

# *Sensitivity of tropical cyclones to convective parameterization schemes in RegCM4*

Article

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## Abstract

25  
26 This study investigates the sensitivity of simulated tropical cyclones (TC) affecting the  
27 Philippines to convective parameterization schemes (CPS) in the Regional Climate Model  
28 Version 4 (RegCM4). Five ERA-Interim driven RegCM4 simulations at 25-km resolution were  
29 conducted utilizing the CPS of Grell with Arakawa–Schubert closure (GR), Emanuel (EM),  
30 Kain–Fritsch (KF), Tiedtke (TE), and a combined Grell scheme over land and Emanuel over  
31 ocean (GR-EM). Comparisons between observed and modelled TCs covering a 30-year period  
32 (1981–2010) indicate that the EM scheme yields an annual-mean TC frequency that is closest to  
33 observations. The GR-EM scheme, on the other hand, closely reproduces the observed seasonal  
34 patterns of TC tracks, spatial patterns of TC track density and TC-associated rainfall, and TC  
35 lifespan over the PAR. The KF scheme is the only CPS that was able to simulate intense TCs  
36 (maximum wind speed  $> 40 \text{ m s}^{-1}$ ) within the domain. In contrast, both GR and TE schemes  
37 largely underestimated the TC frequency, and were only able to simulate weak TCs (maximum  
38 wind speed  $< 17 \text{ m s}^{-1}$ ). Such underestimation in the TC frequency and intensity in the GR and  
39 TE simulations can be attributed to the dry mid-tropospheric environment and the absence of a  
40 large area with positive low-level relative vorticity over the Pacific Ocean, which inhibit TC  
41 formation and further development over the area. These findings will be helpful in deciding  
42 which CPS is more appropriate to use in conducting TC-related model simulations in the context  
43 of the Philippine domain.

44

45

46 Keywords: regional climate modeling, sensitivity experiments, tropical cyclones, western North  
47 Pacific, the Philippines

## 48 **1 Introduction**

49       The Philippines is highly exposed to natural hazards such as tropical cyclones (TC) due to  
50 its geographic location. The country is situated in the western North Pacific (WNP) basin, where  
51 environmental conditions for TC formation are optimal. An assessment of TC data from 1951 to  
52 2013 shows that, on average, 9 out of 19 TCs entering the Philippine Area of Responsibility  
53 (PAR; enclosed by the dashed lines in Fig. 1) make landfall over the country annually (Cinco et  
54 al. 2016). These TCs can have disastrous impacts, and the economic losses due to TCs from  
55 1970 to 2009 have been estimated at \$6.2 billion (Gupta 2010). Furthermore, an annual  
56 increasing trend in TC-associated economic loss and damage has been observed over recent  
57 years (Lansigan et al. 2000; Blanc and Strobl 2016; Cinco et al. 2016; Bagtasa 2017). The  
58 projected increase in occurrence of more intense TCs in the future (e.g., Gallo et al. 2019),  
59 highlights the need for further understanding of TCs, including the ability (or inability) of  
60 climate models to simulate their different characteristics in order to have confidence in model  
61 projections.

62       Global climate models (GCMs) are useful for investigating the climate system, including  
63 possible future changes in TC activity (e.g., Bengtsson et al. 2007; Sugi et al. 2009; Tang and  
64 Camargo 2014). However, multi-decadal simulations using GCMs generally have coarse  
65 horizontal resolutions (typically between 100 and 300 km) because of the vast computational  
66 resources needed to run the models, and thus have been found to be unable to simulate all  
67 characteristics of TCs well (Strachan et al. 2013). While such limitations of GCMs have been  
68 addressed recently because of computational advancements and concerted efforts shared by  
69 scientists (e.g., Haarsma et al. 2016), conducting long-term high-resolution model simulations  
70 using GCMs remains a big challenge for most institutes in developing countries with insufficient

71 infrastructure. In turn, regional climate models (RCMs), which only need modest computing  
72 resources, are widely used to complement GCMs, particularly for resolving processes important  
73 at smaller spatial scales (e.g., Giorgi and Gutowski 2015). For instance, Jin et al. (2016) used a  
74 number of RCMs to investigate the present day TC climatology and obtained more credible and  
75 reliable estimates of future TC activity over the WNP. RCMs have also been used to provide  
76 high-resolution future projections of TC activity over the Central America (Diro et al. 2014),  
77 Vietnam (Wang et al. 2017), as well as in the Philippines (Gallo et al. 2019).

78       Although high-resolution model simulations have been achieved with the aid of RCMs,  
79 many sub-grid scale processes are still parameterized in the RCMs, particularly for simulations  
80 with horizontal resolutions  $> 5$  km (e.g., Fuentes-Franco et al. 2017; Shen et al. 2019). In a  
81 number of studies, it has been demonstrated that the convective parameterization plays an  
82 important role in capturing various TC characteristics including their development (Pattanayak et  
83 al. 2012), subsequent tracks (Prater and Evans 2002; Rao and Prasad 2007; Pattanayak et al.  
84 2012; Sun et al. 2015), intensity (Knutson and Tuleya 2004; Kanada et al. 2012; Biswas et al.  
85 2014), and frequency (e.g., Yoshimura et al. 2006; Zhao et al. 2012). Nevertheless, different  
86 results have been obtained from studies that have investigated the sensitivity of TCs to  
87 convective parameterization schemes (CPS). For instance, Mohandas and Ashrit (2014) have  
88 used the Weather Research and Forecasting (WRF) model, and showed that the Kain–Fritsch  
89 scheme reproduced the observed track and structure of TCs over the Indian Ocean more  
90 accurately than the other CPS. In another study, simulations of TCs using RegCM4 over the  
91 Central American Coordinated Regional Climate Downscaling Experiment (CORDEX) domain  
92 showed that the Emanuel convection scheme produces a more realistic number of TCs than the  
93 Grell scheme (Diro et al. 2014). Subsequently, Fuentes-Franco et al. (2017) showed that the

94 Kain–Fritsch scheme was able to simulate observed TC activity better than the Emanuel scheme  
95 over the same domain. Shen et al. (2019) also showed that the Kain–Fritsch scheme outperforms  
96 other CPS in WRF simulations conducted over the CORDEX – East Asia domain, primarily  
97 because of the better representation of large-scale environmental factors important to TC  
98 activity.

