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Author/s:

Diro, GT;Giorgi, F;Fuentes-Franco, R;Walsh, KJE;Giuliani, G;Coppola, E

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Tropical cyclones in a regional climate change projection with RegCM4 over the CORDEX Central America domain --Manuscript Draft--

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Corresponding Author:	Gulilat Tefera Diro, PhD International Centre for Theoretical Physics Trieste, ITALY
Corresponding Author Secondary Information:	
Corresponding Author's Institution:	International Centre for Theoretical Physics
Corresponding Author's Secondary Institution:	
First Author:	Gulilat Tefera Diro, PhD
First Author Secondary Information:	
Order of Authors:	Gulilat Tefera Diro, PhD Filippo Giorgi, PhD Ramon Fuentes-Franco, MSc Kevin J. E. Walsh, PhD Graziano Giuliani, MSc Erika Coppola, PhD
Order of Authors Secondary Information:	
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Tropical cyclones in a regional climate change projection with RegCM4 over the CORDEX Central America domain

G.T. Diro^{1*}, F. Giorgi¹, R. Fuentes-Franco¹, K.J.E. Walsh,² G. Giuliani.¹, E. Coppola¹

¹Earth System Physics Section, The Abdus salam ICTP, Trieste, Italy

² School of Earth Sciences, University of Melbourne, Victoria, Australia

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*Correspondence to: Gulilat Tefera Diro, Centre ESCER, University of Quebec at Montreal (UQAM), 201 President Kennedy Avenue, PK2220, Montreal, Canada ; email: diro@sca.uqam.ca, Tel: +1 514-987-3000 (ext 1959)

Abstract

The characteristics of tropical cyclones (TCs) over the Central America Coordinated Regional Downscaling Experiment (CORDEX) domain are examined for present and future climate conditions using the regional climate model RegCM4. RegCM4 is first tested in a 22 year (1982-2003) simulation with boundary forcing from the ERA-Interim reanalysis, showing a generally good performance in reproducing the observed TC climatology. Four scenario simulations (1970-2100) are generated using two model configurations and two driving global models (MPI and HadGEM). The simulations employing the Grell convection scheme produced too few TCs, while those using the Emanuel convection scheme reproduced the observed climatology, especially when driven by the MPI global model. The simulation of TCs was thus sensitive to both the model convection scheme and the forcing GCM. Comparison of future and present day TC statistics indicates that the frequency of future TCs decreases over the tropical Atlantic and the East Pacific coastal areas while it increases over the western areas of the East Pacific and the northern areas of the Atlantic. We also find an increase in the frequency of intense TCs and long lasting TCs, along with a northward shift of TC tracks over the Atlantic. Conclusions on the changes in TC activity are not found to be sensitive to the inclusion of SST thresholds in the detection procedure. These findings provide encouraging indications for the use of the CORDEX framework in the study of TCs and are suggestive of important effects of global warming on the characteristics of TCs in the tropical Atlantic and Pacific basins.

1 Introduction

Tropical Cyclones (TCs) are one of the high impact weather and climate events affecting Central and North America, as the region is surrounded by favorable conditions for the formation of TCs. Given the devastating nature of TCs, there is an interest in how their frequency, duration and intensity may change under greenhouse gas forced global warming. Many modeling studies analyzed the characteristics of TCs in future climate projections using Global Circulation Models (GCMs) (e.g. Bengtsson *et al.*, 2007; Yoshimura *et al.*, 2006; Oouchi *et al.*, 2006; Knutson *et al.*, 2010; Murakami and Wang, 2010; Wehner *et al.*, 2010; Murakami *et al.*, 2012a,b). These studies however give contradictory results especially on changes in the frequency of TCs under global warming scenarios in specific ocean basins, most noticeably the Atlantic. For instance Bengtsson *et al.* (2007) and Yoshimura *et al.* (2006) found a decrease in the number of TCs, while Oouchi *et al.* (2006) and Wehner *et al.* (2010) found an increase, and others (Murakami and Wang (2010)) found no significant change or results dependent on the model configuration and resolution (Murakami *et al.*, 2012b). Most of the above studies find better agreement on the increase of the frequency of the most intense TCs in a warmer climate, a result consistent with the theoretical models of Emanuel (1987) and Holland (1997). Recently Knutson *et al.* (2010) reviewed modeling studies on TCs and climate change and concluded that the frequency of global TC (genesis) activity will decrease in the future, but their average intensity, along with the number of intense TCs, will increase. They also noted that there remains

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9 a large uncertainty in regional TC activity changes, implying the need for further
10 regional investigations. One of the uncertainties in the assessment of future regional
11 TC activity is associated with the uncertainties in the projected patterns of SST
12 changes (Vecchi and Soden , 2007; Sugi *et al.* , 2009). In addition, although GCMs
13 using a resolution of the order of 100km capture the origin and spatial distribution
14 of TCs, they have more problems in reproducing other TC characteristics, such as
15 maximum wind speed (Yoshimura *et al.*, 2006). Oouchi *et al.* (2006); Bengtsson *et al.*
16 (2007); Murakami and Wang (2010); Murakami and Sugi (2010); Murakami *et al.*
17 (2012b) recently showed that GCMs running at a high resolution can better capture
18 the fine scale features associated with TCs compared to low resolution models. An
19 alternative approach to simulate TC activity is to downscale the GCM output using
20 statistical-dynamical methods (Emanuel, 2006), statistical methods Villarini *et al.*
21 (2012) or regional climate models (RCMs) at higher spatial resolution over a specific
22 region.

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45 RCMs have indeed been used for studying the influence of global warming on
46 future TC activity in different ocean basins (e.g., Knutson *et al.*, 1998; Knutson
47 and Tuleya, 2004; Knutson *et al.*, 2008; Nguyen and Walsh, 2001; Walsh *et al.*,
48 2004; Stowasser *et al.*, 2007; Semmler *et al.*, 2008; Nguyen and Walsh, 2001; Walsh
49 and Ryan, 2000; Walsh *et al.*, 2004). RCM studies covering the North Atlantic re-
50 gion have employed different experiment designs. For instance, Knutson and Tuleya
51 (2004); Knutson *et al.* (1998); Hill and Lackmann (2011) initialize the TC by inserting
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9 hurricane-like idealized vortices in their RCM rather than directly downscaling a given
10 GCM. Knutson *et al.* (2007) ran a high resolution RCM over the Atlantic domain to
11 reproduce the present day characteristics of TCs using lateral boundary conditions
12 from the NCEP reanalysis and nudging not only in the buffer zone but also in the
13 interior model domain. Their experiment reproduced well the recent multi-decadal
14 increase in the TC activity. Semmler *et al.* (2008) studied future changes (A2 emission
15 scenario) in North Atlantic cyclone frequency and intensity using the Rossby Centre
16 RCM (RCA3) driven by a coupled ECHAM5-OM1 model and found an increase in
17 the frequency of intense cyclones along with a decrease in the frequency of TCs with
18 wind speed greater than 18 m s^{-1} . From the studies above it is clear that RCMs
19 can be useful tools to study the evolution of the characteristics of TCs under global
20 warming conditions.
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39 Here we present results from a series of scenario simulations conducted with the
40 ICTP regional model RegCM4 (Giorgi *et al.*, 2012) driven by two different GCMs
41 under present day and future climate (8.5 W m^{-2} representative concentration path-
42 way, orRCP8.5) (Taylor *et al.*, 2012) for the Central America domain specified in the
43 CORDEX framework (Giorgi *et al.*, 2009). This domain covers the north Atlantic and
44 Eastern Pacific basins, and thus offers the opportunity to assess the simulation of TC
45 characteristics under forcing from increased Greenhouse Gas (GHG) concentrations.
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9 physics configurations. Therefore, we have an ensemble of 4 model runs (two GCMs,
10 two RCM configurations), which allows us to assess the sensitivity of the results to
11 these different factors. In addition, as reference we analyze a simulation in which the
12 RCM is driven by a reanalysis of observations.
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19 Our analysis addresses first the performance of the model in reproducing observed
20 TC characteristics over the basin (frequency, intensity, track) and then the changes in
21 these characteristics in the scenario simulations. TCs are identified with the use of a
22 detection and tracking algorithm similar to Nguyen and Walsh (2001) and Walsh *et al.*
23 (2004) with and without the inclusion of an SST threshold as a detection criterion.
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34 **2 Data, Models, and Methods**

