High-resolution regional climate model projections of future tropical cyclone activity in the Philippines

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1 INTRODUCTION

Tropical cyclones (TCs) present a major threat to human life and livelihoods in tropical coastal regions around the world. The Philippines is highly exposed to TCs generated in the western North Pacific (WNP) region, with an average of 20 TCs entering the Philippines Area of Responsibility (PAR; see Figure 1) each year (Cinco et al., 2016). Many of these, including very intense damaging TCs, impact directly on the Philippines. In particular, Typhoon Haiyan (locally named Yolanda), which hit the Philippines in November 2013, was the most intense TC ever to make landfall. It caused significant damage and resulted in over 6,300 deaths (Mas et al., 2015; Takagi and Esteban, 2016). With the occurrence and characteristics of TCs expected to be affected by climate change (IPCC, 2013), the impact of Typhoon Haiyan highlights the need to better understand how TC activity affecting the Philippines may change in the future.
Past variability and changes in TC attributes (e.g., genesis locations, trajectories, intensities, associated rainfall) have been widely investigated for the WNP region (e.g., Webster et al., 2005; Wu et al., 2006; Kossin et al., 2007; Kubota and Chan, 2009; Wu and Zhao, 2012; Cinco et al., 2016) with contrasting conclusions about whether or not there have been significant changes in TC behaviour in recent decades. Moreover, the potential impact of a changing climate on the future behaviour of WNP TCs has been receiving growing attention. The Intergovernmental Panel on Climate Change (IPCC) fifth Assessment Report (AR5) suggests a tendency for an overall decreased TC frequency but an increase in the relative number of intense (category 4 and 5 on the Saffir–Simpson scale) TCs in the WNP; an increase in the frequency of the strongest TCs is considered “more likely than not” at the ocean basin scale (IPCC, 2013).

Climate models are the main source of information for assessing the potential impacts of climate change at global and regional scales and can be used for assessing future changes in TC activity. Previous modelling studies have projected future decreases in the globally averaged frequency of TCs by 6–34% by the end of the 21st century but there is low confidence in projected changes for individual ocean basins (Hijioka et al., 2013). The projected decrease in global TC frequency is believed to result from a projected decrease of vertical motions in deep convective systems as well as in the relative humidity of the mid-layers of the atmosphere in the Tropics, a result consistent with many global warming studies (Bengtsson et al., 2007; Emanuel et al., 2008; Zhao et al., 2009).

While global climate models (GCMs) can be useful for inferring changes in the annual number of TCs and their geographical distribution, evidence from the literature demonstrates the need for high spatial resolution model simulations to realistically capture the processes relevant to the formation and evolution of intense TCs (e.g., Bengtsson et al., 2007; Manganello et al., 2012; Strachan et al., 2013; Walsh et al., 2013). In particular, the simulation of TC intensity depends crucially on model resolution (Strachan et al., 2013; Rathmann et al., 2014). For example, Manganello et al. (2012) demonstrated gains in accuracy when using a 10-km resolution model to investigate TCs in the North Atlantic. The use of a regional climate model (RCM) is therefore valuable when investigating the impact of climate change on the intensity of TCs.

Previous high-resolution studies typically project a future shift in intensity towards stronger events, with an increase in intensity of 2–11% by the end of the century (e.g., Knutson et al., 2010; Murakami et al., 2012; Emanuel, 2013). However, it is worth noting that modelling studies are often unable to draw conclusions about very strong TCs, even with high-resolution simulations.

Confidence in projections of WNP TC activity from RCMs is limited by the performance of the GCMs that provide the boundary conditions. Han et al. (2016) find that biases in TC numbers and tracks vary between atmosphere-only GCMs. Roberts et al. (2015) suggest deficiencies in atmosphere-only GCMs in simulating differences between WNP TC activity for different phases of El Niño–Southern Oscillation (ENSO), reducing our confidence of projections in TC activity based on coupled atmosphere–ocean GCMs. These findings are relevant to RCM projections as it is unlikely that downscaling will eliminate such biases. An exploration of the implications of these GCM deficiencies is therefore necessary when investigating the impact of climate change on TCs.