99       Given the known importance of the choice of CPS to TCs in RCM simulations, the present  
100 study aims to investigate the sensitivity of TCs to CPS found in the Regional Climate Model  
101 Version 4 (RegCM4) focusing on the Philippine domain. Identifying the most appropriate CPS  
102 will better inform which scheme to use when performing TC modeling studies for the country.  
103 The paper is organized as follows. In Section 2, the datasets and RCM used in this study, as well  
104 the CPS used in the simulations are described. Then, in Section 3, the simulated climatological  
105 TC characteristics are compared with observations in terms of frequency, seasonality, track,  
106 intensity, and associated rainfall. The large-scale environmental factors that could explain the  
107 simulation of each CPS are discussed in Section 4. Finally, the key findings and conclusions are  
108 summarized in Section 5.

## 109 **2 Data and methods**

### 110 **2.1 Model description and design of the experiments**

111       The present study utilizes the RegCM4, which is a hydrostatic, compressible, sigma-  
112 pressure vertical coordinate-based RCM for long-term regional climate simulations (Giorgi et al.  
113 2012). Specifically, the RegCM-4.4.5.5 version of the model is used, which has already been  
114 used in recent studies to provide climate change projections for the Philippines (i.e., Gallo et al.  
115 2019; Villafuerte et al. 2020). The model is run at a horizontal resolution of 25 km covering the  
116 area bounded by the region (0°–30°N, 110°–160°E; Fig. 1). This domain was chosen to include a

117 larger portion of the WNP, where TCs entering the PAR are most likely to originate (Gallo et al.  
118 2019).

119 Five RegCM4 model simulations were conducted using the initial and lateral boundary  
120 conditions taken from the ERA-Interim reanalysis (hereafter referred as ERAI; Berrisford et al.  
121 2011) covering the period from 00UTC 01 December 1980 to 18UTC 31 December 2010, and  
122 employing several different CPS. The analysis of the model simulations covers a 30-year period  
123 from 00UTC 01 January 1981 to 18UTC 31 December 2010 to allow a one-month model spin-  
124 up. The same model options for the other parameterization schemes, including the planetary  
125 boundary layer (PBL), land surface, and radiative transfer were utilized in all simulations, i.e.  
126 Holtslag PBL (Holtslag et al. 1990), CLM4.5 land surface model, explicit moisture scheme  
127 (SUBEX) (Pal et al. 2000), Zeng ocean flux scheme (Zeng et al. 1998), and CCM3 radiative  
128 transfer.

129 Among the CPS applied in this study are the Emanuel (Emanuel 1991), Grell with Arakawa-  
130 Schubert closure (Grell 1993), Kain-Fritsch (Kain and Fritsch 1990), and Tiedtke (Tiedtke  
131 1996). The Emanuel (EM) scheme triggers when the level of buoyancy exceeds the cloud base  
132 level. Cloud mixing is episodic, inhomogeneous, and convective fluxes are based on a model of  
133 sub-cloud-scale updrafts and downdrafts (Emanuel and Zivkovic-Rothman, 1999). The Grell  
134 (GR) scheme considers the point where the lifting parcel reaches the moist convection level as  
135 the triggering point for convection. An updraft and a penetrative downdraft compose the two  
136 steady-state circulations that makes up the clouds (Grell 1993). The GR scheme in RegCM4 has  
137 two closure types: (1) Arakawa–Schubert (AS) (Arakawa and Schubert 1974) and (2) Fritsch–  
138 Chappell (FC) (Fritsch and Chappell 1980). In this study, the GR simulation uses the AS closure  
139 wherein buoyant energy is released immediately at each time step. The Kain–Fritsch (KF)

140 scheme uses a one-dimensional entraining and detraining plume model where negatively buoyant  
141 parcels are assumed to detrain from the clouds, while positively buoyant parcels tend to entrain  
142 into the clouds. This allows the model to modulate the mean thermodynamic characteristics  
143 between convective clouds and the environment (Kain and Fritsch, 1990). The Tiedtke (TE)  
144 scheme triggers convection when moisture convergence becomes greater than the boundary layer  
145 moisture flux (Tiedtke 1989). The estimation of precipitation depends on the CPS over land or  
146 ocean. For example, over tropical oceans, GR underestimates precipitation while EM  
147 overestimates it for very intense events (Giorgi et al. 2012). To minimize such biases, the  
148 RegCM4's ability to mix two schemes was considered in this study, i.e. GR scheme over land  
149 and EM scheme over the ocean (GR-EM) (Giorgi et al. 2012). A brief description of the  
150 RegCM4 simulations conducted in this study and their distinguishing features are summarized in  
151 Table 1.

## 152 **2.2 TC detection and observed dataset**

153 The TC detection algorithm employed in this study follows the method used in Gallo et al.  
154 (2019), which has also been used in a number of studies that have investigated TC climatologies  
155 from RCM simulations (e.g., Manganello et al. 2012; Redmond et al. 2015; Liang et al. 2017;  
156 Wang et al. 2017). Specifically, the TRACK software developed by Hodges (1995), which was  
157 later improved to widen its applicability (i.e., Hodges 1996, 1999; Bengtsson et al. 2007), is used  
158 to identify and track TC-like vortices (TCLVs) from the 6-hourly model outputs. The TC  
159 detection and tracking algorithm involves six stages:

- 160 1. The vorticity fields at different pressure levels (850-, 500-, 300-, and 200-hPa) of the  
161 troposphere are calculated.

