

Hurricanes and climate: the U.S. CLIVAR working group on hurricanes

Kevin J.E. Walsh, Suzana J. Camargo, Gabriel A. Vecchi, Anne Sophie Daloz, James Elsner, Kerry Emanuel, Michael Horn, Young-Kwon Lim, Malcolm Roberts, Christina Patricola, Enrico Scoccimarro, Adam H. Sobel, Sarah Strazzo, Gabriele Villarini, Michael Wehner, Ming Zhao, James P. Kossin, Tim LaRow, Kazuyoshi Oouchi, Siegfried Schubert, Hui Wang, Julio Bacmeister, Ping Chang, Fabrice Chauvin, Christiane Jablonowski, Arun Kumar, Hiroyuki Murakami, Tomoaki Ose, Kevin A. Reed, R. Saravanan, Y. Yamada, Colin M. Zarzycki, Pier Luigi Vidale, Jeffrey A. Jonas and Naomi Henderson

High-resolution climate models can now simulate many aspects of tropical cyclone climate, but a theory of tropical cyclone formation remains elusive.

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1 Affiliations: Walsh, Horn – University of Melbourne, Parkville, Victoria, Australia;
2 Camargo, Sobel, Henderson – Lamont-Doherty Earth Observatory, Columbia University,
3 Palisades, New York; Sobel, Jonas – Columbia University, New York, New York; Vecchi,
4 Zhao, Murakami – Geophysical Fluid Dynamics Laboratory, Princeton, New Jersey; Daloz –
5 University of Wisconsin-Madison, Space Science and Engineering Center, Madison,
6 Wisconsin; Elsner, Strazzo, LaRow – Florida State University, Tallahassee, Florida; Emanuel
7 – Massachusetts Institute of Technology, Cambridge, Massachusetts; Lim -- NASA Goddard
8 Space Flight Center, GMAO, and Goddard Earth Sciences Technology and Research / I. M.
9 Systems Group, Greenbelt, Maryland; Schubert – NASA Goddard Space Flight Center,
10 GMAO, Greenbelt, Maryland; Roberts – UK Met Office, Exeter, United Kingdom;
11 Scoccimarro – Istituto Nazionale di Geofisica e Vulcanologia (INGV) and Centro Euro-
12 Mediterraneo sui Cambiamenti Climatici (CMCC), Bologna, Italy; Villarini – University of
13 Iowa, Iowa City, Iowa; Wehner – Lawrence Berkeley National Laboratory, Berkeley,
14 California; Kossin – NOAA/NCDC, Asheville, North Carolina; Oouchi, Yamada –
15 JAMSTEC, Yokohama, Kanagawa, Japan; Wang, Kumar – NOAA NCEP, College Park,
16 Maryland; Bacmeister, Reed – National Center for Atmospheric Research, Boulder,
17 Colorado; Patricola, Chang, Saravanan – Texas A&M University, College Station, Texas;
18 Chauvin – Meteo-France, Toulouse, France; Jablonowski, Zarzycki – University of
19 Michigan, Ann Arbor, Michigan; Ose – MRI/JMA, Tsukuba-city, Ibaraki, Japan; Vidale –
20 University of Reading, Reading, United Kingdom; Jonas – NASA/Goddard Institute for
21 Space Studies, New York, New York.

Corresponding author: Kevin Walsh, School of Earth Sciences, University of Melbourne,
3010, Victoria, Australia. +61-3-8344-6523. kevin.walsh@unimelb.edu.au.

22

23 *Abstract*

24

25 While a quantitative climate theory of tropical cyclone formation remains elusive,
26 considerable progress has been made recently in our ability to simulate tropical cyclone
27 climatologies and understand the relationship between climate and tropical cyclone
28 formation. Climate models are now able to simulate a realistic rate of global tropical cyclone
29 formation, although simulation of the Atlantic tropical cyclone climatology remains
30 challenging unless horizontal resolutions finer than 50 km are employed. This article
31 summarizes published research from the idealized experiments of the Hurricane Working
32 Group of U.S. CLIVAR (CLimate VARIability and predictability of the ocean-atmosphere
33 system). This work, combined with results from other model simulations, has strengthened
34 relationships between tropical cyclone formation rates and climate variables such as mid-
35 tropospheric vertical velocity, with decreased climatological vertical velocities leading to
36 decreased tropical cyclone formation. Systematic differences are shown between experiments
37 in which only sea surface temperature is increased versus experiments where only
38 atmospheric carbon dioxide is increased, with the carbon dioxide experiments more likely to
39 demonstrate the decrease in tropical cyclone numbers previously shown to be a common
40 response of climate models in a warmer climate. Experiments where the two effects are
41 combined also show decreases in numbers, but these tend to be less for models that
42 demonstrate a strong tropical cyclone response to increased sea surface temperatures. Further
43 experiments are proposed that may improve our understanding of the relationship between
44 climate and tropical cyclone formation, including experiments with two-way interaction
45 between the ocean and the atmosphere and variations in atmospheric aerosols.

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47

48 ***Introduction***

49 The effect of climate change on tropical cyclones has been a controversial scientific issue for
50 a number of years. Advances in our theoretical understanding of the relationship between
51 climate and tropical cyclones have been made, enabling us to understand better the links
52 between the mean climate and the potential intensity (PI; the theoretical maximum intensity
53 of a tropical cyclone for a given climate condition) of tropical cyclones. Improvements in the
54 capabilities of climate models, the main tool used to predict future climate, have enabled
55 them to achieve a considerably improved and more credible simulation of the present-day
56 climatology of tropical cyclones. Finally, the increasing ability of such models to predict the
57 interannual variability of tropical cyclone formation in various regions of the globe indicates
58 that they are capturing some of the essential physical relationships governing the links
59 between climate and tropical cyclones.

60 Previous climate model simulations, however, have suggested some ambiguity in projections
61 of future numbers of tropical cyclones in a warmer world. While many models have projected
62 fewer tropical cyclones globally (Sugi et al. 2002; Bengtsson et al. 2007a; Gualdi et al. 2008;
63 Knutson et al. 2010), other climate models and related downscaling methods have suggested
64 some increase in future numbers (e.g. Broccoli and Manabe 1990; Haarsma et al. 1993;
65 Emanuel 2013a). When future projections for individual basins are made, the issue becomes
66 more serious: for example, for the Atlantic basin there appears to be little consensus on the
67 future number of tropical cyclones (Knutson et al. 2010) or on the relative importance of
68 forcing factors such as aerosols or increases in carbon dioxide (CO₂) concentration. One
69 reason could be statistical: annual numbers of tropical cyclones in the Atlantic are relatively
70 small, making the identification of such storms sensitive to the detection method used.

71 Further, there is substantial spread in projected responses of regional tropical cyclone (TC)
72 frequency and intensity over the 21st century from downscaling studies (Knutson et al. 2007;
73 Emanuel 2013a). Interpreting the sources of those differences is complicated by different
74 projections of large-scale climate, and by differences in the present-day reference period and
75 sea surface temperature (SST) datasets used. A natural question is whether the diversity in
76 responses to projected 21st century climate of each of the studies is primarily a reflection of
77 uncertainty arising from different large-scale forcing (as has been suggested by, e.g., Villarini
78 et al. 2011; Villarini and Vecchi 2013b; Knutson et al. 2013) or whether this spread reflects
79 principally different inherent sensitivities across the various downscaling techniques, even
80 including different sensitivity of responses within the same model due to, for instance, the use
81 of different convective parameterizations (Kim et al. 2012). A similar set of questions relate
82 to the ability of models to generate observed changes in TC statistics when forced with a
83 common forcing dataset.

84 The preceding questions motivated the design of a number of common idealized experiments
85 to be simulated by different atmospheric general circulation models. Following on from
86 experiments described in Yoshimura and Sugi (2005), Held and Zhao (2011) have designed a
87 series of experiments using a high-resolution global atmospheric model (HiRAM): using
88 present-day climatological, seasonally-varying monthly SSTs (that is, the same
89 climatological monthly-average seasonal cycle of SSTs repeating every year; the “climo”
90 experiment); specifying interannually-varying monthly SSTs (monthly SSTs that vary from
91 year to year, as observed; “amip”); application of a uniform warming of 2K added to the
92 climatological SST values (“2K”); employing SSTs at their climatological values but where
93 the CO₂ concentration was doubled in the atmosphere (“2CO₂”); and an experiment with a
94 combined uniform 2K SST increase and doubled carbon dioxide (“2K2CO₂”). The purpose
95 of these common experiments is to determine whether responses would be robust across a

96 number of different, high-resolution climate models (see Table 1). This would then establish
97 better relationships between climate forcings and tropical cyclone occurrence, a key goal in
98 work towards the development of a climate theory of tropical cyclone formation. To facilitate
99 this goal, U.S. CLIVAR established the Hurricane Working Group (HWG). Another goal of
100 this group is to provide a synthesis of current scientific understanding of this topic. The
101 following sections summarize our understanding of climate controls on tropical cyclone
102 formation and intensity and the results of the HWG experiments analyzed to date, as well as
103 other issues such as tropical cyclone rainfall. The focus of this work is on tropical cyclone
104 formation, due to the very fine horizontal resolutions needed to generate good simulations of
105 tropical cyclone climatological intensity distributions. A concluding section outlines avenues
106 for further research.

107 **Tropical cyclone formation**

108 At present, there is no climate theory that can predict the formation rate of tropical cyclones
109 from the mean climate state. It has been known for many years that there are certain
110 atmospheric conditions that either promote or inhibit the formation of tropical cyclones, but
111 so far an ability to relate these quantitatively to mean rates of tropical cyclone formation has
112 not been achieved, other than by statistical means through the use of semi-empirically-based
113 genesis potential indices (GPIs; see, for instance, Menkes et al. 2012). Increasingly,
114 numerical models of the atmosphere are being used to pose the kind of questions that need to
115 be answered to address this issue.

116 *The ability of climate models to simulate the present-day tropical cyclone climatology*

117 A starting point for the simulation of changes in TC climatology is the ability of climate
118 models (often known as general circulation models; GCMs) to simulate the current
119 climatology of TCs in the “climo” HWG experiment or other similar current-climate

120 simulations. In the HWG climo experiment, Figure 1 shows the simulated global TC numbers
121 range from small values to numbers similar to observed (Zhao et al. 2013a; Shaevitz et al.
122 2014). Better results can also be obtained from higher-resolution versions of the HWG
123 models (finer than 50 km horizontal resolution), including an ability to generate storms of
124 intense tropical cyclone strength, as shown by Wehner et al. (2014a) for a higher-resolution
125 version of the NCAR-CAM5 model than that shown in Fig. 1. In addition, the tropical
126 cyclone formation rate in the GSFC-GEOS5 model as shown in Fig. 1 has been improved
127 following the development of the new version of the model (see Figure 4 in Shaevitz et al.
128 2014).

