, certain limitations to this index are addressed in Tippett et al. (2011) and an alternative GPI is proposed. Due to available data and computational time, we opt to use the version of the Tippett et al. (2011) GPI (referred to as GPI-T) that utilizes relative humidity at 600 mb, rather than the column-integrated water vapor parameterization. The resulting GPI is defined as:

\[ \exp (-5.8 + 1.03 (\min(\eta, 3.7)) + 0.05 \mathcal{H} + 0.56 T + 0.15 V + \log \cos \phi) \]
where \( \min(\eta, 3.7) \) is the clipped 850 mb absolute vorticity in \( 10^5 \text{s}^{-1} \), \( H \) is the 600 mb relative humidity in percent, \( T \) is the relative SST in °C, and \( V \) is the magnitude of the vertical wind shear between 850 mb and 200 mb in \( \text{m s}^{-1} \); the values for the various constant multipliers from Line 6 of Table 1 in Tippett et al. (2011). The values are then multiplied by 40 as the coefficients were defined based on GPI frequency per 40 years.

The CMIP3 experiment uses the same model produced GPI from Vecchi and Soden (2007) for each of the 17 models. For the CMIP5 experiment, both GPI-EN and GPI-T are calculated for comparison for each of the 26 models. The seasonal (June – November) GPI is calculated for the first 20 years ([2001-2020], CMIP3; [1-20], CMIP5) and last 20 years ([2081-2100], CMIP3; [121-140], CMIP5) of each scenario simulation. As calculated with the large-scale steering flow, the difference in GPI between the two 20-year averages is also computed for each model and then averaged to form the ensemble mean. For the simulations, the storm count of a given TC is weighted by the associated GPI value at that storm’s genesis location. Thus, all of the CTRL tracks are weighted by both the first and last 20-year averaged GPI, and the CC tracks are weighted by the last 20-year averaged GPI for each model and the respective ensemble mean. As discussed in CSVK13, the GPI spatial distribution is similar to observations, and thus we do not anticipate a significant contribution from areas where TCs do not historically occur. Likewise, no attempt to account for changes in TC frequency or intensity is included in this study, except what may be indirectly accounted for through use of the two genesis potential indices.
3.4.a. Projected Changes in TC Tracks

As the climate warms, the projected changes in TC tracks for the WNP are similar to those found in the North Atlantic (CSVK13). For each simulation the tracks are reclassified into the three track categories (SM, RCL, and RCO) to statistically analyze changes in track type frequencies with a two-tailed binomial test (see CS12). There is a statistically significant decrease in SM TCs and corresponding statistically significant increase in RCO TCs for each simulation (Fig. 3.11a,b,c). The projected decreases of ~4-6% in SM TCs and increases of ~5-7% in RCO TCs are statistically significant at least to the 90% level and are robust across experiments. Although there is some variability between the sign of change for RCL TCs in the experiments, the pattern of more recurvature of TCs is prevalent. However, there is not the same model robustness associated with the sign of change for these results as found in the North Atlantic (CSVK13).

To further visualize the projected changes in TC tracks, the difference in storm count is plotted in Figure 3.11d,e,f for each experiment. The track difference is between the CC tracks weighted by the last 20-year average GPI and the CTRL tracks weighted by the first 20-year average GPI. In all three spatial distributions, there is a decrease of ~3-5 TCs per decade throughout the Philippines and South China Sea and an increase in the central WNP of ~1-3 TCs per decade. There is also a slight increase near southern Japan, suggesting that the TCs systematically recurve more throughout the region. Regardless of the experiment, the resulting storm counts are very spatially similar suggesting robustness in the results.
To further evaluate the projected changes in TC tracks, the changes in genesis location and large-scale steering flow are examined for the ensemble mean field and their relative contribution to changes in TC tracks is analyzed.

3.4.b. Changes in genesis location

The projected change in GPI is shown in Figure 3.12 for each experiment. Overall the models robustly agree on a positive increase in GPI throughout the region; however, there is variation in the location of the peak change in GPI. A majority of the largest changes are projected outside of the MDR, and thus do not have a large impact on MDR-forming TC tracks. Within the MDR, all three projections show a slight increase in the north and west. More northward forming TCs are more likely to recurve as they are directed out of the easterlies by the β drift. Conversely, more westward forming TCs tend to threaten land (SM, RCL) due to their relative proximity. Both the CMIP3 and CMIP5 GN GPs are similar in spatial structure, with the CMIP5 being a larger change; however, the CMIP5-T GPI has a large change along the equator. This difference is most likely due in part to the use of the 600mb relative humidity rather than the column-integrated water vapor parameterization; however, further analysis on this matter is left for future work, as it does not impact the results of the study. All of the projected changes are relatively small in comparison to the first 20-year average GPI (contours) in the MDR, thus will likely have minimal impacts on changes in TC tracks.

To examine the contribution of changes in GPI to changes in TC tracks, we use the CTRL tracks and weight them by the first and last 20-year averaged GPI for each experiment. The resulting changes in TC track frequency are small and not statistically significant (Fig. 3.13a,b,c). The corresponding difference in storm count is also very
small (Fig. 3.13d,e,f). Thus, regardless of simulation or GPI used, there is only a very small contribution to changes in TC tracks from projected changes in genesis location.

3.4.c. Changes in the large-scale steering flow

The projected change in the large-scale steering flow is shown in Figure 3.14 for CMIP3 and CMIP5. The plotted fields are the average of all the deep-layer steering flows when a TC is present (NCEP-NCAR reanalysis, Fig. 3.14a) and the corresponding multi-model ensemble mean of the anomalous deep-layer steering flows that are interpolated on to reanalysis winds for CMIP3 (Fig. 3.14b) and CMIP5 (Fig. 3.14c). In both the CMIP3 and CMIP5 experiments anomalous westerlies are found across the South China Sea and Philippines, extending out into the southern portion of the WNP. These robust wind anomalies correspond to a weakening of the easterlies and allow more time for the \( \beta \) drift to steer TCs northward.

Not surprisingly due to the small changes in GPI, the changes in TC tracks associated with the large-scale steering flow are much more substantial. The changes in TC track frequency mirror the projected changes in TC tracks from the combined effects of the large-scale steering flow and genesis location (Fig. 3.15a,b). The projected changes result in a decrease of ~5-6% for SM TCs and increase of ~5-7% in RCO TCs that are statistically significant at least for the 90% level. Only changes in RCO TCs in the CMIP3 experiment are robust, with 12 out of the 17 models projecting an increase.

When we examine the difference in the storm counts between the CC tracks and CTRL tracks for each experiment, we see a similar spatial pattern to Figure 3.11d,e,f with the combined impact. There is a projected decrease of ~3-5 TCs per decade over the South China Sea and Philippines and an increase of ~1-3 TCs per decade over the central
WNP. These results suggest that the primary contribution to TC tracks is from changes in the large-scale steering flow.

