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Abstract

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

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

1 Introduction

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

Global climate models (GCMs) are useful for investigating the climate system, including possible future changes in TC activity (e.g., Bengtsson et al. 2007; Sugi et al. 2009; Tang and Camargo 2014). However, multi-decadal simulations using GCMs generally have coarse horizontal resolutions (typically between 100 and 300 km) because of the vast computational resources needed to run the models, and thus have been found to be unable to simulate all characteristics of TCs well (Strachan et al. 2013). While such limitations of GCMs have been addressed recently because of computational advancements and concerted efforts shared by scientists (e.g., Haarsma et al. 2016), conducting long-term high-resolution model simulations using GCMs remains a big challenge for most institutes in developing countries with insufficient infrastructure. In turn, regional climate models (RCMs), which only need modest computing resources, are widely used to complement GCMs, particularly for resolving processes important at smaller spatial scales (e.g., Giorgi and Gutowski 2015). For instance, Jin et al. (2016) used a number of RCMs to investigate the present day TC climatology and obtained more credible and reliable estimates of future TC activity over the WNP. RCMs have also been used to provide high-resolution future projections of TC activity over the Central America (Diro et al. 2014), Vietnam (Wang et al. 2017), as well as in the Philippines (Gallo et al. 2019).

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

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

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

2 Data and methods

2.1 Model description and design of the experiments

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

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

Among the CPS applied in this study are the Emanuel (Emanuel 1991), Grell with Arakawa-Schubert closure (Grell 1993), Kain-Fritsch (Kain and Fritsch 1990), and Tiedtke (Tiedtke 1996). The Emanuel (EM) scheme triggers when the level of buoyancy exceeds the cloud base level. Cloud mixing is episodic, inhomogeneous, and convective fluxes are based on a model of sub-cloud-scale updrafts and downdrafts (Emanuel and Zivkovic-Rothman, 1999). The Grell (GR) scheme considers the point where the lifting parcel reaches the moist convection level as the triggering point for convection. An updraft and a penetrative downdraft compose the two steady-state circulations that makes up the clouds (Grell 1993). The GR scheme in RegCM4 has two closure types: (1) Arakawa–Schubert (AS) (Arakawa and Schubert 1974) and (2) Fritsch–Chappell (FC) (Fritsch and Chappell 1980). In this study, the GR simulation uses the AS closure wherein buoyant energy is released immediately at each time step. The Kain–Fritsch (KF) scheme uses a one-dimensional entraining and detraining plume model where negatively buoyant parcels are assumed to detrain from the clouds, while positively buoyant parcels tend to entrain into the clouds. This allows the model to modulate the mean thermodynamic characteristics between convective clouds and the environment (Kain and Fritsch, 1990). The Tiedtke (TE) scheme triggers convection when moisture convergence becomes greater than the boundary layer moisture flux (Tiedtke 1989). The estimation of precipitation depends on the CPS over land or ocean. For example, over tropical oceans, GR underestimates precipitation while EM overestimates it for very intense events (Giorgi et al. 2012). To minimize such biases, the RegCM4's ability to mix two schemes was considered in this study, i.e. GR scheme over land and EM scheme over the ocean (GR-EM) (Giorgi et al. 2012). A brief description of the RegCM4 simulations conducted in this study and their distinguishing features are summarized in Table 1.

2.2 TC detection and observed dataset

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

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

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

Similar thresholds enumerated above are employed in identifying TCLVs for the ERAI and all RegCM4 simulations despite the coarser resolution of the former than the latter. A resolution-dependent TC detection and tracking (e.g., Walsh et al. 2007) is not used in this study to see how downscaling improves the representation of TCs. It also allows a direct comparison of TC-associated rainfall, which is defined as the rainfall within the 500 km radial distance from the 6-hourly positions of the TC center following Zhang et al. (2019).