35 **2.1 Data: observed tropical cyclone and hurricane data**

36 **Data**

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39 The dataset of observed TCs (obtained from the Unisys Web site
40 <http://weather.unisys.com/hurricane/>) is produced by the Tropical Prediction Cen-
41 tre/National Hurricane Centre of the US. It consists of six hourly best-track data and
42 contains information such as the central location of named TCs and the associated
43 maximum wind speed and sea level pressure for both the Atlantic and East Pacific
44 basins. Here we consider only the TCs with intensity corresponding to 1-min sus-
45 tained surface wind of $17.5ms^{-1}$ or greater. We use only the portion of the dataset
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9 covering the period 1982-2003 to evaluate the RegCM simulation, since this is the
10 period covered by the reference simulations.
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15 **Experiment design and analysis**

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19 The climate model used here is the latest version of the Abdus Salam International
20 Centre for Theoretical Physics (ICTP's) Regional climate model (RegCM4) which is
21 described by Giorgi *et al.* (2012). RegCM4 has a hydrostatic dynamical core and
22 multiple physics options. In all the present runs we use an updated version of the
23 radiation scheme of the Community Climate Model (CCM3) (Kiehl *et al.*, 1996), a
24 modified version of the planetary boundary layer scheme of Holtslag *et al.* (1990),
25 and the resolvable scale precipitation scheme of Pal *et al.* (2000). Here we use two
26 of the model cumulus convection schemes, those of Grell (Grell, 1993) and Emanuel
27 (Emanuel, 1991), which were found to better simulate the climate of the region in a
28 series of preliminary experiments. The main difference between these two schemes is
29 that in the Grell scheme, convection is activated after a parcel is lifted in the updraft
30 and reaches the level of moist convection whereas in the Emanuel scheme, convection
31 is set off when the level of buoyancy is higher than the cloud base (Giorgi *et al.*,
32 2012). A mixed convection configuration is also available in the latest version of
33 RegCM4 whereby the Emanuel and Grell schemes are used over land and ocean grid
34 points, respectively, and vice versa (Giorgi *et al.*, 2012). The model has two options to
35 represent land surface processes, namely the Biosphere Atmosphere Transfer Scheme
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9 (BATS, Dickinson *et al.*, 1993) and the Common Land Model (CLM, Oleson *et al.*,
10 2008). Here the diurnal SST scheme of Zeng and Beljaars (2005) is also used, which
11 calculates the diurnal evolution of the ocean skin temperature based on energy budget
12 considerations. A number of these schemes were tested in preliminary experiments by
13 Diro *et al.* (2012), who found that the model climatology over the Central America
14 CORDEX domain is sensitive to both convection and land surface parameterization,
15 with different schemes performing better over different sub-regions. We thus decided
16 to conduct scenario experiments with two distinct model configurations:
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- 30 1. 'Perfect' Boundary Condition experiment: The configuration for this experi-
31 ment is the same as in the study conducted by Fuentes-Franco *et al.* (2013)
32 and is analyzed for the period between 1982-2003. The initial and six-hourly
33 lateral boundary driving fields are from the ERA-interim reanalysis (Dee and
34 Co-authors, 2011) interpolated onto a 1.5° by 1.5° horizontal grid. Over the
35 ocean, Sea Surface Temperatures (SST) from the National Oceanic and Atmo-
36 spheric Administration (NOAA) optimal interpolation (OI) weekly SST data
37 (Reynolds *et al.*, 2002) are used. Land surface processes are represented via
38 the BATS (Dickinson *et al.*, 1993) scheme while convection is described by
39 the mixed parameterization using the Grell scheme over land and the Emanuel
40 scheme over the ocean. Fuentes-Franco *et al.* (2013) provides a detailed anal-
41 ysis of a number of aspects of this simulation, including a TC analysis based,
42 however, on different detection criteria than used here.
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9 2. The scenario experiment: In this experiment, we conducted an ensemble of four
10 integrations, all starting in 1970 and ending in 2100 with GHG forcing from the
11 Reference and RCP8.5 greenhouse gas scenario. The ensemble is composed by
12 Reference and RCP8.5 greenhouse gas scenario. The ensemble is composed by
13 two RegCM4 configurations each driven by two GCMs for lateral and surface
14 two RegCM4 configurations each driven by two GCMs for lateral and surface
15 boundary conditions. In the first configuration (Grell-BATS), the model uses
16 the Grell convection scheme and the BATS land surface package, while the sec-
17 ond (Eman-CLM) includes the MIT convection parameterization and CLM for
18 the land surface. These two configurations are thus quite different, to the point
19 of possibly being considered as two different RCMs. Both model configurations
20 are forced by the HadGEM2-ES (Collins *et al.*, 2011) and MPI-ESM (Zanchettin
21 *et al.*, 2012) global model output taken from the Climate Model Intercompari-
22 son Project phase 5 (CMIP5) dataset (Taylor *et al.*, 2012). HadGEM2-ES has
23 a resolution of 1.875 by 1.25 degrees in the horizontal and 38 levels in the ver-
24 tical, whereas MPI-ESM has a horizontal resolution of 1.875 x 1.875 degrees
25 and 47 hybrid sigma-pressure levels in the vertical. Though the integrations
26 are carried out from 1970 -2100, we selected the period 1982-2003 to represent
27 present day conditions (Control) consistently with the perfect boundary con-
28 ditions (reference) experiment, and the period 2078-2099 (same length as the
29 Control period) to represent future conditions. All analysis is carried out and
30 compared for these two periods.
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9 The model domain follows the CORDEX (Giorgi *et al.*, 2009) specifications and covers
10 a large region encompassing Central America (15W - 145W and 25S-42N). Twelve grid
11 points in each direction are allocated for each lateral buffer zone where an exponential
12 nudging is used to combine the model fields and the boundary conditions (Giorgi *et al.*,
13 1993). Our analysis focuses on the inner regions of the domain covering the Central
14 America continental area and adjacent ocean regions(0 - 40N, 20W - 140W) where
15 the TC tracks are located. Following CORDEX, the model horizontal grid spacing
16 is 50km, while in the vertical 18 terrain following σ levels are used as in Diro *et al.*
17 (2012) and Fuentes-Franco *et al.* (2013).
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34 **2.2 Methods for detection and tracking**

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37 The TC detection method employed here is similar to that used in earlier studies
38 by Nguyen and Walsh (2001) and Walsh *et al.* (2004). However, since the detection
39 threshold of various variables depends on the model resolution, here the thresholds
40 are modified to obtain an optimal match with observations. They are:
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- 48 • The relative vorticity at 850hPa must be greater than $1.0 \times 10^{-5} \text{ s}^{-1}$
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52 • There must be a closed pressure minimum within the radius of 100km. This
53 minimum pressure is then defined as the center of the cyclone. Note that use
54 of a 100km radius improves the TC distribution near the coasts.
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60 • The minimum surface pressure satisfying the above criteria is at least 2 hPa
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9 lower than the averaged surface pressure over the surrounding 2X2 grid boxes.

