

1 **Characteristics of tropical cyclones in high-resolution models of**  
2 **the present climate**

DANIEL A. SHAEVITZ<sup>1</sup>

SUZANA J. CAMARGO<sup>2\*</sup>, ADAM H. SOBEL<sup>1,2,3</sup>, JEFFREY A. JONAS<sup>4,5</sup>,  
DAEYHUN KIM<sup>2</sup>, ARUN KUMAR<sup>6</sup>, TIMOTHY E. LAROW<sup>7</sup>, YOUNG-KWON LIM<sup>8</sup>,  
HIROYUKI MURAKAMI<sup>9</sup>, MALCOLM J. ROBERTS<sup>10</sup>, ENRICO SCOCCIMARRO<sup>11</sup>,  
HUI WANG<sup>6</sup>, MICHAEL F. WEHNER<sup>12</sup>, MING ZHAO<sup>13</sup>

*1 Department of Applied Physics and Applied Mathematics, Columbia University, New York, NY*

*2 Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY*

*3 Department of Earth and Environmental Sciences, Columbia University, New York, NY*

*4 Center for Climate System Research, Columbia University, New York, NY*

*5 NASA Goddard Institute for Space Studies, New York, NY*

*6 NOAA/NWS/NCEP Climate Prediction Center, College Park, MD*

*7 Center for Ocean Atmospheric Prediction Studies, Florida State University, Tallahassee, FL*

*8 NASA Goddard Space Flight Center, Greenbelt, MD*

*9 International Pacific Research Center, University of Hawaii at Manoa, Honolulu, HI*

*10 Met Office, Hadley Center, Devon, United Kingdom*

*11 Istituto Nazionale di Geofisica and Vulcanologia, Bologna, Italy  
and Centro Euro-Mediterraneo per i Cambiamenti Climatici, Lecce, Italy*

*12 Lawrence Berkeley National Laboratory, Berkeley, CA, and University of California, Berkeley, Berkeley, CA*

*13 NOAA Geophysical Fluid Dynamics Laboratory, Princeton, NJ*

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*\*Corresponding author address:* Suzana J. Camargo Lamont-Doherty Earth Observatory Columbia University PO Box 1000, Palisades, NY 10960.

E-mail: [suzana@ldeo.columbia.edu](mailto:suzana@ldeo.columbia.edu)

## ABSTRACT

4  
5 The global characteristics of tropical cyclones (TCs) simulated by several climate models  
6 are analyzed and compared with observations. The global climate models were forced by  
7 the same sea surface temperature (SST) in two types of experiments, using a climatological  
8 SST and interannually varying SST. TC tracks and intensities are derived from each model's  
9 output fields by the group who ran that model, using their own preferred tracking scheme;  
10 the study considers the combination of model and tracking scheme as a single modeling  
11 system, and compares the properties derived from the different systems. Overall, the ob-  
12 served geographic distribution of global TC frequency was reasonably well reproduced. As  
13 expected, with the exception of one model, intensities of the simulated TC were lower than  
14 in observations, to a degree that varies considerably across models.

# 1. Introduction

The impact of tropical cyclones (TCs) on society makes it important to understand how their characteristics might change in the future. Global climate models, also known as General Circulation Models (GCMs), are important tools for studying this problem. In a GCM, one has the ability to simulate the climate organically; if the model has sufficient resolution and physics to provide a plausible simulation of TCs as well, then one can use the model to examine how climate controls the statistical properties of TCs. One can explore, in particular, the behavior of TCs under different climate scenarios.

Many studies (e.g. Manabe et al. 1970; Bengtsson et al. 1982; Vitart et al. 1997; Camargo et al. 2005) have shown that GCMs, even at relatively low resolution, are capable of generating storms that have similar characteristics as observed TCs. More recently, studies that have used higher resolution atmospheric GCMs forced with prescribed sea surface temperatures (SSTs) (e.g. Bengtsson et al. 2007a; LaRow et al. 2008; Zhao et al. 2009) have demonstrated these high-resolution models' remarkable ability to simulate realistic distributions of TCs.

In order to use GCMs for projections of possible future changes in TC activity, it is necessary to assess their ability to reproduce the characteristics of observed TCs in the present climate. These characteristics include the climatological spatial, temporal, and intensity distributions as well as the interannual variability of TCs. This work is an intercomparison of the ability of 9 high-resolution GCMs to simulate TCs. The models have resolutions that vary from 28 to 130 km, with different parameterizations. Two of the models have done simulations at multiple resolutions, while a single resolution is available for our analysis of the other models.

The simulations analyzed were performed for the U.S. CLIVAR Hurricane Working Group. The objective of this working group was to have a better understanding of the differences among high-resolution models in simulating TC activity, in the present climate as well as in future climate scenarios. In order to do that, a set of common experiments with the same forcings and fixed SST was performed by all modeling groups. Here we analyze the

42 characteristics of TC activity in the simulations of climate produced by the working group  
43 over SST distributions derived from observations taken in the late 20th century (1981-2005  
44 for the climatology simulations and 1981-2009 for the interannual simulations).

45 Observed TC tracks and intensities are derived from atmospheric measurements — in situ  
46 and remote — by human forecasters. With climate models, it is necessary to apply objective  
47 tracking schemes to the model output fields to obtain the tracks and intensities. The criteria  
48 applied to the models can be different than those applied to observations; a model storm is  
49 not necessarily required to meet the same thresholds for intensity as an observed one would  
50 be in order to be classified as a TC. It has been found that when allowance is made for the  
51 fact that model TCs are weaker and larger than those observed, the resulting spatio-temporal  
52 distributions of TC tracks resemble those observed enough to be useful — for example, in  
53 seasonal forecasting — even in quite low-resolution models (Camargo and Barnston 2009;  
54 Camargo et al. 2010).

55 In the present study, we examine the TCs derived from each model’s output by the group  
56 who ran that particular model, using their own preferred tracking scheme. We consider the  
57 combination of model and tracking scheme to be a “modeling system” and compare the  
58 outputs from each system. In the interests of brevity, we will refer to these modeling systems  
59 below simply as “models”, taking the tracking scheme as implicit, though our expectations  
60 about the sensitivities of the results to tracking schemes are discussed in several points.

61 This approach implicitly makes allowances for the different resolutions and physics of  
62 each model, resulting in different TC intensities. It is consistent with the way each model  
63 has been used in previous single-model studies. Using each group’s own tracks also allows  
64 each model to be seen in the best light, to the extent that tracking schemes have tunable  
65 parameters whose adjustment can allow some gross aspects of the statistics to be brought  
66 closer to those observed.

67 It is also of interest to compare the different models using the same tracking scheme,  
68 so that the differences in results are purely attributable to the differences in the models

69 themselves. This work is underway and will be reported in due time.

70 This paper is organized as follows. The data, models, and experiments are discussed  
71 in section 2. Results from the climatological and historical forced models are described in  
72 section 3. Finally, conclusions are given in section 4.

## 73 **2. Models and data**

74 The data used for this study consists of TC tracks from nine GCMs. The models were  
75 forced with two different SST boundary conditions, climatologically averaged SSTs and  
76 monthly interannually varying SSTs. The SSTs were obtained from the Hadley Centre Sea  
77 Ice and Sea Surface Temperature (HadISST) data set (Rayner et al. 2003). Each group used  
78 the output of their simulations to detect and track the model TCs, using their own tracking  
79 algorithm. Tracks for these TCs were generated and their characteristics were analyzed here.  
80 The sensitivity of the models to the different tracking schemes is currently being analyzed  
81 by members of the working group.

82 Output from nine GCMs were analyzed in this study, as summarized in table 1, namely:  
83 Community Atmospheric Model version 5.1, or CAM5.1 (Wehner et al. 2013); European  
84 Center for Medium range Weather Forecasting - Hamburg, or ECHAM5 (Roeckner 2003;  
85 Scoccimarro et al. 2011); Florida State University, or FSU (LaRow et al. 2008); NASA  
86 Goddard Earth Observing System Model version 5, or GEOS-5 (Rienecker et al. 2008);  
87 National Center for Environmental Prediction Global Forecasting System, or GFS (Saha  
88 et al. 2013); NASA Goddard Institute for Space Studies, or GISS (Schmidt 2013); Met  
89 Office Hadley Centre Model version 3, or HadGEM3 (Walters et al. 2011); Geophysical Fluid  
90 Dynamics Laboratory High Resolution Atmosphere Model, or HiRAM (Zhao et al. 2009);  
91 and Meteorological Research Institute, or MRI (Mizuta et al. 2012; Murakami et al. 2012).  
92 The model resolutions vary from 28 to 111 km. The models have different tracking schemes,  
93 most of them with very similar characteristics, based on the original tracking schemes in

94 Bengtsson et al. (1982) and Vitart et al. (2007). These tracking schemes look for vortices  
95 with a minimum of sea level pressure, a maximum of low-level vorticity and a warm core  
96 (Camargo and Zebiak 2002; Walsh 1997; Vitart et al. 2003; Zhao et al. 2009; Murakami  
97 et al. 2012). The main difference among the schemes is how they define the warm core and  
98 the thresholds used to define the model TC. An exception is the HadGEM3, which uses a  
99 tracking scheme originally developed for extra-tropical (cold core) cyclones (Hodges 1995)  
100 and modified to track warm core vortices (Bengtsson et al. 2007a; Strachan et al. 2013).