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

The identified TC MWS are then classified according to the current TC categories operationally being used by the Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA) namely, 1) tropical depression (TD): MWS < 17 m s^{-1}; 2) tropical storm (TS): MWS ranging from 17 to 25 m s^{-1}; 3) severe tropical storm (STS): MWS ranging from 26 to 33 m s^{-1}; 4) typhoon (TY): MWS ranging from 34 to 61 m s^{-1}; and 5) super typhoon (STY): MWS > 61 m s^{-1}. As the study focuses mainly on TCs affecting the Philippines, only those TCs that developed, entered, and/or existed over the PAR (see, Fig. 1) were considered in the analyses. The PAR is among the agreed areas of responsibility for providing storm warnings and shipping forecasts back in the mid-1960s (WMO 1966). Since then, PAGASA has been using the PAR for monitoring TCs and in providing TC-related warnings to the public (e.g., Cinco et al. 2016).

3 Results

3.1 TC frequency

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

The distributions of annual TC frequency derived from the observations, ERAI, and the RegCM4 simulations are also shown at the right hand side of Fig. 2. Higher (lower) interannual variations are noted in EM, GR-EM, and KF (ERAI, GR, and TE) than the observations. The EM scheme simulates the closest 30-year average annual TC frequency in the PAR at 12.9 TCs per year compared to the observed annual mean TCs of 16.8 TCs per year. The KF scheme, on the other hand, overestimates the climatological mean annual TC frequency at 22.5 TCs per year, while the GR and TE simulate an average of 1.4 and 1.2 TCs per year, respectively. In general, the models tend to underestimate the annual-mean TC frequency, except for the RegCM4 simulation with KF scheme. Similar results of overestimation for KF (Shen et al. 2019), underestimation for EM (Fuentes-Franco et al. 2017), and non-detection of TCLVs for the GR schemes (Diro et al. 2014) were reported using ERAI-driven RCM simulations applied in different regions of the world. It is also worth noting that fewer TCs occurring over the PAR are similarly detected from the raw ERAI data (Fig. 2). Among the RegCM4 experiments, the EM scheme tends to reproduce the most realistic annual TC frequency in the PAR, consistent with the findings of Diro et al. (2014) over the Central American region.

3.2 TC spatial density

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

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

3.3 TC-associated rainfall

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

The percentage of TC-rain contribution in the RegCM4-simulation using EM is higher by approximately 5–10% than the ERAI over the large areas of the Pacific Ocean and the SCS (contours in Fig. 4b). The center of maximum TC-rain contribution over the ocean, northeast of the Philippines, is also shifted more to the north in the EM simulation. The spatial pattern of TC-rain contribution of the GR-EM experiment is almost similar to EM, although smaller in magnitude (Fig. 4d). An overestimated TC-rain contribution (as much as 20% higher than the ERAI) is noted for KF over the entire domain (Fig. 4f). Because few TCs are forming over the Pacific Ocean and only a handful of TCs were detected in the GR and TE, the annual mean contribution of TC-associated rainfall is severely underestimated for these simulations (Fig. 4c and f, respectively); it did not reach 5% anywhere in the domain. Among all RegCM4 simulations, the GR-EM best represents the spatial pattern and magnitude of TC-associated rainfall over the domain.

3.4 TC seasonality

The monthly average number of TCs that existed in the PAR from 1981 to 2010 is shown in Fig. 5. Based on observations (thick solid line in Fig. 5) TCs are less active in the PAR during the months of January–April and gradually increases from May until it reaches the peak TC activity in July–September. Then, the TC activity over the PAR decreases in the following months from October until December. These main characteristics of the TC annual cycle are well reproduced by the ERAI, although with consistently fewer number of TCs. On the other hand, some of these key features are similarly reproduced in the five RegCM4 experiments. For instance, the low TC activity over the PAR from January–April is generally reproduced by the RegCM4 experiments, except for some overestimation in the KF, EM, and GR-EM simulations. The RegCM4 simulations also captured the start of having more active TCs in May and June. The TC peak season over the PAR that occurs during the months of July–September is reproduced by the KF, EM, and GR-EM simulations, despite the overestimation in KF and underestimation in EM and GR-EM. All model experiments tend to underestimate TC activity over the PAR in October. The observed TCs over the PAR in December are overestimated by the KF, EM, and GR-EM schemes. The pronounced seasonality of TC activity over the PAR, on the other hand, is not observed in the GR and TE simulations.