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- 13 • The 10m surface wind speed must exceed 17.5m s^{-1}
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16 • The total tropospheric temperature anomaly calculated by summing the tem-
17 perature anomalies at 700, 500 and 300hPa around the center of the cyclone
18 must be greater than zero.
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21 • The minimum pressure at the center of the cyclone at the genesis must be over
22 ocean points where the SST is higher than 26°C .
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31 In the current climate, tropical cyclones typically form only if the SST is above
32 about 26°C (e.g. Gray, 1975). Here, we apply this threshold to both current and
33 future climate simulations. However, we also test the impact of removing this SST
34 threshold on the differences in tropical cyclone formation between current and future
35 climate.
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43 Tracking is then performed on those grid points satisfying the above detection
44 criteria. The following procedure is used to create a tracking database
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- 48 1. For each detected cyclone point, a check is performed on each six hourly sample
49 to see whether there are cyclones during the 24 hour period within a radius of
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57 6 X 6 longitude-latitude grid boxes.
- 58 2. If there are some cyclones detected satisfying the previous condition, then the
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65 closest cyclone is chosen as belonging to the same track as the initial one.

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9 3. To qualify as a track, there must be more than one detection within the next
10 24 hours and within a 6 X 6 longitude-latitude grid boxes.
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17 **3 Results and Discussion**

18 **3.1 Result from the ERA-Interim runs**

19 **Tropical Cyclone tracks and frequency of occurrence**

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25 Before analyzing the results from downscaling of the GCMs, it is useful to assess the
26 model performance when forced with re-analysis surface and boundary conditions,
27 as this is more representative of the model's inherent behavior. Figure 1 (Top two
28 panels) shows the spatial distribution of tropical cyclone tracks and the number of
29 occurrences within 1X1 degree grid box squares from observations and from the ERA-
30 interim forced RegCM4 simulation during the active July to October (JASO) season.
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The convection scheme of this RegCM4 run is the mixed parameterization (Emanuel over ocean, Grell over land). The tracks of simulated TCs show realistic features, such as starting from the Northern Atlantic and moving towards the west and the north. The track density, computed by counting the number of tropical cyclones within a 1X1 degree box (Fig 1 second row) also indicates that the model captures the spatial pattern of the climatology of TC counts, such as the maximum concentration over the tropical Pacific and minimum over the eastern Atlantic. However, the simulated number of TCs is generally overestimated in the Atlantic and underestimated over

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9 the East Pacific. This result is consistent with that of Fuentes-Franco *et al.* (2013)
10 who used a different detection methodology employing pressure, precipitation and
11 wind speed, although the detected climatological values here match the observed
12 dataset better. Fuentes-Franco *et al.* (2013) attributed the model overestimation of
13 the TC counts over the Atlantic to an underestimation of the vertical wind shear.
14 In addition, the simulated tracks do not travel as far north as the observed tracks.
15 This is likely related to the best track data retaining storms that either have begun
16 or have completed a transition to extra tropical status, thus leading to longer tracks
17 (e.g., Evans and Hart, 2003).
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32 Figure 2 (bottom panel) shows the standardized year to year variability in TC
33 count over the North Atlantic and East Pacific. It can be seen that the interannual
34 variability over the North Atlantic is realistically simulated by RegCM4 ($R=0.57$),
35 although there is a bias in the variability and mean number of TC counts. Over this
36 basin it is noted that the number of TC counts increases with time in the observations
37 which is in agreement with previous studies (e.g. Knutson *et al.*, 2008). The model
38 also captures this upward trend in the TC counts but the slope is lower than in the
39 observations. The inter-annual variability over the East Pacific on the other hand is
40 less well reproduced ($R=0.27$) by RegCM4. It should be stressed that we do not have
41 any data assimilation in the interior of the domain, so that the simulation of TCs is
42 affected by the internal variability and chaotic behavior within the model which will
43 tend to degrade the year to year agreement with observations.
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9 The mean annual cycle of the TC count over the entire Central America CORDEX
10 domain, as well as separately for the East Pacific and north Atlantic basins, is shown in
11 Fig. 2 (top panel). Generally speaking, the average number of grid points where TCs
12 are detected is near zero in the beginning of the year, increases in July, reaches a peak
13 in September and finally decreases throughout the Autumn. This pattern, including
14 the peak timing is well reproduced by the RegCM4, although the September peak is
15 overestimated due to the overestimation of TCs in the Atlantic basin. Comparison
16 of the annual cycle of each basin reveals that the TC activity over the East Pacific
17 matures during the early summer months and persists for the remainder of the season,
18 with a slight enhancement in September, thereby showing a longer season compared
19 to the Atlantic. The model however underestimates the amount of TCs during the
20 peak season in the East Pacific. Over the north Atlantic most of the TC activity is
21 concentrated near the peak month of September.

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42 Overall, these results suggest that RegCM when forced with ERA-interim reanal-
43 ysis can reproduce most of the main characteristics of the observed TCs such as
44 the spatial pattern and the basic features of the annual cycle. More analysis of TC
45 characteristics in this run is presented by Fuentes-Franco *et al.* (2013).
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54 **3.2 Present day (Control) simulation of Tropical cyclones**

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58 The tropical cyclone track density from multiple GCM forcing and multiple RCM
59 physics configurations in the present day (Control) period is shown in Figure 1 (bot-
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9 tom panel) and Supplementary Figure 1. The Emanuel convection scheme produces
10 TC numbers close to the observed track density under driving conditions from the
11 MPI GCM (Fig. 1 (bottom two panels)). The Grell convection scheme produces
12 low TC counts irrespective of the GCM used to drive the model, although the MPI
13 forced run simulates more TC than the HadGEM2 forced run (Supplementary Figure
14 1). The impact of convection scheme on the TC representation was already noticed
15 by several studies such as Kim *et al.* (2012); Yoshimura *et al.* (2006); Murakami
16 *et al.* (2012a). For instance, Murakami *et al.* (2012a) noted that the Arakawa Schu-
17 bert (AS) scheme produced very few TCs over the Atlantic and East Pacific oceans
18 compared with the Yoshimura and Kain -Fritsch schemes. Yoshimura *et al.* (2006)
19 also found a sensitivity of TC frequency to the convection scheme. They found that
20 the Kuo scheme produced very few TC occurrences especially over the Atlantic basin
21 when a TC wind speed intensity of 15ms^{-1} or more was considered. Our results
22 thus confirm previous studies in indicating a strong sensitivity of TC occurrence to
23 convection scheme. Inter-comparison of the simulated TC track density (Figure 1
24 bottom panel and Supplementary Figure 2) reveals that also the driving GCM has a
25 strong impact in the formation of TCs, with the MPI-ESM forcing producing more
26 TCs than the HadGEM2-ES one in both RegCM configurations. The HadGEM2-ES
27 forced run with the Emanuel convection scheme produces a realistic number of TCs in
28 the NW Atlantic and over the East Pacific but misses much of the TC activity south
29 of 25N over the Atlantic ocean. Over the Eastern Pacific, HadGEM2-ES reproduces
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9 the maximum TC counts well. One of the reasons why the HadGEM2-ES forced
10 RegCM simulation produces less TCs over the Atlantic south of 25N is because the
11 SSTs of HadGEM2 used as lower boundary condition for the RegCM4 are lower than
12 both the MPI and observed SST from HadISST (supplementary Figure 3).Camargo
13 (2013) and Sheffield *et al.* (2013) also noted that, although the TC counts (especially
14 the intense ones) are underestimated in all CMIP5 GCMs because of their low resolu-
15 tion, HadGEM2 shows the largest underestimation in the present day climate. They
16 also found that the MPI model produced the best TC track over the Atlantic. This
17 highlights the importance of reliable surface and lateral boundary forcing in order
18 to achieve a realistic simulation of TC climatology with a RCM. The above analysis
19 suggests that out of two GCM forcings and the two RegCM4 physics configurations,
20 the RegCM4 configured with the Emanuel convection scheme and MPI-ESM surface
21 and boundary forcing produced a realistic simulation of TC frequency for present day
22 climate conditions.