101 We compare the model TCs characteristics with the observed TC data. For the North  
102 Atlantic and eastern and central North Pacific the best-track datasets from the National  
103 Hurricane Center is used (Landsea and Franklin 2013; NHC 2013). In the case of the  
104 western North Pacific, North Indian Ocean and southern hemisphere, the TC data is from  
105 the best-track datasets from the Joint Typhoon Warning Center (Chu et al. 2002; JTWC  
106 2013).

## 107 **3. Results**

### 108 *a. Climatology*

#### 109 1) TC FREQUENCY

110 There are on average approximately 80 TCs observed every year across the globe (Emanuel  
111 2003). Figure 1 shows the distribution of the number of TCs per year for all models along  
112 with the observations. There are large differences in the number of TCs between the different  
113 models. Different models run at approximately the same resolution do not have similar mean  
114 numbers of TCs (e.g. the LR CAM5.1, FSU, GFS, and GISS models all have resolutions of  
115 roughly 100 km, but the mean number of TCs per year varies from about 10 to over 100.)

116 At the same time, the absolute number of TCs in each model is somewhat dependent on  
117 the tracking scheme applied; higher thresholds result in fewer TCs. Application of strictly

118 uniform tracking schemes, with no allowance for the different intensities in different models  
119 (whether due to resolution or other factors) would almost certainly produce even larger  
120 differences in the total numbers of TCs from model to model. By using each group’s own  
121 tracking scheme, we allow some compensation for the different TC intensities, in order to  
122 allow more productive comparison between other aspects of the results, such as the spatial  
123 and seasonal distributions of TC genesis and tracks, in the way that they would be shown  
124 in single-model studies by the individual groups.

125 The three resolutions of the HadGEM3 model show an increase in the number of TCs  
126 with increasing resolution, though it does not increase linearly. The tracking algorithm for all  
127 resolutions of the HadGEM3 model use the same threshold for the 850-hPa relative vorticity  
128 after being filtered to a standard spectral resolution of T42 as described in Strachan et al.  
129 (2013). Thus, the increase in the number of TCs with increasing resolution is not an artifact  
130 of the tracking scheme.

131 Figure 2 shows the mean number of TCs formed per year in each ocean basin. The total  
132 number of TCs formed in each basin per year is shown at the top of the figure and the  
133 percentage of all TCs that formed in each basin is shown at the bottom. Due to the large  
134 differences in the total numbers of global TCs reported by each model, it is more illustrative  
135 to compare the percentages of the TCs that form in each basin, rather than the total number  
136 of TCs, to the observations.

137 There are clear differences between the models in the distribution of TCs across, par-  
138 ticularly in the North Atlantic and Pacific. Several of the models (ECHAM5, GISS, and  
139 all resolutions of the HadGEM) have percentages much lower than that observed in the  
140 North Atlantic. Three of the models (ECHAM5, FSU, and GISS) have a significantly lower  
141 percentage than that observed in the Eastern North Pacific, while the CAM5.1 (at both reso-  
142 lutions) and the GEOS-5 model have a much higher percentage than observed in the Eastern  
143 North Pacific. In the Western North Pacific, the CAM5.1 models have smaller percentages  
144 than observed, and the ECHAM5 and GISS models have larger percentages than observed.



145 This is consistent with previous studies that have found that low-resolution models tend to  
146 have a large percentage of TCs in the Western North Pacific and very few TCs in the North  
147 Atlantic (Camargo et al. 2005; Camargo 2013).

148 One interesting observation is that there is a larger difference in TC distributions among  
149 the different models, than among different resolutions of the same model. The TC distri-  
150 butions of the different resolutions of the CAM5.1 and HadGEM3 models are very similar.  
151 This suggests that the global and regional distributions of TCs is mainly determined by  
152 the characteristics of the models (e.g. parameterizations, convection scheme), with model  
153 resolution not being as important. While the tracking schemes are also different, our ex-  
154 pectation is that the usage of different tracking schemes reduces the apparent differences  
155 between models, particularly in overall TC frequency. As will be seen below, the intensities  
156 of the simulated TCs are quite different in different models, and the different thresholds in  
157 the tracking schemes adjust for this to a large degree. If the same tracking scheme (including  
158 the specific thresholds) used to detect TCs in HiRAM were applied to the GISS model, for  
159 example, very few TCs would be detected.

160 In order to study the geographic patterns of TC occurrence, we will use track density,  
161 defined as the total number of TCs that pass through a  $5^\circ \times 5^\circ$  box per year. Figure 3 shows  
162 the track density distributions for all models and observations. The distribution of observed  
163 track density shows a region of very high density off the western coast of Central America  
164 and the eastern coast of Asia, along with regions of high density in the North Atlantic, South  
165 Indian, and off the eastern coasts of Australia and India.

166 Consistent with the basin averages, the models have different patterns of track density.  
167 The GISS model has a similar pattern to the observations, with some key differences. The  
168 most striking difference is the lack of a region of high track density off the eastern coast  
169 of Central America, which is notoriously difficult to simulate with lower resolution GCMs  
170 (Camargo et al. 2005). Other differences include a higher density around India, the region  
171 of high density off the eastern coast of Asia extending further to the east, and a lower

172 density in the North Atlantic. The HiRAM model has a remarkably similar pattern to the  
173 observations globally. The FSU model has higher density in the North Atlantic and South  
174 Indian along with lower density off the eastern coast of Central America. The ECHAM5  
175 model has very low density in the North Atlantic and South Indian, but similar density  
176 patterns to the observations in the Western Pacific and South Pacific. The ECHAM5 model  
177 also has a localized region of very high density directly on the eastern coast of India. The  
178 high resolution CAM5.1 model has a region of very high density off the western coast of  
179 Central America that extends too far westward and has much lower density off the eastern  
180 coast of Asia than the observations. The low resolution HadGEM3 model has small regions  
181 of high density in the correct locations. The higher resolution HadGEM3 models have higher  
182 density in these regions, which expand covering larger areas. The global mean density in the  
183 lower resolution CAM5.1, GEOS-5, and GFS models are much lower than observed.

184 In addition to track density, it is useful to study where the simulated TCs form, or  
185 genesis density. Figures 4 shows the genesis density of all the models and observations.  
186 Genesis density is defined as the total number of TCs that form in a  $5^\circ \times 5^\circ$  box per  
187 year. The overall differences in the patterns of the genesis density between the models and  
188 observations are similar to the differences in the track density described above. Consistent  
189 with the observations, all the models have narrower meridional bands of high genesis density  
190 as compared to track density. This occurs because the TCs tend to form in low-latitudes  
191 and travel poleward, causing the track density to have a greater meridional spread than the  
192 genesis density.

193 It can be easier to distinguish patterns in the distributions by examining certain spatial  
194 or temporal dimensions. The top panel of Fig.5 shows the genesis as a function of latitude of  
195 each model and the observations. Only the highest resolution simulations of the CAM5.1 and  
196 HadGEM3 models are shown. The observations have a large peak at  $10^\circ$  north, a smaller peak  
197 at  $10^\circ$  south, and no TC formation directly at the equator. All of the models have peaks at  
198 roughly the same latitudes as the observations, with the exception of the FSU model, whose

199 peaks are closer to the equator, and the ECHAM5 model, whose peaks are further poleward  
200 than the observations. In addition, the FSU model is the only model that has significant  
201 non-zero genesis at the equator. The ECHAM5 model’s southern hemisphere peak has  
202 a fatter tail and has non-zero genesis extending to higher latitudes than the observations  
203 and all other models. Although the GEOS-5 and NCEP models have fewer TCs than in  
204 observations, but the maxima in genesis location occur at roughly the same latitudes and  
205 with similar relative magnitude as the observations.

206 The middle panel of Fig.5 shows the genesis as a function of longitude for the models and  
207 observations. The observations have two sharp peaks at roughly  $90^\circ$  and  $250^\circ$  (corresponding  
208 to the maxima in the South Indian and western coast of Central America in Fig. 4), a broader  
209 peak at roughly  $150^\circ$  (corresponding to the maxima off the eastern coast of Asia in figure 4),  
210 and near-zero genesis near the dateline. Three of the models (GISS, FSU, and ECHAM5)  
211 have much lower Central American  $250^\circ$  peak than the observations, with the GISS model  
212 producing virtually no TCs. The FSU model has peaks at  $55^\circ$  (off the eastern coast of Africa)  
213 and  $310^\circ$  (North Atlantic) that are not present in any other model or the observations. The  
214 ECHAM5 model has a very strong peak at  $85^\circ$  (off the eastern coast of India). The HiRAM  
215 model exhibits a pattern remarkably similar to the observations.