129

130 The annual cycle of formation is reasonably well simulated in many regions, although there is
131 a tendency for the amplitude of the simulated annual cycle to be less than observed. A
132 common factor in many such model assessments is the poorer performance at simulating
133 Atlantic tropical cyclone formation than for other basins, although recent finer-resolution
134 models give an improved simulation. Figure 2 illustrates this point, showing Atlantic results
135 from Mei et al. (2014), from a 25-km resolution version of the HiRAM model, demonstrating
136 the performance of this higher-resolution version of the model. Strachan et al. (2013) also
137 found that the observed inter-hemispheric asymmetry in tropical cyclone formation, with
138 Northern Hemisphere formation rates being roughly twice those in the Southern Hemisphere,
139 was not well captured by a high-resolution GCM.

140 *Why do GCMs generally produce a decrease in future global tropical cyclone numbers?*

141 Most GCM future projections indicate a decrease in global tropical cyclone numbers,
142 particularly in the Southern Hemisphere: Knutson et al. (2010) give decreases in the Northern
143 Hemisphere ranging from roughly zero to 30%, and in the Southern Hemisphere from 10 to
144 40%. Previous explanations of this result have focused on changes in tropical stability and the

145 associated reduction in climatological upward vertical velocity (Sugi et al. 2002, 2012;
146 Oouchi et al. 2006; Held and Zhao 2011) and on increased mid-level saturation deficits
147 (drying) (e.g. Rappin et al. 2010). In this argument, the tropical cyclone frequency reduction
148 is associated with a decrease in the convective mass flux and an overall related decrease in
149 tropical cyclone numbers. Zhao et al. (2013a) compare the HWG model responses for the
150 various simulations, using the Geophysical Fluid Dynamics Laboratory (GFDL) tropical
151 cyclone tracking scheme (Knutson et al. 2008; Zhao et al. 2009). They find that most of the
152 models show decreases in global tropical cyclone frequency for the 2CO₂ run of 0-20%. The
153 changes in TC numbers are most closely related to 500 hPa vertical velocity, with Figure 3
154 showing close agreement between changes in tropical cyclone formation and changes in this
155 variable. Here, Figure 3b shows the annual mean vertical velocity as an average of monthly
156 mean vertical velocity weighted by monthly climatological TC genesis frequency over each
157 4°×5° (latitude by longitude) grid box from the control simulation. This relationship between
158 TC frequency and vertical velocity was the closest association found among a suite of
159 analyzed variables that included precipitation, 600 hPa relative humidity and vertical wind
160 shear. In addition, Camargo et al. (2014) use a number of GPIs applied to the output of the
161 GFDL HiRAM model to show that in order to explain the reduction in TC frequency, it is
162 necessary to include saturation deficit and potential intensity in the genesis index. While the
163 response of the models in the other HWG experiments is more ambiguous, no model
164 generated a substantial increase in global TC frequency for any experiment.

165

166 The simulated decrease in global tropical cyclone frequency does not appear to be sensitive to
167 the use of a particular parameterization scheme for convection. Murakami et al. (2012) use a
168 60-km horizontal resolution version of the MRI atmospheric GCM to demonstrate that
169 patterns of future SST change appear more important in causing future changes in tropical

170 cyclone numbers rather than the choice of the convective parameterization used in their suite
171 of experiments. As the resolution of climate models becomes finer, the need for convective
172 parameterization will become less as microphysical representations of convective processes
173 become more appropriate. Oouchi (2013) has reported simulations of tropical cyclones using
174 a global non-hydrostatic model (NICAM) run without convective parameterization. It is
175 anticipated that this type of simulation will become increasingly important in the future (e.g.
176 Yamada and Satoh 2014).

177 The HWG experiments are atmosphere-only climate model experiments and do not include
178 an interactive ocean. In general, however, ocean-atmosphere coupled climate models tend to
179 give similar results to uncoupled atmospheric climate models' results in their response to an
180 imposed greenhouse-induced climate change. Kim et al. (2014), using the GFDL CM2.5
181 coupled model at a horizontal atmospheric resolution of about 50 km, also note a strong link
182 in their model simulations between decreases in tropical cyclone occurrence and decreases in
183 upward mid-tropospheric vertical velocity in tropical cyclone formation regions. Like the
184 atmosphere-only models, they also simulate too few storms in the Atlantic. The response to
185 increased CO₂ in their model is a substantial decrease in tropical cyclone numbers in almost
186 all basins. Other future changes include a slight increase in storm size, along with an increase
187 in tropical cyclone rainfall. In the coordinated CMIP5 (Taylor et al. 2012) coupled ocean-
188 atmosphere model experiments, while there is a significant increase in TC intensity (Maloney
189 et al. 2013), TC frequency changes are not as robust and are dependent on tracking scheme
190 (Camargo 2013, Tory et al. 2013a, Murakami et al. 2014).

191 Not all methods for determining TC numbers identify a decrease in future numbers, however.
192 Emanuel (2013a,b) uses a downscaling method in which incipient tropical vortices are
193 “seeded” into large-scale climate conditions provided from a number of different climate
194 models, for current and future climate conditions. The number of “seeds” provided to each set

195 of climate model output is tuned so that the model in question reproduces the observed
196 number of tropical cyclones (about ninety) in the current climate. This same number of seeds
197 is then provided for the future climate conditions generated by the climate models. In contrast
198 to many models, this system generates more tropical cyclones in a warmer world when forced
199 with the output of climate models running the CMIP5 suite, even when the host CMIP5
200 model itself produces reduced TC frequency (Camargo 2013; Tory et al. 2013a; Murakami et
201 al. 2014). Analogous results are produced by the same methodology using climate fields from
202 selected HWG model outputs (Figure 4).

203 In the HWG experiments, simulated tropical cyclone numbers are most likely to have a small
204 decrease in the 2K2CO₂ experiment, with a clear majority of models indicating this (Fig. 3).
205 Numbers are also considerably more likely to decrease in the 2CO₂ experiment, but in the 2K
206 experiment, there is no genuine preferred direction of future numbers. Overall, the tendency
207 of decreases in tropical cyclone numbers to be closely associated with changes in mid-
208 tropospheric vertical velocity suggests a strong connection between the two, and one that
209 many other future climate model projections of tropical cyclone numbers also demonstrate.
210 Note that increased saturation deficit, another variable shown to be related to decreases in
211 tropical cyclone numbers, might be expected to accompany a decrease in vertical velocity
212 over the oceans.

213 *Do the new generation of higher-resolution climate models simulate tropical cyclones in the*
214 *North Atlantic better? Do they simulate a similar tropical cyclone response to climate*
215 *change, thus giving more confidence in our prediction?*

216 While most models predict fewer tropical cyclones globally in a warmer world, the difference
217 in the model response becomes more significant when smaller regions of the globe are
218 considered. This appears to be a particular issue in the Atlantic basin, where climate model

219 performance has been often poorer than in other formation basins (e.g., Camargo et al. 2005,
220 Walsh et al. 2013, Camargo 2013, Tory et al. 2013). Since good model performance in
221 simulating the current climate has usually been considered an essential pre-condition for the
222 skilful simulation of future climate, this poor Atlantic performance poses an issue for the
223 confidence of future tropical cyclone climate in the Atlantic region.

224 The most recent climate models have begun to simulate this region better, however, most
225 likely due to improved horizontal resolution (Manganello et al.2012; Strachan et al. 2013;
226 Roberts et al.,2014; Zarzycki and Jablonowski 2014). Best results appear to be achieved at
227 horizontal resolutions finer than 50 km. Roberts et al. (2014) suggest that this may be related
228 to the ability of the higher resolution models to generate easterly waves with higher values of
229 vorticity than at lower resolution (see also Daloz et al. 2012a). Zhao et al. (2013) note that
230 more than one of the HWG models produced a reasonable number of tropical cyclones in the
231 Atlantic. Even so, Daloz et al. (2014) showed that the ability of the HWG models to
232 represent the clusters of Atlantic tropical cyclones tracks is inconsistent and varies from
233 model to model, especially for the tracks with genesis over the eastern part of the basin.

234 Knutson et al. (2013) and Knutson (2013) employ the ZETAC regional climate model and
235 global HiRAM model, combined with the GFDL hurricane model, to show that in addition to
236 simulating well the present-day climatology of tropical cyclone formation in the Atlantic,
237 they are also able to simulate a reasonably realistic distribution of tropical cyclone intensity.
238 Manganello et al. (2012) showed a similar ability in a high-resolution GCM (see below for
239 more on intensity). These simulations mostly show a decrease in future numbers of Atlantic
240 storms.

241 Substantial increases in observed Atlantic tropical cyclone numbers have already occurred in
242 the past 20 years, likely driven by changes in the Atlantic Meridional Mode (AMM; Servain

243 et al. 1999; Vimont and Kossin 2007; Kossin et al. 2010) on decadal time scales and the
244 Atlantic Multidecadal Oscillation (AMO; Delworth and Mann, 2000) on multi-decadal
245 timescales. A number of detailed explanations of changes in TC numbers related to these
246 climate variations have been suggested, ranging from changes in upper-tropospheric
247 temperatures (Emanuel et al. 2013, Vecchi et al. 2013) to the “relative-SST” argument of
248 Vecchi and Soden (2007), namely that increases in TC numbers are related to whether local
249 SSTs are increasing faster than the tropical average. Changes in tropospheric aerosols have
250 also been implicated (Villarini and Vecchi 2013b). Camargo et al. (2013) and Ting et al.
251 (2013, 2014) show that the effect of Atlantic SST increases alone on Atlantic basin potential
252 intensity is considerably greater than the effect on Atlantic basin PI of global SST changes.
253 Figure 5 shows that regression coefficients that indicate the strength of this relationship are
254 considerably larger for SSTs forced by the AMO (left panels) than for the global climate
255 change signal (right panels), for a range of both current climate and future climate
256 simulations. This suggests that increases in local PI are likely related to whether the local
257 SST is increasing faster than the global average or not. Ting et al. (2014) show that by the
258 end of this century, the change in PI due to climate change should dominate the decadal
259 variability signal in the Atlantic, but that this climate change signal is not necessarily well
260 predicted by the amplitude in the relative SST signal. Knutson (2013) finds that relative SST
261 appears to explain the predicted evolution of future Atlantic TC numbers reasonably well (see
262 also Villarini et al. 2011).

263 The issue of the relative importance of large-scale climate variations for tropical cyclone
264 formation in the Atlantic region is related to the ability of dynamical seasonal forecasting
265 systems to predict year-to-year tropical cyclone numbers in the Atlantic. In general, despite
266 the challenges of simulating tropical cyclone climatology in this basin, such models have
267 good skill in this region (LaRow et al. 2011; Schemm and Long 2013; Saravanan et al. 2013).