The work described here builds on these previous studies, providing new information to increase our understanding of plausible future TC changes over the Philippines and neighbouring seas. We present and compare the results of RCM projections generated during a UK Met Office collaboration with the Philippine Atmospheric Geophysical and Astronomical Services Administration (PAGASA). Three RCMs—HadGEM3-RA, RegCM4, and HadRM3P—were used to downscale historical and future simulations of selected GCMs (see section 2.1 for details), taken from the multi-model ensemble developed in the fifth phase of the Coupled Model Intercomparison Project (CMIP5; Taylor et al., 2012), over the WNP. TCs were identified and analysed in these simulations using the TRACK vortex tracking software (Hodges, 1995).

In section 2 we describe the approach taken to GCM selection, downscaling and TC tracking. We then present the main results from the analysis of RCM simulations; section 3 focuses on the validation of model output compared to observations, and section 4 presents the results of the future projections. In section 5 we discuss the strengths and limitations of the modelling approach and discuss how the results strengthen our knowledge of future TC activity in the Philippines. Finally, in section 6 we consider the broader
relevance of the results for guiding adaptation decision-making.

2 | METHODS

2.1 | Experimental design

The design of the RCM simulations considered a range of important factors, including sampling different global and regional models to explore model uncertainty, representation of TC processes, accounting for climate variability, and computational cost. To sample GCM uncertainty, simulations with the HadGEM3-RA regional model (see Moufouma-Okia and Jones, 2015 for a detailed description) downscaled three GCMs: HadGEM-2ES, CNRM-CM5, and MRI-CGCM3 (GCM selection criteria described below in section 2.2). The HadGEM2-ES model was also downscaled using HadRM3P (Jones et al., 2004; Massey et al., 2015) and RegCM4 (Giorgi et al., 2012) to sample RCM uncertainty. RCM simulations using the ERA-Interim reanalysis data set (Dee et al., 2011) as boundary data have also been run to provide additional data for RCM validation.

The simulations with HadGEM3-RA were conducted at a resolution of approximately 12-km, close to the 10-km resolution used in Manganello et al. (2012). This 12-km setup was judged to be fine enough to represent TCs much better than in the GCMs but is still sufficiently coarse to allow downscaling of multiple GCMs at reasonable computational cost. This enables the simulations to capture the development of TCs as they track towards the Philippines. In contrast, the simulations using HadRM3P and RegCM4 were conducted at a 25-km resolution as this was the highest resolution available, or tested in a similar environment, for these models at the time of the study.

A series of sensitivity tests compared different domain sizes. A domain extending to 160°E was chosen to cover the main development region for TCs that affect the Philippines (Figure 1). Simulations were conducted for time periods covering 1971–2005 and the mid-21st century period from 2035 to 2064; the historical period was selected as 35 years to enable a moving window of 30 years for analysis to account for any decadal variability, and the future 30-year period was selected to centre on 2050 as the extent of the time horizon for relevant planning decisions in the Philippines. Due to computational resource constraints, we chose to sample different GCMs and RCMs for a single greenhouse gas (GHG) concentration scenario, RCP8.5, representing the “worst case” of available scenarios.

2.2 | GCM selection

CMIP5 includes over 40 GCMs but downscaling simulations from all of these would have been prohibitively computationally expensive and it was necessary to select a small subset to downscale. We first disregarded GCMs for which data were not available to generate RCM boundary conditions. Following recently established good practice in selecting GCMs for downscaling (e.g., McSweeney et al., 2015a), we then aimed to select GCMs that would provide a small ensemble of simulations with realistic representations of relevant aspects of the observed climate and that would sample as much of the uncertainty in future changes in relevant aspects of the climate as possible. Our selection process focused on the simulation by the GCMs of large-scale drivers of WNP TCs, excluding those which had implausible representations of these, and then the range of projected changes in the remaining subset of GCMs. The CNRM-CM5, HadGEM2-ES, and MRI-CGCM3 GCMs were deemed to have a reasonable representation of these drivers relative to other CMIP5 GCMs and provided an ensemble of simulations with a range of different responses to the greenhouse forcing and thus were selected for downscaling (Daron et al. 2016).