- 162 2. The 850-hPa relative vorticity is then filtered to a spectral resolution of T42, on the  
163 original grid, to reduce noise resulting in more reliable tracking. All levels are also  
164 filtered to a T63 resolution to be used in the TCLV identification.
- 165 3. The tracking is performed by first identifying the vorticity maxima  $> 5.0 \times 10^{-6} \text{ s}^{-1}$ .  
166 These are then initialized into tracks using a nearest neighbor method and then refined  
167 by minimizing a cost function for track smoothness subject to adaptive constraints. All  
168 systems are initially tracked.
- 169 4. The vorticity maxima in the T63 filtered fields are iteratively added to the tracks  
170 within a  $5^\circ$  radius in order to identify the TCLV.
- 171 5. An initial identification is performed by applying criteria to all tracks that last longer  
172 than two days. Following Gallo et al. (2019) and Bengtsson et al. (2007), the  
173 identification criteria are applied only over the ocean, exclude systems that do not  
174 have a warm core, and do not cover the whole troposphere. This stage ensures  
175 adherence to a warm core and a coherent vertical structure for the TCLV.
- 176 6. Finally, the maximum sustained wind speeds (MWS) is identified in the vicinity of the  
177 vortices. Detected storms that do not reach  $17 \text{ m s}^{-1}$  in their entire lifecycle are  
178 eliminated, following the same limit for the tropical storm (TS) category used in the  
179 JMA TC intensity scale.

180 Similar thresholds enumerated above are employed in identifying TCLVs for the ERAI and  
181 all RegCM4 simulations despite the coarser resolution of the former than the latter. A resolution-  
182 dependent TC detection and tracking (e.g., Walsh et al. 2007) is not used in this study to see how  
183 downscaling improves the representation of TCs. It also allows a direct comparison of TC-

184 associated rainfall, which is defined as the rainfall within the 500 km radial distance from the 6-  
185 hourly positions of the TC center following Zhang et al. (2019).

186 The spatial and temporal characteristics of simulated TCs are compared to the TC “best  
187 track” data from the Japan Meteorological Agency (JMA), which is the designated body of the  
188 World Meteorological Organization (WMO) as the Regional Specialized Meteorological Center  
189 (RSMC) to cover TC forecasts and analysis over the WNP ( $0^{\circ}$ – $60^{\circ}$ N,  $100^{\circ}$ – $180^{\circ}$ E). Six-hourly  
190 information of the TC MWS and locations are derived using the Dvorak technique (JMA 2018),  
191 which uses visible and infrared images from geostationary and polar-orbiting weather satellites  
192 (Barcikowska et al. 2012). The Dvorak current intensity (CI) number (Dvorak, 1975) is  
193 converted to its equivalent 10-minute MWS using the Koba conversion table (Koba et al. 1989).  
194 Although different methods are used for both the JMA observations and the model simulations in  
195 showing TC activity, Barcikowska et al. (2012) determined that the JMA best track dataset  
196 provides more reliable CI parameters than other datasets found in the WNP. Thus, it is the most  
197 appropriate dataset for studies investigating the TC climatology.

198 The identified TC MWS are then classified according to the current TC categories  
199 operationally being used by the Philippine Atmospheric, Geophysical and Astronomical Services  
200 Administration (PAGASA) namely, 1) tropical depression (TD):  $MWS < 17 \text{ m s}^{-1}$ ; 2) tropical  
201 storm (TS): MWS ranging from 17 to 25  $\text{m s}^{-1}$ ; 3) severe tropical storm (STS): MWS ranging  
202 from 26 to 33  $\text{m s}^{-1}$ ; 4) typhoon (TY): MWS ranging from 34 to 61  $\text{m s}^{-1}$ ; and 5) super typhoon  
203 (STY):  $MWS > 61 \text{ m s}^{-1}$ . As the study focuses mainly on TCs affecting the Philippines, only  
204 those TCs that developed, entered, and/or existed over the PAR (see, Fig. 1) were considered in  
205 the analyses. The PAR is among the agreed areas of responsibility for providing storm warnings  
206 and shipping forecasts back in the mid-1960s (WMO 1966). Since then, PAGASA has been

207 using the PAR for monitoring TCs and in providing TC-related warnings to the public (e.g.,  
208 Cinco et al. 2016).

## 209 **3 Results**

### 210 **3.1 TC frequency**

211 The time series of annual number of TCs in the PAR based on the JMA observations, ERAI,  
212 and the five RegCM4 experiments are compared in Fig. 2. The frequency of observed TCs over  
213 the PAR varies interannually; there are years where TCs are more active (e.g., in 1986, 1993–  
214 1994, and 2004), while at times, TCs occur less frequently (e.g., from 1997 to 2002; thick black  
215 curve in Fig. 2). These year-to-year variations in the occurrence of TCs over the PAR are  
216 captured to some extent by the ERAI (gray curve) and the RegCM4 experiments, although with  
217 some notable discrepancies. For instance, the observations recorded the lowest TC count in 2002  
218 (10 TCs), while all of the five experiments simulate higher number of TCs over the PAR in that  
219 particular year relative to the other years. Such discrepancies in the year-to-year variations with  
220 the RegCM4-simulated TCs and observations led to insignificant and low correlation coefficients  
221 ( $r < 0.20$ ,  $p > 0.05$ ). It is also noted that there is an insignificant correlation ( $r = 0.48$ ,  $p > 0.05$ )  
222 between the ERAI and the JMA's time series of annual TC frequency over the PAR.