Due to the similarity of the results in the WNP to the results found in the North Atlantic (CSVK13), we examine the global change in the large-scale steering flow. Figure 3.16 shows the ensemble mean, global, zonal deep-layer steering flow, monthly averaged June-November wind field for CMIP3 and CMIP5. The spatial distribution is very similar between the two experiments; however, the strength of the changes is more pronounced in the CMIP5 experiment. Interestingly, there is a dipole that is projected over the Northern Atlantic that weakens the steering flow circulation, allowing for more recurvature of TCs. However in the WNP, a similar dipole is not present and only a spatially limited anomalous weakening of the easterlies over the Philippines and South China Sea occurs to promote recurvature. In the CMIP5 experiment, these anomalous westerlies are connected with a somewhat larger global signal.

3.5. Summary and Discussion

In this study we examine the impact of natural and anthropogenic climate variability on WNP TC tracks. We create a control climatology of TC tracks that form in the MDR over the period 1976-2010 by classifying observed tracks into three track categories based on region of threat. SM TCs threaten the Philippines and southern China, RCL TCs threaten Taiwan, eastern China, Korea, and Japan, and RCO TCs recurve into the open ocean never threatening land. There are distinctive tracks and large-scale circulations between the track categories that are similar to those found in the North Atlantic (CS12).
We modified the BAM from CS12 by adjusting the $\beta$ drift component to fit the WNP TC tracks, and it successfully captures the average track of each track category until around 7 days. Then, we use the BAM to determine importance of differences in genesis location compared to changes in the large-scale steering flow by uniformly seeding the MDR. Similar to the North Atlantic (CS12), the changes in observed tracks between RCL and RCO TCs are largely driven by differences in the steering flow, whereas SM TCs are primarily caused by their southward genesis location.

Next, we examine natural climate variability by classifying TCs, or a given season, into the phases associated with ENSO, PDO, and IMR. Natural climate variability provides a basis for testing both the relative sensitivity of the region to climate variability and the ability of the BAM to capture observed shifts in TC tracks associated with climate variability. None of the changes in TC track frequencies are found to be statistically significant; however, there are influential changes in the large-scale circulation for ENSO and IMR that lead to changes in observed average TC tracks. Anomalous low SLP in the MDR contributes to an anomalous steering flow that is favorable for open ocean recurvature of TCs during El Niño. For the positive phase of the IMR, a slight increase in anomalous SLP is found on the northwestern edge of the central WNP that contributes to a slight westward shift in the average track.

The BAM successfully captures the observed differences in average TC tracks; however, it does tend to recurve too sharply after 6-7 days for all of the climate modes analyzed. The uniform seeding experiment yields a large change in the average track between El Niño and La Niña suggesting a large contribution from changes in the large-scale steering flow associated with the observed shift in TC tracks, although the shift in
TC genesis towards the southeast is large and still contributes. A small difference in the average track of IMR between the two phases is also found, suggesting that the difference in the large-scale steering flow contributes to the observed difference in track. There are no major impacts found associated with PDO.

To examine the impact of anthropogenic climate change on TC tracks, we use the BAM to simulate TC tracks in a future climate where we alter the large-scale steering flow and genesis location. For the large-scale steering flow, we calculate monthly wind anomalies that are the difference in the 20-year average from the beginning and end of the 21st century (CMIP3) and 140-year increased CO₂ simulation (CMIP5). These monthly wind anomalies are then added to the NCEP-NCAR reanalysis winds (CTRL tracks) to create the CC tracks. For changes in genesis location, we use two GPIs, with GPI-EN used in both the CMIP3 and CMIP5 experiments and GPI-T used only in the CMIP5 experiment. The first and last 20-year average GPI is calculated for each experiment and then used to weight the CTRL and CC tracks based on genesis location.

The projected changes in TC tracks from changes in the large-scale steering flow and genesis location result in a statistically significant decrease in SM TCs (~4-6%) and increase in RCO TCs (~5-7%). The track frequency shifts correspond spatially to a decrease of ~3-5 TCs per decade in the Philippines and South China Sea and increase of ~1-3 TCs per decade in the central WNP. These results are consistent with those found in previous studies (Wu and Wang 2004, Murakami et al. 2011, Yokoi et al. 2012).

We then separate the relative contributions from changes in genesis location and the large-scale steering flow and find that the primary contribution is associated with changes in the large-scale steering flow, similar to the results in the North Atlantic.
Anomalous westerlies across the South China Sea and Philippines weaken the tropical easterlies and steer TCs away from the region, promoting TC recurvature. The impact from changes in genesis is still valuable, but the contribution is very small and not statistically significant. These findings differ from those in Murakami et al. (2011) and Yokoi et al. (2012), who attribute an eastward shift in genesis to be the primary contribution to the increase in recurving TC tracks. The reason for the inconsistencies in the results is most likely due to differences in methodologies. We use a control climatology from observations/reanalysis and then examine multi-model ensemble mean changes; whereas in Murakami et al. (2011) and Yokoi et al. (2012), they are running high-resolution models and examining the output directly for TC frequency, genesis, and tracks, where their control climatology is model produced. For example, we use the historical genesis distribution to initialize the BAM and then weight the tracks by GPI, whereas they use model-estimated genesis.

