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Projections of Southern Hemisphere Tropical Cyclone Track Density using CMIP5 models

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Abstract

A recently validated technique for detecting and tracking tropical cyclones (TCs) in coarse resolution climate models was applied to a selected group of 12 models from the Coupled Model Intercomparison Project (CMIP5) to assess potential changes in TC track characteristics in the Southern Hemisphere (SH) due to greenhouse warming. Current-climate simulations over the period 1970 – 2000 were first evaluated against observations using measures of TC genesis location and frequency, as well as track trajectory and lifetime, in seven objectively defined genesis regions. The 12-model (12-M) ensemble showed substantial skill in reproducing realistic TC climatology over the evaluation period. To address potential biases associated with model interdependency the analysis was repeated with an ensemble of five independent models (5-M). Results from both the 12-M and 5-M models were very similar, instilling confidence in the models for climate projections. Projected changes in TC track density between the current- and future-climate (2070–2100) simulations under the Representative Concentration 8.5 Pathways (RCP8.5) were also assessed. Overall, projection results showed a substantial decrease ($\sim 1\text{--}3$ per decade) in track density over most parts of the SH by the end of the twenty-first-century. This decrease was attributed to a significant reduction in TC numbers ($\sim 15\text{--}42\%$) consistent with changes in large-scale environmental parameters such as relative vorticity, environmental vertical wind shear and relative humidity. This study has important implications for regional-scale climate change and adaptation pathways for the vulnerable regions in the SH, particularly the small island countries in the Pacific.

1. Introduction

The frequency of tropical cyclone (TC) impacts on coastal communities is directly determined by the annual number and mean trajectory of localized TCs. Improving clarity of the relationship between these characteristics and human-induced global warming can therefore help target future planning and preparation efforts to high-risk areas in the Southern Hemisphere (SH). Potential changes to future TC track densities will have regional-scale consequences to communities situated among the three TC basins in the SH, namely the South Indian basin (0 – 50°S; 30 – 90°E), the Australian region (0 – 50°S; 90 – 160°E) and the southwest Pacific basin (0 – 50°S; 160°E – 120°W).

Determinants of TC track density can be separated into two main components: genesis location and frequency, and the overall track direction. A number of previous studies undertaken on TC frequency projections in the SH (e.g., Murakami et al. 2012; Sugi and Yoshimura 2012; Tory et al. 2013c; Rathmann et al. 2014) have generally indicated a mild decrease in the hemisphere-wide numbers with reasonably high confidence. However, an exception was a downscaling effort (Emanuel, 2013) that found an increase in TC activity in the South Indian and western Australian regions. In contrast to TC frequency, there has been little consensus on TC track projections for the SH basins (Christensen et al. 2013; Walsh et al. 2016), potentially due to relatively fewer studies in these basins and a focus on the Northern Hemisphere in recent years (e.g., Camargo 2013; Daloz et al. 2015; Wang and Wu 2015; Kossin et al. 2016; Nakamura et al. 2017; Park et al. 2017). This highlights the need for more robust quantitative assessments of projected changes in TC track densities for the SH basins using new and innovative approaches.

In recent years, attention has begun to shift towards TC track projections as numerous modelling and analytical techniques have been developed and refined to better evaluate the

complexities of TC tracks in climate models. This includes improvements in the often-used climate models from the Coupled Model Intercomparison Project (such as CMIP5, Taylor et al. 2012) in reproducing realistic large-scale environmental conditions that affect TC formation (e.g., CCiA 2015; Moise et al. 2015; Chand et al. 2017) and advances in track analysis techniques (e.g., Gaffney 2004; Nakamura et al. 2009; Nakamura et al. 2017; Shen et al. 2018). There have also been substantial improvements in detection (and tracking) of TCs in climate models, including the Okubo-Weiss-Zeta scheme (OWZ; Tory et al. 2013a) that can circumvent detector dependence on model resolution, which is often cited as a limitation of TC projection studies (e.g., Walsh et al. 2007; Horn et al. 2014; Daloz et al. 2015). The primary aim of this study is to use state-of-the-art analysis techniques to determine if a consensus on track density changes can be achieved for the SH using CMIP5 models under a high emission scenario (RCP8.5; Section 2). The two main aspects of TC track density changes (i.e. frequency and track direction) are investigated in seven separate study regions that are objectively identified by a cluster analysis.