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

The most active TC season of JAS illustrates that TCs generally affect the northern regions of the Philippines (third column from the left of Fig. 6). Also, TCs tend to exit either to the north or northwest of the PAR. Such TC trajectories are well captured by the ERAI and to some extent in the EM, GR-EM, and KF simulations, although KF indicates more westward moving tracks (Fig. 6f). Similar to the AMJ season, GR and TE fail to simulate TCs in a large area east of the PAR over the Pacific Ocean (Fig. 6d and g, respectively). During the OND season, the JMA best track data indicates that most of the TCs move westward making landfall over the northern and central Philippines, although some TCs tend to re-curve and move away from the country toward higher latitudes (rightmost panel of Fig. 6a). Such pattern is well represented in the ERAI and to some extent, in the EM, GR-EM, and KF experiments, although shifted more to lower latitudes affecting the southern regions of the Philippines (rightmost panel of Fig. 6b, c, e, and f, respectively). Furthermore, there appears to be more TCs originating south of 5°N in the model simulations. As noted in the other seasons, relatively fewer (more) TCs were detected in the GR and TE (KF) in OND. Among the five RegCM4 experiments used in this study, GR-EM best represents the observed TC tracks for the JAS and OND seasons.

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

3.5 TC intensity

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

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

3.6 TC lifespan

The lifespan of each of the TCs that existed in the PAR from 1981 to 2010 is summarized in Fig. 8. On average, the TCs last for about 150 h over the entire domain for the observations (marked by the horizontal line inside the box in Fig. 8a). The ERAI and RegCM4 simulated TCs, on the other hand, tend to have longer lifecycles, and wider variations among the individual TCs as characterized by the higher interquartile range (the area covered by the boxes in Fig. 8a). This extended TC lifecycle for all experiments and the reanalysis is associated with the densely extended TC tracks over the eastern part of the domain over the Pacific Ocean and more westward tracks of the TCs for the majority of the seasons (as shown in Fig. 6). TCs with such characteristics typically have longer lifespans because they stay at lower latitudes longer (Shen et al. 2019). These longer lifecycles obtained from the model-simulated TCs as compared to the best track data can also be attributed to the uncertainty in observations of weak storms (e.g., Hodges et al. 2017).

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

4 Discussion

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

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

Over the WNP, TC formation and subsequent development occur under favorable conditions such as positive values of 850-hPa relative vorticity and weak vertical wind shear (Jin et al. 2016). The RegCM4-simulated climatological mean 850-hPa relative vorticity and vertical wind shear (i.e., the difference in the zonal winds between the 850 hPa and 200 hPa levels) are compared with the ERAI (Fig. 9). The 850-hPa relative vorticity in the ERAI is characterized by a northwest-southeast elongated positive belt extending from the SCS to the WNP between 5°–23°N, with the maximum center over the SCS. The positive belt of the relative vorticity is associated with the monsoon trough, a vital factor for TC genesis in the region (Holland 1995; Wu 2012). The northwest-southeast orientation of the positive vorticity belt is likewise obtained by the RegCM4 experiments, although the belt is disconnected at different parts over the domain. For both the EM and GR-EM experiments, the positive vorticity zone located northwest of the Philippines over the SCS is disconnected (Fig. 9b and d, respectively). The KF experiment, on the other hand, shows a more extended positive vorticity belt to the northeast of the Philippines (Fig. 9e). The location of positive vorticity zone east of the Philippine landmass up to 140°E is slightly shifted to the north for the three CPS experiments (EM, GR-EM, and KF), which leads to the location of TC formation more to the north thereby having more TCs passing north of the domain, freeing much of the central portion of the Philippines (see, Fig. 6). A wide area of positive vorticity located east of the Philippines is absent in both the GR and TE experiments (Fig. 9c and f, respectively). This in turn, inhibits the formation of TCs over the Pacific Ocean resulting in a large underestimation of TCs in these experiments. The simulated vertical wind shear of all CPS experiments generally captures the observed spatial pattern, wherein low values of vertical wind shear dominates over the regions east of 140°E and north of 15°N of the entire domain. According to Gray (1979), vertical wind shear values of less than 10 m s^{-1} are favorable for TC formation and development. Since the locations of areas with favorable vertical wind shear that are simulated by all CPS experiments are generally similar, this implies that the vertical wind shear is not a dominant environmental factor that affects the TCs in the RegCM4 simulations conducted in this study.