In this study, we focused on the impact of natural and anthropogenic climate variability on TC tracks in the WNP. The results have many similarities to those found in previous studies in the North Atlantic (CS12, CSVK13), which suggest similarities in the underlying climate for TCs in these two regions as well as projected changes in the future. We recognize that the projected anthropogenic-related changes in TC tracks may not be as favorable to the coastlines in other parts of the world, but leave the analysis of those basins to future work.
Figure 3.1: (a) The genesis location of all TCs in the WNP from 1976-2010, where green are straight-moving (SM), red are recurving landfall (RCL), and blue are recurving ocean (RCO) genesis locations for TCs that form in the main development region (MDR) as defined by (b). (b) The average tracks and track classification boundaries for the three track categories based on region of threat. The black line denotes the average track where the surrounding ellipses are ±1 standard error. The gray box defines the boundaries of the MDR.
Figure 3.2: The spatial MDR genesis distributions for (a) SM, (b) RCL, and (c) RCO TCs, in number of TCs per 2.5° grid box.
Figure 3.3: The average SLP and deep-layer steering flow (black arrows) for all TCs classified as (a) SM, (b) RCL, and (c) RCO, with the TC vortex removed.
Figure 3.4: The average SLP and deep-layer steering flow (black arrows) for TCs classified as (a) SM, (b) RCL, and (c) RCO relative to the 35-yr climatological mean, where the TC vortex is removed. The black contours denote the standard errors for SLP at 0.5, 0.75, and 1 mb.
**Figure 3.5:** The difference in SLP and the deep-layer steering flow (black arrows) from the anomaly fields in Figure 4 for (a) SM-RCO, (b) SM-RCL, and (c) RCL-RCO. The black contours denote the standard error of the SLP at 0.5, 0.75, and 1 mb.
Figure 3.6: The storm count for all 428 TC tracks included in (a) observations and (b) the BAM simulated control run (CTRL tracks), where each 5°x5° grid box is in number of TCs per season. Each TC is counted only once per grid box for its duration.
Figure 3.7: (a) The average track for each track category (SM, RCL, and RCO) in observations and as simulated by the BAM. (b) The average tracks for each track category when the MDR is uniformly seeded.
Figure 3.8: The TC track frequency distribution in percentage for each track type by the phases of (a) ENSO, (b) PDO, and (c) IMR where green is SM, red is RCL, and blue is RCO TCs. The values in parentheses denote the number of TCs included in the frequency distribution for each season or phase.
Figure 3.9: The difference in the average SLP and deep-layer steering flow (black arrows) for all TCs classified (a) in an El Nino season minus La Nina season, (b) as positive minus negative phase PDO, and (c) in a positive season minus negative season IMR. The black contours denote the standard error for SLP at 0.5, 0.75, and 1 mb. The two plotted tracks are the 10-day average track for all TCs included in a given classified, with the ellipses being ± 1 standard error for 0, 3, 6, and 9 days, respectively. The points show the corresponding genesis locations for each TC included in a given phase classification.
Figure 3.10: (a,c,e) The average track of all TCs included in a given phase classification for observed and BAM-simulated tracks. (b,d,f) The uniformly seeded average track of all TCs included in a given phase classification. (a,b) ENSO, (c,d) PDO, (e,f) IMR.
Figure 3.11: The projected changes in (a,b,c) TC track frequency and (d,e,f) the spatial distribution of TC storm count between the CC tracks weighted by the last 20-year average GPI and the CTRL tracks weighted by the first 20-year average GPI for the (a) CMIP3 experiment weighted by GPI-EN, (b) CMIP5 experiment weighted by GPI-EN, and (c) CMIP5 experiment weighted by GPI-T.
Figure 3.12: The projected change in GPI between the first and last 20-year average for (a) CMIP3 – GPI-EN, (b) CMIP5 – GPI-EN, and (c) CMIP5 – GPI-T, where the contours are the first 20-year average GPI respectively. The vertical dashes are where 12 or more of the CMIP3 models (a) or 18 or more of the CMIP5 models (b,c) agree on the sign of change.
Figure 3.13: As in Figure 3.11, except for the difference in the first and last 20-year average GPI weighted CTRL tracks.
Figure 3.14: (a) The corresponding NCEP-NCAR reanalysis deep-layer steering flow averaged over all MDR forming TCs for their duration from 1976-2010. (b,c) The ensemble mean anomalous deep-layer steering flow difference averaged over all MDR forming TCs for their duration for (b) CMIP3 ([2081-2100]-[2001-2020]) and (c) CMIP5 ([121-140]-[1-20]). The red arrows denote where 12 or more of the CMIP3 (b) and 18 or more of the CMIP5 models (c) agree on the zonal sign of change.
Figure 3.15: As in Figure 3.11, except for the difference in the CC and CTRL tracks, where (a,c) are for CMIP3 and (b,d) are for CMIP5.
Figure 3.16: The global, ensemble mean, anomalous, zonal deep-layer steering flow difference averaged over June-November for (b) CMIP3 ([2081-2100]-[2001-2020]) and (c) CMIP5 ([121-140]-[1-20]).
CHAPTER 4

Tropical Cyclone Tracks During the Last Glacial Maximum

4.1. Background

Climate variability impacts the distribution and frequency of tropical cyclones (TCs) in different and complex ways (e.g. Camargo et al. 2007, Kim et al. 2011, Colbert and Soden 2012, Colbert et al. 2013a,b). By analyzing the Last Glacial Maximum (LGM), approximately 21,000 years before present, which has large variations in the climate compared to potential future climates, we gain clues into how the climate responds to changes and how to better predict climate responses in the future.

In order to develop boundary conditions for past climates in model simulations, we rely on paleo proxy records. Frappier et al. (2007a) suggested that the LGM has a sufficiently different climate from present that a robust signal for changes in TCs could be detected through paleo records. Currently, many paleo records are not at the spatial or temporal scale to detect changes during the LGM for TCs, but there is promise for obtaining such records in the future as we currently have storm records up to 7,000 years before present (Frappier et al. 2007a). Precipitation based proxies are of particular interest for detecting TC events due to the low stable oxygen and hydrogen isotopic values found in TC rainfall that can mask other climatic rainfall signals (Frappier 2013). When these isotopes are not washed away by sea-level rise, they can be found in corals, otoliths, tree rings, and cave stalagmites (Lawrence and Gedzelman 1996, Lawrence 1998, Patterson 1998, Gedzelman et al. 2003, Miller et al. 2006, Frappier et al. 2007a,b, Nott et al. 2007). In contrast to previous hypotheses, the records have hinted at climate
variability in TC frequency and magnitude on even centennial and multi-centennial timescales (Nott 2004, Nott et al. 2007).

Paleo records and model simulations have highlighted many differences in climate during the LGM relative to today. Globally, the LGM had lower concentrations of trace gases, additional land area due to lower sea level, a cooler global temperature in the atmosphere and oceans with around a 2-3°C reduction in the tropical oceans, an equatorward displacement of the Intertropical Convergence Zone (ITCZ), increased trade winds, reduced precipitation in monsoon regions, and a drier and more stable atmosphere (Hobgood and Cerveny 1988, Chiang et al. 2003, Braconnot et al. 2007). In the Atlantic region, there was reduced extratropical storminess (Braconnot et al. 2007, Li and Battisti 2008). In the Pacific, the LGM had an enhanced atmospheric overturning circulation and a southward shift in the North Pacific Subtropical High (DiNezio et al. 2011).

As the records currently do not include a high enough resolution to analyze TCs in the LGM, we rely on models to test hypotheses on changes in TCs. Many of the atmospheric conditions during the LGM are considered unfavorable for TC development, intensification, and sustainability (e.g. drier atmosphere, cooler tropical oceans). However, it is hypothesized that TCs had potential to form in the more unfavorable environment, but with reduced frequency, intensity, and precipitation (Hobgood and Cerveny 1988). Additionally, a recent study by Korty et al. (2012) examined potential changes in genesis and the thermodynamic processes necessary for tropical cyclogensis to occur during the LGM. They found an increase in genesis over the Central and Western North Pacific, decreases in genesis over the North Atlantic and much of the Indian Ocean, and strong model agreement in 7 models from the Paleoclimate Modeling
Intercomparison Project second phase (PMIP2). The PMIP model simulations tend to underestimate the tropical cooling and large-scale drying, however they are more consistent with paleo records than model simulations from the first phase (Pinot et al. 1999, Braconnot et al. 2007).

Although both natural and anthropogenic climate variability may be of more immediate interest, especially for seasonal forecasts and projected impacts of rising CO$_2$ on coastlines (e.g. sea level rise, ocean acidification, and TCs), the LGM provides insight into how the climate responds to large changes. Understanding how the climate responds to past climates provides clues into how the climate may change in the future. The LGM has a reduction of CO$_2$ to around half the amount of the pre-industrial control leading to it being used as an approximate opposite for anthropogenic climate change scenarios. However, it is important to note that changes in the LGM cannot be directly inferred to be the opposite response as the climate system may respond differently in the future (Lea 2004, DiNezio et al. 2011).