We surveyed existing literature on the CMIP5 GCMs to assess their representation of relevant aspects of the observed climate and supplemented this information with our own analysis. The spatial resolution of the CMIP5 GCMs is too coarse to realistically represent TCs but they do simulate less intense TC-like vortices (TCLVs). Information on the simulation of genesis locations, tracks, and seasonality of these vortices from McSweeney et al. (2015b) suggested that the eight GCMs bcc-csm1-1-m, CanESM2, CMCC-CM, CNRM-CM5, HadGEM2-CC, HadGEM2-ES, MIROC-ESM-CHEM, and MRI-CGCM3 had a better simulation of TCLVs than the other CMIP5 GCMs assessed. Of these, bcc-csm1-1-m, CanESM2, and CMCC-CM were disregarded as they had deficient simulations of observed SST patterns in western Pacific (Brown et al., 2015; F. Graham, personal communication). MIROC-ESM-CHEM was disregarded due to its particularly poor simulation of the southwest monsoon (McSweeney et al., 2015b). Our own comparison of patterns of simulated seasonal mean surface temperature, sea level pressure, and mid-level relative humidity against the ERA-40 reanalysis (Uppala et al., 2005) also revealed more significant biases in MIROC-ESM-CHEM than in the remaining five GCMs. McSweeney et al. (2015b) illustrated changes in WNP TCLV frequency between 1971–2002 and 2064–2095 for RCP8.5 for the four remaining (and other) GCMs (their fig. 3.8). HadGEM2-CC and HadGEM2-ES showed less frequent and weaker TCLVs, CNRM-CM5 showed less frequent but stronger TCLVs, and MRI-CGCM3 showed more frequent and stronger TCLVs. Noting the similarity in the results for HadGEM2-CC and HadGEM2-ES and the more extreme change in TCLV frequency in HadGEM2-ES than in HadGEM2-CC, we selected CNRM-CM5, HadGEM2-ES, and MRI-CGCM3 for downscaling to maximize the sampling of distinct future climate changes.
2.3 Analysing TCs from model data sets with TRACK

In order to extract and analyse the TCs simulated by the RCMs, we use the TRACK software package (Hodges, 1995; 1996; 1999; Bengtsson et al., 2007). TRACK identifies vortices in gridded atmospheric data sets and has been widely used to analyse TCs in atmospheric models, including in recent studies examining TCs simulated by climate models (e.g., Manganello et al., 2012; 2014). In this study we apply TRACK to 3-hourly output from HadGEM3-RA simulations and 6-hourly output from the HadRM3P and RegCM4 simulations to generate information on TC tracks and associated wind speeds. There are six stages in this process:

1. Calculate vorticity fields for pressure levels throughout the troposphere (850, 500, 300, and 200 hPa).
2. Spectrally filter (equivalent to a T5-63 filter, i.e., half wavelength of 4,000–300 km) the 850 hPa vorticity fields to T42 resolution to reduce the noise at higher resolutions and produce more reliable coherent tracks (e.g., Liang et al., 2017; Wang et al., 2017). The vorticity fields at all levels are then filtered to T63 resolution.
3. Identify tracks of near-surface atmospheric vortices using 850 hPa relative vorticity field maxima within a 5° radius window.
4. Disregard TCs that do not have warm cores extending throughout the troposphere (which is a known physical property of real TCs), i.e., vorticity maxima must decrease with altitude.
5. Identify maximum wind speeds in the vicinity of the vortices.
6. Disregard storms below TC strength (associated wind speed maxima below 17 m/s, limit between a tropical depression and a storm in JMA’s tropical cyclone intensity scale).