223 The distributions of annual TC frequency derived from the observations, ERAI, and the  
224 RegCM4 simulations are also shown at the right hand side of Fig. 2. Higher (lower) interannual  
225 variations are noted in EM, GR-EM, and KF (ERAI, GR, and TE) than the observations. The EM  
226 scheme simulates the closest 30-year average annual TC frequency in the PAR at 12.9 TCs per  
227 year compared to the observed annual mean TCs of 16.8 TCs per year. The KF scheme, on the  
228 other hand, overestimates the climatological mean annual TC frequency at 22.5 TCs per year,  
229 while the GR and TE simulate an average of 1.4 and 1.2 TCs per year, respectively. In general,

230 the models tend to underestimate the annual-mean TC frequency, except for the RegCM4  
231 simulation with KF scheme. Similar results of overestimation for KF (Shen et al. 2019),  
232 underestimation for EM (Fuentes-Franco et al. 2017), and non-detection of TCLVs for the GR  
233 schemes (Diro et al. 2014) were reported using ERAI-driven RCM simulations applied in  
234 different regions of the world. It is also worth noting that fewer TCs occurring over the PAR are  
235 similarly detected from the raw ERAI data (Fig. 2). Among the RegCM4 experiments, the EM  
236 scheme tends to reproduce the most realistic annual TC frequency in the PAR, consistent with  
237 the findings of Diro et al. (2014) over the Central American region.

### 238 **3.2 TC spatial density**

239 The spatial density of TCs was obtained based on the 6-hourly TC center location following  
240 the track of model-simulated and observed TCs that existed in the PAR during the period 1981–  
241 2010, and then binned in each of the  $2^\circ \times 2^\circ$  grid boxes covering the entire domain (Fig. 3).  
242 Based on observations (Fig. 3a), the main concentration of TC activity is found largely over the  
243 Pacific (northeastern section of the PAR) extending over the northern section of the Philippines  
244 and the South China Sea (SCS; locally known as the West Philippine Sea). The TC spatial  
245 density derived from the ERAI closely resembles that of observations, although with  
246 underestimated values over the areas north of  $10^\circ\text{N}$  and some overestimation over the regions  
247 south of  $7^\circ\text{N}$  (Fig. 3b). For the RegCM4 simulations, the EM, GR-EM, and KF (Fig. 3c, e, and f,  
248 respectively) capture the general pattern of observed maximum spatial track density location  
249 over the northeastern section of the PAR, although shifted more to the north in the model  
250 simulations. It is also noted that the KF overestimated the TC occurrence over much of the  
251 domain (Fig. 3f).

252 The TC track density based on the GR and TE simulations (Fig. 3d and g, respectively) are  
253 mainly concentrated over the SCS and the northern section of the PAR; both of them fail to  
254 capture the main TC activity east of the PAR over the Pacific Ocean. Among the five RegCM4  
255 experiments, GR-EM shows the most similar spatial pattern of TC track density with the  
256 observations, although with noted overestimation over lower latitudes and fewer land falling TCs  
257 over the northern portion of the Philippines.

### 258 **3.3 TC-associated rainfall**

259 The TC-associated rainfall was obtained within the 500 km radial distance from the center  
260 of the TCs. Based on ERAI, this rainfall amounts to an annual average ranging from 50 mm to  
261 more than 300 mm (Fig. 4a). A southeast-northwest elongated area characterizes the spatial  
262 distribution of TC-associated rainfall, following the general pattern of TC tracks. The maximum  
263 TC-associated rainfall (exceeding 300 mm, on the average) is located over the Philippine Sea; it  
264 accounts to about 10–15% of the annual rainfall over the region (contours in Fig. 4a). As with  
265 the ERAI, the spatial pattern of TC-associated rainfall follows the general pattern of TC tracks in  
266 the RegCM4 simulations. Hence, the earlier noted discrepancies with the observed TC tracks  
267 propagate to the TC-associated rainfall. The EM, GR-EM, and much more, the KF simulation,  
268 overestimated the TC-associated rainfall over much of the domain, particularly over the areas  
269 south of 10°N (Fig. 4b, d, and e, respectively). In contrast, the RegCM4 simulations using GR  
270 and TE schemes underestimated the TC-associated rainfall over the entire domain (Fig. 4c and f,  
271 respectively); this is primarily because of the largely underestimated number of TCs as shown  
272 earlier.

273 The percentage of TC-rain contribution in the RegCM4-simulation using EM is higher by  
274 approximately 5–10% than the ERAI over the large areas of the Pacific Ocean and the SCS

275 (contours in Fig. 4b). The center of maximum TC-rain contribution over the ocean, northeast of  
276 the Philippines, is also shifted more to the north in the EM simulation. The spatial pattern of TC-  
277 rain contribution of the GR-EM experiment is almost similar to EM, although smaller in  
278 magnitude (Fig. 4d). An overestimated TC-rain contribution (as much as 20% higher than the  
279 ERAI) is noted for KF over the entire domain (Fig. 4f). Because few TCs are forming over the  
280 Pacific Ocean and only a handful of TCs were detected in the GR and TE, the annual mean  
281 contribution of TC-associated rainfall is severely underestimated for these simulations (Fig. 4c  
282 and f, respectively); it did not reach 5% anywhere in the domain. Among all RegCM4  
283 simulations, the GR-EM best represents the spatial pattern and magnitude of TC-associated  
284 rainfall over the domain.