We examine possible changes in TC track distribution between the LGM and Pre-industrial Control (PiCon) scenarios and find a decrease in Northern Hemisphere (NH) and Southern Hemisphere (SH) TCs, with a slight increase in the Central North and South Pacific. The methodology is discussed in Section 4.2. The results, including a discussion on changes in TC track distribution, genesis, frequency, and the large-scale steering flow, are discussed in Section 4.3, and a summary with further discussion of the results is provided in Section 4.4.
4.2. Methodology

To determine how large changes in the large-scale environment impact TC tracks, we examine the difference in TC track distribution between the LGM and PiCon scenarios. PiCon is used as the control experiment, where no natural or anthropogenic forcing is included, and is similar to the present day climate. The LGM simulates the expected climate approximately 21,000 years before present, when there were large ice sheets covering a large portion of the NH.

For both the LGM and PiCon scenarios, the model output from 7 of the Coupled Model Intercomparison Project version 5 (CMIP5) models (Table 3, Taylor et al. 2012) and the GFDL CM2.1 model (Delworth et al. 2006) are used. For each model and scenario, monthly data for a 10-year period is chosen, approximately 50 years into the model run depending on data availability. The data is then re-gridded to 2.5° resolution to be consistent with the required input to the Beta and Advection Model (BAM, see Section 4.2.b) used in this study.

4.2.a. Genesis Potential Index and TC Frequency

One impact on TC tracks is from changes in the genesis location. As there is no global record of observed TCs during the LGM, we rely on a Genesis Potential Index (GPI, Emanuel and Nolan 2004) to act as a representation of possible genesis locations. GPI is defined as follows:

\[ |10^5 \eta|^{3/2} \left( \frac{\mathcal{H}}{50} \right)^3 \left( \frac{V_{pot}}{70} \right)^3 (1 + 0.1V_{shear})^{-2} \]

where \( \eta \) is the 850 mb absolute vorticity in s\(^{-1} \), \( \mathcal{H} \) is the 700 mb relative humidity in percent, \( V_{pot} \) is the maximum potential intensity (MPI, Emanuel 1995) in m s\(^{-1} \), and \( V_{shear} \) is the magnitude of the vertical wind shear between 850 mb and 200 mb in m s\(^{-1} \).
Although the Emanuel and Nolan (2004) GPI has known limitations and there are other Genesis Potential Indices (Tippett et al. 2011), we choose to use this GPI as it produced the best fit with the BAM (see Section 4.2.b).

The GPI is calculated for every month over the 10-year period for each model. The mean GPI for each month is computed as the average over the 10-year period, creating a representative year. Each month in the representative year is then averaged across the 8 models creating an ensemble mean GPI for each month. The averaging is done for both scenarios, and then used in the BAM to locate grid points for TC track initialization (see Section 4.2.b).

To analyze the relative contribution from each of the parameters included in GPI (i.e. 850 mb absolute vorticity, 700 mb relative humidity, MPI, and vertical wind shear), a parameter controlled GPI is calculated where only one parameter, e.g. MPI, is set to the LGM scenario value and the other three are held constant at their PiCon scenario values, similar to methodologies used in Camargo et al. (2007). This calculation is done for all four parameters and the same averaging method described above is used to obtain an ensemble mean for each parameter controlled GPI. The difference between the parameter controlled GPI and the PiCon GPI is then computed to obtain the relative contribution of each parameter to changes in the LGM GPI. The averaged ensemble mean for each GPI parameter is also computed for further analysis of the large-scale environmental differences between the LGM and PiCon scenarios. As an additional environmental parameter, the relative sea surface temperature (SST) is computed and defined as the difference in the local SST from the 35°N to 35°S tropical mean SST.
normalized by the difference in the tropical mean SST between the LGM and PiCon, as done in Vecchi and Soden (2007).

Another potential impact on TC tracks is from changes in TC frequency. In order to obtain a measure for determining the change in TC tracks that includes possible variations in TC frequency, a monthly ratio between GPI and TC frequency is determined. The monthly TC frequency is calculated as the average global TC frequency per month from 1970 to 2011 (adapted from Maue 2011). This results in an average global TC frequency of ~87 TCs per year. The monthly ratio is then defined as follows:

\[
    r_n = \frac{f_n}{\sum GPI_n}
\]

where \( r_n \) is the ratio in number of TCs per unit GPI, \( f_n \) is the average global TC frequency, \( \sum GPI_n \) is the global sum of GPI from 30°S to 30°N, excluding 5°S to 5°N, where the GPI is greater than 0.25, and \( n \) is the month. The resulting ratio for each month is based on the ensemble mean GPI for the PiCon scenario, which we assume has a similar TC frequency to the present day climate.

4.2.b. Beta and Advection Model and TC Tracks

TC tracks are also influenced by changes in the large-scale circulation, which steers a TC. As done in previous studies (Colbert and Soden 2012, Colbert et al. 2013a,b) the BAM is used as a tool to create TC tracks under different climate scenarios. The created tracks are then used in determining climatological changes in TC tracks due to variations in the large-scale circulation and TC genesis.

The BAM uses a deep layer steering flow, defined as:

\[
    V = 0.25V_{850\text{mb}} + 0.5V_{500\text{mb}} + 0.25V_{200\text{mb}}
\]
where $\mathbf{V}$ is the horizontal wind field, and an empirically fit $\beta$-drift. The $\beta$-drift adds a necessary northwest or southwest poleward deviation from the large-scale circulation for the NH and SH respectively. In the BAM, the $\beta$-drift is comprised of two variables, the $\beta$-drift speed and $\beta$-drift angle, which can be adjusted to provide the best fit for a given data set. We choose to use the BAM $\beta$-drift from Colbert and Soden (2012), which has a constant $\beta$-drift angle of 315° (NH) and 225° (SH) and a $\beta$-drift speed that varies between 1.5 and 5 ms$^{-1}$ depending on the TC’s angle of trajectory. Although there can be variability in the $\beta$-drift parameterization between basins (Colbert et al. 2013b), we chose to use the same BAM parameterization globally as this version has the best fit in previous work when examining climate variability (Colbert and Soden 2012, Colbert et al. 2013a).

Departing from the methodologies in previous work with the BAM (Colbert and Soden 2012, Colbert et al. 2013a,b), the monthly deep layer steering flow is used to advect the TCs, rather than 6-hourly data. The reduction in time resolution is due to limited data availability for the LGM scenario. As done with the GPI, the deep layer steering flow is averaged for each month over the 10-year period to form a representative year, and then averaged across models to form the 8-model ensemble deep layer steering flow for a representative year. The averaging is done for both scenarios.

The ensemble mean GPI is used to determine initialization grid points for the TC tracks. TCs are only initialized between 30°N and 30°S, excluding 5°N to 5°S, where the GPI is greater than 0.25 for a given 2.5° grid point. The minimum threshold is chosen to remove small GPI valued areas that may skew the results unrealistically and add unnecessary computational time. Then, the ensemble mean deep layer steering flow is used in the BAM to advect the TCs for 7 days. The deep layer steering flow is linearly
interpolated between months to the 1-hour temporal resolution required for the BAM. It is expected that changes in the deep layer steering flow over the 7 days will be minimal and it is noted that the monthly winds are lacking synoptic scale features that can affect the steering flow of a TC. This procedure is repeated for each scenario. The temporal averaging is chosen to help limit interannual variability (e.g. El Niño South Oscillation) in any given model, while the ensemble averaging is chosen to help limit model bias.