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45 The annual cycle from the present day control run forced with HadGEM2-ES and
46 MPI-ESM (Fig 2) suggests that the RegCM4 (CLM-EMAN) configuration forced with
47 both GCMs reproduces generally well the observed annual cycle of TC frequency
48 especially over the eastern Pacific (data from the Grell-BATS runs are not shown
49 because they heavily underestimated the TC count). Both GCM forced runs, however,
50 shift the peak of TC season by about one month over the Atlantic basin, though the
51 ERA-interim forced run using the Emanuel scheme over ocean reproduced it quite
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9 well. This again indicates the importance of accurate boundary forcing. Note that,
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11 interestingly, over the East Pacific both GCM forced runs reproduce the annual cycle
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13 of TC occurrences better than the ERA-interim forced run.
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18 **3.3 Future changes: TC frequency and Duration**

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22 In order to assess the future changes in TC characteristics, we only analyze the
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24 runs employing the MPI-ESM driving field and the Emanuel convection scheme, as
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26 the Grell scheme and the HadGEM2-ES driving field did not produce a realistic
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28 climatology of TCs in the present day period. Figure 1 (bottom right panel) shows
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30 the future TC track density from the RegCM4 simulation. The RegCM4 simulation
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32 yields an increase in TC frequency over the western areas of the East Pacific and
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34 also a slight increase in the northern part of the domain, but a decrease over the
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36 eastern Pacific close to the coasts of Central America and over most areas of the
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38 tropical Atlantic. This is suggestive of a poleward shift in the TC occurrence and/or
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40 track, which could also imply that more cyclones will reach the northeast coasts of
41
42 the United States. Such poleward shift in TC tracks with global warming was also
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44 reported for the Australia region by Walsh *et al.* (2004) and Lavender and Walsh
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46 (2011), and may be associated with higher SSTs over the northern ocean regions
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48 creating a more conducive environment for the sustainability of TCs further north
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50 or even for the formation of new TCs. Figure 3 (top panel) shows the TC genesis
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52 frequency for the present and future climate, which leads to conclusions consistent
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9 with the track analysis i.e. greater genesis over the western areas of the Eastern Pacific
10 and lower genesis over the tropical Atlantic and Eastern Pacific coastal regions. The
11 comparison of the future and present day TC genesis frequency over the Central
12 America domain clearly shows a decrease in the total number of TC genesis in the
13 future climate period. The reduction of TC frequency over the Atlantic is consistent
14 with the RCM study of Knutson *et al.* (2008) and the high resolution global model
15 study of Bengtsson *et al.* (2007), although results from other modeling studies suggest
16 an increase in the number of TCs over the North Atlantic (e.g. Oouchi *et al.*, 2006).
17 Villarini *et al.* (2011) emphasized the role of the SST projections over the Atlantic as
18 one of the reasons for the uncertainty in the projection of Atlantic cyclone frequency.
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35 The decrease in TC frequency over the tropical Atlantic from the MPI-ESM forced
36 run is in line with an increase in wind shear in future climate conditions (Supplemen-
37 tary Figure 4) which is consistent with the result obtained by Vecchi and Soden
38 (2007). In addition, the stronger upper troposphere static stability (supplementary
39 Figure 5) in future climate conditions also contributes to the decrease in TC fre-
40 quency. The slight decrease in the vertical wind shear (supplementary Figure 4,
41 which is also shown in Camargo , 2013) over the northern boundary of the domain
42 over the Atlantic ocean could also contribute to the increase the TC frequency there.
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44 The height-longitude temperature profile averaged over the Atlantic and the East
45 Pacific (supplementary Figure 5) indicates that future climate warming is observed
46 throughout the troposphere with a maximum at around 200mb over the Atlantic
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9 and East Pacific. This increase of warming with height is consistent with the result
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11 Knutson and Tuleya (2004) and Hill and Lackmann (2011) , who suggest that it is a
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13 consequence of moist convection.
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17 The annual cycle of TC occurrence in the future period (Figure 2) shows that the
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19 characteristics of the change in the two ocean basins are different, For instance in the
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21 Atlantic basin, the MPI forced run shows a reduction in all months, and maximum
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23 at the beginning of the cyclone season. On the other hand, over the eastern Pacific
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25 basin, the simulation shows a marked increase in the TC frequency during the peak
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27 month, though there is a slight reduction in July. The dominant change (when the
28
29 whole CORDEX domain is considered) in the annual cycle is the weakening of TC
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31 activity during the early phase of the TC season and the intensification of the activity
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33 towards late summer/autumn, thereby shifting the annual cycle towards later times
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35 of the year.
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43 The simulated tracks for the present day and future climate under the RCP8.5
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45 scenario (Figure 1 third row) indicate that over the eastern Pacific not only the
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47 number of TC tracks becomes higher but that the tracks also move further north
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49 compared to present day conditions. This increase in TC activity over the eastern
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51 Pacific could be linked to the decrease in vertical wind shear in the future climate
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53 and the increase in SST, whereas the decrease of TC in the coastal regions (Fig. 1
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55 bottom panel) could be due to the shift in the genesis region to the western areas of
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57 the East Pacific. This westward shift in the genesis resembles the events that occur
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9 during a positive phase of ENSO, as warm ENSO years are associated to a shift of
10 the TC activity from the eastern Pacific towards the central Pacific (e.g. Camargo
11 *et al.*, 2008).
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16 The TC tracking over the Atlantic (Figure 1 third row) shows generally lower
17 number of tracks but, as in the East Pacific, tracks that are longer and travel further
18 distances. In fact, Figure 3 (bottom panel), which shows the histogram of the duration
19 of tracks for the present and future climate periods, reveals that although the number
20 of TCs with short duration decreases (especially those lasting less than four days)
21 the number of long lasting TCs show a slight increase, which is likely linked to the
22 sustainability of cyclones to travel north due to the higher SSTs.
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36 **3.3.1 Intensity**