268 This skill is clearly assisted by models being well able to simulate the observed interannual
269 variability of tropical cyclone formation in this region, as shown by Emanuel et al. (2008),
270 LaRow et al. (2008), Knutson et al. (2007), Zhao et al. (2009), LaRow et al. (2011), Knutson
271 (2013), Patricola et al. (2014), Roberts et al. (2014) and Wang et al. (2014). This suggests
272 that tropical cyclone formation in the Atlantic basin is highly related to the climate variability
273 of the environmental variables in the basin rather than to the stochastic variability of the
274 generation of precursor disturbances in the basin. This also suggests that provided the
275 challenge of simulating the tropical cyclone climatology in this region can be overcome, and
276 provided that the relative contributions of the existing substantial decadal variability and the
277 climate change signal can be well quantified, simulations in this basin may achieve more
278 accurate predictions of the effect of climate change on tropical cyclone numbers.

279 While the Atlantic basin has been a particular focus of this work, the basin with the greatest
280 annual number of tropical cyclones is the northwest Pacific. The HWG simulations mostly
281 show decreases in numbers in this basin for the 2K2CO₂ experiment. This is in general
282 agreement with results from previous model simulations of the effect of anthropogenic
283 warming on tropical cyclone numbers. Some recent results for predictions in other regions of
284 the globe suggest some consensus among model predictions. For instance, Li et al. (2010),
285 Murakami et al. (2013), Murakami et al. (2014), Kim et al. (2014) and Roberts et al. (2014)
286 suggest that the region near Hawaii may experience an increase in future tropical cyclone
287 numbers. Walsh et al. (2013) and Zhao et al. (2013) indicate that HWG and other model
288 projections tend to produce more consistent decreases in TC numbers in the Southern
289 Hemisphere than in the Northern Hemisphere. The cause of this interhemispheric
290 inhomogeneity is currently uncertain but it is speculated that it is due to fundamental
291 differences caused by the land-sea distribution in the two hemispheres.

292 *What is the tropical cyclone response of climate models to an imposed, common increase in*
293 *SST? How sensitive is the simulation of tropical cyclone variability to differences in SST*
294 *analysis?*

295 Previous work has shown that tropical cyclone numbers decrease in response to the
296 imposition of a uniform ocean warming (Yoshimura and Sugi 2005; Held and Zhao 2011).
297 The relevant experiment here is the 2K experiment of the HWG modelling suite. In general,
298 of those HWG models that generate a substantial number of tropical cyclones, slightly more
299 models show global numbers that decrease rather than increase, although the difference is not
300 large.

301 Some insight has been previously provided into the issue of the sensitivity of GCM results to
302 the specification of the forcing SST data set. Po-Chedley and Fu (2012) conduct an analysis
303 of the CMIP5 AMIP simulations and it is noted that the HWG models participating in the
304 CMIP5 AMIP experiments used a different SST data set (HadISST, Rayner et al. 2003 – the
305 one used for the HWG experiments) than the one recommended for the CMIP5 AMIP
306 experiments (the “Reynolds” data set; Reynolds et al. 2002). These HWG models have a
307 weaker and more realistic upper tropospheric warming over the historical period of the AMIP
308 runs, suggesting that there is some sensitivity to the specification of the SST data sets. This
309 difference in SST data sets could conceivably have an effect on tropical cyclones in these
310 models, through changes in either formation rates due to changes in stability or through
311 changes in intensity caused by effects on PI. This issue remains unresolved at present.

312 *How does the role of changes in atmospheric carbon dioxide differ from the role played by*
313 *SSTs in changing tropical cyclone characteristics in a warmer world?*

314 The HWG experiments indicate that it was more likely for tropical cyclone numbers to
315 decrease in the 2CO₂ experiments than in the 2K experiments (Fig. 3a). Zhao et al. (2013a)

316 show that, for several of the HWG models, decreases in mid-tropospheric vertical velocity
317 are generally larger for the 2CO₂ experiments than for the 2K experiments (Fig. 3b). For the
318 2CO₂ experiment, the decrease in upward mass flux has previously been explained by Sugi
319 and Yoshimura (2004) as being related to a decrease in precipitation caused by the decrease
320 in radiative cooling aloft. This is caused by the overlap of CO₂ and water vapour absorption
321 bands, whereby an increase in CO₂ will reduce the dominant radiative cooling due to water
322 vapor. This argument assumes that tropical precipitation rates are controlled by a balance
323 between convective heating and radiative cooling (Allen and Ingram 2002). The simulated
324 decrease in precipitation was combined with little change in stability. In contrast, in their 2K
325 experiment, precipitation increased but static stability also increased, which was attributed to
326 a substantial increase in upper troposphere temperature due to increased convective heating.
327 Yoshimura and Sugi (2005) note that these effects counteract each other and may lead to little
328 change in the upward mass flux, thus leading to little change in tropical cyclone formation
329 rates for the 2K experiment, as seen in their results. A thorough analysis of the HWG
330 experiments along these lines has yet to be performed, however.

331 The 2K and 2CO₂ may also have different effects on the intensity of storms. If fine-
332 resolution models are used, it is possible to simulate reasonably well the observed distribution
333 of intensity (see below). The model resolutions of the HWG experiments are in general too
334 coarse to produce a very realistic simulation of the observed tropical cyclone intensity
335 distribution. Nevertheless, some insight into the overall effects of these forcings on intensity
336 of storms can be obtained, particularly when compared with the almost resolution-
337 independent PI theory. First, Held and Zhao (2011) showed that one of the largest differences
338 between the results of the 2K and 2CO₂ experiments conducted for that paper was that PI
339 increased in the 2K experiments but decreased in the 2CO₂ experiment, due to the relative
340 changes in surface and upper tropospheric temperatures in the two cases. In addition,

341 directly-simulated intense tropical cyclone (hurricane) numbers decrease more as a fraction
342 of their total numbers in the 2CO₂ experiment than they did in the 2K experiment, consistent
343 with the PI results. A similar behavior is seen in the HWG experiments, although apart from
344 the HiRAM model results, there is a general suppression of storms across all intensity
345 categories rather than a preferential suppression of hurricane-intensity storms (Zhao et al.,
346 2013a). In contrast, previous model simulations at higher resolutions than employed for the
347 HWG experiments have tended to indicate an increase in the number of more intense storms
348 (e.g. Knutson et al. 2010).

349 *How does air-sea interaction modify the climate response of tropical cyclones?*

350 If the SST field from a coupled ocean atmosphere is applied as the lower boundary condition
351 for a specified-SST “time slice” AGCM run, it has been shown previously that the resulting
352 atmospheric climate differs from the original atmospheric climate of the corresponding
353 coupled ocean-atmosphere model run (Timbal et al. 1997). Thus, the presence of air-sea
354 interaction itself appears to be important for the generation of a particular climate.

355 This issue is not addressed directly through the design of the HWG experiments. Emanuel
356 and Sobel (2013) show by an analysis of thermodynamic parameters associated with tropical
357 cyclone intensity that SST should not be considered a control variable for tropical cyclone
358 intensity on time scales longer than about two years, rather it is a quantity that tends to co-
359 vary with the same control variables (surface wind, surface radiative fluxes, and ocean lateral
360 heat fluxes) that control potential intensity. Thus it can be argued that simulations that used
361 specified SSTs risk making large errors in potential intensity, related to their lack of surface
362 energy balance. Nevertheless, Kim et al. (2014) use the GFDL coupled model running at a
363 resolution of 50 km to show that the inclusion of coupling does not necessarily change the
364 direction of the tropical cyclone frequency response. As a result, these runs also show

365 decreases in the global number of tropical cyclones and also under-simulate current climate
366 numbers in the Atlantic. It is noted that this might be due to a cold bias in the SST simulation
367 in the Atlantic. Daloz et al. (2012b), using a stretched configuration of CNRM-CM5 with a
368 resolution of up to 60 km over the Atlantic, also showed an underestimate of tropical cyclone
369 activity when coupling was introduced.

370 *Are the results sensitive to the choice of cyclone tracking scheme?*

371 An essential first step in the analysis of any tropical cyclone detection scheme is to select a
372 method for detecting and tracking the storms in the model output. A number of such schemes
373 have been developed over the years; they share many common characteristics but also have
374 some important differences. They fall into five main categories, although some schemes
375 contain elements of more than one category:

- 376 (1) Structure-based threshold schemes, whereby thresholds of various structural
377 parameters are set based on independent information, and storms detected with
378 parameter values above these thresholds are declared to be tropical cyclones (e.g.,
379 Walsh et al. 2007);
- 380 (2) Variable threshold schemes, in which the thresholds are set so that the global number
381 of storms generated by the model is equal to the current-climate observed annual
382 mean (e.g. Murakami et al. 2011);
- 383 (3) Schemes in which model output is first interpolated onto a common grid before
384 tracking (e.g., the feature tracking scheme of Bengtsson et al. 2007b; Strachan et al.
385 2013);
- 386 (4) Model-threshold dependent schemes, in which the detection thresholds are adjusted
387 statistically, depending upon the formation rate in a particular model, originally

388 developed for seasonal forecasting with basin-dependent thresholds (e.g., Camargo
389 and Zebiak 2002); and

390 (5) Circulation based schemes, in which regions of closed circulations and enhanced
391 vorticity with low deformation are identified based on the Okubo-Weiss-Zeta
392 diagnostic (Tory et al. 2013b).

393

394 It is possible to make arguments for and against each type of scheme, but clearly the change
395 in tropical cyclone numbers of the climate model simulations should not be highly dependent
396 on the tracking scheme used, and if the direction of the predicted change is sensitive to this,
397 this would imply that the choice of the tracking scheme is another source of uncertainty in the
398 analysis. To examine this issue, results from the HWG simulations are compared for different
399 tracking schemes. In general, after correction is made for differences in user-defined
400 thresholds between the schemes, there is much more agreement than disagreement on the sign
401 of the model response between different tracking schemes (Horn et al. 2014; Fig. 6).

402 Nevertheless, it is possible to obtain a different sign of the response for the same experiment
403 by using a different tracking scheme. In the case of CMIP5 models, changes in TC frequency
404 in future climates was clearly dependent on the tracking routine used, especially for the
405 models with poor TC climatology (see Camargo 2013, Tory et al. 2013a, Murakami et al.
406 2014). This could simply be a sampling issue caused by insufficient storm numbers in the
407 various intensity categories rather than any fundamental difference between the model
408 responses as estimated by the different tracking schemes or the effect of user-specific
409 threshold detection criteria. This may still imply that results from such simulations should be
410 examined using more than one tracking scheme.