216 Another metric of interest is the seasonal cycle of TC formation. The bottom panel  
217 of Fig. 5 shows global genesis as a function of month for models and observations. The  
218 observations show a fairly smooth seasonal cycle with a clear maximum between August  
219 and September and a minimum around April. In general, the models have a significantly  
220 weaker seasonal cycle than the observations, i.e. the difference between the number of TCs  
221 in the second half of the year and the first half of the year is less than the difference in the  
222 observations.

223 The TC seasonal cycle varies in the different basins, so we examine the seasonal cycle in  
224 each basin individually in Figure 6. The basins in the northern hemisphere typically have  
225 a broad peak in the second half of the year and few TCs in the first half of the year, with

226 exception of the North Indian Ocean. In the Western North Pacific, the GISS, HiRAM, FSU,  
227 HR HadGEM3, and ECHAM5 models are able to roughly reproduce the peak in the second  
228 half of the year, while the other models have no peak. In the Eastern North Pacific, the  
229 HiRAM3, HR HadGEM3, HR CAM5.1, and GFS models are able to reproduce the August  
230 peak while the other models have very low density throughout the year in this basin. In the  
231 North Atlantic, the HiRAM3, FSU, HR CAM5.1, and GFS models reproduce the second  
232 half of the year peak. Also of note is that the FSU model has a peak in the Western North  
233 Pacific that is roughly three months later than in observations, while it has a peak in the  
234 North Atlantic roughly one month earlier than observed. Most models are able to capture  
235 the bimodal distribution in the North Indian Ocean, with exception of the ECHAM5. All  
236 models are able to reproduce the observed peak in the early part of the year in the South  
237 Pacific and Australian basins. In contrast, in the South Indian basin, the CAM5.1 and FSU  
238 models have the wrong seasonality with a peak in the second half of the year.

## 239 2) TC INTENSITY

240 Along with the frequency of TCs, it is important to examine TC intensity. Although  
241 the global climate models here are considered “high-resolution”, it is not expected that they  
242 would be able to reproduce the most intense TCs (category 4 and 5 hurricanes), which  
243 would require even higher resolution to be able to simulate those intensities (see e.g. Bender  
244 et al. (2010)). A significant fraction of the models here do not come anywhere near those  
245 intensities.

246 The accumulated cyclone energy (ACE) of a TC is the sum of the squares of the TC’s  
247 maximum wind speed, sampled at 6-hourly intervals whenever the maximum wind speed is  
248 at least tropical storm strength (35 kt). Adding the ACE of individual TCs can produce a  
249 total ACE for a spatial or temporal region, e.g. a basin ACE or a seasonal ACE. Thus, a  
250 larger value of total ACE could correspond to stronger TCs, more TCs, and/or TCs that  
251 last longer. Figure 7 shows the total ACE (averaged per year) for each basin. The top panel

252 shows the total ACE of each basin and the bottom panel shows the percentage of the global  
253 ACE that occur in each basin. The observations have large values of ACE in the Western  
254 North Pacific and South Pacific, a low ACE in the North Indian, and roughly 10% of the  
255 global ACE in each of the other four basins. All models are able to reproduce the large ACE  
256 percentage in the Western North Pacific, with the ECHAM5 and FSU models having a very  
257 low ACE percentage in the Easter North Pacific. Only the ECHAM5 model has a relatively  
258 large ACE percentage in the South Pacific, while the GEOS-5 model has an anomalously  
259 high ACE percentage in the North Indian Ocean.

260 The top panel of figure 8 shows the distribution of the maximum wind speed achieved by  
261 each TC in all models and the observations. The vertical lines represent boundaries of the  
262 Saffir-Simpson hurricane intensity scale (Saffir 1977). The models seems to separate into four  
263 regimes of intensities. The HR CAM5.1 has an intensity distribution similar to observations,  
264 with a significant number of category 2 hurricanes and even the ability to produce the most  
265 intense TCs, i.e. categories 4 and 5 storms. The HiRAM, FSU, and HR HadGEM3 models  
266 have many tropical storms and category 1 TCs and some category 2 TCs. The ECHAM5,  
267 GEOS-5, and GFS models have mostly tropical storms. The GISS model's TCs are almost  
268 all of tropical depression intensity, with only a very small number of weak tropical storms.  
269 The difference between the intensity distributions among the models can not simply be a  
270 result of the models' resolution. For example, the GEOS-5 model has a horizontal resolution  
271 similar to the HiRAM model, but has significantly weaker TCs. On the other hand, the  
272 FSU models has some of the strongest TCs, but does not have one of the highest resolutions  
273 among the models.

274 In order to better understand the effect of model resolution on simulated TC intensities,  
275 it is instructive to examine the differences in the intensity distributions of the models in  
276 multiple horizontal resolutions. Histograms of the maximum wind speeds for the CAM5.1  
277 and HadGEM3 models in various resolutions are shown in the middle and bottom panels  
278 of Fig. 8. As expected, both the CAM5.1 and HadGEM3 models show an increase in the

279 mean TC intensity with higher resolution. The increase in intensity of the HR HadGEM3  
280 and HR CAM5.1 models can be also seen as an elongation of the tails of the distributions  
281 into higher TC categories.

### 282 3) TC LIFE-TIME

283 TC life-time distributions in models and observations are shown in Fig. 9, with the TC  
284 life-time histograms of the CAM5.1 and HadGEM3 models in different resolution given in  
285 the middle and bottom panels, respectively. There is a large variation in the TC life-time  
286 among the models. The ECHAM5, GISS, and HR HadGEM3 models have TCs lasting  
287 longer than 40 days, while the GEOS-5 and GFS models have very few TCs lasting more  
288 than 10 days. This is most likely due to the different tracking schemes used, as they consider  
289 different criteria for when to form and end a TC. Of particular note is that for the models  
290 with simulations in multiple resolutions, the TCs in the higher resolution simulations have  
291 a slightly longer average duration than in the low-resolution ones.

#### 292 *b. Interannual variability*

293 In the previous section, we analyzed the model simulations forced with climatologically  
294 SSTs, which characterizes the typical TC properties in the models, but does not simulate the  
295 TC interannual variability. Well known modes of climate variability in the atmosphere and  
296 ocean, most notably the El-Niño Southern Oscillation (ENSO), have been shown to affect  
297 the frequency and characteristics of TCs (Camargo et al. 2010). In order to evaluate the  
298 ability of the models to accurately simulate the interannual variability of TCs, the models  
299 were also run while forced with historical monthly varying SST, as opposed to climatological  
300 mean SSTs. The number of ensemble members and years of the simulations are shown in  
301 Table 2.

302 Figure 10 shows the total number of TCs globally per year for the models and observations

303 (top panel), as well as for the Western North Pacific, Eastern North Pacific, and North  
304 Atlantic, separately<sup>12</sup>. The global number of TCs in the models is similar to the observed  
305 numbers in all the models, but the global interannual variability is not well captured by the  
306 models. The three individual basins shown here present a greater similarity between the  
307 observations and model results, with the exception of the GISS model which has very few  
308 TCs in the North Atlantic and Eastern North Pacific and the FSU model which has very  
309 few TCs in the Eastern North Pacific.

310 In order to quantify the ability of the models to reproduce the interannual variability of  
311 observed TCs in different basins, we calculate the correlation coefficient between the models  
312 and observations ACE per year in each basin in Table 3. Since the GISS model's TCs have  
313 very weak intensities that seldom exceed the ACE threshold of 35 kt, we define another  
314 metric, the model-ACE (MACE), as the sum of the squares of the TC's maximum wind  
315 speed, sampled at 6-hourly intervals without any intensity threshold (as was done in ? for  
316 low-resolution models). The correlations of the models' yearly MACE in each basin with the  
317 yearly ACE of the observations also shown in Table 3. The correlations in the North Atlantic  
318 and Pacific basins are much higher than the other basins. In particular, the FSU and HiRAM  
319 models have a correlation coefficient of 0.7 in the North Atlantic and the GEOS-5 model has  
320 a correlation coefficient of 0.7 in the Western North Pacific basin.

321 Figure 11 shows the difference of genesis density for El Niño and La Niña years. El Niño  
322 and La Niña seasons are defined for the northern and southern Hemispheres in table 4<sup>3</sup>. The

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<sup>1</sup>The FSU model interannual simulation was only performed between June and November of each year and the tracking scheme was only done in the North Atlantic and North Pacific basins.

<sup>2</sup>The GEOS-5 model used different physical parametrizations (minimum entrainment threshold for parameterized deep convection in the modified Relaxed Arakawa-Schubert convection scheme, as well as a different time step) in the climatological and interannual simulations, which led a very different TC global frequency between those runs.

<sup>3</sup>Using the warm and cold ENSO (El Niño Southern Oscillations) definitions of the Climate Prediction Center, available at [http://www.cpc.ncep.noaa.gov/products/analysis\\_monitoring/ensostuff/ensoyears.shtml](http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml).