The TC-detection and tracking scheme of Tory et al. (2013a) is applied to CMIP5 models after having undergone scrupulous validation in ERA-Interim data in terms of annual numbers (Tory et al. 2013b) and tracks (Bell et al. 2018). The latter study provided an objective definition of a “TC track” for applications in coarse resolution model data and also recommended discarding short-lived TCs (< 2-days) for optimal performance. Prior application of the scheme in CMIP5 models (e.g., Tory et al. 2013c; Chand et al. 2017) found that some models failed to realistically simulate a reasonable global climatology of TCs, thus limiting the present study to only 12 CMIP5 models that were deemed satisfactory by those studies. Moreover, when interpreting results from multi-model ensembles, we also acknowledge the concerns raised by Sanderson et al. (2015) that statistical interdependence between CMIP5 models needs to be considered in their construction.

The outline of this paper is as follows. Section 2 contains the data, definitions and methods used in the study. Section 3 provides assessment and validation of models and climate projection results. Section 4 discusses the physical mechanisms that drive significant projected changes in TC track densities. Finally, a summary, discussion of results and prospects of future work are given in Section 5.

2. Data, Definitions and Methods

a. Observational data

The International Best Track Archive for Climate Stewardship (IBTrACS-WMO v03r08, Knapp et al. 2010) data over the observationally consistent period (1989-2013) is used to define the observed TC track climatology and to give a baseline of TC characteristics. For the purpose of this study, an observed TC track is defined to begin at a point when the storm first reaches the 10-minute sustained wind speed of 17 m s^{-1} ; storms not reaching this intensity at any time of their lifetime are excluded from the analysis. Tracks are terminated if a forecast centre no longer tracks them (i.e. track information ceases in the database) or if they encounter an objectively diagnosed subtropical jet (Tory and Dare 2015) after which the storm has likely to have lost its physical TC characteristics.

b. CMIP5 model data

Twelve models from the Coupled Model Intercomparison Project phase 5 (CMIP5, Taylor et al. 2012) are used in this study (Table 1). Note that CMIP5 experiments contain the current generation of climate models that provide a wide array of platforms to test current and future climate scenarios (e.g., Knutti et al. 2013). The two scenarios assessed in this work are (1) the current-climate simulation over the period 1970 – 2000 for model evaluation and assessment, and (2) the future-climate simulation over the period 2070 – 2100 under the Representative Concentration Pathway 8.5 (RCP8.5) for projection analyses. Note that the RCP8.5

represents an 8.5 W m^{-2} increase in radiative forcing values in the year 2100 as compared to the pre-industrial emission levels (Riahi et al. 2011) and was chosen to best elucidate any changing TC behaviour in a warmer climate.

c. Multi-model ensembles and significance tests

Differences between model physics parameterisations, as well as deficiencies in models to resolve atmospheric processes, can create potential biases in the results of projection analyses. In this study, we statistically reduce some of these biases by combining results of all models together to form a multi-model ensemble. In the analysis, results are considered statistically robust if large proportions of models agree on the sign and magnitude of the change. A statistical significance test to evaluate the robustness is determined at the 95% level and is based on a binomial distribution (e.g., Chand et al. 2017). Thus for a 12-model ensemble, the number of models required to attain the 95% level of significance is 10. However, this test assumes model independence, and based on the analysis of Knutti et al. (2013) and Sanderson et al. (2015), some models may be in violation of this assumption. As a result, we additionally employed a smaller set of independent models for all our analyses (see Appendix A for details). This “smaller” multi-model ensemble is comprised of five models and requires all models to agree on the sign of change to achieve the 95% significance.

d. Detection and tracking

The Okubo-Weiss-Zeta (OWZ) TC detection and tracking scheme (Tory et al. 2013a) is used in this study to detect and track TCs in all models. The OWZ scheme has undergone scrupulous validation in reanalysis data in terms of annual TC numbers and genesis positions (Tory et al. 2013b) and more recently in terms of tracks at 12-hr intervals (Bell et al. 2018). Key details of the OWZ detector and tracker are provided in Tory et al. (2013a) while a short

summary of the scheme is provided in the appendix of this paper for easy reference (Appendix B).