### 285 **3.4 TC seasonality**

286 The monthly average number of TCs that existed in the PAR from 1981 to 2010 is shown in  
287 Fig. 5. Based on observations (thick solid line in Fig. 5) TCs are less active in the PAR during  
288 the months of January–April and gradually increases from May until it reaches the peak TC  
289 activity in July–September. Then, the TC activity over the PAR decreases in the following  
290 months from October until December. These main characteristics of the TC annual cycle are well  
291 reproduced by the ERAI, although with consistently fewer number of TCs. On the other hand,  
292 some of these key features are similarly reproduced in the five RegCM4 experiments. For  
293 instance, the low TC activity over the PAR from January–April is generally reproduced by the  
294 RegCM4 experiments, except for some overestimation in the KF, EM, and GR-EM simulations.  
295 The RegCM4 simulations also captured the start of having more active TCs in May and June.  
296 The TC peak season over the PAR that occurs during the months of July–September is  
297 reproduced by the KF, EM, and GR-EM simulations, despite the overestimation in KF and

298 underestimation in EM and GR-EM. All model experiments tend to underestimate TC activity  
299 over the PAR in October. The observed TCs over the PAR in December are overestimated by the  
300 KF, EM, and GR-EM schemes. The pronounced seasonality of TC activity over the PAR, on the  
301 other hand, is not observed in the GR and TE simulations.

302 The TC tracks aggregated for each quarter of the year: January–March (JFM), April–June  
303 (AMJ), July–September (JAS), and October–December (OND), are compared in Fig. 6. There  
304 are some noted discrepancies between the observed and model-simulated seasonal TC tracks  
305 covering the 30-year period (1981–2010). During the least active TC season of JFM (leftmost  
306 column of Fig. 6), the observed TC tracks generally propagate in a westward direction making  
307 landfall over the central portions of the Philippines. This westward propagation of the TCs are  
308 somewhat captured by the EM, GR-EM, and KF RegCM4 simulations despite the fewer TCs in  
309 the ERAI, but in greater number and with trajectories passing more to the southern region of the  
310 Philippines. For the pre-TC season months of AMJ (second column from the left of Fig. 6), the  
311 observations exhibit a re-curving pattern towards the northeast of the PAR. For the EM, GR-EM,  
312 and KF experiments, the re-curving pattern tends to be shifted to the east by about 4–6° (Fig. 6c,  
313 e, and f, respectively). There are also more TC tracks in KF than observed over the SCS (Fig.  
314 6f). Meanwhile, GR and TE fail to simulate much of the TCs that are generally formed south of  
315 15°N over the Pacific Ocean (Fig. 6d and g, respectively). Among the RegCM4 experiments,  
316 GR-EM best represents the TC tracks during JFM, while EM and GR-EM simulations best  
317 capture the AMJ TC tracks.

318 The most active TC season of JAS illustrates that TCs generally affect the northern regions  
319 of the Philippines (third column from the left of Fig. 6). Also, TCs tend to exit either to the north  
320 or northwest of the PAR. Such TC trajectories are well captured by the ERAI and to some extent

321 in the EM, GR-EM, and KF simulations, although KF indicates more westward moving tracks  
322 (Fig. 6f). Similar to the AMJ season, GR and TE fail to simulate TCs in a large area east of the  
323 PAR over the Pacific Ocean (Fig. 6d and g, respectively). During the OND season, the JMA best  
324 track data indicates that most of the TCs move westward making landfall over the northern and  
325 central Philippines, although some TCs tend to re-curve and move away from the country toward  
326 higher latitudes (rightmost panel of Fig. 6a). Such pattern is well represented in the ERAI and to  
327 some extent, in the EM, GR-EM, and KF experiments, although shifted more to lower latitudes  
328 affecting the southern regions of the Philippines (rightmost panel of Fig. 6b, c, e, and f,  
329 respectively). Furthermore, there appears to be more TCs originating south of 5°N in the model  
330 simulations. As noted in the other seasons, relatively fewer (more) TCs were detected in the GR  
331 and TE (KF) in OND. Among the five RegCM4 experiments used in this study, GR-EM best  
332 represents the observed TC tracks for the JAS and OND seasons.

333 Figure 6 further reveals that stronger TCs generally occur during the latter half of the year.  
334 KF was able to capture stronger TCs occurring in JAS, but not in OND. Similar to the ERAI, all  
335 RegCM4 experiments tend to simulate mainly the weaker TCs (i.e. TD and TS), underestimate  
336 the number of STS and TY, and do not simulate any STY occurrences for any given season. The  
337 GR and TE schemes were only able to simulate up to TS categories, which are mostly located at  
338 higher latitudes approximately over 12°–18°N and 15°–25°N, respectively; while EM and GR-  
339 EM fail to capture numerous landfalling intense TCs. Among the five RegCM4 experiments  
340 using different CPS, the KF scheme best captures the TC intensities in most of the seasons  
341 analyzed.

### 342 **3.5 TC intensity**

343 Figure 7 compares the kernel density plots obtained from the TC lifetime highest MWS of  
344 observation, reanalysis, and the RegCM4 simulations. Figure 7 shows the broad range covered  
345 by the distribution of the highest MWS of the TCs observed in the PAR from 1981 to 2010 (thick  
346 black curve in Fig. 7). Most of the observed TCs obtain their lifetime highest MWS in the range  
347 from 20 to 50 m s<sup>-1</sup>, with a few reaching > 60 m s<sup>-1</sup>. In contrast, the ERAI and RegCM4  
348 simulations produce distributions that are skewed towards weak to moderate wind speed values,  
349 and fail to simulate TCs with the strongest intensities (i.e. no TC intensity above 50 m s<sup>-1</sup>). Such  
350 results were similarly found by Shen et al. (2019) for the simulated TCs conducted over the  
351 CORDEX-East Asia region, attributing the weaker TCs to coarse resolution model simulations.