323 observations have a larger and stronger peak in genesis density off of the western coast of  
324 Central America in El Niño months than La Niña months. As the GISS and FSU models  
325 have very few TCs in this region, they are unable to reproduce this difference, while the  
326 HiRAM and GEOS-5 models are able to reproduce the difference.

327 A well known impact of ENSO on TC development is for average formation location to  
328 shift to the south and east in the Western North Pacific and to shift to the south and west  
329 in the Eastern North Pacific during El Niño years (Chia and Ropelewski 2002). Figure 12  
330 shows the mean position of TC formation in the Western and Eastern North Pacific, split  
331 between La Niña and El Niño years. In the Western North Pacific, the models are able  
332 to reproduce the southwest shift in El Niño years, with exception of the FSU model which  
333 has an eastern shift. In the Eastern North Pacific, all the models are able to simulate the  
334 southwest shift in El Niño years.

## 335 4. Conclusions

336 This work has described an intercomparison of several high-resolution atmospheric mod-  
337 els of the present climate, forced with both climatological and historical SSTs, in their ability  
338 to simulate the characteristics of TCs seen in observations. Model TCs were compared to  
339 observational TCs in terms of frequency as well as spatial, temporal, and intensity distri-  
340 butions. A range of tracking schemes were applied by each individual group to derive TC  
341 tracks and intensities for all models, consistent with the way in which results from these  
342 models have been shown previously in single-model studies.

343 Overall the models were able to reproduce the geographic distribution of TC track den-  
344 sity in the observations, with the HiRAM model, in particular, demonstrating the most  
345 similarity to observations. TC formation off the eastern coast of Central America was the  
346 most difficult region to correctly simulate, with the HiRAM, HR CAM5.1, and HadGEM3  
347 models demonstrating superior performance.



348 All models have a weaker seasonal cycle than observations, with relatively too few TCs  
349 in the second half of the year and relatively too many TCs in the first half of the year. The  
350 models reproduce the observational seasonal cycle to varying degrees in each basin, with the  
351 HiRAM model showing arguably the best match to observations overall.

352 There is a wide range in TC intensities between the different models. Some, but not all,  
353 of this difference can be seen as a consequence of resolution, with higher resolution models  
354 being able to simulate stronger TCs. This effect can be most readily seen in the CAM5.1  
355 and HadGEM3 models which were run at multiple resolutions.

356 In the simulations forced with historical SSTs, the models were able to reproduce the  
357 interannual variability of TC frequency in the North Pacific and Atlantic basins, with the  
358 HiRAM and GEOS-5 models showing particularly high correlation with observations in those  
359 basins. All models were also able to reproduce the general geographic shift in TC formation  
360 location during El Niño and La Niña years.

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TABLE 1. Table of model parameters. LR: Low Resolution, MR: Medium Resolution, HR: High Resolution. Roeckner/Scoccimarro: Roeckner (2003) and Scoccimarro et al. (2011). Hodges/Bengtsson: Hodges (1995) and Bengtsson et al. (2007b). Mizuta/Murakami: Mizuta et al. (2012) and Murakami et al. (2012)

Model	Resolution	Approx Res (km)	Reference	Tracking Scheme
LR CAM5.1	100 km	100	Wehner et al. (2013)	Prabhat et al. (2012)
HR CAM5.1	1/4°	28	Wehner et al. (2013)	Prabhat et al. (2012)
ECHAM5	T159	84	Roeckner/Scoccimarro	Walsh (1997)
FSU	T126	106	LaRow et al. (2008)	Vitart et al. (2003)
GEOS-5	1/2°	56	Rienecker et al. (2008)	Vitart et al. (2003)
GFS	T126	106	Saha et al. (2013)	Zhao et al. (2009)
GISS	1°	111	Schmidt (2013)	Camargo and Zebiak (2002)
LR HadGEM3	N96	130	Walters et al. (2011)	Hodges/Bengtsson
MR HadGEM3	N216	60	Walters et al. (2011)	Hodges/Bengtsson
HR HadGEM3	N320	40	Walters et al. (2011)	Hodges/Bengtsson
HiRAM	50 km	50	Zhao et al. (2009)	Zhao et al. (2009)
MRI	TL319	60	Mizuta/Murakami	Murakami et al. (2012)

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TABLE 2. Models that performed interannual simulations.

Model	Number of Ensembles	Years
FSU	3	1982-2009
GEOS-5	2	1982-2009
GISS	3	1981-2009
HiRAM	3	1981-2009
MRI	1	1981-2003



TABLE 3. Correlation of yearly ACE and model-ACE (MACE) in each basin and the yearly observed ACE, shown as ACE / MACE. Basins are defined as: SI (South Indian), AUS (Australian), SP (South Pacific), NI (North Indian), WNP (Western North Pacific), ENP (Easter North Pacific), NATL (North Atlantic).

Model	SI	AUS	SP	NI	WNP	ENP	NATL
FSU	-	-	-	-	0/0	0.5*/0.5*	0.7*/0.7*
GEOS-5	0/0	-0.1/-0.2	0.5*/0.4*	-0.2/-0.2	0.7*/0.7*	0.4*/0.5*	0.6*/0.6*
GISS	0/0	-0.3/0	-0.2/-0.2	-0.2/0.2	0.3/0.2	0/0.7*	0/0.4
HiRAM	0.2/0.2	0.4*/0.4*	0.1/0.1	-0.1/-0.1	0.5*/0.5*	0.6*/0.6*	0.7*/0.7*
MRI	0.2/0.2	-0.4*/-0.4*	0.1/0.1	-0.1/-0.1	0.3/0.3	0.4*/0.4*	0.6*/0.6*

TABLE 4. El Niño and La Niña seasons for the northern and southern hemispheres, using the warm and cold ENSO (El Niño Southern Oscillations) definitions of Climate Prediction Center. The northern (southern) hemisphere seasons definitions as based on the state of ENSO in the August - October (January - March) seasons. Note that the southern hemisphere TC seasons are defined from July to June, encompassing 2 calendar years.

Northern Hemisphere	
El Niño	1982, 1986, 1987, 1991, 1994, 1997, 2002, 2004, 2006, 2009
La Niña	1983, 1985, 1988, 1995, 1998, 1999, 2000, 2007
Southern Hemisphere	
El Niño	1982/83, 1986/87, 1987/88, 1991/92, 1994/95, 1997/98, 2002/03
La Niña	1980/81, 1984/85, 1988/89, 1995/96, 1998/99, 1999/00, 2000/01, 2005/06, 2007/08, 2008/09

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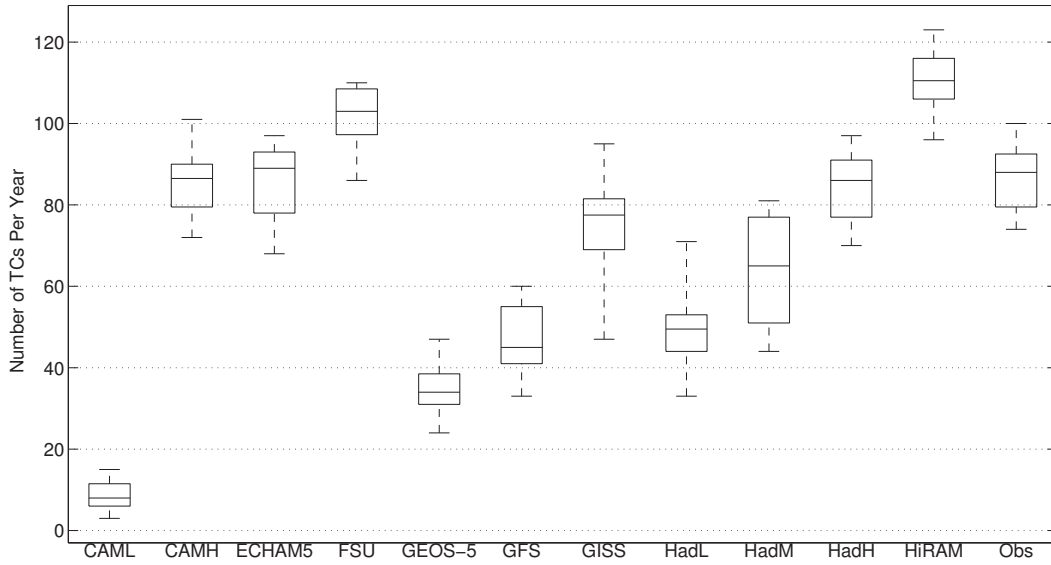