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39 Analysis of the simulated maximum wind speed associated with the TCs (Fig. 3, bottom
40 panel) shows that, although the number of low intensity TCs decreases in the future,
41 the number of TCs with intense wind speed actually increases. It is important to
42 notice that the intensity of cyclones (as measured by maximum wind speed) in the
43 present day simulation is generally weaker than in the observations (Supplementary
44 Figure 6 and Figure 3 middle row left panel). Here, however we focus on the compar-
45 ison of the wind speed between the present and future simulations. Figure 3 (middle
46 panel) shows the spatial pattern of maximum wind speed in the RegCM4 simulations
47 for the present day and future climate. This comparison reveals an increase in the
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9 number of TCs with intense wind speed. In addition, the change in intense TC is
10 more coherent and pronounced over the Eastern Pacific than the Atlantic.
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14 This change in the TC intensity found in the future climate conditions could be
15 attributed to either future projected regional SST changes compared to the tropical
16 mean (Villarini and Vecchi , 2012) or future changes in vertical wind shear, given
17 that future stabilization tends to reduce the TC occurrence. The increase in in-
18 tense TC under GHG forcing is also reported in previous GCM (e.g Oouchi *et al.*,
19 2006) and RCM studies (e.g Knutson *et al.*, 2008; Knutson and Tuleya, 2004; Walsh
20 *et al.*, 2004), as well as theoretical estimates using thermodynamical considerations
21 (Emanuel, 1987; Holland, 1997).
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36 **3.4 Sensitivity to the removal of SST threshold from the de-** 37 **tection criteria** 38 39 40

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42 In this section, we analyse the impact of removing the SST threshold from the list
43 of detection criteria. Fig 4 shows the characteristics of TCs in the present and
44 future climate from the MPI driven RegCM run when the SST threshold criterion
45 is removed. As expected, the number of detected cyclones are higher both in the
46 present and future climate compared to the case when the SST detection criterion
47 is used, however the pattern and change in the characteristics of TCs are similar
48 between the two cases. For instance, the frequency of future tropical cyclones is
49 found to be lower in the tropical Atlantic but higher in the Eastern Pacific (except
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9 over the coastal areas), which is consistent with that obtained when including the
10 SST detection threshold (compare Fig. 1, rows 3 and 4 with Fig. 4, rows 1 and
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12 2) Similar conclusions can also be drawn in terms of change in the intensity and life
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14 cycle of TCs, i.e. the frequency of weak and short lived cyclone decreases in the
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16 future period, while that of intense and long lived cyclones show a slight increase or
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18 no change (compare Fig. 3). These results suggest that the inclusion of SST as a
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20 TC detection criterion does not strongly modify our conclusions concerning changes
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22 in TC activity.
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32 **4 Summary and conclusions**

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36 In this study, the ICTP RegCM4 was used to investigate the characteristics of TCs
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38 in current and future climate conditions to address the issue of how the TC statistics
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40 surrounding Central America might change under increased GHG forcing. Analysis
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42 of TC frequency and annual cycle produced by RegCM4 when forced by re-analysis
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44 boundary conditions and observed SSTs shows that the model captures most of the
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46 features of the observed TC climatology, although the number of TCs is overestimated
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48 over the Atlantic sector and underestimated over the Pacific.
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53 Investigation of the sensitivity of the TC climatology to convection scheme and
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55 driving GCM shows the following:
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- 59 • The Grell convection scheme produces very few TC counts whereas the Emanuel
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61 scheme produces a realistic climatology of TC occurrences.
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- The HadGEM2-ES forced RegCM4 produces unrealistic TC counts over the tropical Atlantic because of a cold SST bias there but it reproduces the TC frequency over the East Pacific.
- The MPI-ESM forced RegCM-Emanuel configuration reproduces well the TC climatology for the present climate and proves to be the best combination to study TC characteristics in future climate conditions.

Our results for the future climate projections under the RCP8.5 scenario indicate the following:

- Results from the RegCM4-Emanuel configuration suggest that the future frequency of the most intense TCs and the number of TCs with longer life cycle (especially those lasting longer than a week) slightly increase.
- The overall frequency of TCs decreases in the Atlantic and coastal regions of the Pacific but increases over the western areas of the East Pacific. The increase in the region is likely due to a decrease in the wind shear over the East Pacific. The decrease over the Atlantic can likely be attributed to the increase in vertical wind shear and stability in the upper troposphere.
- Over the Atlantic the TCs decrease in frequency but also shift towards higher latitudes.
- On the sub seasonal scale, the TC activity is reduced more during the beginning of the TC season compared to the end of the season.

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Another important point dealt in this study is the use of SST threshold for cyclone detection, and our analysis shows that removing this threshold does not substantially modify most of our conclusions. This issue, however, needs to be addressed in more detail for other regions and models to determine the reasons for the apparent lack of sensitivity to this threshold. Our results provide encouraging indications towards the capability of the CORDEX framework to study the future evolution of TC characteristics in the Central America domain, even at relatively coarse regional model resolutions. As more simulations become available, more robust assessments can be completed, in particular of the uncertainties associated with GCM forcing and physics configurations. It will also be important to investigate the sensitivity of the results to model resolution and to undertake a similar study for other CORDEX domains that are prone to TC formation.

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Figure 1: Cyclone track and track density during JASO season. Top panel: Cyclone track from HURR dataset with criteria wind speed $> 17.5 \text{ ms}^{-1}$ (left) and from RegCM4 forced with ERA-Interim reanalysis (right). Second panel from the top: cyclone track density - number of cyclones per 1×1 degree box (bottom) for the same data as in the first row. Third row: Cyclone track from MPI driven RegCM4 simulation for the present day (left) and future climate with RCP85 scenario (right). Bottom panel: Cyclone track density for the same simulation as in the third row. The convection scheme of for the ERA-interim driven RegCM4 run is the mixed parameterization (Emmanuel over the ocean, Grell over the land) , whereas for the MPI driven RegCM4 run the convection scheme is Emanuel everywhere.

Figure 2: Top panel: Annual cycle of tropical cyclone formation over North Atlantic (left), East Pacific (middle) and the entire CORDEX Central America domain (right) bottom panel: inter-annual variability of TC over North Atlantic (left), East Pacific (right)

Figure 3: MPI driven RegCM4 TC characteristics during JASO season. Top panel: TC genesis density for the present (left) and future RCP85 climate (right). Middle panel: Cyclone Intensity (maximum wind speed [m s^{-1}]) for the present day (left) and future RCP85 climate (right). Bottom panel: Histogram of life cycle of TCs for present day and for the future (RCP85) climate (left) and the wind speed distribution for present and future simulation (right)

Figure 4: MPI driven RegCM tropical cyclone characteristics during JASO obtained from the outputs that remove SST threshold from the detection criteria.Top panel: Cyclone track for MPI driven RegCM output of the present day (left) and future RCP85 scenario (right). Second row from the top: cyclone track density for the same data as in the top panel. Third row: Cyclone Intensity (maximum wind speed [m s^{-1}]) for the present day (left) and future RCP85 scenario (right). bottom panel: Histogram of life cycle of TCs for present day and for the future (RCP85) MPI driven RegCM4 run (left) and the wind speed distribution for present and future simulation of MPI driven RegCM output (right).

Reviewers' comments:

Reviewer #1:

Recommendation: Need major revision.

Major Comment 1.

The authors did not address the most important point of my initial review. They continue to use a TC genesis scheme that requires the cyclone at genesis time to be over an ocean point where SST is higher than 26 deg C.

The authors do not justify why this questionable criterion is needed. Is it to eliminate extratropical storms? They have a separate warm core criterion that is supposed to do this. Other authors have used other features along with warm core to distinguish tropical and extratropical, without resorting to using a fixed SST threshold. In response, they claim that the fixed SST criterion essentially doesn't matter since "most of the results in the paper would be the same even if a different future threshold were used." If that is the case, then take out the flawed criterion, which would show that it doesn't matter. That also begs the question of why it is included in the first place. By leaving it in one would be encouraging future authors to make the same mistake in doing such an analysis. On the other hand, I'm not convinced that it doesn't matter for some features, such as the interesting poleward expansion (toward southern California) of NE Pacific TC genesis. The authors need to take out the fixed SST criterion so that we can see if this is a robust feature or an artifact of their (flawed) fixed SST criterion for genesis.