352 Figure 7 further reveals that stronger TCs were achieved in the downscaled RegCM4  
353 experiments (i.e., EM, GR-EM, and KF) when compared to the ERAI, signifying the added value  
354 of downscaling as noted in a number of studies (e.g., Diro et al. 2014; Jin et al. 2016; Fuentes-  
355 Franco et al. 2017). It also stresses the crucial role of CPS in simulating TC intensities. Despite  
356 the higher resolution in GR and TE simulations relative to the ERAI, they tend to produce TCs  
357 with weaker intensities. The EM and the combined GR-EM schemes have an almost similar  
358 distribution of lifetime highest 6-hourly MWS for all TCLVs that existed in the PAR. Among the  
359 RegCM4 simulations conducted in this study, the KF scheme was able to simulate stronger TCs.  
360 These results further support the findings of Fuentes-Franco et al. (2017) and Shen et al. (2019)  
361 even if applied in different regions of the world.

### 362 **3.6 TC lifespan**

363 The lifespan of each of the TCs that existed in the PAR from 1981 to 2010 is summarized in  
364 Fig. 8. On average, the TCs last for about 150 h over the entire domain for the observations

365 (marked by the horizontal line inside the box in Fig. 8a). The ERAI and RegCM4 simulated TCs,  
366 on the other hand, tend to have longer lifecycles, and wider variations among the individual TCs  
367 as characterized by the higher interquartile range (the area covered by the boxes in Fig. 8a). This  
368 extended TC lifecycle for all experiments and the reanalysis is associated with the densely  
369 extended TC tracks over the eastern part of the domain over the Pacific Ocean and more  
370 westward tracks of the TCs for the majority of the seasons (as shown in Fig. 6). TCs with such  
371 characteristics typically have longer lifespans because they stay at lower latitudes longer (Shen et  
372 al. 2019). These longer lifecycles obtained from the model-simulated TCs as compared to the  
373 best track data can also be attributed to the uncertainty in observations of weak storms (e.g.,  
374 Hodges et al. 2017).

375 Inside the PAR, TCs are observed to stay for about 90 h on average based on the JMA  
376 observations (horizontal line inside the black box in Fig. 8b). Again, ERAI and all RegCM4  
377 experiments overestimate the TC duration inside the PAR (Fig. 8b), which can be due to the  
378 tendency of the simulated TCs for a westward track instead of re-curving to the northwest  
379 direction (see, Fig. 6). Among all experiments, the RegCM4 experiment using GR-EM scheme  
380 best simulates the TC life span over the PAR.

## 381 **4 Discussion**

382 To further investigate the biases obtained by the RegCM4 experiments conducted in this  
383 study on TC activity over the PAR, the large-scale conditions governing the formation and  
384 development of TCs are discussed in this section. Past studies have pointed out that TC  
385 formation and their subsequent movements are greatly influenced by how the large-scale  
386 circulation is simulated by the model (e.g. Au-Yeung and Chan 2012; Jin et al. 2016; Liang et al.

387 2017; Shen et al. 2019). Here, we focus on analyzing the most active TC season (JAS) over the  
388 PAR.

389 Over the WNP, TC formation and subsequent development occur under favorable conditions  
390 such as positive values of 850-hPa relative vorticity and weak vertical wind shear (Jin et al.  
391 2016). The RegCM4-simulated climatological mean 850-hPa relative vorticity and vertical wind  
392 shear (i.e., the difference in the zonal winds between the 850 hPa and 200 hPa levels) are  
393 compared with the ERAI (Fig. 9). The 850-hPa relative vorticity in the ERAI is characterized by  
394 a northwest-southeast elongated positive belt extending from the SCS to the WNP between 5°–  
395 23°N, with the maximum center over the SCS. The positive belt of the relative vorticity is  
396 associated with the monsoon trough, a vital factor for TC genesis in the region (Holland 1995;  
397 Wu 2012). The northwest-southeast orientation of the positive vorticity belt is likewise obtained  
398 by the RegCM4 experiments, although the belt is disconnected at different parts over the domain.  
399 For both the EM and GR-EM experiments, the positive vorticity zone located northwest of the  
400 Philippines over the SCS is disconnected (Fig. 9b and d, respectively). The KF experiment, on  
401 the other hand, shows a more extended positive vorticity belt to the northeast of the Philippines  
402 (Fig. 9e). The location of positive vorticity zone east of the Philippine landmass up to 140°E is  
403 slightly shifted to the north for the three CPS experiments (EM, GR-EM, and KF), which leads  
404 to the location of TC formation more to the north thereby having more TCs passing north of the  
405 domain, freeing much of the central portion of the Philippines (see, Fig. 6). A wide area of  
406 positive vorticity located east of the Philippines is absent in both the GR and TE experiments  
407 (Fig. 9c and f, respectively). This in turn, inhibits the formation of TCs over the Pacific Ocean  
408 resulting in a large underestimation of TCs in these experiments. The simulated vertical wind  
409 shear of all CPS experiments generally captures the observed spatial pattern, wherein low values

410 of vertical wind shear dominates over the regions east of 140°E and north of 15°N of the entire  
411 domain. According to Gray (1979), vertical wind shear values of less than 10 m s<sup>-1</sup> are favorable  
412 for TC formation and development. Since the locations of areas with favorable vertical wind  
413 shear that are simulated by all CPS experiments are generally similar, this implies that the  
414 vertical wind shear is not a dominant environmental factor that affects the TCs in the RegCM4  
415 simulations conducted in this study.