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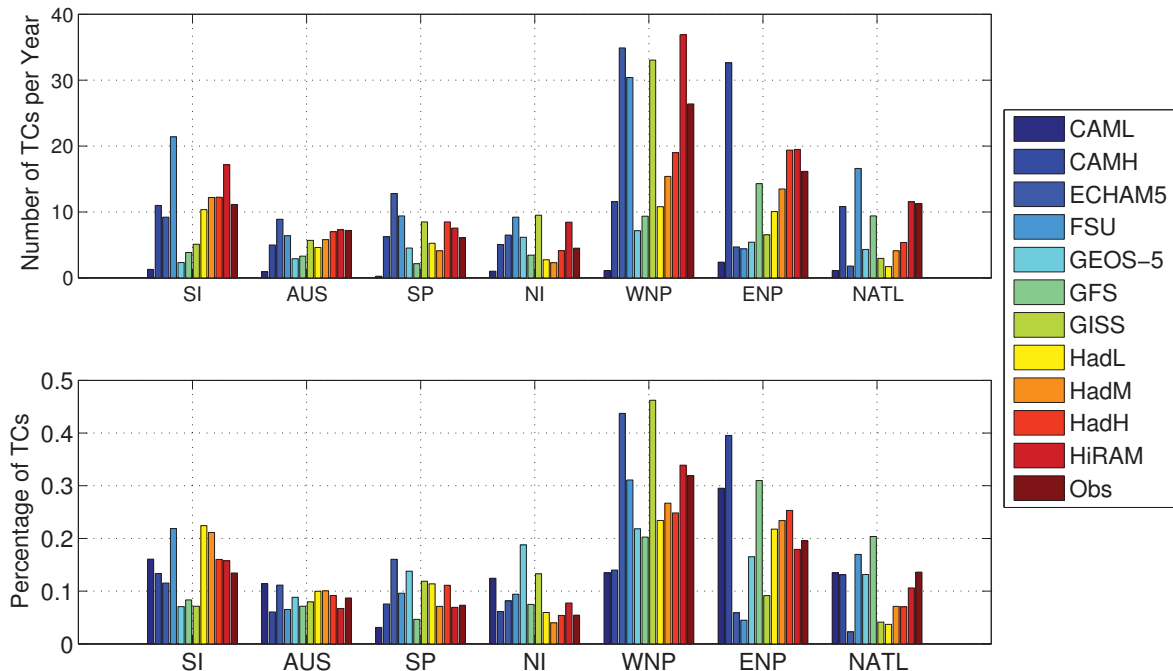


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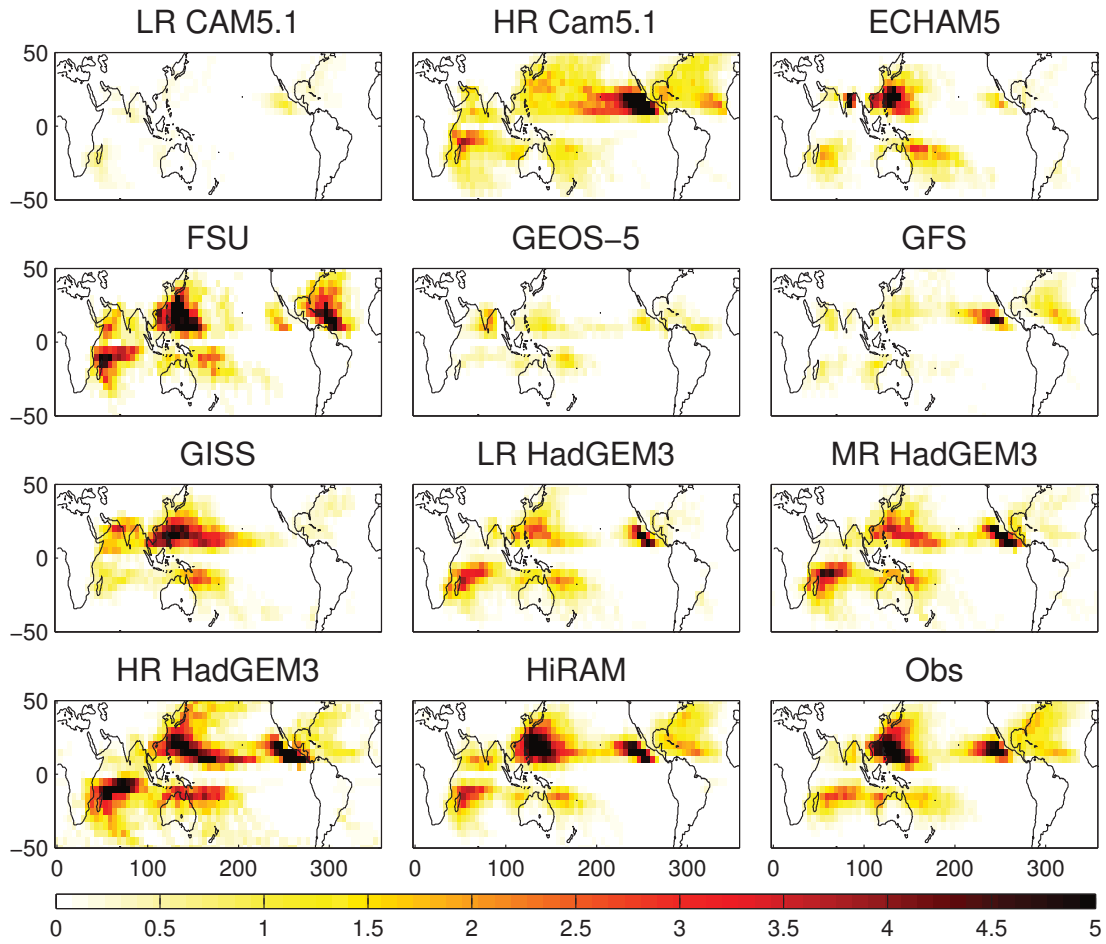


FIG. 3. TC track density in models and observations. Track density is defined as the mean number of TC transits per  $5^\circ \times 5^\circ$  box per year.