Once the tracks are created, TC track distribution is computed to visualize the TC tracks. A 5°x5° global grid is constructed and populated when a TC passes through a given 5° grid box. However, the likelihood of genesis must be taken into account. Thus, the tracks are weighted by the GPI-frequency value, which is the value of GPI multiplied by the monthly frequency ratio at the initialization point of the track. The GPI-frequency value is added to the initialization grid box and every new 5° grid box that the TC passes through for each 6-hourly time step. This is repeated for every track in each month and scenario. The same monthly frequency ratios are used in both scenarios as discussed in Section 4.2.a. This allows for changes in TC frequency to be accounted for in the TC track distribution.

Figure 4.1a shows the cumulative track distribution for the representative year in the PiCon scenario. Overall, the BAM captures a majority of the track distribution seen in observations (Fig. 1n from Camargo 2013, included as Fig. 4.1b). However, the track distribution is greater than observed for certain regions, including the western United States, southern Australia, Central South Pacific, and South Atlantic. Some of the errors are due to the fit of the BAM; however, other errors are due to bias in the large-scale
variables, e.g. high values of mid-level moisture, that are included in GPI and the large-scale circulation of the CMIP5 models (Camargo 2013).

To isolate the impacts of the large-scale steering flow from genesis, an additional analysis is completed. To remove the impact of genesis, the PiCon scenario GPI, multiplied by the monthly ratio, is used to weight the tracks created from the ensemble mean large-scale steering flow during the LGM and PiCon scenarios for each month. This allows for tracks with the same initialization point to have the same weighting between the scenarios. The resulting cumulative TC track density is calculated for each scenario.

4.3. Results

4.3.a. Tropical cyclone tracks

As done in Figure 4.1a, the cumulative TC track distribution for the LGM scenario is also computed (not shown). Figure 4.2a shows the difference in the annual cumulative track density between the LGM and PiCon scenarios. The most striking feature is a large reduction in TC tracks over a majority of the NH and in the South Indian and Australian region in the SH. Conversely, the Central North and South Pacific have an increase in TC tracks during the LGM. Decreases in the North Atlantic, North Indian, and Eastern Australian region of approximately 0.5 TCs per year, result in a reduction of up to 50% in TC tracks from the PiCon scenario, whereas the same decrease of approximately 0.5 TCs per year in the Eastern and Western North Pacific result in approximately a 25% and 15% reduction in TC tracks, respectively, from the PiCon scenario. Additionally, an approximate decrease of 0.2 TCs per year in the South Indian result in a reduction of up
to 20% in TC tracks from the PiCon scenario. Increases in the Central North and South Pacific between 0.1 and 0.4 TCs per year result in increases of up to 20% in TC tracks compared to the PiCon scenario.

To further examine the changes in the TC track distribution, we divide the track distribution plots into the present day NH TC season (JJASON, Fig. 4.2b) and the SH TC season (DJFMAM, Fig. 4.2c). As in Figure 4.2a, the difference in the cumulative track distribution between the LGM and PiCon is shown for the given months of a season. As expected, the changes in TC distribution across the NH occur primarily during the NH TC season and the changes in the SH TC distribution occur primarily during the SH TC season. The increase and decrease in TC tracks for the South Pacific and Southwest Indian, respectively, during the NH season are a result of early and late SH season TCs and do not occur during the peak of the NH season (Fig. 4.3b). Likewise, the decrease in TC tracks for the North Indian and Western North Pacific during the SH season are due to early and late NH season TCs and do not occur during the peak of the SH season (Fig. 4.3c).

4.3.b. Genesis

To further understand the changes in TC track distribution, TC genesis is examined annually and for each TC season. Figure 4.3 shows the difference in the average ensemble mean GPI annually and for each respective TC season. The vertical dashes are where 6 or more of the 8 models agree on the sign of change. The resulting differences in GPI have a similar spatial distribution to the TC track distribution change (Fig. 4.2), suggesting that changes in the genesis location and TC frequency are the primary contribution to changes in TC tracks.
The difference in the annual GPI has strong model agreement for a decrease in GPI over the North Atlantic, Eastern and Western North Pacific, North and South Indian. Likewise there is strong model agreement for an increase in GPI in the Central North and Central South Pacific, as well as a slight increase in the South Atlantic. However, the notable increase in GPI in the Southwest Pacific near Australia does not have strong model agreement. When further subdivided by season (Fig. 4.3b,c), all the changes found in the annual difference (Fig. 4.3a) are more prominent. As with the TC track distribution, the changes in the GPI in the SH during the NH season (Fig. 4.3b) occur before or after the peak of the NH season. Similarly, the decrease in GPI in the North Indian and North Pacific during the SH season (Fig. 4.3c) occur before or after the peak of the SH season. Additionally, slight decreases in GPI in the Southwest Pacific are found during the SH season, but there is not strong model agreement.

In order to determine the relative contribution of each GPI parameter to the annual changes in GPI between the LGM and PiCon, the difference in the annual averaged ensemble mean parameter controlled GPI (see Section 4.2.a) and the annual averaged ensemble mean PiCon GPI is shown in Figure 4.4 for each parameter. The more similar the difference for each parameter is to the difference when all parameters vary (Fig. 4.3a), the larger that parameter’s relative contribution is to changes in GPI. For the North Atlantic region, the decrease in GPI during the LGM is primarily from changes in the 700 mb relative humidity and MPI, whereas changes in vertical wind shear weaken the decrease in GPI for the Central North Atlantic. For the Eastern North Pacific and South Indian, the decrease in GPI is resultant from changes in the 700 mb relative humidity and vertical wind shear primarily with additional contributions from changes in
MPI. For the Western North Pacific, a decrease in GPI is from changes in vertical wind shear and MPI primarily with a contribution from changes in the 700 mb relative humidity. The increase in Central North and Central South Pacific GPI during the LGM is due primarily to changes in vertical wind shear, whereas the increase in the Southwest Pacific GPI is due primarily to changes in MPI. Additionally in the South Pacific, the 700 mb relative humidity acts to weaken the increase in GPI. Contributions from changes in the 850 mb absolute vorticity are found to be small in comparison to the other three parameters (Fig. 4.4d).

As the contributions from changes in MPI, 700 mb relative humidity, and vertical wind shear were the most influential, the difference in the annual averaged ensemble mean of each parameter is shown in Figure 4.5. As in Figure 4.3, the vertical dashes are where 6 or more of the 8 models agree on the sign of change. Favorable TC genesis parameters would be an increase in MPI and 700 mb relative humidity and a decrease in vertical wind shear. There is a decrease in MPI across a majority of the NH and conversely an increase in MPI for a majority of the SH; however, there is not strong model agreement except in the Atlantic and Southeastern Pacific (Fig. 4.5a).