411 *Climatological controls on formation*

412 It has been recognized for some time that one consequence of a warmer climate is an increase
413 in the typical threshold of the initiation of deep convection, a precursor of tropical cyclone
414 formation (Dutton et al. 2000; Evans and Waters 2012; Evans 2013). This threshold varies
415 within the current climate as well (Evans 2013). The search for relevant diagnostics of
416 tropical cyclone formation that can be derived from the mean climate has led to the
417 formulation of GPI parameters that statistically relate tropical cyclone formation to
418 climatological mean values of parameters that are known to influence tropical cyclone
419 formation (Gray 1979; Royer et al. 1998; Emanuel and Nolan 2004; Emanuel 2010; Tippett
420 et al. 2011; Bruyère et al. 2012; Menkes et al. 2012; Kerty et al. 2012). GPIs usually include
421 values of atmospheric variables such as vertical wind shear, PI, mid-tropospheric relative
422 humidity and SST. Another large-scale environmental factor that should be considered is the
423 ventilation, the import of cooler, drier air, which was shown to have an important influence in
424 both tropical cyclogenesis and intensification (Tang and Emanuel 2012). Changes in TC
425 frequency in future climates have also been related to the ventilation index for the CMIP5
426 models (Tang and Camargo 2014).

427 The potential of such a technique is obvious: it could serve as a diagnostic tool to determine
428 the reasons for changes in tropical cyclone numbers in a particular climate simulation,
429 without the need to perform numerous sensitivity experiments, or (ultimately) it could enable
430 the diagnosis of changes in tropical cyclone formation rate from different climates without
431 the need to run a high-resolution GCM to simulate the storms directly, similar to what was
432 done in the present climate for diagnostics of TC genesis modulation by the El Niño-Southern
433 Oscillation (Camargo et al. 2007a) and the Madden-Julian Oscillation (Camargo et al. 2009).
434 Kerty et al. (2013) and Kerty et al. (2012a,b) show results where the GPI is used to diagnose
435 the rate of tropical cyclone formation for a period 6,000 years before the present, showing
436 considerable changes in GPI, with mostly decreases in the Northern Hemisphere and

437 increases in the Southern Hemisphere. It is noted, however, that while GPIs appear to have
438 some skill in estimating the observed spatial and temporal variations in the number of tropical
439 cyclones (Menkes et al. 2012), there are still important discrepancies between their estimates
440 and observations. In addition, there can be similar differences between GPI estimates and
441 directly-simulated tropical cyclone numbers, which appears to be better in models with
442 higher resolution (Camargo et al. 2007b; Walsh et al. 2013; Camargo 2013). A potential
443 limitation of the GPI methodology for application to a different climate is that it is trained on
444 present-day climate. This was demonstrated in the 25km version of the CAM5 GCM, where
445 decreases in GPI estimated for the 2CO₂ experiment were consistent with the direct
446 simulation but increases in GPI estimated for the 2K and 2K2CO₂ were inconsistent with the
447 direct simulation of changes in tropical cyclone numbers (Wehner et al 2014b; see also
448 Camargo 2013 and Camargo et al. 2014).

449

450 The role of idealized simulations in understanding the influence of climate on tropical
451 cyclones is highlighted by Merlis et al. (2013). A series of idealized experiments with land
452 areas removed (so-called “aquaplanet” simulations) show that the position of the Intertropical
453 Convergence Zone (ITCZ) is crucial for the rate of generation of tropical cyclones. If the
454 position of the ITCZ is not changed, a warmer climate leads to a decrease in tropical cyclone
455 numbers, but a poleward shift in the ITCZ leads to an increase in tropical cyclone numbers.
456 With a new generation of climate models being better able to simulate tropical cyclone
457 characteristics, there appears to be increased scope for using models to understand
458 fundamental aspects of the relationship between climate and tropical cyclones.

459 *Sensitivity of results to choice of convection scheme*

460 Murakami et al. (2012) shows experiments investigating the sensitivity of the response of
461 TCs to future warming using time slice experiments. Decreases in future numbers of tropical
462 cyclones are shown for all experiments irrespective of the choice of convection scheme. Note
463 that there also appears to be a considerable sensitivity of tropical cyclone formation to the
464 specification of the minimum entrainment rate (Lim et al. 2014). As this is decreased
465 (equivalent to turning off the cumulus parameterization), the number of tropical cyclones
466 increases. The sensitivity of the TC frequency to other convection scheme parameters
467 (fractional entrainment rate and rate of rain reevaporation) was also shown in Kim et al.
468 (2012) with the GISS model, with a larger entrainment rate causing fewer TCs but an
469 increase in rain reevaporation substantially increasing TC numbers. One issue that needs to
470 be examined is that an increase in tropical storm numbers due to changes in the convective
471 scheme to more realistic values is not necessarily accompanied by an improvement in the
472 simulation of the mean climate state. A similar issue occurs in the simulation of the
473 intraseasonal variability in climate models, where there is a systematic relationship between
474 the amplitude of the intraseasonal variability in the models and mean state biases in climate
475 simulations (Kim et al. 2011).

476

477 **Tropical cyclone intensity**

478

479 Work in the past couple of decades has led to the generally accepted theory that the potential
480 intensity of tropical cyclones (PI) can be quantified by thermodynamic arguments (Emanuel
481 1986; Emanuel 1988; Holland 1997; see also Knutson et al. 2010). While the focus of the
482 HWG has been on numerical model simulation, the use of theoretical diagnostics such PI has
483 been an important part of efforts to understand the results produced by the models.

484

485 Emanuel and Sobel (2011, 2013) outline some of the important unresolved theoretical issues
486 related to maximum tropical cyclone intensity, including the physics of air-sea interaction at
487 very high wind speeds, the existence and magnitude of super-gradient winds in the hurricane
488 boundary layer, horizontal mixing by eddies, and the radial structure and characteristics of
489 the outflow temperature (see also Wang et al. 2014; Ramsay 2014). In addition, most tropical
490 cyclones do not reach their maximum intensities (Wing et al. 2007, Kossin and Camargo
491 2009), and while factors that inhibit their intensification are well known (e.g., vertical wind
492 shear, dry mid-tropospheric air, and land surfaces), less certain is the precise quantitative
493 response of tropical cyclones to changes in these quantities. Ideally, there should be a strong
494 correspondence between the theoretical PI and the simulated maximum intensity of storms in
495 a model climatology of tropical cyclones.

496 *Simulation of the intensity distribution of tropical cyclones*

497 While it is clear that simply increasing the resolution does not necessarily improve intensity
498 distribution (Shaevitz et al. 2014), results from the HWG simulations indicate that a very
499 significant improvement in a GCM's ability to simulate both TC formation and intensity
500 occurs at resolutions finer than 50km, with good results shown at 25 km (Strachan et al.
501 2013; Roberts et al. 2014; Lim et al. 2014; Wehner et al. 2014b; Mei et al. 2014). In addition,
502 if such high resolution is employed, it is possible to simulate reasonably well the observed
503 intensity distribution of tropical cyclones (Bender et al. 2010; Lavender and Walsh 2011;
504 Murakami et al. 2012; Knutson 2013; Chen et al. 2013; Zarzycki and Jablonowski 2014).
505 Figure 7 illustrates this for the 25 km version of the CAM-SE model, with typical simulated
506 wind speeds (red crosses) for intense storms being only slightly lower for the same central
507 pressure than in the observations (blue crosses). This is due to the model at this resolution not
508 being quite able to simulate pressure gradients that are as large as those observed.
509 Nevertheless, Manganello et al. (2012) showed that there remained some discrepancies in the

510 wind-pressure relationship between observations and even very high horizontal resolution (10
511 km) simulations.

512 **Other issues**

513 *Future TC precipitation*

514 Previous work has shown a robust signal of increasing amounts of precipitation per storm in a
515 warmer world (Knutson and Tuleya 2004; Manganello et al. 2012; Knutson 2013; Kim et al.
516 2014; Roberts et al. 2014). The size of this signal varies a little between simulations, from
517 approximately 10% to 30%. Knutson (2013) shows that this increase in precipitation close to
518 the center of the storm appears to be greater than the Clausius-Clapeyron rate of 7% per
519 degree of warming, due to the additional source of moisture supplied by the secondary
520 circulation (inflow) of the tropical cyclone.

521

522 Villarini et al. (2014) and Scoccimarro et al. (2014) have investigated the response of
523 precipitation from landfalling tropical cyclones in the HWG experiments (Fig. 8).
524 Scoccimarro et al. (2014) find that compared to the present day simulation, there is an
525 increase in TC precipitation for the scenarios involving SST increases. For the 2CO₂ run, the
526 changes in TC rainfall are small and it was found that, on average, TC rainfall for that
527 experiment tends to decrease compared to the present day climate. The results of Villarini et
528 al. (2014) also indicate a reduction in TC daily precipitation rates in the 2CO₂ scenario, of
529 the order of 5% globally, and an increase in TC rainfall rates when SST is increased, both in
530 the 2K and 2K2CO₂ runs, about 10-20% globally. The authors propose an explanation of the
531 decrease in precipitation in the 2CO₂ runs is similar to that described by Sugi and Yoshimura
532 (2004) above, while the increases in the 2K runs are a result of increased surface evaporation.

533 A number of issues are identified for future work, including the need to stratify the rainfall
534 rate by intensity categories and an examination of the extra-tropical rainfall of former TCs.

535

536 *Novel analysis techniques*

537 Strazzo et al. (2013a,b) present results in which a hexagonal regridding of the model output
538 variables and tracks enable some analysis of their interrelationships to be performed
539 efficiently. Once this is done for the HWG experiments, it is noted that one can define a
540 “limiting intensity” that is the asymptotic intensity for high return periods. The sensitivity of
541 this limiting intensity to SST is lower in the models than in the observations, perhaps a
542 reflection of the lack of high-intensity storms in most HWG model simulations. This
543 technique can also be used to establish performance metrics for the model output in a way
544 that can be easily analyzed statistically.

545 Strazzo et al. (2013a, b) and Elsner et al. (2013) use this novel analysis technique to show
546 that the sensitivity of limiting intensity to SST is 8 m/s/K in observations and about 2 m/s/K
547 in the HiRAM and FSU models (Figure 9). They speculate that the lower sensitivity is due to
548 the inability of the model-derived TCs to operate as idealized heat engines, likely due to
549 unresolved inner-core thermodynamics that then limit the positive feedback process between
550 convection and surface heat fluxes that is responsible for TC intensification. They further
551 speculate that GCM temperatures near the tropopause do not match those in the real
552 atmosphere, which would likely influence the sensitivity estimates.

553

554 **Gaps in our understanding and future work**

555 In summary, the HWG experiments have shown systematic differences between experiments
556 in which only sea surface temperature is increased versus experiments where only
557 atmospheric carbon dioxide is increased, with the carbon dioxide experiments more likely to
558 demonstrate the decrease in tropical cyclone numbers previously shown to be a common
559 response of climate models in a warmer climate. Experiments where the two effects are
560 combined also show decreases in numbers, but these tend to be less for those models that
561 demonstrate a strong tropical cyclone response to increase sea surface temperatures. Analysis
562 of the results has established firmer links between tropical cyclone formation rates and
563 climate variables such as mid-tropospheric vertical velocity, with decreased climatological
564 vertical velocities leading to decreased tropical cyclone formation. Some sensitivity in the
565 experimental results has been shown to the choice of tropical cyclone detection and tracking
566 scheme chosen, suggesting that at the current state of the art, it would be useful to employ
567 more than one tracking scheme in routine analysis of such experiments. Diagnosis of tropical
568 cyclone rainfall in the experiments shows support for previously-proposed theoretical
569 arguments that relate changes in warmer-world rainfall to the competing influences of
570 increases in sea surface temperatures and increased carbon dioxide, providing further support
571 for future projections of increased rainfall from tropical cyclones. Higher-resolution versions
572 of some of the HWG models are now able to generate a good simulation of climatological
573 Atlantic tropical cyclone formation, previously a difficult challenge for most models, and
574 models of even higher resolution are now also able to simulate good climatological
575 distributions of observed intensities.