The authors also argue that the issue of whether a fixed SST threshold is appropriate is still a relatively open scientific question.

If it is true that a fixed SST threshold applies to TC genesis, under, say, 2 degrees C of tropical SST warming, this could be a much more important result for future climate change than anything else they report in the paper. Such a remarkable claim would need extraordinary evidence to support it, however, and they provide none.

In short, the paper is not publishable so long as the authors rely on a tropical cyclone identification scheme which uses a fixed (climate independent) SST threshold to determine whether a "TC genesis" has occurred.

Reply: Since observed tropical cyclones form over SSTs higher than 26C in the current climate (e.g. Gray, 1975), we thought that it would be an interesting test to see what would happen if we kept this threshold in the future climate as well. We do take the reviewer's point, though, and have also made an analysis of the TC characteristics in both present and future climate without using SST as one of the criteria in the detection procedure to see if the results are robust. We have now added a section 'sensitivity to the removal of SST' to discuss these results obtained from a detection procedure that doesn't consider SST as a criteria.

With regard to the specific comments made by the reviewer above, we find that, as expected, slightly more tropical cyclones are detected when the SST threshold is removed, but we also find that the simulated response to future climate change is remarkably similar to that seen when the SST threshold is included. This also includes the poleward expansion of NE Pacific TC genesis referred to by the

reviewer, which occurs in a similar fashion when the SST threshold is either retained or removed (compare Fig. 1, rows 3 and 4 with Fig. 4, rows 1 and 2). We find it particularly interesting that we don't seem to be detecting a much larger number of storms in poleward regions of this domain in the future climate when we remove the SST threshold. We do not suggest that the SST threshold for tropical cyclone genesis will remain constant in a warmer world, which indeed as the reviewer states would be an extraordinary claim, just that the SST threshold in this cyclone detection scheme does not appear to be a crucial factor in determining the response of changes in tropical cyclone numbers in these simulations.

Minor comments

2. p. 12, line 48, change equatorial to tropical

Reply: Corrected

3. p. 18, line 32, here could reference Villarini et al. J. Climate (2011) DOI:10.1175/2011JCLI3853.1, in particular the role of relative SST projections in explaining differences in Atlantic TC frequency projections.

Reply: Thanks for the comment, we have now cited the above reference at the relevant place

4. p. 19, line 48, the proposed connection to ENSO events here makes no sense as is. Do the authors mean to connect the TC changes to SST changes that resemble those during an ENSO warm event in some way for example?

Reply: Thanks for spotting the error, we have corrected the sentence and now reads as following. This westward shift in the genesis resembles the events that occur during a positive phase of ENSO, as warm ENSO years are associated to a shift of the TC activity in the eastern Pacific towards the central Pacific (e.g. Camargo et al., 2008).

5. p. 20, line 20. Is the increase in duration true for the Atlantic in isolation? That would be especially surprising given the reduction of genesis occurring in the deep tropics (favoring long tracks?) in the Atlantic basin.

Reply: True, it would be interesting to look at the two basins separately, but in this study we analysed the total cyclones from the combined Atlantic and East Pacific data.

6. p. 20. Missing from the discussion of intensity is any discussion of the limitation of the model in its present-day simulation of intensity. Please add an observed intensity distribution to the histogram, and note the limitations of the model (not unexpected given the relatively coarse resolution). Also the 26 m/sec threshold mentioned here may not really be meaningful as an absolute threshold given the models poor overall distribution of intensity.

Reply: Thanks for the comment, we have now added text that notes that the model underestimates the intensity of cyclones in the present day simulation.

'Analysis of the simulated maximum wind speed associated with the TCs (Fig. 3, bottom panel) shows that, although the number of low intensity TCs decreases in the future, the number of TCs with intense wind speed actually increases. It is important to notice that the intensities of cyclones (as measured by

maximum wind speed) in the present day simulation is generally weaker than those in the observations (Supplimentary Figure 6 and Figure 3 [middle left panel]). Here, however we focus on the comparison of the wind speed between the present and future simulation. Figure 3 (middle panel) shows the spatial pattern of maximum wind speed in RegCM4 simulations for the present day and future climate.....'

7. p. 22, line 37 "can likely be attributed..."

Reply: suggestion accepted

Reviewer #3: Recommendation: Minor Revision

General Comment:

This paper investigates the changes in tropical cyclone (TC) activity associated with climate change in the CORDEX Central America Domain (North Atlantic and East Pacific) by downscaling CMIP5 results using a regional climate model. Although there have been many modeling studies on the TC activity changes associated with climate change, there remains a large uncertainty in the regional TC activity changes. As this paper provides some new result and contributes to reduce the uncertainty in the regional changes in TC activity, the paper is basically worth publishing.

The authors properly revised the original manuscript. I recommend the paper be accepted after some minor revisions.

Specific Comments:

Page 2, Line 43: "eastern Pacific" should be "East pacific"

Reply: suggestion accepted

Page 2, Line 43: "the Central Pacific" should be "western part of the East Pacific". (throughout the paper "non-coastal area of the East Pacific" or "off-shore area of the East Pacific" or simply "most part of the East Pacific" may be better than "western part of the East Pacific" because the increase is found most part of the East Pacific except for the coastal area)

Reply: Central Pacific is changed to the western part of the East Pacific

Page 12, Line 48: "equatorial Pacific" should be "tropical Pacific".

Reply: comment well taken

Page 12, Line 53: "Eastern Pacific" should be "East Pacific".

Reply: changed

Page 13, Line 61: Add "(top panel)" after "Fig.2".

Reply: Added

Page 14, Line 56-58: "Clearly, the Emanuel convection scheme produces more TC events than Grell scheme and these TC numbers are close to" should be "The Emanuel convection scheme produces TC numbers close to". [TC number of Grell scheme is not shown in Fig.3]

Reply: Suggestion accepted and changed accordingly

Page 15, Line 14: Add "(supplementary Figure 1)" after "HadGEM2 forced run".

Reply: we have added now

Page 16, Line 42: "BATS-grell" should be "Grell-BATS".

Reply: Changed

Page 18, Line 42: "Atlantic" should be "the Atlantic".

Reply: thanks for the comment , we have now corrected it

Page 18, Line 42: Delete "Western part of"

Reply: Deleted

Page 18, Line 48: "Central Pacific" should be "East Pacific".

Reply: Changed

Page 20 Line 37: Delete "in both simulations".

Reply: deleted

Page 22, Line 32: "Western part" should be "western part".

Reply: Changed

Page 22, Line 35: "the Central Pacific" should be "the western part of the East Pacific" or "the region".

Reply: now "the Central Pacific" is changed to "the region"

Page 22, Line 37: "Equatorial Pacific" should be "East Pacific"

Reply: changed

Page 22, Line 57: Delete "from two ensembles".

Reply: deleted

Fig.3 Bottom panels: It is better to show, as in top and middle panels, TC genesis density, for present density in the left and future minus present density in the right, rather than showing TC genesis location by black dots.