Additionally, the difference in relative SST (see Section 4.2.a) is plotted as contours over the MPI (Fig. 4.5a). The largest changes in MPI correspond to the largest changes in the relative SST suggesting that although there is a tropical oceans reduction in absolute SST of 2-3°C during the LGM (Braconnot et al. 2007), it is the change relative to the tropical mean that is important for changes in TC genesis. The decrease in MPI in the North Atlantic, Eastern and Western North Pacific and increase in MPI in the South Pacific contribute to the respective decreases and increases in GPI during the LGM. For the 700
mb relative humidity, there is a large decrease in moisture for a majority of the NH, especially in the North Atlantic, with additional decreases in the South Indian and Southwest Pacific (Fig. 4.5b). The drying of the mid-level in the North Atlantic and South Indian contribute largely to the decrease in GPI for those regions. Conversely, a majority of the SH has an increase in moisture along with the Eastern and Central North Pacific. There is strong model agreement for a majority of the changes in the 700 mb relative humidity. There is a decrease in both the NH and SH vertical wind shear poleward of 20° and an increase between 10°N and 10°S, with select model agreement in regions. The decreases in vertical wind shear in the Central North and South Pacific contribute to increases in GPI in both regions, whereas the increase in vertical wind shear in the Western North Pacific contributes to the decrease in GPI during the LGM.

When comparing the model suggested difference in GPI between the LGM and PiCon for the CMIP5 models, there are many similarities to the difference suggested from the PMIP2 models examined in Korty et al. (2012). Both analyses indicate a decrease in GPI in the Eastern North Pacific and South Indian, and an increase in GPI in the Central North Pacific and South Pacific. However, Korty et al. (2012) suggested an increase in GPI in the Western North Pacific, southern portion of the Eastern North Pacific, Eastern North Atlantic, and western and eastern South Indian next to Madagascar and Australia respectively. These differences in GPI were not found in our analysis, and in many cases we found a difference of the opposite sign for the same region. When comparing the GPI parameters, the vertical wind shear is very similar in spatial pattern. Korty et al. (2012) uses 600 mb relative humidity, rather than 700 mb relative humidity used in this study, but the resulting spatial pattern is similar. The primary difference
occurs with the MPI calculation. Although many of the large changes correspond spatially, Korty et al. (2012) found a decrease in MPI in the South Indian and Southwest and Central South Pacific whereas we find an increase in MPI. Similarly, Korty et al. (2012) had an increase in MPI in the Central North Pacific and Eastern North Atlantic that we did not find in our analysis. Some of these discrepancies in the GPI and MPI are likely due to potential changes in the models themselves from the PMIP2 experiment, as well as from differences in chosen GPI calculations.

From the difference in GPI, we calculate changes in TC frequency. As the monthly ratio remains constant between the two scenarios, we can use it to estimate potential changes in TC frequency. Figure 4.6 shows the ensemble mean changes in TC frequency between the LGM and PiCon scenarios. A Poisson distribution test is used to determine a p-value for each change, where a p-value of 0.05 or less is considered statistically significant. Figure 4.6 illustrates the changes in TC frequency between the LGM and PiCon scenarios annually and for each TC season. A statistically significant annual global reduction in TC frequency during the LGM is found with a decrease of approximately 16.5 TCs per year (p=0.036). This change is due primarily to a statistically significant decrease of approximately 12.5 TCs per year (p=0.042) during the NH TC season and a decrease of approximately 4 TCs per year (p=0.220) during the SH TC season.

4.3.c. Large-scale steering flow

Although changes in TC genesis contribute largely to the changes in the TC track distribution during the LGM, changes in the large-scale steering flow may also have an impact. Figures 4.7 shows the difference in the ensemble mean average deep layer
steering flow for the zonal (u) winds, both annually and subdivided for each TC season. The difference in the annual zonal deep layer steering flow (Fig. 4.7a) shows anomalous easterlies across the North Atlantic from 10°N to 30°N and anomalous westerlies surrounding the equatorial region of the Atlantic and Eastern Pacific. Additionally, anomalous westerlies occur over much of the North Pacific from 25°N to 40°N and in the Atlantic north of 25°N, whereas the SH is dominated by anomalous easterlies. There is high model agreement for all the suggested changes in the zonal steering flow.

During the NH TC season, in the North Atlantic, the anomalous easterlies shift north beginning at 20°N and become slanted as they extend to 40°N (Fig. 4.7b). Additionally, the anomalous westerlies along the equator expand north into the Eastern Caribbean. During the SH TC season, the anomalous easterlies along the southern tip of Africa and Madagascar extends further north than in the annual average and the easterlies in the South Pacific are more prominent (Fig. 4.7c).

Figure 4.8a shows the difference in the annual averaged ensemble mean deep layer steering flow between the LGM and PiCon scenarios for the vector wind field. Figure 4.8b is the difference in TC track distribution when the changes in the large-scale steering flow are isolated by weighting both the LGM and PiCon tracks by the PiCon GPI (see Section 4.2.b). In the SH, the anomalies easterlies result in small changes which steer TCs towards the coastlines of Southern Africa and Eastern Australia. Changes in the NH are much more prominent with a large increase in TC tracks that recurve in the Eastern and Western North Pacific and North Atlantic. In the Western North Pacific, anomalous southwesterlies steer TCs away from the coastline, whereas the anomalous westerlies in the Eastern North Pacific steer TCs into the western United States and
Mexico. The strong anomalous anticyclonic circulation over the North Atlantic also steers TCs away from the Caribbean and along the eastern coastline of the United States. Although the changes in the NH are large, the increases in TC track distribution are not found when the impact of GPI is included (Fig. 4.2a). Thus the change in GPI is the primary contribution to the differences in the TC track distribution, with changes in the large-scale circulation having a minimal impact.

4.4. Summary and Discussion

Although there is substantial interest with potential changes in TCs over the next century due to anthropogenic warming, important insights can be found from examining TCs in past climates. The LGM is a vastly different climate from the present and future projected climate, thus an analysis examining changes in TCs during the LGM leads to further understanding on how the climate responds to large variations in the climate and provides insight into understanding potential future changes. We examined changes in TC tracks during the LGM through analyzing changes in TC genesis and the large-scale steering flow. A BAM is used to simulate tracks for the LGM and PiCon scenarios.

A large decrease in TC track distribution is found for both the NH and SH, except in the Central North and South Pacific, during the LGM. When compared to the PiCon TC track distribution, a TC reduction of up to 50% for the North Atlantic, North Indian, and eastern Australian region, 25% for the Eastern North Pacific, 20% for the South Indian, and 15% for the Western North Pacific is found. Conversely an increase of up to 20% in TC tracks is found in the Central North and South Pacific.
The changes in the TC track distribution are primarily due to corresponding changes in GPI, which result in a statistically significant global reduction in TCs during the LGM of approximately 16.5 TCs per year. Through an analysis of the relative contribution of each GPI parameter, changes in MPI, 700 mb relative humidity, and vertical wind shear are found to be the most influential, with varying contributions in different regions. A large decrease in MPI in the North Atlantic and Western North Pacific contributes to the decrease in GPI found in those regions. Conversely, an increase in MPI is found for a majority of the SH, contributing to an increase in GPI in the Southwest Pacific. The MPI corresponds to changes in the relative SST, rather than the absolute SST, suggesting that it is the change relative to the tropical mean SST that is important for TC genesis. This suggests an explanation for how an increase in MPI and TC genesis can occur in an environment where there is a global cooling of the absolute SST. A large drying of the 700 mb relative humidity is found in the North Atlantic, Eastern Pacific, and South Indian contributing to decreases in GPI for those regions. Reduced vertical wind shear in the Central North and South Pacific is found to be the primary contributor to the increase in GPI in those regions, whereas an increase in vertical wind shear in the Western North Pacific contributes to a decrease in the GPI.