576 A number of issues are identified by the HWG as requiring further investigation. The
577 influence of the inclusion of an interactive ocean clearly is a further step needed to improve
578 the realism of the results of the HWG experiments. Designing common experiments for
579 models that include air-sea interaction is challenging, but may be aided by the addition of a

580 simple slab or mixed-layer ocean with specific lateral fluxes to represent advective processes
581 as a boundary condition. The inclusion of this simplified form of air-sea interaction will
582 partially address the important issue of the inconsistency of the surface flux balance in
583 experiments that employ specified SSTs and the resulting effects on variables such as
584 potential intensity. Additionally, there is scope for the use of coupled ocean/atmosphere
585 models in tropical cyclone simulation experiments (e.g. Vecchi et al. 2014). These
586 experiments might be performed with or without selected modifications to the coupling
587 methods, using so-called “partial coupling” (e.g. Ding et al. 2014), to enable a better
588 understanding of how hurricanes influence the climate, as opposed to an understanding of
589 how the climate influences hurricanes, as examined in the HWG experiments. There is also
590 some scope for the use of ocean-only models in this topic (e.g. Vincent et al. 2012; Bueti et
591 al. 2014).

592 A series of systematic experiments could be devised to examine the relative role of Atlantic
593 versus global SST anomalies on the generation of tropical cyclones in the Atlantic basin (see
594 Lee et al. 2011). Some results presented at the workshop indicate some support for the
595 “relative SST” explanation of increases in tropical cyclone activity in the Atlantic in the past
596 two decades, which could be further investigated by such experiments. A related topic is the
597 relative role of future decadal and interannual variability in this basin when combined with
598 the effects of anthropogenic warming. Patricola et al. (2014) investigate the possible effects
599 of combinations of extreme phases of the AMM and ENSO. Figure 10 shows that strongly
600 negative AMM activity, combined with strong El Niño conditions, inhibits Atlantic TC
601 activity, but even with very positive AMM conditions, strong El Niño conditions still lead
602 only to average Atlantic TC activity. Thus any future climate change projection would ideally
603 need to include information on changes in the periodicity and amplitude of the AMM and
604 ENSO. Similarly, a factor that is not investigated in the HWG experiments is the role of

605 changing atmospheric aerosols in the Atlantic basin (e.g., Villarini and Vecchi 2013a,b). It
606 would be possible to design a series of experiments to investigate this, similar to the HWG
607 experiments.

608 Now that there is a critical mass of HWG experiments available for analysis, there may be
609 some scope for using the experiments in an inter-comparison process, to determine if there
610 are common factors that lead to improved simulations of both the mean atmospheric climate
611 and of tropical cyclone climatology. This would be facilitated by the use of novel analysis
612 techniques associating the changes in tropical cyclone occurrence simulated in these
613 experiments with changes in fundamental climate variables, along the lines of those already
614 established by existing analysis of the HWG suite. Strong links between changes in tropical
615 cyclone formation rate and fundamental measures of tropical circulation, and stronger
616 quantification of these links, will ultimately lead to a clearer understanding of the relationship
617 between tropical cyclones and climate.

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Table 1: List of participating modeling centers, models, horizontal resolution and experiments performed.

Center	Model	Horizontal resolution (km at equator)	Experiments run
LBNL	CAM5.1	222, 111, 25	climo, amip, 2CO ₂ , 2K, 2K2CO ₂
CMCC	CMCC/ECHAM5	84	climo, 2CO ₂ , 2K, 2K2CO ₂
CNRM	CNRM	50	amip
FSU	FSU/COAPS	106	climo, amip, 2CO ₂ , 2K
NOAA GFDL	HiRAM	50	climo, amip, 2CO ₂ , 2K, 2K2CO ₂
NOAA GFDL	C180AM2	50	climo, 2CO ₂ , 2K, 2K2CO ₂
NASA-GISS/Columbia	GISS	111	climo, amip, 2CO ₂ , 2K, 2K2CO ₂
NASA GSFC	GEOS5	56	climo, amip, 2CO ₂ , 2KSST, 2K2CO ₂
Hadley Centre	HadGEM3	208	climo, 2K, 2CO ₂
Hadley Centre	HG3-N216	92	climo, 2K, 2CO ₂
Hadley Centre	HG3-N320	62	climo, 2K, 2CO ₂
JAMSTEC	NICAM	14	control and greenhouse runs
MRI	MRI-AGCM3.1H	50	amip-style, 2K, 2CO ₂ and greenhouse runs
NCEP	GFS	106	climo, amip, 2CO ₂ , 2K, 2K2CO ₂
TAMU	WRF	27	climo, amip, 2K2CO ₂
MIT	CHIPS (downscaling)	Variable	climo, 2CO ₂ , 2K, 2K2CO ₂

LBNL: Lawrence Livermore National Laboratories; CMCC: Centro Euro-Mediterraneo per i Cambiamenti Climatici; FSU: Florida State University; NOAA GFDL: National Oceanic and Atmospheric Administration Geophysical Fluid Dynamics Laboratory; NASA-GISS: NASA Goddard Institute for Space Studies; JAMSTEC: Japan Agency for Marine-Earth Science and Technology; MRI: Meteorological Research Institute of Japan; NCEP: National Centers for Environmental Prediction; TAMU: Texas A&M University; MIT: Massachusetts Institute of Technology

Figure Captions

Figure 1. Tropical cyclone formation rates from IBTrACS (Knapp et al. 2010) observations and the “climo” run of the HWG experiments, using the GFDL tropical cyclone tracking scheme: relative distribution (shaded) and total annual-mean numbers (in panel titles). From Zhao et al. (2013).

Figure 2. (a) Observed and (b) simulated geographical distribution of the climatological TC track density (unit: days per year) during the North Atlantic hurricane season calculated at each $8^{\circ}\times 8^{\circ}$ grid. From Mei et al. (2014).

Figure 3. Comparison between changes in (a) tropical cyclone formation for various models for the 2K (here labelled P2K) and 2CO₂ experiments versus (b) TC genesis as weighted by changes in mid-tropospheric vertical velocity, as described in the text. From Zhao et al. (2013b).

Figure 4. Global tropical cyclone frequency using the downscaling methodology of Emanuel (2013) forced by climate fields derived from the HWG model output, for the HWG models and experiments as indicated.

Figure 5. Regression of PI on Atlantic Multidecadal Oscillation (left panels) and climate change signals for the CMIP5 multi-model ensemble (right panels), for historical and two future climate simulations using the rcp4.5 and rcp8.5 greenhouse gas emissions scenarios (van Vuuren et al. 2011). Units are $\text{ms}^{-1}\text{K}^{-1}$ of SST index (AMO or CMIP5). From Ting et al. (2014).

Figure 6. Percentage change in TC numbers in each model for the three altered climate experiments relative to the present-day experiment, as tracked by the CSIRO, Zhao, and individual group tracking schemes, after homogenisation in duration, wind speed, and latitude of formation. Asterisks indicate statistical significance to at least the $p = 0.05$ level.

Figure 7. Comparison between North Atlantic observed (blue) and simulated (red) wind-pressure relationships during the 1980-2002 period for the high-resolution (0.25°) CAM-SE model, for central tropical cyclone pressure and 10 m wind speed. From Zarzycki and Jablonowski (2014).

Figure 8. Changes in TC related precipitation amount in the 2CO₂ (blue), 2K (green) and 2K2CO₂ (red) experiments as a function of latitude. Results are shown with respect to the climo experiment. Solid thin lines represent CMCC results. Dashed thin lines represent GFDL results. The solid thick lines represent the average of the two models. Units are [%]. The amount of rainfall associated TCs is computed by considering the daily precipitation in a $10^\circ \times 10^\circ$ box around the center of the storm (right panel), and a smaller window closer to the storm center ($6^\circ \times 6^\circ$, left panel). From Scoccimarro et al. (2014).

Figure 9. The sensitivity of limiting intensity to SST ($\text{m s}^{-1} \text{ }^\circ\text{C}^{-1}$) for observed TCs (top left panel) and three runs of the GFDL HiRAM model, indicated by the slope of the blue line. The gray shading represents the 95% confidence interval while the vertical black bars depict uncertainty, obtained through a bootstrapping technique, about the limiting intensity estimates.

Figure 10. Seasonal Accumulated Cyclone Energy (ACE; 10^4 kt^2 , denoted next to mark) of Atlantic tropical cyclones from regional climate model (RCM) simulations forced by the imposed lower boundary conditions and Pacific SST of the 1999 La Niña (filled circle) and 1987 El Niño (open circle) and Atlantic SST (corresponding August-October averaged AMM index on the x-axis), with the RCM 1980-2000 mean Atlantic ACE (dash). Each mark represents one season-long integration. From Patricola et al. (2014).