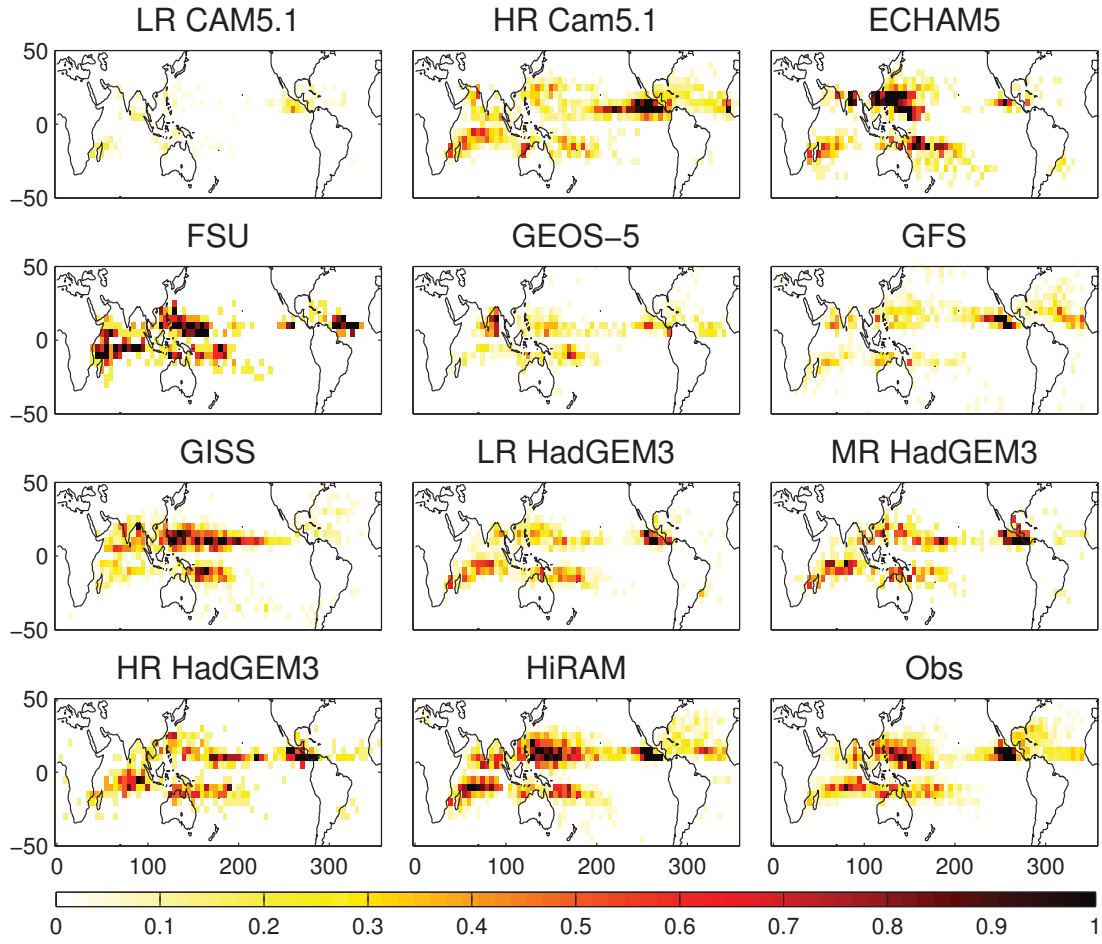


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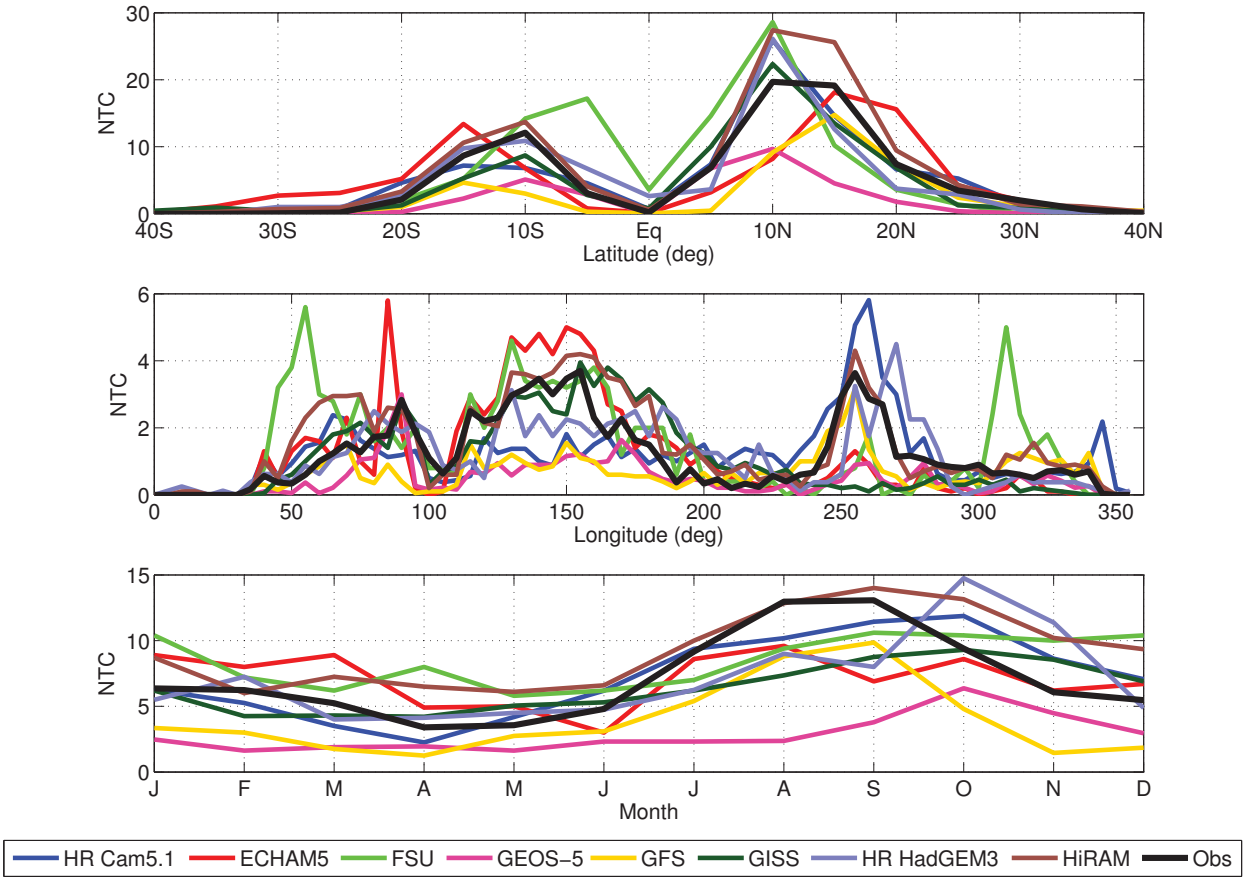


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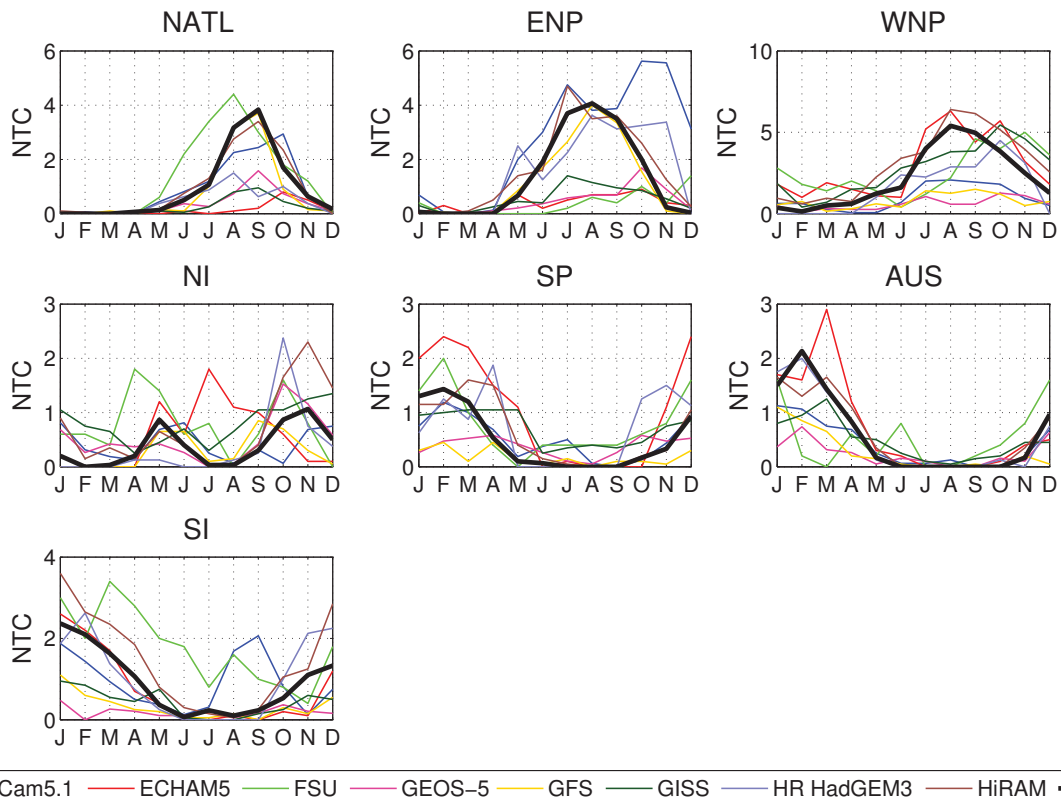


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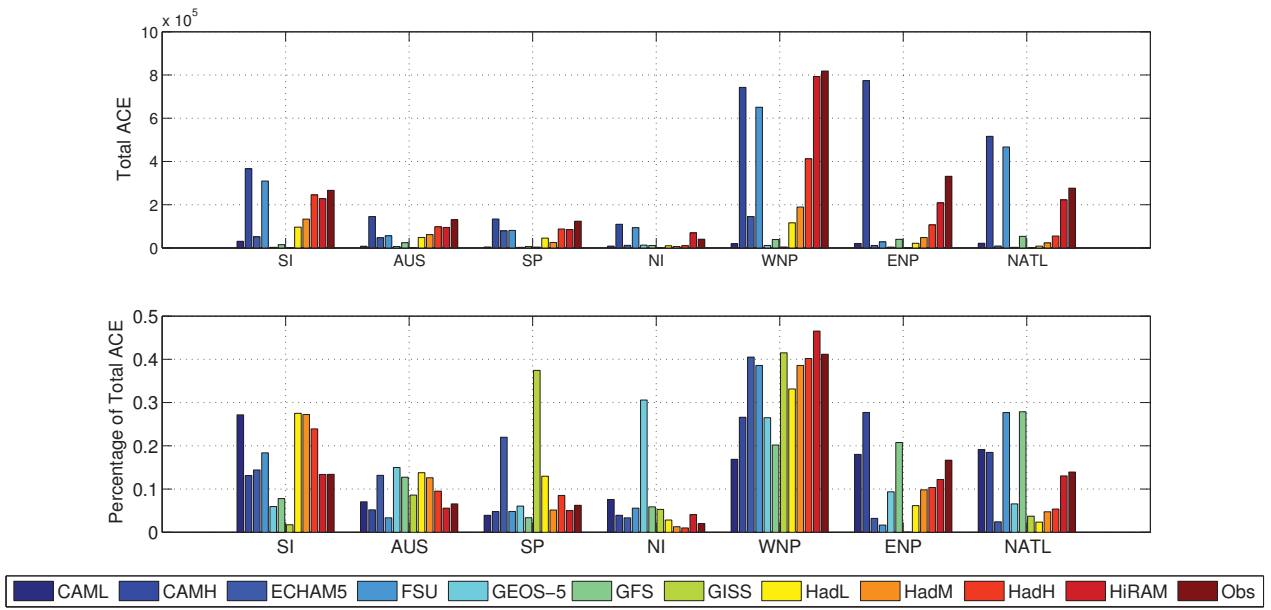