Crucially, the Bell et al. (2018) track validation study identified a limitation of the tracking scheme, in that it detected a higher than expected frequency of short-duration TC tracks in ERA-Interim. This limitation also affected TC tracks in models, and so necessary steps are taken to minimise its impact on projection results. Further analysis following Bell et al. (2018) revealed that most of the short-duration tracks in models were likely to be associated with detector-related errors and as such, a more accurate climatology was found when TC tracks less than 2-days in lifetime were removed from the analysis (Fig. 1).

To be consistent with the definition of the observed TC tracks, the objective TC track definition established in Bell et al. (2018) is also used here. This definition states that a TC track detected by the OWZ scheme commences from a position analogous to that of a TC first reaching a 10-minute sustained wind speed of 17 m s^{-1} , and terminates where a TC either dissipates or encounters an objectively diagnosed subtropical jet.

e. Cluster analysis

The probabilistic curve-clustering technique of Gaffney (2004) is used to group TC tracks of similar properties (in space and time) over the entire SH. TCs in certain sub-regions with more erratic tracks have undergone further cluster analysis to elucidate more meaningful patterns (see Section 3). Implementation of the clustering technique follows prior studies (e.g., Camargo et al. 2007; Chand and Walsh 2009) where linear regression mixtures are fitted to each track with a pre-defined number of clusters, $k=7$ in this case (e.g., Ramsay et al. 2012; Bell et al. 2018), to produce a zonally consistent solution for the SH basins (Fig. 2).

f. Seven meridional-bounded regions

Information provided by cluster analysis from the best-track observations (Fig. 2a) are represented as kernel density estimates that enclose 75% of the TC genesis positions in each cluster to allow a direct comparison with the models. However, when the analysis was repeated for the models¹ (Fig. 2b), a slight shift in the cluster position was found (e.g., meridional location of the Indian Ocean clusters). We note that when comparing TC number results in different climate scenarios, changing orientations of corresponding clusters could mask actual changes (or even produce spurious results), making comparisons difficult. This issue is further exacerbated by the large geographical size of the study area under consideration and the high number of clusters used.

Therefore, we decided to use the clustering results from the observations to define geographically consistent regions for ease of comparison. That is, we use the 75% genesis contour of each cluster in IBTrACS to define consistent regions for the entire experiment (including models) instead of re-clustering each new set of model data. Given that clusters are largely adjacent to each other across the hemisphere, simple meridional lines were used to define the seven regions (R1–R7, Fig. 2). The positions of the meridional lines were carefully chosen and adjusted to achieve as distinct regions as possible, including taking into consideration the general track-type of TCs in neighbouring clusters.

¹ Note that biases exist in models causing TCs to be detected in the far eastern South Pacific (east of 225°E). These detections are excluded from this cluster analysis to avoid creating an additional arbitrary cluster.

3. Evaluation and Projection of TC Track Density Change

a. Regional genesis density and TC numbers

Changes in TC track density is dependent on both TC numbers (also used interchangeably with genesis frequency throughout the paper) and track directions. We start by evaluating the ability of the 12 CMIP5 models (hereafter collectively referred to as the 12-M ensemble) to simulate regional-scale (R1–R7) TC genesis locations and frequency in the SH.

It is evident from the analysis that the 12-M CMIP5 models can realistically simulate spatial patterns of the observed genesis density estimates reasonably well in most regions (Fig. 2). However, an exception is the eastern South Pacific region (i.e. farther east of R7) where a number of TCs are detected by the models that were not present in the observations as also noted in prior studies (e.g., Tory et al. 2013; Chand et al. 2017). This could be potentially due to climate model biases in simulating overly zonal orientation of the South Pacific Convergence Zone (SPCZ)² in the eastern Pacific (e.g., Brown et al. 2012; Grose et al. 2014). In addition, Tory and Ye (2018) investigated the different constraints that restrict TC formation in a selection of CMIP5 models. They found these models were unable to correctly simulate the cool sea-surface temperatures and associated dry middle-troposphere that inhibits TC formation in this region. The average annual number of TCs detected by the 12-M ensemble in current-climate simulation were also found to compare well with the observed climatology (Table 2). However, some slight overestimations were noted, particularly near Madagascar (R1) where an additional ~2 TCs per year were detected.