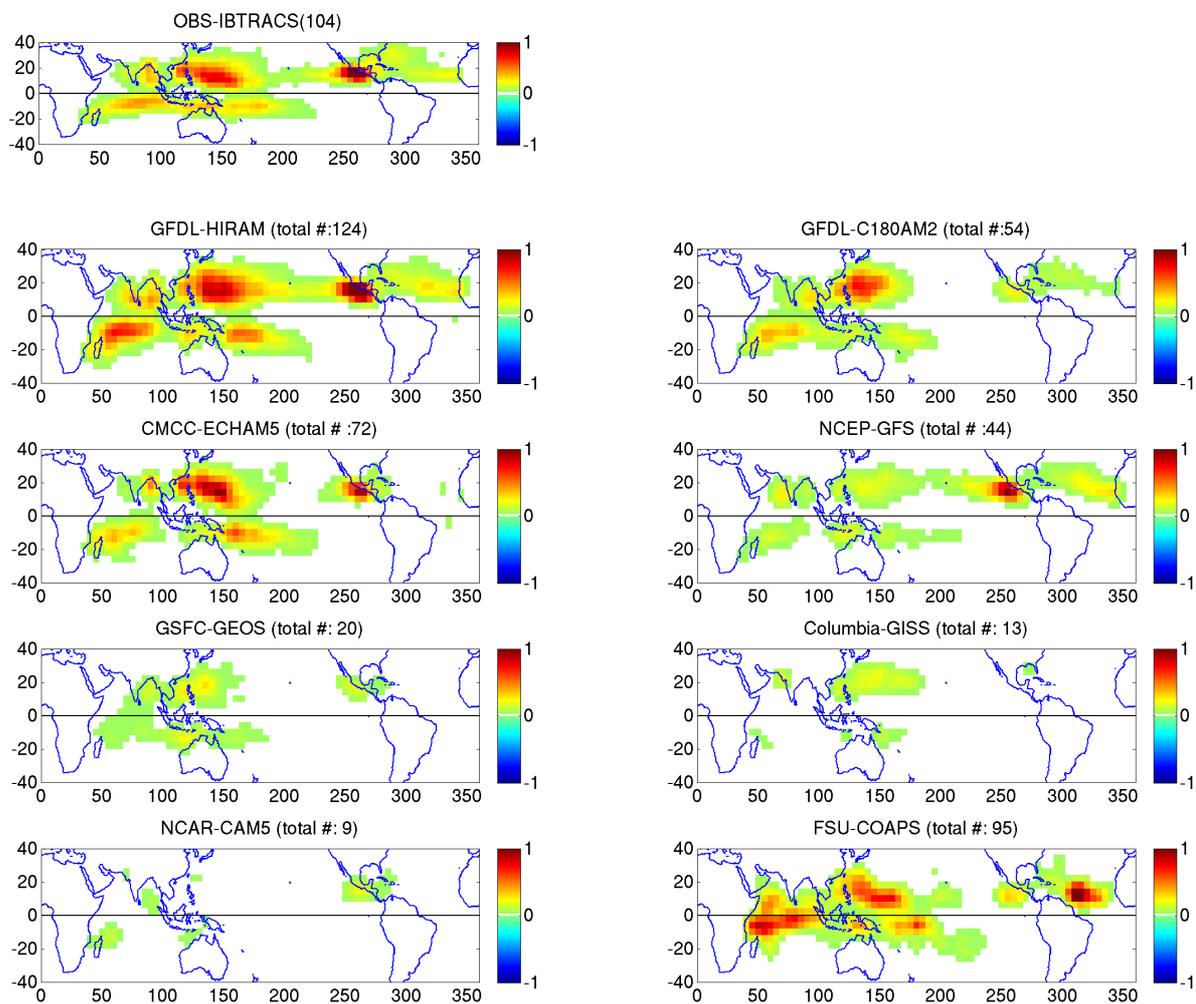


Figure 1. Tropical cyclone formation rates from IBTrACS (Knapp et al. 2010) observations and the “climo” run of the HWG experiments, using the GFDL tropical cyclone tracking scheme: relative distribution (shaded) and total annual-mean numbers (in panel titles). From Zhao et al. (2013).

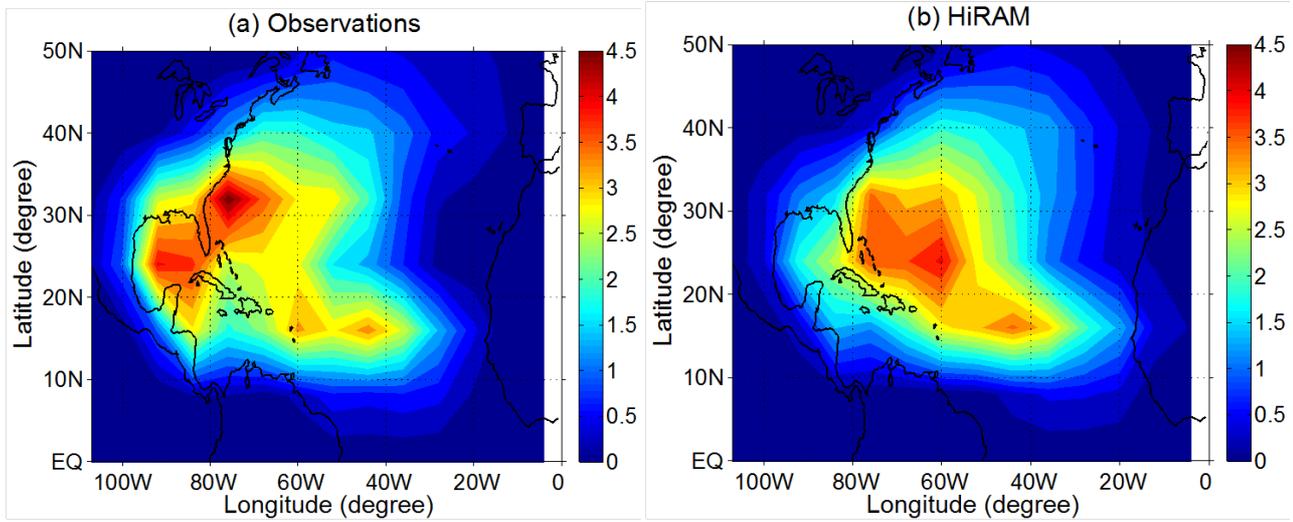


Figure 2. (a) Observed and (b) simulated geographical distribution of the climatological TC track density (unit: days per year) during the North Atlantic hurricane season calculated at each $8^{\circ}\times 8^{\circ}$ grid. From Mei et al. (2014).

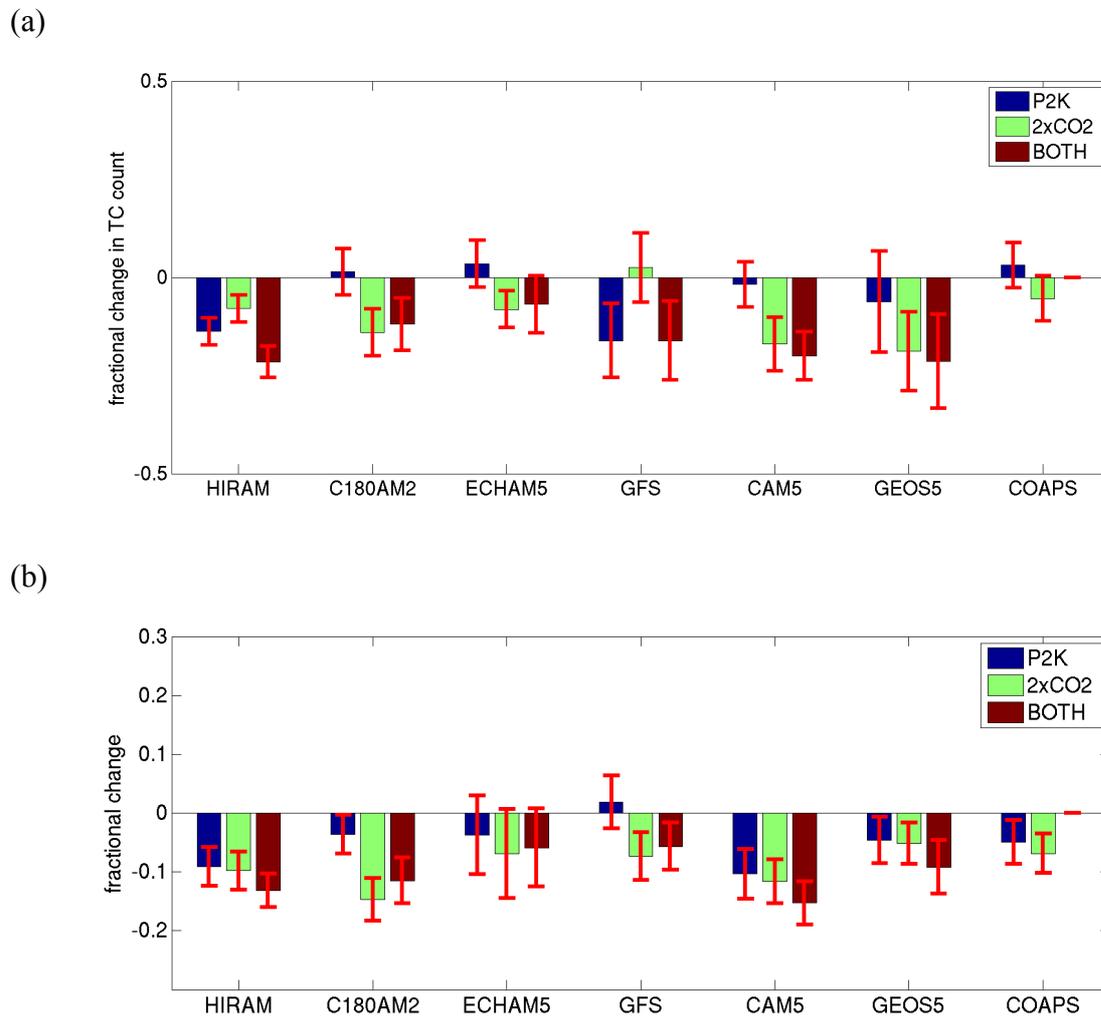


Figure 3. Comparison between changes in (a) tropical cyclone formation for various models for the 2K (here labelled P2K) and 2CO₂ experiments versus (b) TC genesis as weighted by changes in mid-tropospheric vertical velocity, as described in the text. From Zhao et al. (2013b).