3 RESULTS: VALIDATION OF SIMULATIONS

In this section we examine the ERA-Interim reanalysis-driven simulations and GCM-driven simulations for the present period as a basis for interpreting the future projections. We compare the results from the historical downscaled simulations with the Japan Meteorological Agency (JMA) best track data set for the WNP. JMA uses the Dvorak technique (Dvorak, 1975) to estimate TC position and intensity (described as 10-min maximum sustained wind speed) using visible and infrared imageries from geostationary and polar-orbiting weather satellites (Barcikowska et al., 2012), completed by ship and surface observations. A complete description of the process can be found on the WMO website (https://www.wmo.int/pages/prog/www/tcp/documents/JMAoperationalTCanalysis.pdf).

The frequency, annual variability, and seasonality of TCs, the density, and the individual TC tracks and the maximum sustained wind speed are compared to the JMA observations. Only TCs that entered the PAR (see Figure 1) are considered; with the exception of the track density analysis which considers tracks across the RCM domain.

3.1 TC frequency and annual variability

Comparing the downscaled ERA-Interim simulations to the JMA observations, we see that the magnitude of year-to-year variability is well captured by all RCMs (Figure 2a), though there appears to be a weak correlation in the pattern of variability over the observed time series (Pearson correlation coefficient between all three simulations and the observations lower than 0.2). The results show a comparable average and median frequency for the HadRM3P simulation but lower values for HadGEM3-RA and RegCM4. The simulations are also unable to reproduce a realistic number of the intense TCs (maximum wind speed above 33 m/s, corresponding to the typhoon categories). The absolute frequency of intense TCs from the HadRM3P model is very similar to the observations (Figure 2b) but the model overestimates the total number of TCs, meaning that the distribution of TC intensities is biased low.

By design we do not expect the coupled atmosphere–ocean GCM-driven simulations to reproduce the year-to-year variations of the observational data set, since they are not forced with observed SSTs, but we can validate the overall distributions of TC attributes. The HadGEM3-RA/HadGEM2-ES and HadGEM3-RA/MRI-CGCM3 simulations show comparable distributions of TC frequency and variability, though slightly underestimate overall TC frequencies with fewer intense events than observed (Figure 2c,d). Conversely, both frequency and variability obtained for the HadGEM3-RA/CNRM-CM5 and RegCM4/HadGEM2-ES simulations are too high compared to the observed JMA values. The HadRM3P/HadGEM2-ES frequency and variability are close to the observations but some issues are visible for individual years with no TCs (1991, 1999) as shown by the discontinuous curve in Figure 2c,d.

3.2 TC seasonality

The seasonal distribution of TCs obtained from the ERA-Interim-driven simulations is in good agreement with the observed data sets (Figure 3a,b). The HadRM3P simulation is close to the observational distribution, whereas HadGEM3-RA follows the same seasonal pattern with lower values, as seen in section 3.1. The RegCM4 simulation, however, produces too many TCs during the DJF season and not enough during SON.
The GCM-driven simulations show a good consistency with the observations, with peak activity during August or September (i.e., within the observed peak TC season) and few TCs between January and April (Figure 3c,d). However, the number of early season (June and July) TCs is substantially underestimated by all but the HadGEM3-RA/CNRM-CM5
and the RegCM4/HadGEM2-ES simulations. This RegCM4 simulation also produces too many TCs during the DJF season, as observed with the ERA-Interim-driven simulation. The CNRM-CM5-driven simulation overestimates the frequency of TCs through the whole year.

The spatial distribution of TCs shows a clear seasonal cycle in the observations and in the simulations. This is visible in Figure 4, showing the latitude of the exit points from the PAR (or the lysis point if the TC disappears within the area). The TCs occurring in winter and spring appear to be mainly located in the southern area of the domain, whereas TCs occurring in summer and autumn, far more frequent, cross the domain boundary in its northern half. The ERA-Interim-driven simulations consistently reproduce this cycle, especially during the main season (July–September). However, the TCs cross the domain at a more southern latitude from October to March, even though the general pattern is similar to observations. The GCM-driven simulations produce similar behaviour, especially for the CNRM-CM5 simulations which produce TCs too far to the south during the first half of the year. The RegCM4/HadGEM2-ES simulation is the only exception, with TCs propagating too far north on average from December to March.