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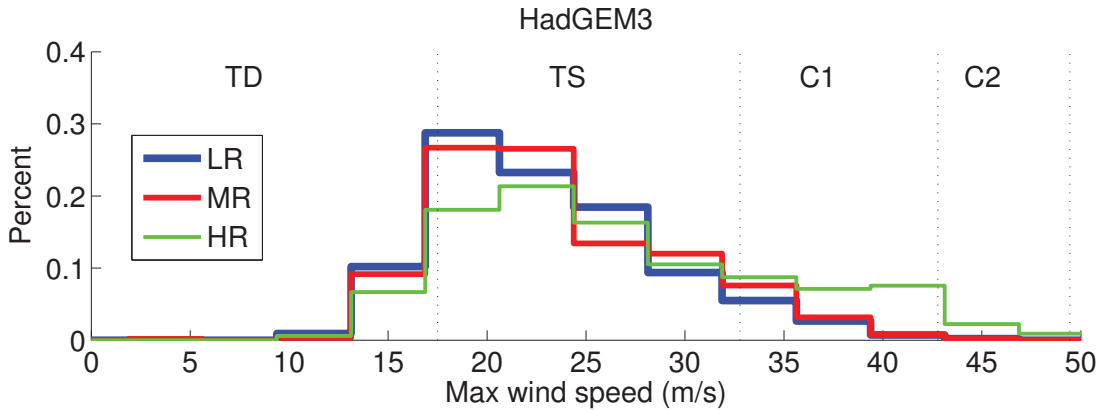
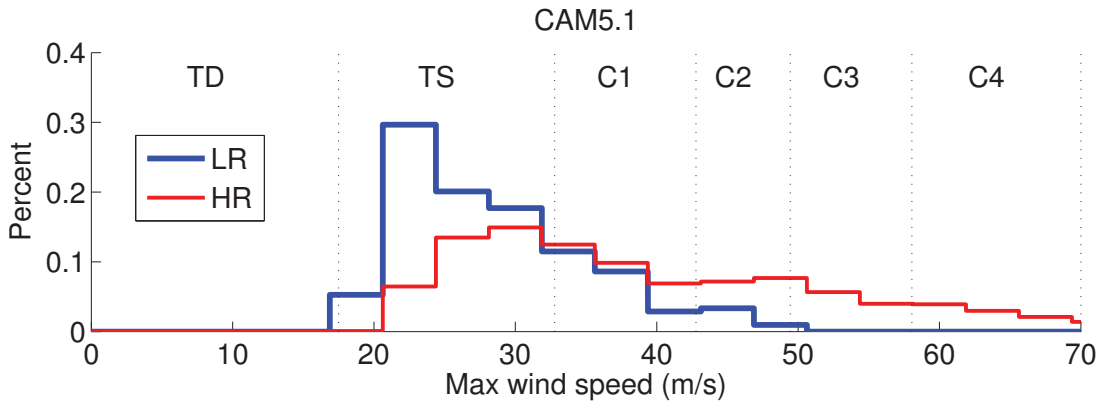
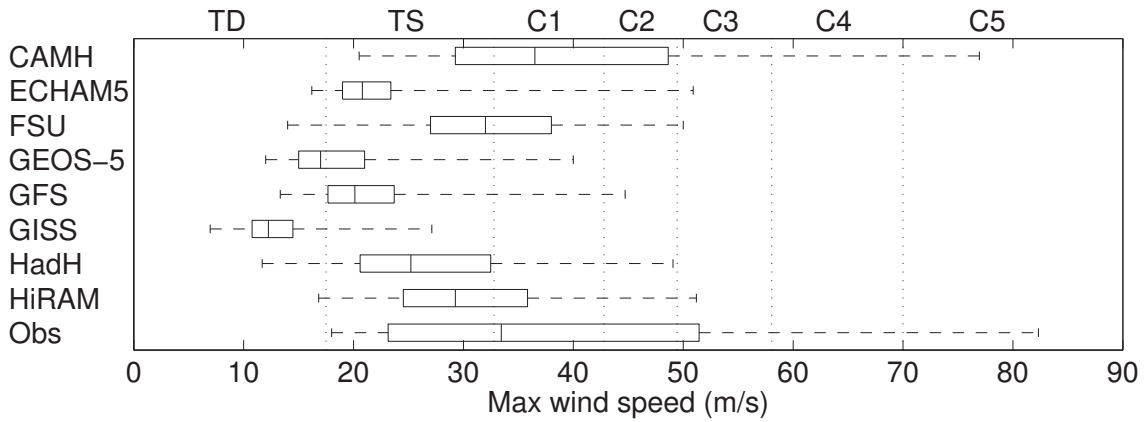


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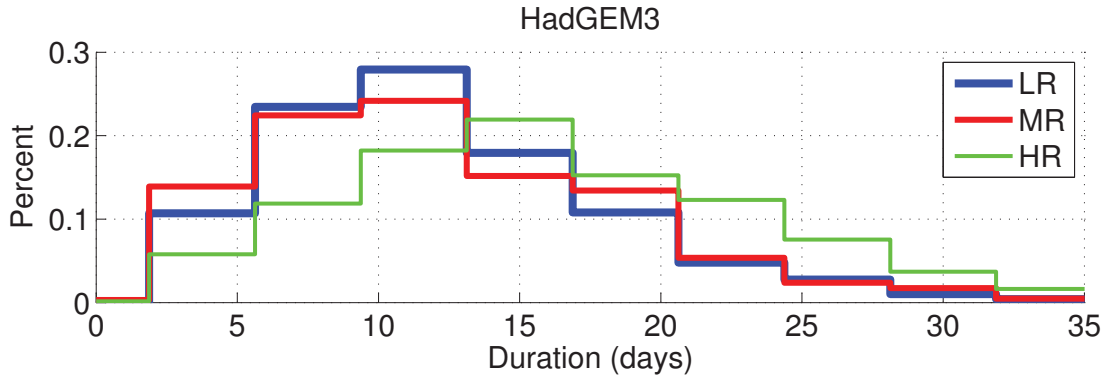
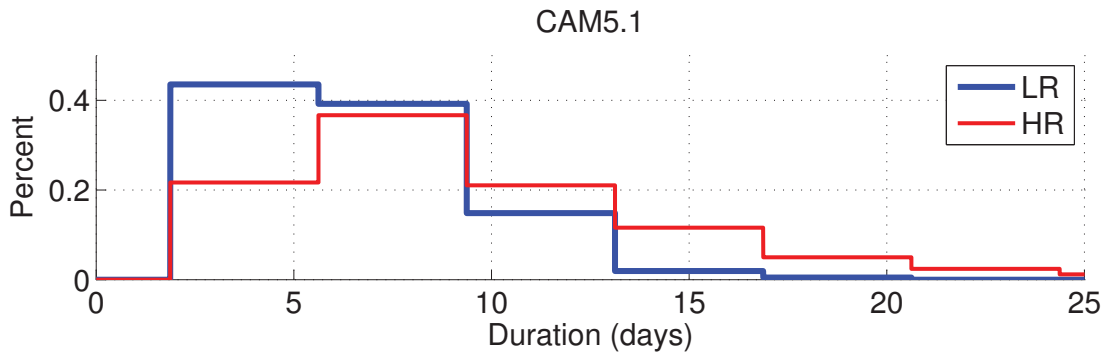
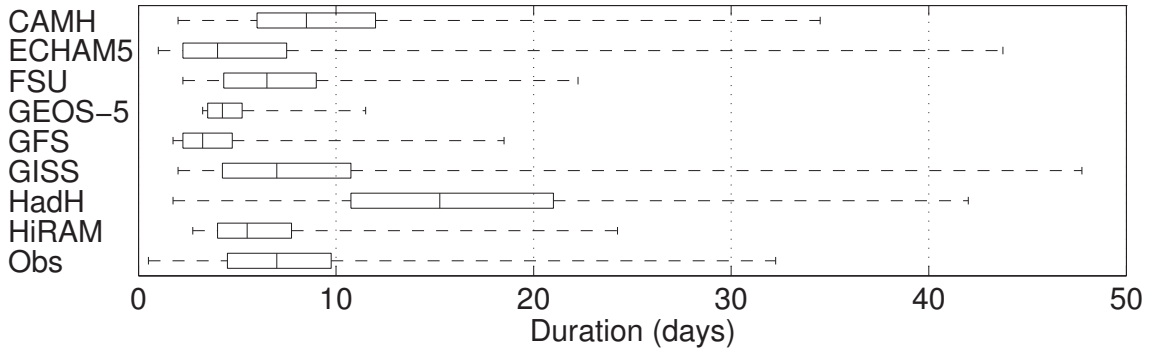