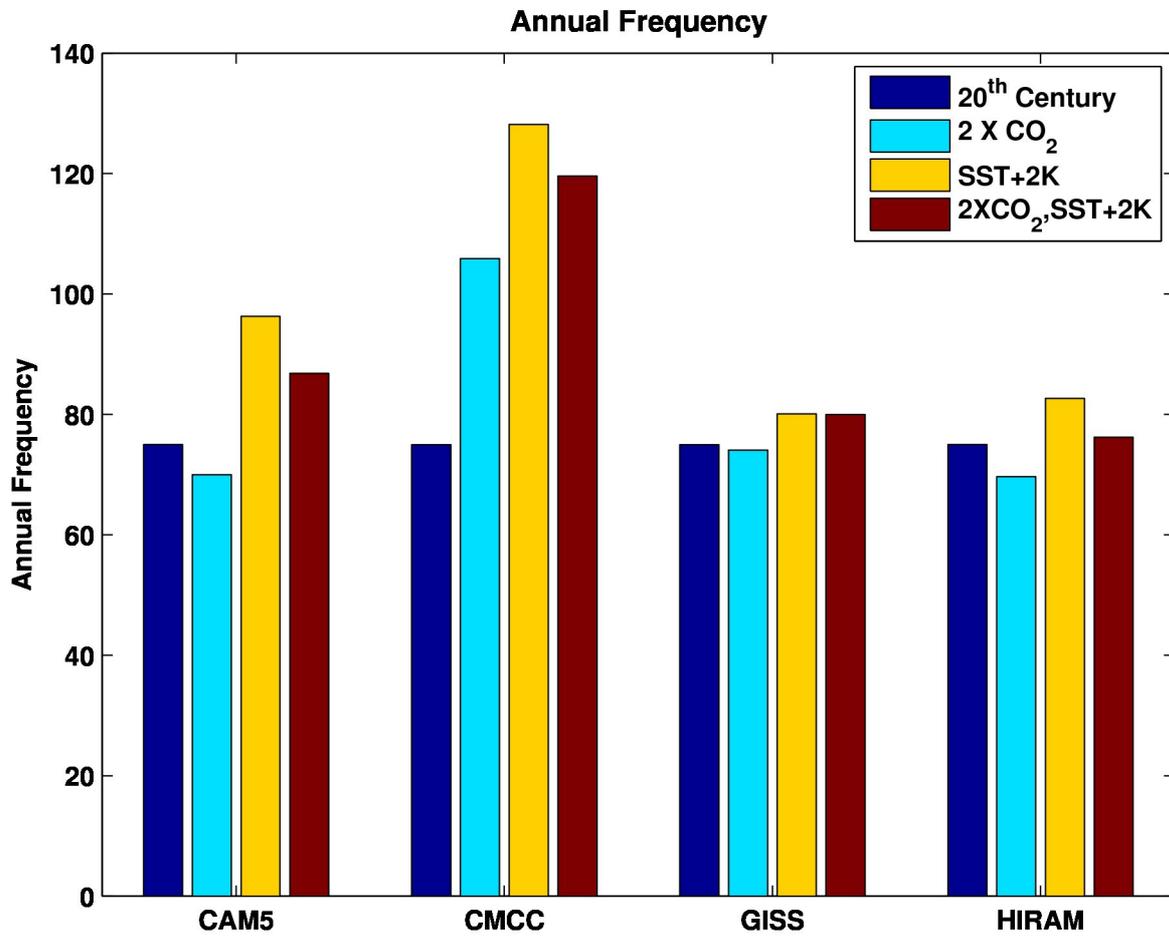


Figure 4. Global tropical cyclone frequency using the downscaling methodology of Emanuel (2013) forced by climate fields derived from the HWG model output, for the HWG models and experiments as indicated.

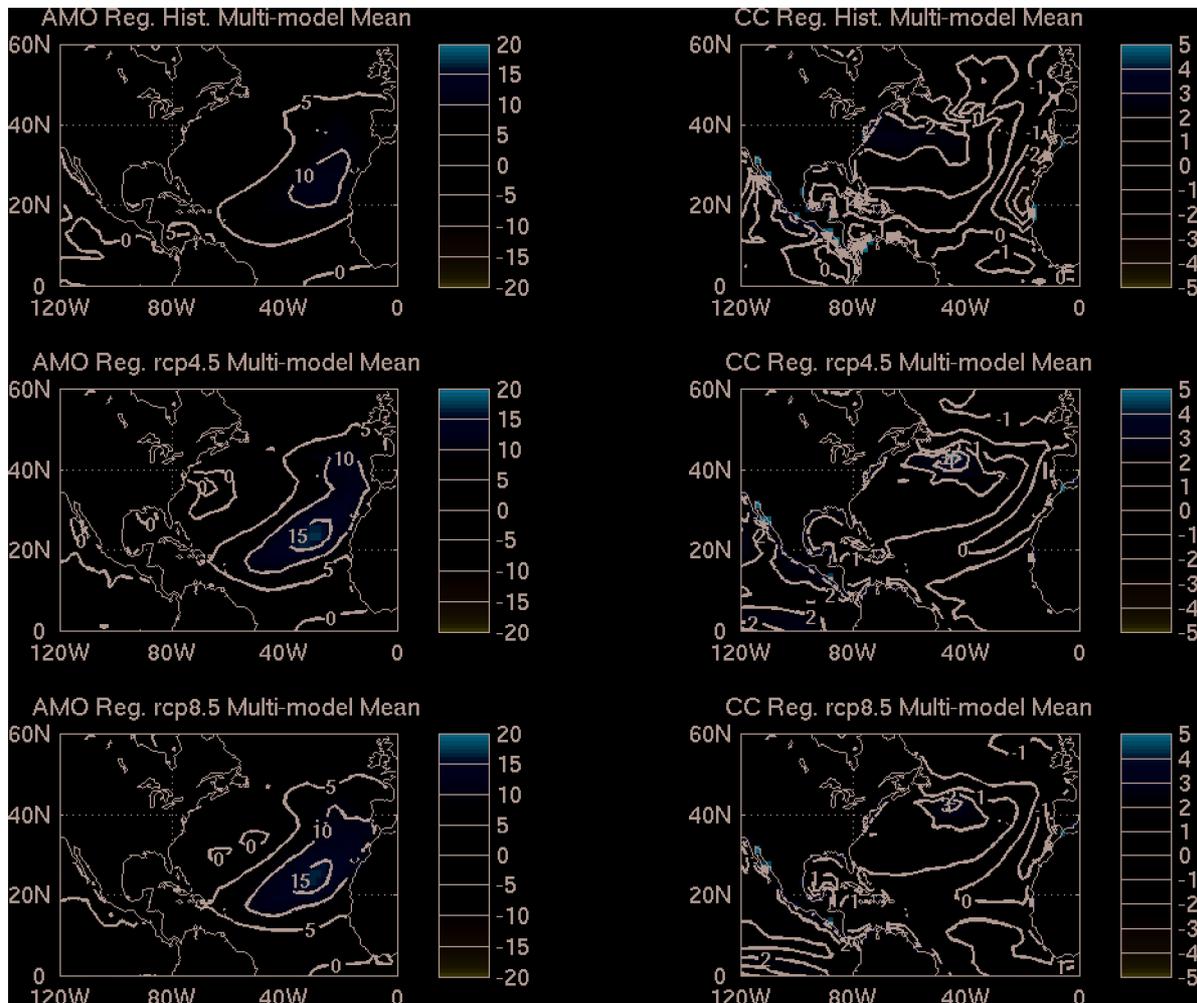
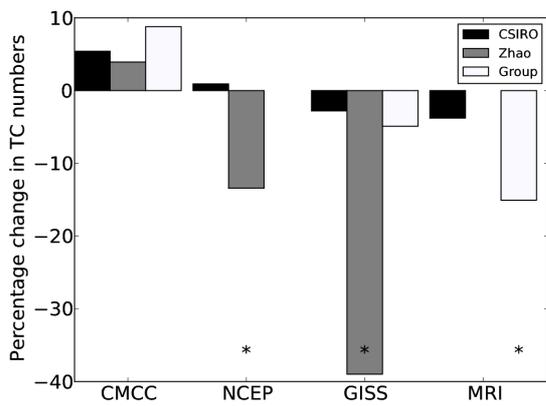
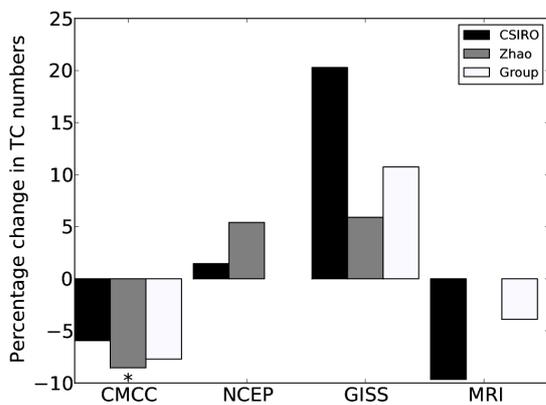


Figure 5. Regression of PI on Atlantic Multidecadal Oscillation (left panels) and climate change signals for the CMIP5 multi-model ensemble (right panels), for historical and two future climate simulations using the rcp4.5 and rcp8.5 greenhouse gas emissions scenarios (van Vuuren et al. 2011). Units are $\text{ms}^{-1}\text{K}^{-1}$ of SST index (AMO or CMIP5). From Ting et al. (2014).

(a)



(b)



(c)

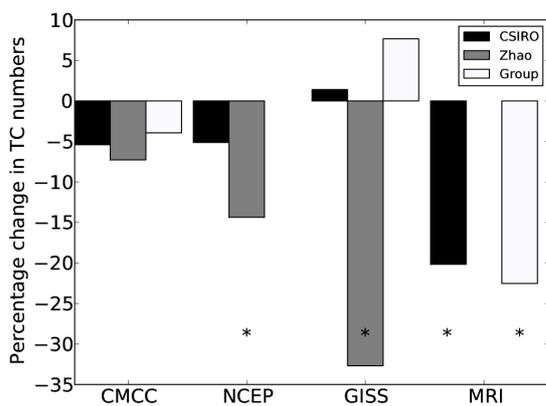


Figure 6. Percentage change in TC numbers in each model for the three altered climate experiments: (a) 2K; (b) 2CO₂; and (c) 2K2CO₂, relative to the present-day experiment, as tracked by the CSIRO, Zhao, and individual group tracking schemes, after homogenisation in duration, wind speed, and latitude of formation. Asterisks indicate statistical significance to at least the $p = 0.05$ level.

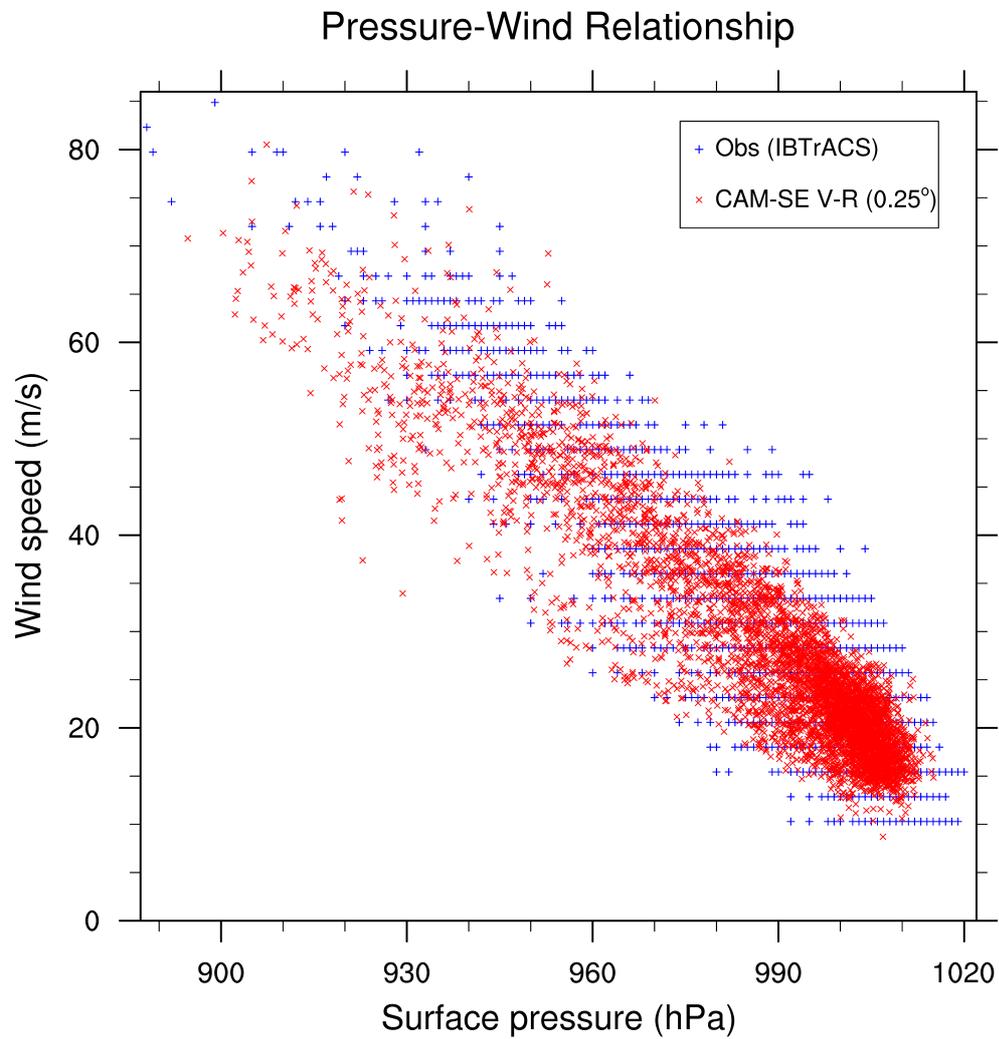


Figure 7. Comparison between North Atlantic observed (blue) and simulated (red) wind-pressure relationships during the 1980-2002 period for the high-resolution (0.25°) CAM-SE model, for central tropical cyclone pressure and 10 m wind speed. From Zarzycki and Jablonowski (2014).