While the spatial distribution of the TCs throughout the year shows good agreement between the observed data set and the models, the general pattern of tracks followed by individual TCs (Figure 5—only five overlapping years shown to clearly depict individual tracks) show some discrepancies, especially in the northern and western parts of the domain. A significant number of TCs follow a recurving track in the observed data set, entering or being generated in the southeastern part of the domain, following a northwestern direction and then recurving towards the northeast to leave the domain. Only a few TCs follow this track in the RCM simulations. Moreover, there are fewer TCs leaving the domain by its northern boundary in the simulations. Some TCs that track towards this boundary appear to be blocked and move westwards; further investigation of this
effect is needed to understand if this is an artefact of the domain location, or an effect of the RCM representation of TCs. The result of this behaviour is a concentration of TCs along a latitudinal line around 23°C14 that artificially increases the number of TCs passing over the northern part of the Philippines. This issue is evident across the RCMs, although especially pronounced for the RegCM4/HadGEM-2ES simulation where TCs occurring in DJF are recurving towards the north and being blocked along that 23° line. This specific behaviour explains the more northern position (on average) of TCs highlighted in Figures 4 and 5 for that simulation.

3.3 | Spatial density

The TC spatial density was also estimated for each grid cell of the domain (Figure 6). The results from the ERA-Interim-driven simulations show reasonable agreement with the observations, especially for the HadGEM3-RA simulation. The density computed for the HadRM3P simulation appears too high compared to the observations in the northern half of the domain whereas the results from the RegCM4 simulations show comparable average values but lower densities over the northern Philippines.

The GCM-driven simulations produce densities that are higher than the observations over the northern part of the domain (HadGEM2-ES) or the whole domain (CNRM-CM5 and MRI-CGM3). The downscaled CNRM-CM5 results show densities that are clearly too high over the western and southern part of the Philippines. This suggests that the models are not able to precisely reproduce the spatial distribution of TCs in the region.

The latitude of the genesis point (genesis density maps in Figure S1, Supporting Information) is consistent between the simulations and the observations, especially for the main genesis location in the southeast of the domain. However, RegCM4 simulations are the only ones able to generate genesis points in the centre of the domain, as observed in the observational data set.

3.4 | TC intensities

The distribution of the maximum intensities (maximum sustained wind speed) was calculated and analysed for the different simulations (Figure 7). Intensities in the JMA observations vary between the imposed 17 m/s lower threshold for TC wind speeds to values greater than 60 m/s. Peaks in the observed distribution appear around 30 and 40 m/s. This might be influenced by measurement precision: wind speeds are measured with a 5-knots increment in the observed data set, which could lead to a multimodal
The results obtained with the ERA-Interim simulations using the HadRM3P and HadGEM3-RA models are comparable with the observational data set, with peaks in the distribution between 25 and 40 m/s. However, TCs with a maximum intensity beyond 50 m/s are absent from those simulations. This is consistent with the lower frequency of intense events produced (Figure 3). The intensities obtained with the RegCM4/ERA-Interim simulations are lower than the observed values, peaking between 25 and 30 m/s. This might be due to the higher number of weak TCs generated during the DJF season by this model. This behaviour is comparable with the RegCM4/HadGEM2-ES simulation, suggesting that might be an effect of the RCM. The other GCM-driven simulations also display distributions that peak between 25 and 40 m/s and are not able to generate wind speeds over 50 m/s (with the exception of HadGEM3-RA/CNRM-CM5 that produces TCs that are more intense than the rest of the models).