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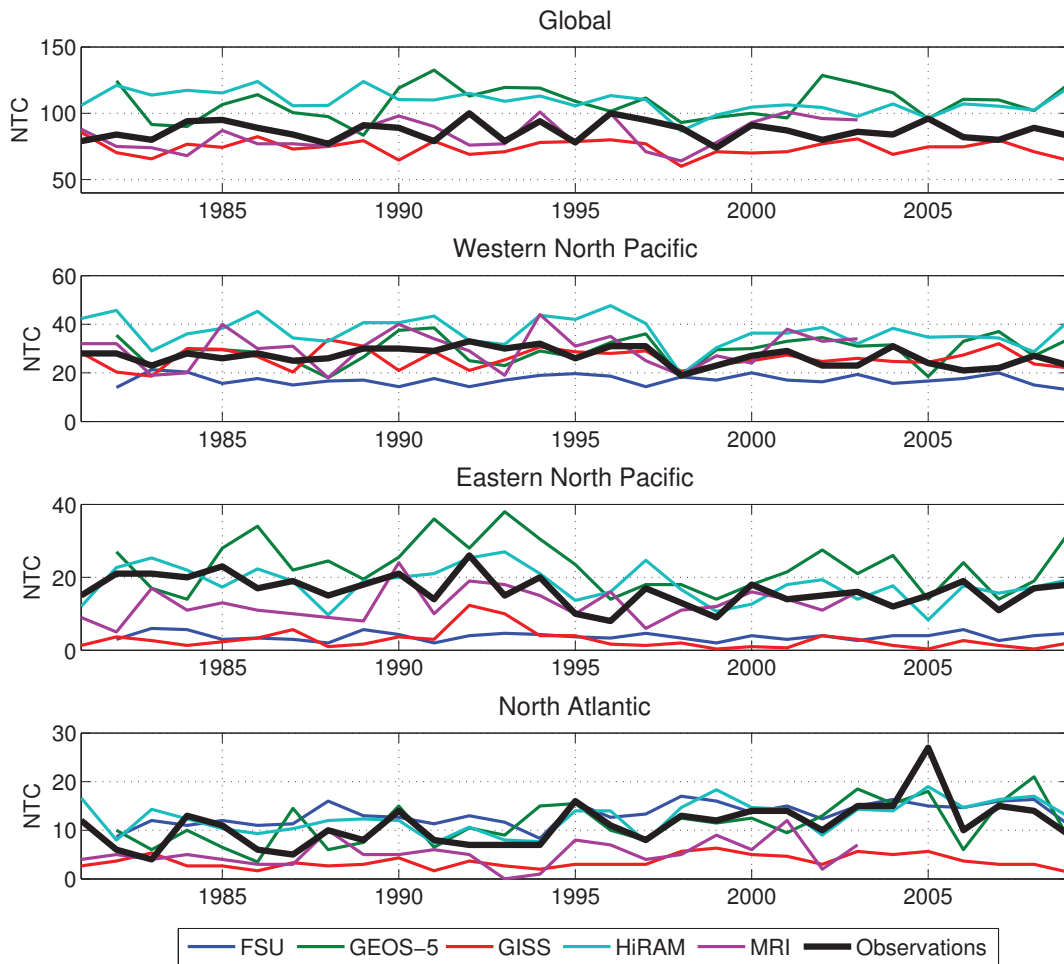


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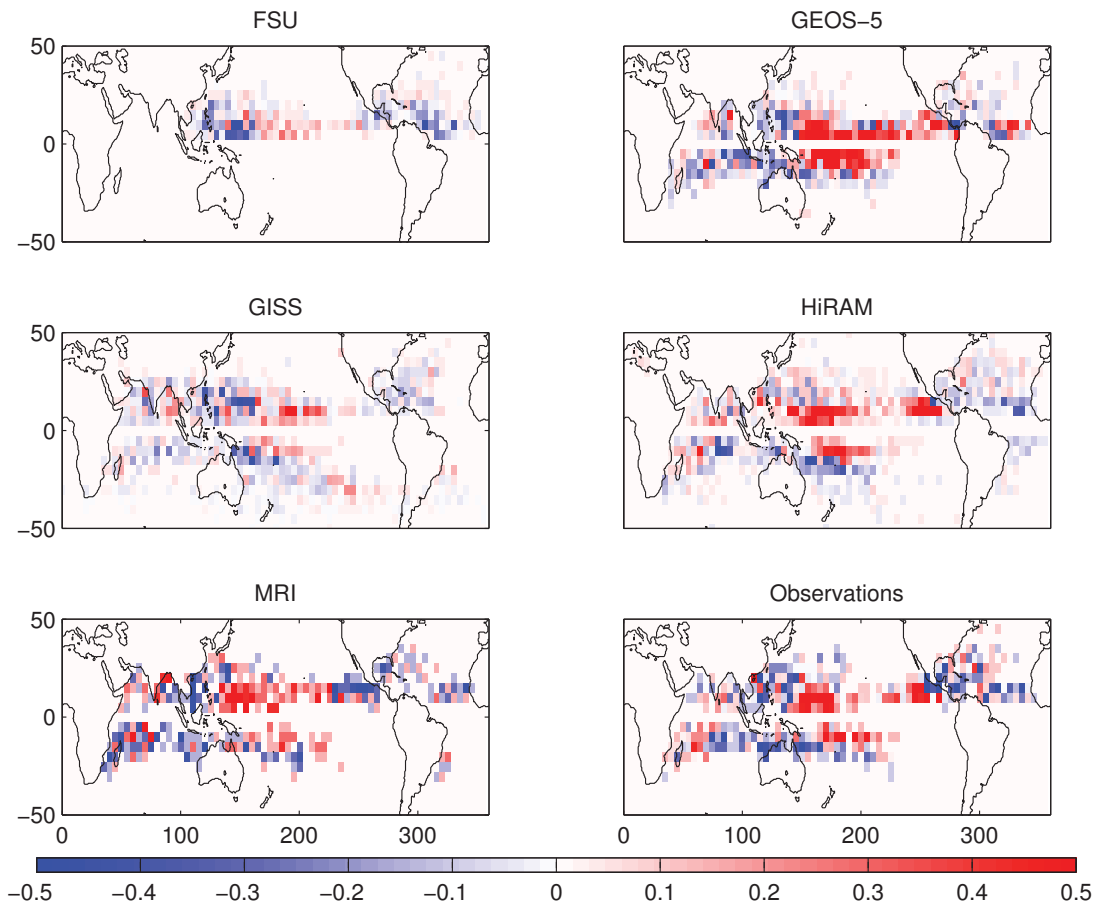


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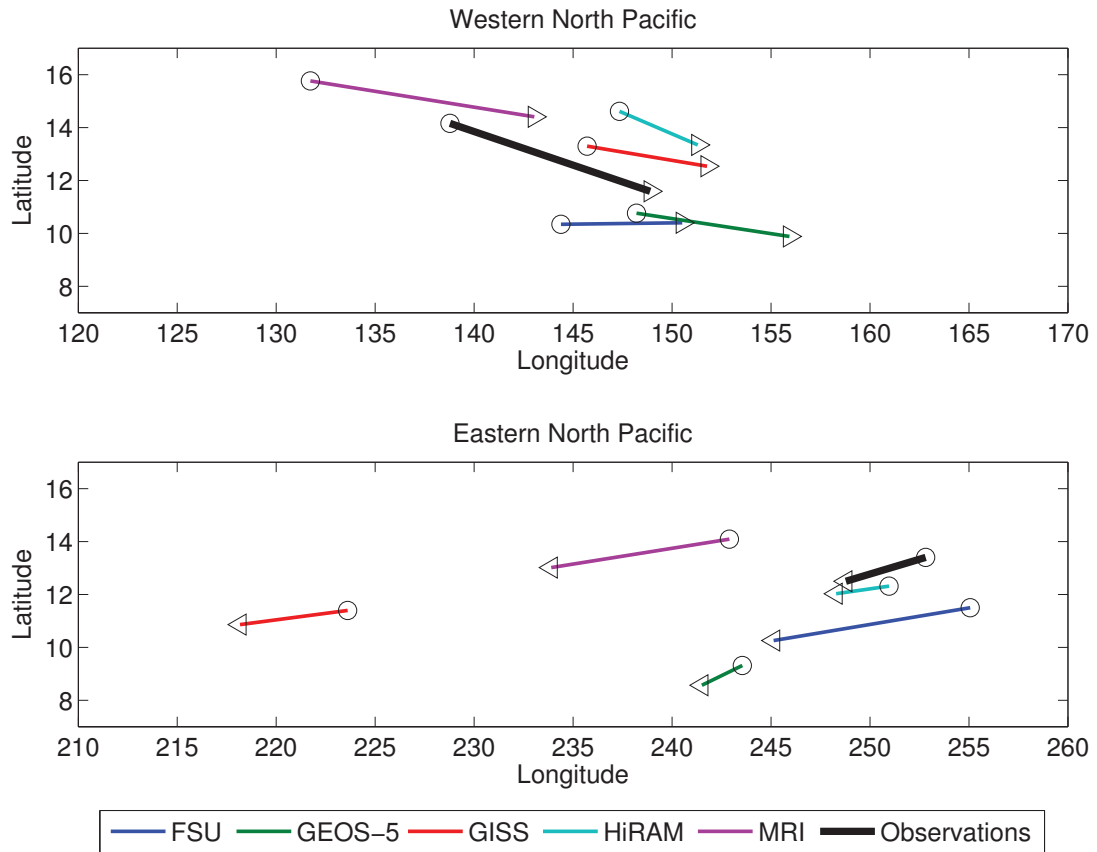


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