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

Drier mid-tropospheric conditions (represented by the 700-hPa relative humidity, shadings in Fig. 10) are observed for the GR and TE experiments over large areas of the domain, particularly over the Pacific Ocean south of 15°N, where most TCs entering the PAR are generated (Fig. 10c and f, respectively). Similar dry bias in GR has been noted in Im et al. (2008) attributing it to the infrequent triggering of the scheme. The dry bias in TE, on the other hand, is attributed by Ali et al. (2015) to the underestimated surface latent heat flux and more stable structure of the atmosphere from the surface up to the mid-tropospheric level. According to Gray (1979), dry mid-tropospheric conditions are unfavorable for TC formation due to the entrainment of dry air causing air parcels to lose buoyancy and inhibit deep convection (Cheung 2004). The relatively drier mid-tropospheric environment in the GR and TE experiments (in comparison to the other CPS and with the ERA-Interim reanalysis) serves as one of the main reasons why there are no TCs forming south of 15°N over the Pacific Ocean in these experiments (see, Fig. 6). In an earlier climate modeling study, Strachan et al. (2013) identified the mid-tropospheric relative humidity as the dominant factor to affect TC activity over the WNP.

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

5 Conclusions

This study has investigated the sensitivity of simulated TCs affecting the Philippines to the different CPS in RegCM4. Five ERAI-driven RegCM4 simulations using different CPS were conducted covering a 30-year period of investigation (i.e., 1981–2010). A TC detection algorithm that looks at the dynamic and thermodynamic characteristics of a system from the 6-hourly output of the model was used to identify the TCs. Results show that the chosen CPS affects different TC characteristics, including the frequency, seasonality, intensity, track, associated rainfall, and lifecycles of the model-simulated TCs over the PAR. Among the five CPS used in the RegCM4 simulations, the EM scheme yielded an annual-mean TC frequency over the PAR that is closest to observations. The combined GR-EM schemes closely reproduced the spatial pattern of the TC track density covering the entire period, the TC-associated rainfall, the seasonal patterns of TC tracks, and the TC lifespan over the PAR. The KF scheme, on the other hand, is the only CPS that was able to simulate stronger TCs within the domain. However, there are some noted discrepancies with the observed and simulated TCs. For instance, the models have some difficulty in capturing the annual frequency of TCs over the PAR; none of them obtained a significant correlation with the observed values. The timing of the pronounced seasonality of TC occurrence over the PAR is also not well captured in the RegCM4 experiments. Furthermore, the TC tracks are slightly displaced in the model simulations.

The biases obtained from the RegCM4 simulations using different CPS can be explained by how realistic the large-scale environmental conditions governing TC formation and subsequent movement are simulated by the model. The pattern of earlier TC re-curvature is due to the weaker WNP subtropical high, while the northward shift of the simulated positive low-level vorticity belt for EM, GR-EM, and much more with the KF, results in the TC genesis being more to the north thereby having more TCs passing north of the domain, deviating away from the central portion of the Philippines (see, Section 3.4). Shen et al. (2019) have similarly noted an overestimation and northward shift of the TC track density over the CORDEX-East Asia domain with the KF scheme, despite using a different RCM, attributing such bias to the extended Intertropical Convergence Zone and overestimated relative humidity over the WNP region. The RegCM4 simulations with GR and TE schemes underestimate the 700-hPa relative humidity over large areas of the domain, particularly east of the Philippines over the Pacific Ocean, which creates a dry environment where deep convection is restricted, thereby inhibiting TC formation and further development. Such conditions lead to almost no TCs forming over the Pacific Ocean for these experiments, agreeing with the earlier findings of Strachan et al. (2013), who showed that the mid-tropospheric relative humidity is the dominant factor that affects TC activity over the WNP.

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

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Figure Captions

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

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

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

Fig. 4 Annual mean TC-associated rainfall (shadings) and percentage contribution to annual total rainfall (contours, units: %) averaged over the 30-year period (1981–2010). Note that the minimum contour displayed is set at 5% with succeeding intervals of 5%, and only those TCs that existed and/or entered the PAR are included

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

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

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

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

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

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

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

Experiment Name	**Convective Parameterization**	**Trigger**	**Entrainment**
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