Overall, these results show that the RCM simulations reproduce the seasonality and, with some biases, the frequency of WNP TCs. However, the frequency of the most intense TCs is under-represented and aspects of the spatial distribution of TCs do not match observations. The implication is that the model results can be used for understanding the impact of climate change on TCs across the Philippines area in general but cannot be used to generate reliable locally specific information at the sub-national scale, especially for the most intense events. It is worth noting that the RegCM4 simulation was not discarded from the study, despite its poor performance, especially regarding the seasonality of TCs. This was because it was the only one able to generate TCs whose genesis location was within the domain, as with some observed TCs (see Figure S1).

This work brings together data sets generated as part of different projects, meaning there are some differences in how the TC tracking method is applied to the data sets. For example, the temporal resolution of model output differs between the HadGEM3-RA simulations (3-hourly) and the HadRM3P and RegCM4 simulations (6-hourly). This can lead to differences in the total number of TCs estimated from the model data. For the coarser temporal resolution data, the central location of a fast-moving TC is more likely to move across more than one grid box from one output period to the next (i.e., over 6 hr). This can lead to an underestimation of
TC frequency in the grid-boxes (e.g., Zolina and Gulev, 2002). However, analysis shows that the bias in TC frequency calculated for 6-hourly data from the HadGEM3RA/HadGEM2-ES simulation, compared with the original 3-hourly data, is similar for both historical and future simulations. Moreover, this analysis shows that the frequency of intense events is not affected by the change in temporal resolution (results not shown). We therefore do not expect the analysis issues resulting from different temporal resolutions to affect the overall results, in terms of the projected change in future TCs. The difference in the temporal resolution can also affect intensity, as the physical time step (i.e., the time between two iterations of the model calculations) differs among models (5 min for HadRM3P, 3 min from HadGEM3-RA, and 1 min for RegCM4). This can affect the maximum wind speeds generated in the simulations, thereby influencing estimations of maximum TC intensities. Therefore, the different distributions obtained from the models cannot be directly quantitatively compared and the analysis presented here focuses on comparisons in the overall distributions of intensities in the models and observations, and their evolution in the future.

4 | RESULTS: PROJECTED CHANGES OF TC FREQUENCY, INTENSITY

Building on the comparisons with observed TC activity and validation of RCM simulations outlined in section 3, we now present the results of the future model projections. The TRACK method was applied to the three GCM-driven simulations (HadGEM2-ES, CNRM-CM5, and MRI-CGCM3) of HadGEM3-RA and the HadGEM2-ES-driven simulations of HADRM3P and RegCM4 for the mid-21st century period (2035–2064) under the RCP8.5 climate forcing scenario. The results shown here include projected changes from the

FIGURE 7 Distribution of maximum intensities (i.e., maximum sustained wind speed) for the eight downscaled simulations and the observations for the overlapping period 1982–2003 [Colour figure can be viewed at wileyonlinelibrary.com]
historical simulations (1971–2005) for TC frequency and intensity. Results for other TC attributes, such as changes in spatial density, are not shown as the validation process showed the model simulations performed poorly in representing these aspects; discussed further in section 5.

4.1 Frequency of TCs

Figure 8 shows the distribution of annual TC frequencies for the five downscaled simulations for the historic (left) and future (right) periods. Most simulations project decreases in the mean and median annual number of TCs entering the PAR, although changes are only statistically significant\(^1\) for HadGEM3-RA/HadGEM2-ES, RegCM4/HadGEM2-ES, and HadGEM3-RA/CNRM-CM5, with a decrease of 21, 13, and 15%, respectively. The remaining simulations (HadRM3P/HadGEM2-ES and HadGEM3-RA/MRI-CGCM3) show no significant change. The changes in the interannual variability (based on the interquartile range) show little agreement across simulations, with a decrease in for two simulations (HadGEM3-RA/CNRM-CM5 and HadGEM3-RA/MRI-CGCM3), no change for HadGEM3-RA/HadGEM2-ES and HadRM3P/HadGEM2-ES, and an increase for RegCM4/HadGEM2-ES.