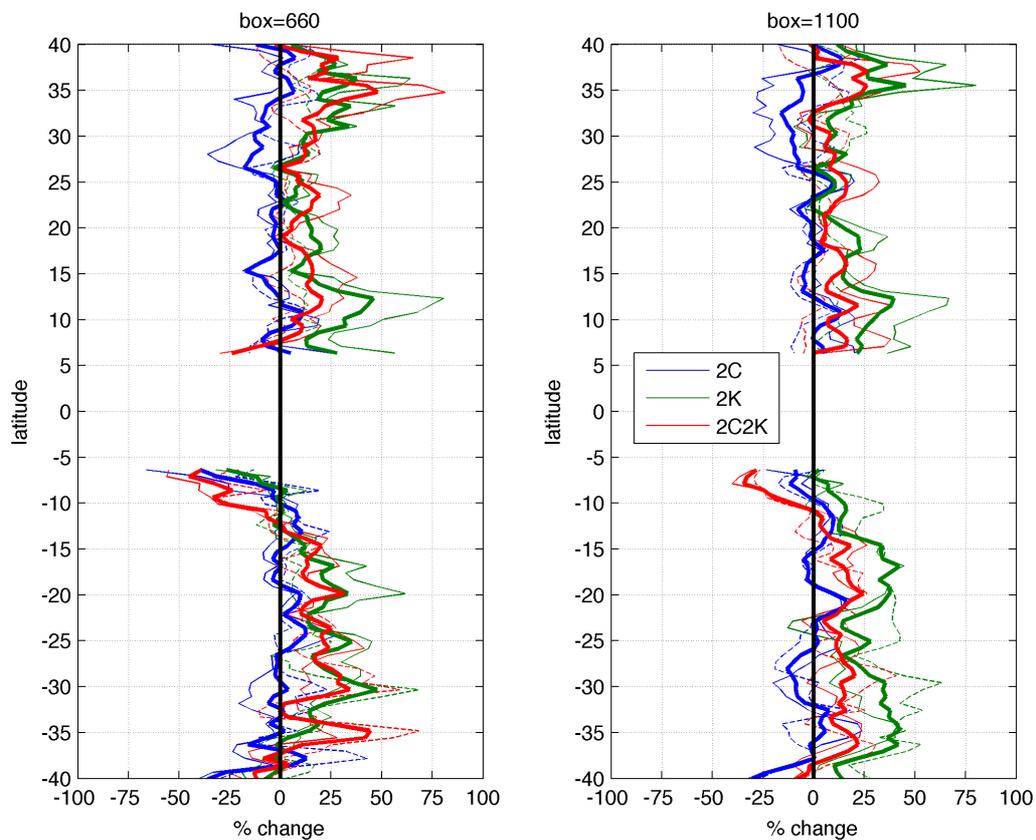


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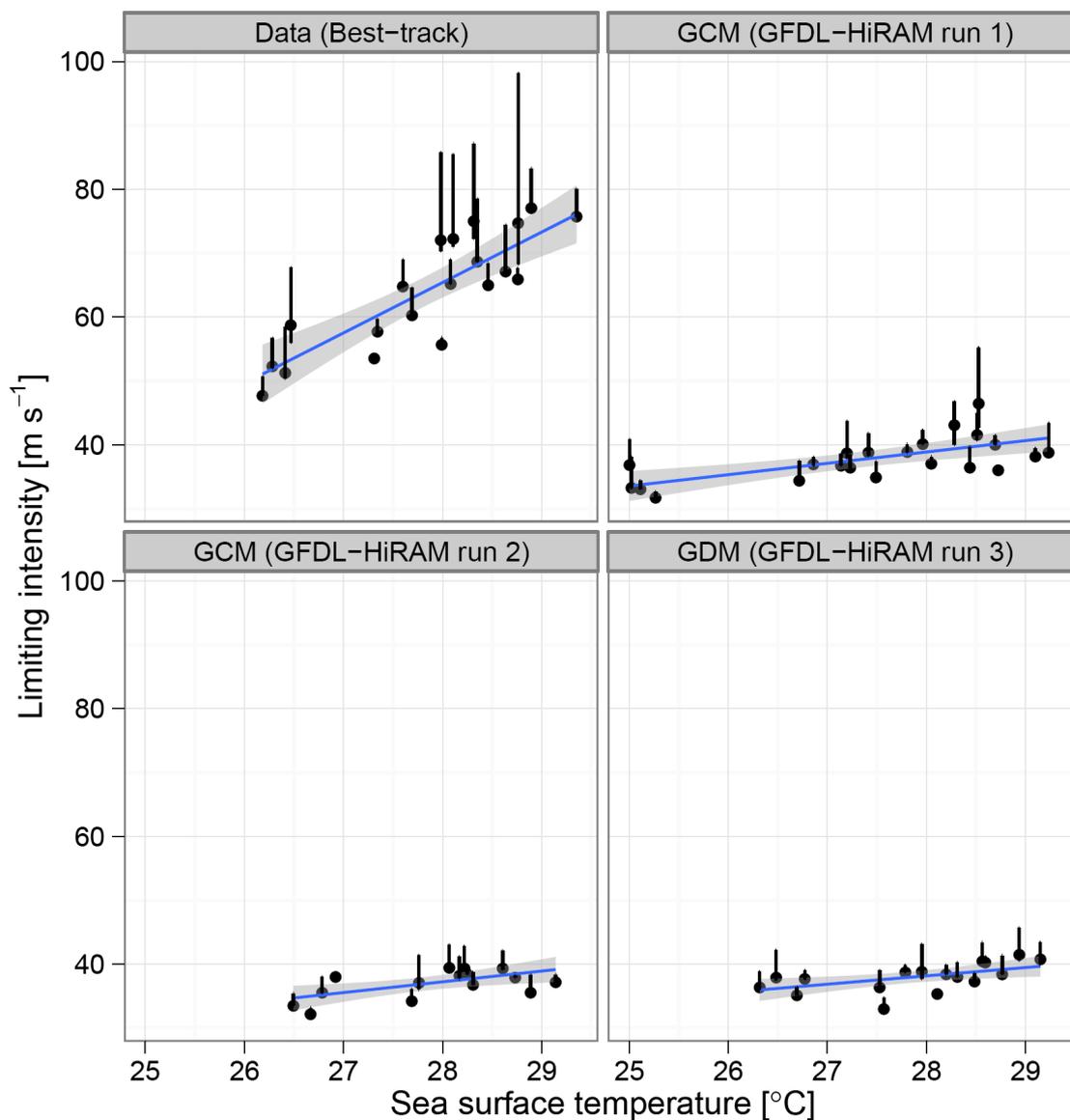


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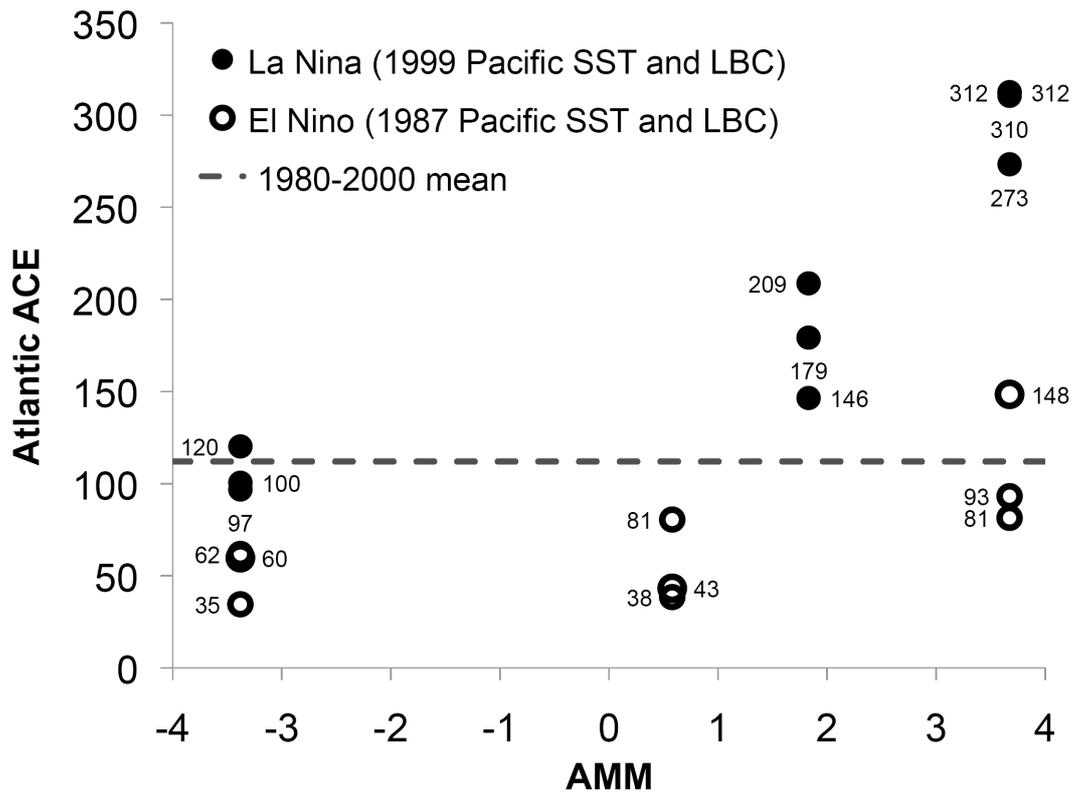


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