416 In addition to the earlier mentioned large-scale environmental factors, the RegCM4-  
417 simulated climatological mean 850-hPa winds, 500-hPa geopotential heights, and 700-hPa  
418 relative humidity are compared with the ERAI in JAS season (Fig. 10). All RegCM4  
419 experiments are able to capture the low-level southwesterly wind flow associated with the  
420 prevailing summer monsoon season in JAS albeit with noted stronger (weaker) southwesterly  
421 flows in the KF (GR and TE) experiment(s). Such stronger southwesterly low-level wind flow in  
422 the KF experiment, relative to the ERAI, can be attributed to the weak and eastward-shifted  
423 WNP subtropical high pressure system; thereby more moisture is transported farther to the east  
424 and northeast of the Philippines (Fig. 10e).

425 Drier mid-tropospheric conditions (represented by the 700-hPa relative humidity, shadings  
426 in Fig. 10) are observed for the GR and TE experiments over large areas of the domain,  
427 particularly over the Pacific Ocean south of 15°N, where most TCs entering the PAR are  
428 generated (Fig. 10c and f, respectively). Similar dry bias in GR has been noted in Im et al. (2008)  
429 attributing it to the infrequent triggering of the scheme. The dry bias in TE, on the other hand, is  
430 attributed by Ali et al. (2015) to the underestimated surface latent heat flux and more stable  
431 structure of the atmosphere from the surface up to the mid-tropospheric level. According to Gray  
432 (1979), dry mid-tropospheric conditions are unfavorable for TC formation due to the entrainment

433 of dry air causing air parcels to lose buoyancy and inhibit deep convection (Cheung 2004). The  
434 relatively drier mid-tropospheric environment in the GR and TE experiments (in comparison to  
435 the other CPS and with the ERA-Interim reanalysis) serves as one of the main reasons why there  
436 are no TCs forming south of 15°N over the Pacific Ocean in these experiments (see, Fig. 6). In  
437 an earlier climate modeling study, Strachan et al. (2013) identified the mid-tropospheric relative  
438 humidity as the dominant factor to affect TC activity over the WNP.

439 The western edge of the WNP subtropical high [represented by the 5880-geopotential meter  
440 (gpm) contour line; e.g., Kim et al. (2015)] is known to be the main steering flow that influences  
441 the track of TCs over the WNP (Ho et al. 2004). Based on the ERAI, the 5880-gpm contour line  
442 extends east of Taiwan over the Pacific Ocean during JAS (Fig. 10a). However, all CPS  
443 experiments underestimate the 500-hPa geopotential height by about 20–30 m indicating a  
444 weaker WNP subtropical high in the RegCM4 simulations (Fig. 10b–f). Such a condition favors  
445 the TCs that are formed southeast of the Philippines over the Pacific Ocean to re-curve over the  
446 ocean and move toward Japan and Korea (Kim et al. 2015). This explains the eastward shift of  
447 the TC tracks and the earlier re-curvature taken by the TCs in the RegCM4 experiments as noted  
448 in Section 3.4.

## 449 **5 Conclusions**

450 This study has investigated the sensitivity of simulated TCs affecting the Philippines to the  
451 different CPS in RegCM4. Five ERAI-driven RegCM4 simulations using different CPS were  
452 conducted covering a 30-year period of investigation (i.e., 1981–2010). A TC detection  
453 algorithm that looks at the dynamic and thermodynamic characteristics of a system from the 6-  
454 hourly output of the model was used to identify the TCs. Results show that the chosen CPS  
455 affects different TC characteristics, including the frequency, seasonality, intensity, track,

456 associated rainfall, and lifecycles of the model-simulated TCs over the PAR. Among the five  
457 CPS used in the RegCM4 simulations, the EM scheme yielded an annual-mean TC frequency  
458 over the PAR that is closest to observations. The combined GR-EM schemes closely reproduced  
459 the spatial pattern of the TC track density covering the entire period, the TC-associated rainfall,  
460 the seasonal patterns of TC tracks, and the TC lifespan over the PAR. The KF scheme, on the  
461 other hand, is the only CPS that was able to simulate stronger TCs within the domain. However,  
462 there are some noted discrepancies with the observed and simulated TCs. For instance, the  
463 models have some difficulty in capturing the annual frequency of TCs over the PAR; none of  
464 them obtained a significant correlation with the observed values. The timing of the pronounced  
465 seasonality of TC occurrence over the PAR is also not well captured in the RegCM4  
466 experiments. Furthermore, the TC tracks are slightly displaced in the model simulations.

467       The biases obtained from the RegCM4 simulations using different CPS can be explained by  
468 how realistic the large-scale environmental conditions governing TC formation and subsequent  
469 movement are simulated by the model. The pattern of earlier TC re-curvedure is due to the  
470 weaker WNP subtropical high, while the northward shift of the simulated positive low-level  
471 vorticity belt for EM, GR-EM, and much more with the KF, results in the TC genesis being more  
472 to the north thereby having more TCs passing north of the domain, deviating away from the  
473 central portion of the Philippines (see, Section 3.4). Shen et al. (2019) have similarly noted an  
474 overestimation and northward shift of the TC track density over the CORDEX-East Asia domain  
475 with the KF scheme, despite using a different RCM, attributing such bias to the extended  
476 Intertropical Convergence Zone and overestimated relative humidity over the WNP region. The  
477 RegCM4 simulations with GR and TE schemes underestimate the 700-hPa relative humidity  
478 over large areas of the domain, particularly east of the Philippines over the Pacific Ocean, which

479 creates a dry environment where deep convection is restricted, thereby inhibiting TC formation  
480 and further development. Such conditions lead to almost no TCs forming over the Pacific Ocean  
481 for these experiments, agreeing with the earlier findings of Strachan et al. (2013), who showed  
482 that the mid-tropospheric relative humidity is the dominant factor that affects TC activity over  
483 the WNP.