4.2 Intensity of TCs

The future distribution of TC maximum intensities has also been investigated. Figure 9 shows the changes in the climatological distributions of TC maximum intensities in the future compared to the historical period. Overall, there are large discrepancies in the intensity distributions across models and any changes projected from the past to the future period are small. There is no change in the mean of the distribution for the HadGEM3-RA/MRI-CGCM3 and only small (non-significant) increases in the mean of the distribution for the HadGEM3-RA/HadGEM2-ES/ and RegCM4/HadGEM2-ES simulations. However, a significant\(^2\) increase in the mean and right tail of the distribution of TC maximum intensities is found for the HadGEM3-RA/CNRM-CM5 and the HadRM3P/HadGEM2-ES simulations.

5 DISCUSSION AND LIMITATIONS

In this study we have explored projected future changes in TC behaviour in different RCM simulations using boundary forcing from multiple GCMs. Though large discrepancies appear among the different simulations, and issues are evident in the tracks of TCs produced in the limited area RCM experiments, there is some consistency among the results towards: (a) no change or a slight decrease in the overall TC frequency across the PAR and (b) no change or a slight increase in the maximum intensity of TCs. Our results build on previous studies described earlier in this paper that have projected future decreases in the globally or regionally averaged frequency of TCs (e.g., Hijioka et al., 2013; IPCC, 2013; Manganello et al., 2014) demonstrating that this conclusion may also apply to the Philippines region. Overall, the model projections presented here increase confidence in the expectation of no change or fewer TCs in the Philippines region by the mid-21st century under a high GHG concentration scenario, but with the potential for an increase in the maximum intensity of those TCs which do occur.

It is notable that all RCM simulations are forced with SSTs that are predicted to be higher in the mid-21st century than in the recent past. Typically increased SSTs are associated with increased TC activity. However, none of the simulations show increasing TC frequencies in the future so other processes must be influencing the formation and propagation of TCs under a warmer climate. Increasing wind shear in some seasons may be one of the key drivers of decreased TC.

**FIGURE 8** Annual TC frequencies for three simulations for the historical 1971–2005 period (left) and future 2036–2065 period (right). The box limits correspond to the 25th and 75th percentile and the whiskers describe the range of values. The median is represented by the middle line in the box and the mean by the circle [Colour figure can be viewed at wileyonlinelibrary.com]
frequencies in the projections, though this change in wind shear is only evident for the HadGEM2-ES-driven simulations (result not shown, see Daron et al., 2016).

Increasing SSTs may still influence the intensity of TCs. There are some small but significant increases in the maximum intensities of TCs for some of the model simulations. This result is consistent with previous research assessed in the IPCC AR5 report (Christensen et al., 2013). However, changes in the frequency of the most intense TCs differ among simulations.

High year-to-year variability exhibited by model simulations in the past and future periods shows that year-to-year variability will likely continue to dominate the climate risks, rather than any systematic change to TC behaviour in a warming climate. Further understanding of the role of internal, large-scale natural variability on the frequency and intensity associated with TCs in the WNP is required. For example, the role of the El Niño–Southern Oscillation and the Pacific Decadal Oscillation on the variability of TCs intensity and frequency under a changing climate needs to be further investigated.

The downscaled simulations inherit biases and errors in the large-scale driving conditions from the driving GCMs. While the GCM selection process eliminated particularly poor performing CMIP5 GCMs in the Philippines region, the GCMs chosen are still imperfect. As it is likely that biases in the driving GCM will be transferred to the downscaled simulation, further investigation and simulations are required for a deeper exploration of GCM uncertainties.

Of particular interest to decision makers is whether or not the model projections can be used as a basis for future information relevant to different regions of the Philippines. The model validation (section 3) reveals some discrepancies between the models and the observations, especially regarding TC trajectories. The limited domain that was chosen enabled us to run simulations at a high resolution, leading to a better representation of TC features. However, this spatial limitation led to significant issues for simulating the trajectories of TCs, especially along the boundaries. The presence of the northern boundary at 30°N means that TCs could be “blocked” (see section 3); TCs that start to recurve might be prevented from doing so and instead move westwards across the northern part of the Philippines. The result is a reduced number of recurving TCs and an overestimation of TC track density over the northern part of the domain.