Reply: Suggestion accepted and we have plotted it accordingly

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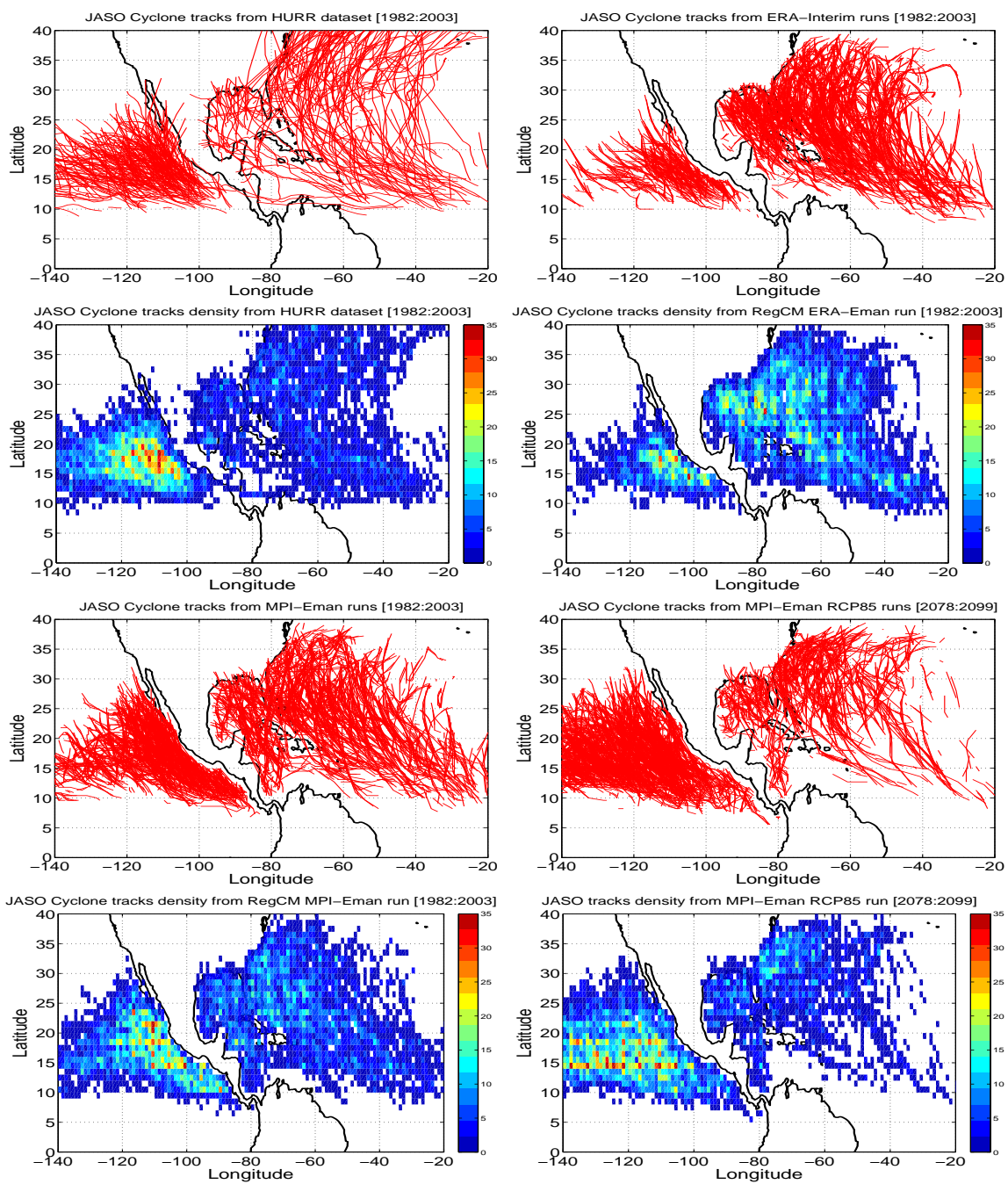


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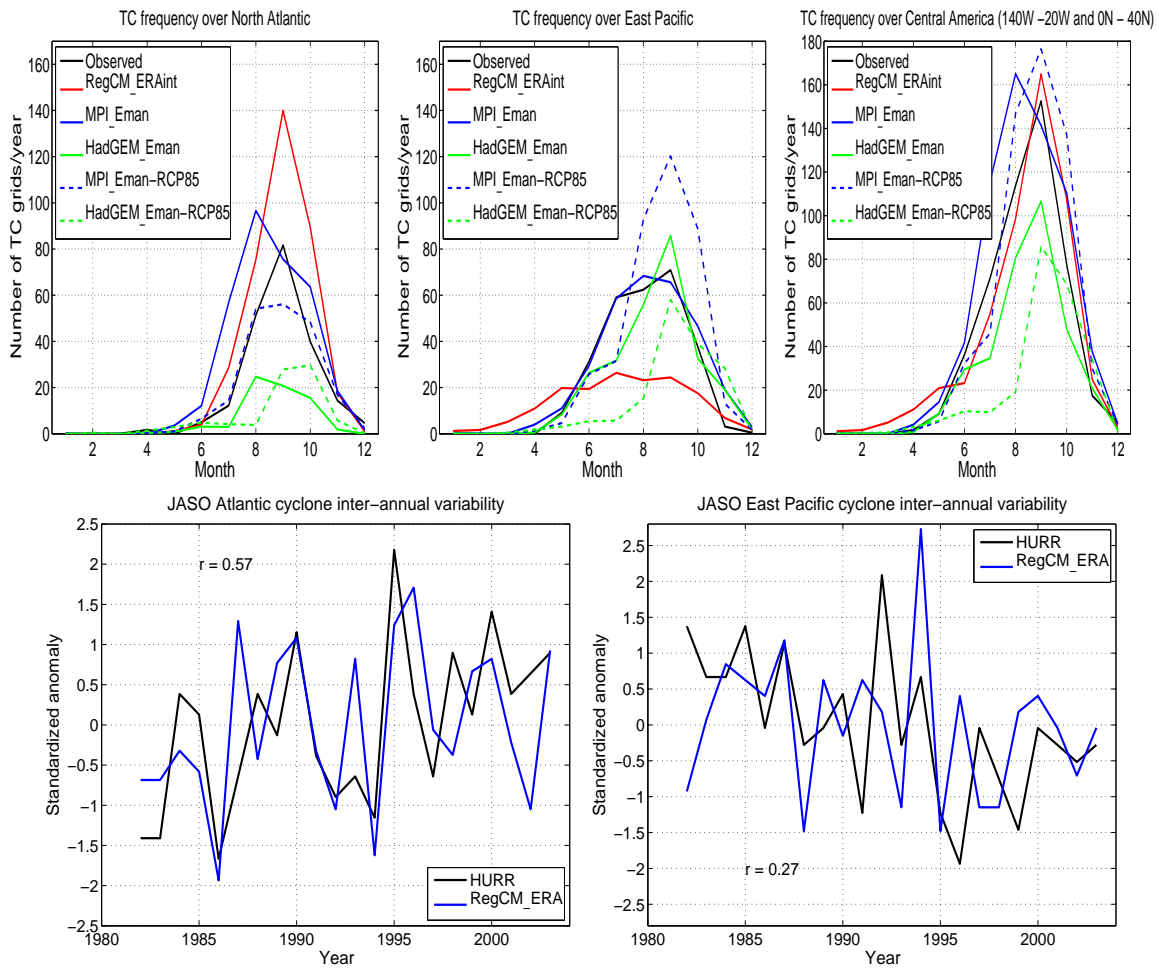