Changes in the deep layer steering flow between the LGM and PiCon scenarios are examined, and isolated from the impact of GPI, to determine their relative contribution. Over the North Atlantic, a strong anomalous anticyclonic circulation results in steering TCs towards the eastern coastline of the United States. Similarly, anomalous southwesterlies in the Western North Pacific steer TCs away from the East Asia coastline. However, anomalous westerlies in the Eastern North Pacific and anomalous easterlies in
the SH steer TCs towards the western United States and Mexican coastline and the south
African and eastern Australian coastlines respectively. Although the NH TC track
distribution changes are relatively large due to changes in the large-scale steering flow,
they are not found in the difference TC track distribution when the impact of GPI is
included. Thus, the contribution of changes in the large-scale steering flow to the
difference in the TC track distribution during the LGM is found to be secondary to
changes in genesis and TC frequency.
Figure 4.1: a) The 8-model ensemble mean cumulative TC track distribution for a representative year of the PiCon scenario. The grid boxes are 5°x5°. b) Observed TC tracks for the period 1980-2005. Fig. 1n from Camargo (2013).
Figure 4.2: The difference in the 8-model ensemble mean cumulative TC track density between the LGM and PiCon scenarios a) annually, b) during the NH TC season (JJASON), and c) during the SH TC season (DJFMAM).
Figure 4.3: As in Figure 4.2, except for the difference in the 8-model ensemble mean GPI between the LGM and PiCon scenarios. The vertical dashes are where 6 or more models agree on the sign of change.
Figure 4.4: The difference in the 8-model ensemble mean GPI between the controlled parameter GPI and PiCon GPI averaged annually for a) MPI, b) 700 mb relative humidity, c) vertical wind shear, and d) 850 mb absolute vorticity. The controlled parameter GPI is calculated as the LGM value for a given parameter with the other three GPI parameters held constant at PiCon values.
Figure 4.5: The difference between the LGM and PiCon scenarios in the 8-model ensemble mean a) MPI (in ms$^{-1}$), b) 700 mb relative humidity (in %), and c) vertical wind shear (in ms$^{-1}$), averaged annually. The vertical dashes are where 6 or more models agree on the sign of change. The contours in a) are the difference in the relative SST, defined as the difference in the local SST from the 35°N-35°S tropical mean SST normalized by the difference the 35°N-35°S tropical mean SST between the LGM and PiCon scenarios.
**Figure 4.6:** The 8-model ensemble mean cumulative TC frequency for the LGM (blue) and PiCon (Red) scenarios for each TC season and annually.
Figure 4.7: As in Fig. 4.3, except for the difference in the 8-model ensemble mean average zonal deep layer steering flow. Units are m s$^{-1}$. 
Figure 4.8: a) The difference in the 8-model ensemble mean deep layer steering flow averaged annually between the LGM and PiCon scenarios. b) As in Figure 4.2a, except for the difference in TC tracks due to changes in the large-scale steering flow only between the LGM and PiCon scenarios. The GPI is held constant at PiCon values for both scenarios.
CHAPTER 5

Conclusions

5.1. Summary and Future Work

To further understand the impact of natural and anthropogenic climate variability on TC tracks, a comprehensive analysis is completed to examine changes in the large-scale steering flow and TC genesis for various climate scenarios. Observational records, reanalysis data, and climate model output for select scenarios are used as a basis for determining changes in the large-scale environmental factors. A BAM, originally developed in Colbert and Soden (2012), is used and adapted for each experiment as a tool to create TC tracks under various conditions and determine potential changes in TC tracks. The BAM allows for the changes in genesis location to be isolated from the changes in the large-scale steering flow, which allows for greater understanding in the attribution of changes in TC tracks found with each experiment.

Present-day natural climate variability is found to have limited and varying impacts on TC tracks. ENSO is found to have the largest impact on TC tracks in both the North Atlantic and WNP, however, for somewhat different reasons. In the North Atlantic, ENSO relates to a shift in the large-scale steering flow pattern that results from a weakening of the North Atlantic Subtropical High and leads to more TCs that recurve into the open ocean during El Niño seasons. In the WNP, ENSO impacts both the genesis location and the large-scale steering flow, but still leads to more TCs recurving into the open ocean during El Niño seasons. Although there are no significant
differences found in the WNP tracks during the two phases of PDO, there may be a signal in the North Atlantic, which is left for future work.

Future impacts from anthropogenic climate change result in statistically significant, but small, changes in TC tracks. Using the A1b (CMIP3) and 1pct2x (CMIP5) scenarios, the projected changes in TC tracks are very similar regardless of the chosen scenario. In the North Atlantic, there is a statistically significant reduction (~5.5%) in TCs that impact the Western Caribbean and Gulf of Mexico and a statistically significant increase (~5.5%) in TCs that recurve into the open ocean. Similarly in the WNP, there is a statistically significant reduction (~4-6%) in TCs that impact the Philippines, and a statistically significant increase (~5-7%) in TCs that recurve into the open ocean. In both regions, the projected change in TC tracks is due primarily to changes in the large-scale steering flow that are more favorable for TC recurvature from anomalous westerlies. However, small changes in genesis location still contribute, especially in the North Atlantic.

The small changes in TC tracks for potential future climates motivated an analysis for TCs in a past climate. Potential TC tracks during the LGM are modeled to provide insight on the impact of large changes in the climate on TC tracks. The TC tracks during the LGM are compared to the Pre-industrial Control, which is used as an approximation similar to the present-day climate. During the LGM, there is a statistically significant reduction in TC frequency of ~16.5 TCs per year. This is resultant from a global decrease in GPI, except in the Central North and South Pacific. Changes in the MPI, 700 mb relative humidity, and vertical wind shear all contribute, varying regionally, to the changes in GPI. Changes in the relative SST are found to be important for analyzing and
predicting changes in MPI and TC genesis. Although changes in the large-scale steering flow are relatively large, the changes in GPI are found to be the primary contribution to changes in TC track distribution. Thus, the pattern of change for the TC track distribution is similar to that of the changes in GPI. TC tracks are found to decrease by ~15-50% for much of the NH and South Indian and increase by ~10-20% for the Central North and South Pacific during the LGM when compared to the Pre-industrial Control.