484 The TC detection thresholds applied uniformly in this study for both the native ERAI  
485 resolution and the downscaled RegCM4 simulations revealed that the higher resolution achieved  
486 through downscaling could either improve or worsen the simulated TCs, which depend on the  
487 chosen CPS (as shown in Sections 3 and 4). This is in agreement with the findings of Murakami  
488 (2014), who showed that even for reanalysis the highest resolution does not always best  
489 represent the properties of TCs, mainly because the simulated TCs are highly dependent on the  
490 model formulation (Schenkel and Hart 2012). The current findings stress the importance of  
491 choosing the appropriate CPS for TC climate simulations given its impacts on various TC  
492 characteristics as similarly noted in earlier studies (e.g., Prater and Evans 2002; Yoshimura et al.  
493 2006; Kanada et al. 2012; Pattanayak et al. 2012; Sun et al. 2015). It has to be noted, however,  
494 that the chosen CPS may interact differently with the other parameterized physical processes in  
495 the model (e.g., Cruz and Narisma 2016; Fuentes-Franco et al. 2017), which may eventually  
496 affect the simulated TCs. Nonetheless, the results obtained in the present study has increased the  
497 confidence of the derived projected future changes in TCs over the Philippines, i.e. the GR-EM  
498 scheme was used in the RegCM4 simulations in Gallo et al. (2019). The results reported here can  
499 also be used (e.g., in selecting the appropriate CPS, investigating the added value of  
500 downscaling, or further model tuning) for TC-related modeling studies in the future.

501

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513

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### 711 **Figure Captions**

712 **Fig. 1** Map showing the geographic extent of the model domain. Shadings indicate surface model  
713 elevation expressed in meters above mean sea level. The area enclosed by the dashed line  
714 covers the Philippine Area of Responsibility (PAR), the region being used by PAGASA for  
715 TC monitoring and in providing TC-related public advisories

716 **Fig. 2** Annual frequency of TCs that existed in the PAR during the period from 1981 to 2010  
717 based on the JMA best track data, ERAI, and the five ERAI-driven RegCM4 simulations  
718 using different CPS. The box and whiskers shown on the right side of the plot are also  
719 provided to depict various characteristics of the annual TC frequency for the entire period;  
720 the box limits correspond to the interquartile range, the whiskers cover the range, and the  
721 horizontal line inside the boxes marks the mean

722 **Fig. 3** TC tracks spatial density maps based on **a** JMA observations, **b** ERAI, and **c – g** the five  
723 CPS RegCM4 simulations. The spatial densities are obtained by taking the total number of  
724 TCs that existed in each of the  $2^\circ \times 2^\circ$  grid box during the period 1981–2010; only those  
725 TCs that existed and/or entered the PAR are included

726 **Fig. 4** Annual mean TC-associated rainfall (shadings) and percentage contribution to annual total  
727 rainfall (contours, units: %) averaged over the 30-year period (1981–2010). Note that the

728 minimum contour displayed is set at 5% with succeeding intervals of 5%, and only those  
729 TCs that existed and/or entered the PAR are included

730 **Fig. 5** Monthly average TC frequency over the PAR obtained from the JMA best track data,  
731 ERAI, and the five RegCM4 simulations using different CPS during the period 1981–2010

732 **Fig. 6** Seasonal tracks of TCs that existed in the PAR based on **a** JMA best track data, **b** ERAI,  
733 and **c – g** the five RegCM4 simulations covering the period 1981–2010. The three-month  
734 seasons used are January to March (JFM), April to June (AMJ), July to September (JAS),  
735 and October to December (OND). Colors correspond to the TC categories operationally  
736 being used by PAGASA namely, Tropical Depression (TD), Tropical Storm (TS), Severe  
737 Tropical Storm (STS), Typhoon (TY), and Super Typhoon (STY)

738 **Fig. 7** Probability density functions (PDFs) fitted from the TC-lifetime highest 6-hourly MWS of  
739 the JMA observations, ERAI, and the RegCM4 simulations. The TCs considered are only  
740 those that existed in the PAR during the period from 1981 to 2010

741 **Fig. 8** Box plots showing the time spent (expressed in hours) of all TCs that existed in the PAR  
742 from 1981 to 2010 over **a** the entire domain and **b** inside the PAR. The boxes cover the  
743 interquartile range while the whiskers correspond to the 10<sup>th</sup> and 90<sup>th</sup> percentiles; the  
744 horizontal line inside the boxes marks the mean

745 **Fig. 9** Climatological mean vertical wind shear (shadings) and positive 850-hPa relative vorticity  
746 (contours;  $\times 10^{-6} \text{ s}^{-1}$ ) during JAS based on **a** ERAI and **b – f** RegCM4 simulations

747 **Fig. 10** Climatological mean 700-hPa relative humidity (shadings), 500-hPa geopotential heights  
748 (contours), and 850-hPa winds (vectors) during JAS based on **a** ERAI and **b – f** RegCM4  
749 simulations

750

751 **Table 1.** Summary of the RegCM4 experiments conducted in this study and their convective  
 752 parameterization scheme features.

<b>Experiment</b>	<b>Convective</b>	<b>Trigger</b>	<b>Entrainment</b>
<b>Name</b>	<b>Parameterization</b>		
EM	Emanuel scheme (Emanuel 1991)	Buoyancy exceeds cloud base level	Sub-cloud scale model variable on buoyancy of parcel
GR	Grell scheme (Grell 1993)	Updraft reaches moist convection level	Single cloud model at the bottom
KF	Kain-Fritsch scheme (Kain and Fritsch 1990)	Perturbation based on low-level vertical motion	Variable to buoyancy of the air parcel
TE	Tiedtke scheme (Tiedtke 1996)	Moisture convergence closure	Moisture convergence under static condition
GR-EM	Grell over land and Emanuel over the ocean schemes	Same as GR and EM applied over land and ocean, respectively	Same as GR and EM applied over land and ocean, respectively

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