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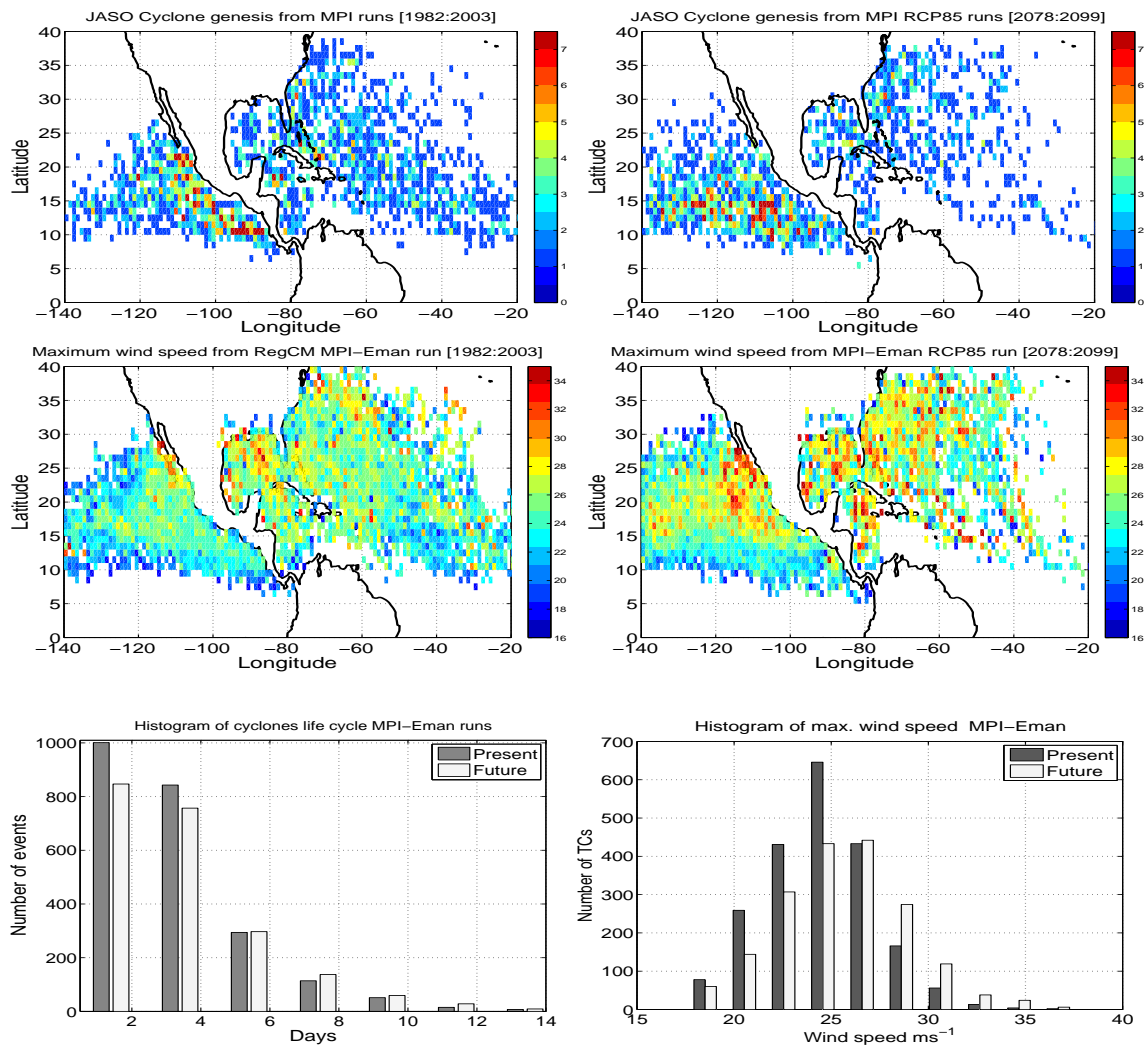


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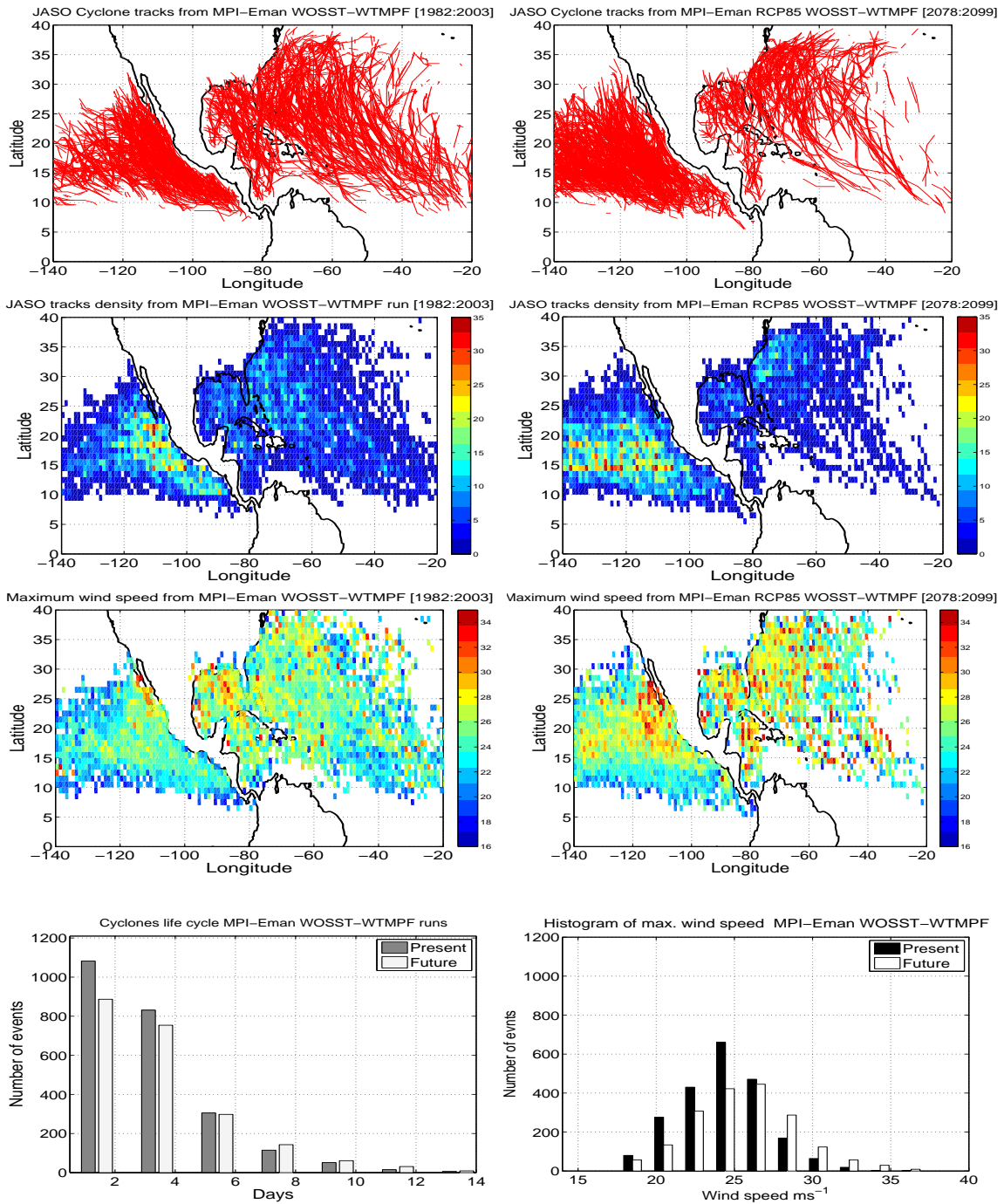


Figure 4:

Supplementary Material

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