When looking at seasonal averages, the simulations are all able to reproduce the wind patterns observed in the reanalysis data sets and no obvious discrepancy can be observed between the RCM and the GCM (example in Figure S2). However, we observe an unusual behaviour during TC events, with what we could describe as “vorticity waves” going eastwards along the northern boundary of the domain. This unrealistic model behaviour, that could be an artefact of the RCM domain during TC events, lowers confidence in
the spatial information that is generated, especially for the northern Philippines. This particular issue may be resolved by moving the northern boundary of the domain further northward, though this would incur further computational cost. Future experiments should consider this issue to ensure more realistic tracks for recurring TCs and remove the erroneous population of TCs from the northern Philippines.

Errors and limitations associated with the modelling preclude a reliable assessment of sub-regional changes in TC activity. However, through a combination of further analysis (e.g., looking at sub-seasonal activity and the likely causes of any changes in the model projections) and additional targeted experiments (e.g., exploring the impact of moving the northern RCM boundary further north), it could be possible to strengthen understanding of the results and potentially provide more conclusive information for landfalling TCs across the northern, central and southern regions of the Philippines. Nevertheless, the work conducted in this study has improved knowledge from existing studies which are ocean basin-wide, and while reliable sub-national projections of TCs under climate change are not yet available, the focus of this study on the Philippines region provides information of greater salience to decision makers than previous studies.

6 CONCLUSION

This paper contributes to knowledge on possible future changes to TCs in the Philippines region, through presenting the results of downscaled CMIP5 GCM simulations, under a high GHG concentration scenario, using multiple RCMs at varying spatial resolutions. The study builds on existing high-resolution climate modelling studies that cover the wider WNP region, and specifically focuses on changes to TCs affecting the Philippines. Results are provided for changes in TC activity by the mid-21st century, thereby aligning with the long-term planning time horizons of many adaptation and investment decisions.

Each simulation produces different changes to TC frequencies and intensities under a warming climate. Some future projections show small but significant decreases in the annual frequency of TCs in the Philippines region, with other simulations showing no change. In addition, some simulations show small but significant increases in the intensity of TCs, with others showing either insignificant increases or no change. These projections are consistent with previous studies in the wider region, such as those reported by the IPCC AR5. The difficulty to simulate accurately all processes relevant to TCs, and to generate reliable projections for future TCs, mean that uncertainties remain. However, the consistency of results at the sub-basin scale among global and regional models, as well as the consistency with previous large-scale studies, represents another layer of information and contributes to building confidence on the future evolution of TCs over the Philippines region.

The biases evident in the model simulations, and the experimental constraints, mean that confidence in model projections remains relatively low, especially for spatial information. Reliable conclusions therefore cannot be drawn at smaller scales to inform projections in different parts of the Philippines. Yet our findings strengthen confidence in the expectation of no change or a small reduction in the frequency of TCs in the Philippines region as well as no change or a small increase in TC maximum intensities. The study also provides a basis for further detailed analysis of high-resolution GCM and RCM projections to improve projections of TCs for the Philippines under a future warmer climate.

Irrespective of whether overall TC numbers and intensities increase or decrease, the model simulations show that year-to-year variability will remain high. This result has significant implications for those involved in making decisions to help build climate resilience and reduce the impacts of climate change. It implies that we should continue to expect years with many damaging TCs and other years with very few. Using information on past typhoons and their impacts remains highly relevant to long-term planning. Combining historical information and knowledge with the additional information produced in this study can help in assessing the robustness of decisions in a changing climate.

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NOTES

1At the 95% confidence level using a two sample t test.
2At the 95% confidence level using a two sample Kolmogorov–Smirnov test.
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**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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