Many aspects of climate variability are still being studied, especially the mechanisms behind climate variations and changes, and their large-scale impacts through regional and global teleconnections (e.g. ENSO, ice dynamics). Nonetheless, the impact of large-scale climate variability on smaller scale features, such as TC tracks, is a complex, but important, relationship to understand. It can be argued that changes in TC tracks are the most important aspect of TC variability to understand and predict as TC tracks impact both TC intensity and coastal regions’ risk calculations. In order to gain a unified understanding, it is necessary to study changes in TC tracks from variations in climates past, present, and future. As this understanding expands, better predictions for potential changes in TC tracks in the future can be achieved.
<table>
<thead>
<tr>
<th>Model name</th>
<th>Country</th>
<th>Reference</th>
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</thead>
<tbody>
<tr>
<td>1 BCCR BCM2.0</td>
<td>Norway</td>
<td>Furevik et al. (2003)</td>
</tr>
<tr>
<td>2 CNRM CM3</td>
<td>France</td>
<td>Salas y Mélia et al. (2006)</td>
</tr>
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<td>3 CSIRO Mk3.0</td>
<td>Australia</td>
<td>Gordon et al. (2002)</td>
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<td>4 GFDL CM2.0</td>
<td>United States</td>
<td>Delworth et al. (2006)</td>
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<td>5 GFDL CM2.1</td>
<td>United States</td>
<td>Delworth et al. (2006)</td>
</tr>
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<td>6 GISS-EH</td>
<td>United States</td>
<td>Schmidt et al. (2006)</td>
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<td>7 GISS-ER</td>
<td>United States</td>
<td>Schmidt et al. (2006)</td>
</tr>
<tr>
<td>8 IAP FGOALS</td>
<td>China</td>
<td>Yu et al. (2004)</td>
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<td>9 INGV SXG</td>
<td>Italy</td>
<td>Scoccimarro et al. (2007)</td>
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<td>10 INM CM3.0</td>
<td>Russia</td>
<td>Volodin and Diansky (2004)</td>
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<td>11 IPSL CM4</td>
<td>France</td>
<td>Marti et al. (2005)</td>
</tr>
<tr>
<td>12 MIROC Hi</td>
<td>Japan</td>
<td>Hasumi and Emori (2004)</td>
</tr>
<tr>
<td>14 MPI ECHAM5</td>
<td>Germany</td>
<td>Jungclaus et al. (2006)</td>
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<td>15 MRI CGCM2.3</td>
<td>Japan</td>
<td>Yukimoto and Noda (2002)</td>
</tr>
<tr>
<td>16 NCAR CCSM3</td>
<td>United States</td>
<td>Collins et al. (2006)</td>
</tr>
<tr>
<td>17 UKMet HadGem1</td>
<td>United Kingdom</td>
<td>Johns et al. (2004)</td>
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Table 1: The 17 CMIP3 models are listed showing which models are used in this study for their wind fields and calculated GPI under the A1b scenario.
<table>
<thead>
<tr>
<th>Model name</th>
<th>Country</th>
<th>Institution</th>
</tr>
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<tbody>
<tr>
<td>ACCESS 1.0</td>
<td>Australia</td>
<td>Commonwealth Scientific and Industrial Research Organization and Bureau of Meteorology</td>
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<td>Australia</td>
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<td>China</td>
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<td>CanESM2</td>
<td>Canada</td>
<td>Canadian Centre for Climate Modelling and Analysis</td>
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<td>CCSM4</td>
<td>United States</td>
<td>National Center for Atmospheric Research</td>
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<tr>
<td>CSM1 (BGC)</td>
<td>United States</td>
<td>National Science Foundation, Department of Energy, National Center for Atmospheric Research</td>
</tr>
<tr>
<td>CNRM-CM5</td>
<td>France</td>
<td>Centre National de Recherches Meteorologiques/Centre Europeen de Recherche et Formation Avancees en Calcul Scientifique</td>
</tr>
<tr>
<td>CSIRO-Mk3.6.0</td>
<td>Australia</td>
<td>Commonwealth Scientific and Industrial Research Organization in collaboration with Queensland Climate Change Centre of Excellence</td>
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<td>FGOALS-s2</td>
<td>China</td>
<td>LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences</td>
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<td>GFDL-ESM2G</td>
<td>United States</td>
<td>NOAA Geophysical Fluid Dynamics Laboratory</td>
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<td>GFDL-ESM2M</td>
<td>United States</td>
<td>NOAA Geophysical Fluid Dynamics Laboratory</td>
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<td>GISS-E2-H</td>
<td>United States</td>
<td>NASA Goddard Institute for Space Studies</td>
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<td>GISS-E2-R</td>
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<td>HadGEM2-ES</td>
<td>United Kingdom</td>
<td>Met Office Hadley Centre</td>
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<td>INM-CM4</td>
<td>Russia</td>
<td>Institute for Numerical Mathematics</td>
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<td>France</td>
<td>Institut Pierre-Simon Laplace</td>
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<td>France</td>
<td>Institut Pierre-Simon Laplace</td>
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<tr>
<td>IPSL-CM5B-LR</td>
<td>France</td>
<td>Institut Pierre-Simon Laplace</td>
</tr>
<tr>
<td>MIROC5</td>
<td>Japan</td>
<td>Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology</td>
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<tr>
<td>MPI-ESM-LR</td>
<td>Germany</td>
<td>Max Planck Institute for Meteorology</td>
</tr>
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<td>MPI-ESM-P</td>
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<td>MRI-CGCM3</td>
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<td>Meteorological Research Institute</td>
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<td>Norwegian Climate Centre</td>
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<tr>
<td>NorESM1-ME</td>
<td>Norway</td>
<td>Norwegian Climate Centre</td>
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</table>

**Table 2:** The 26 CMIP5 models are listed showing which models are used in this study for their wind fields and calculated GPI under the 1pct2x scenario (Taylor et al. 2012).
<table>
<thead>
<tr>
<th>Model name</th>
<th>Country</th>
<th>Institution</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 CCSM4</td>
<td>United States</td>
<td>National Center for Atmospheric Research</td>
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<tr>
<td>2 CNRM-CM5</td>
<td>France</td>
<td>Centre National de Recherches Meteorologiques/Centre Européen de Recherche et Formation Avancées en Calcul Scientifique</td>
</tr>
<tr>
<td>3 FGOALS-g2</td>
<td>China</td>
<td>LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences</td>
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<tr>
<td>4 IPSL-CM5A-LR</td>
<td>France</td>
<td>Institut Pierre-Simon Laplace</td>
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<td>5 MIROC-ESM</td>
<td>Japan</td>
<td>Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology</td>
</tr>
<tr>
<td>6 MPI-ESM-P</td>
<td>Germany</td>
<td>Max Planck Institute for Meteorology</td>
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<tr>
<td>7 MRI-CGCM3</td>
<td>Japan</td>
<td>Meteorological Research Institute</td>
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</table>

Table 3: The 7 CMIP5 models are listed showing which models are used in this study for their wind fields and calculated GPI under the LGM and PiCon scenarios (Taylor et al. 2012).
REFERENCES


Salas-Mélia, D., and coauthors, 2005: Description and validation of the CNRM-CM3 global coupled model. *CNRM, Note de Centre n 103*, pp. 36.