² The SPCZ is the dominant climatic feature in the south Pacific where tropical cyclone activities are often spawned, and any biases in the position and orientation of the SPCZ will have implications on tropical cyclones forming in the region.

We next turn our attention to regional projections of TC numbers between the current- and future-climate simulations from the CMIP5 models (Table 2 and Fig. 3). Results indicate a widespread reduction of TC detections by the late twenty-first century, particularly in the South Indian basin (i.e., regions R1–R4). Here, each region experiences a statistically significant reduction in mean climatological numbers (at the 95% significance level), with the largest reduction (~42 %) occurring in R3 located between 85°E and 105°E. The region north of Australia (R5) experiences about a 15% reduction in TC numbers (though this is not statistically significant), while there is no clear indication of any change off the east coast of Australia (R6). Farther east into the South Pacific (R7), a statistically significant reduction in TC numbers (~15 %) is also found.

We recognize that some models used in these analyses (12-M ensemble) are very similar in physical characteristics and that model interdependence may complicate the interpretation of multi-model ensemble results (Knutti et al. 2013; Sanderson et al. 2015). For this reason, as well as to correct model biases in reproducing TC climatology in the SH (e.g., detections east of R7), our analyses were repeated with a 5-model (5-M) ensemble. Details on the selection of these five models, based on independence (Knutti et al. 2013) and a number of other criteria for statistical bias corrections, can be found in Appendix A. Overall, projection results from the 5-M ensemble were very similar with the 12-M results (Table 2 and Fig. 3), instilling our confidence in the 12-M results.

b. Regional TC tracks

The second aspect of track density change analyzed is the frequency and direction of TC tracks. Here we evaluate the ability of the five independent CMIP5 models (5-M ensemble) to simulate these track characteristics in each region (R1–R7) of the SH. It is important to emphasize that within some regions (R3–R7), there exists distinct westward and eastward

trajectories that are not well captured by the seven mean trajectories (as in Fig. 2). Therefore, we sub-divide these regions by implementing a further cluster analysis with respect to two clusters in an attempt to separate the tracks into two distinct types: eastward and westward moving tracks (Figs 4-6)³. Regional track characteristics are then evaluated with measures of mean track trajectory, mean TC lifetime and the number of eastward and westward moving tracks.

The mean direction of TC tracks detected by the 5-M ensemble in current climate simulations were found to compare quite well with the observed climatology (Figs 4–6). However, the mean TC trajectory lengths were often slightly underestimated in models, for example in R1 and R6-East, potentially due to biases in estimating endpoints of tracks both in observations and models. In contrast to the latter result, the mean TC lifetimes were well replicated in most regions (Table 4), and we note that underestimated TC trajectory lengths were attributed to a slight underestimation of model tracks in the region poleward of 30°S (not shown) rather than underestimated lifetimes. The observed ratios between westward and eastward TC tracks in R3, R5, R6 and R7 were found to compare well with the current-climate 5-M simulations (Table 3). However, we note an overestimation of the model-simulated westward tracks in R4 (where 48% tracked westward), causing a discrepancy with observations (where just 18% tracked westward).

We next examine projected changes in the tracks between the current-climate and future-climate (under RCP8.5) conditions (far right panel in Figs 4–6). For ease of comparison, the 5-M ensemble mean trajectories for the current- (“black tracks”) and future-

³ Note for Region-3 we found a manual split into “eastward” and “westward” more interpretable than those given by cluster analysis. Here, tracks were classified as either “eastward” or “westward” based on their longitude positions at two-thirds of their lifetime in relation to their genesis position. In addition, westward heading model tracks in the South Pacific (Region-7) that do not appear in the observed climatology are separated by an additional cluster (to a total of 3).

(“red tracks”) climate simulations are plotted on the same axis (Fig. 7). Overall, some small shifts in mean genesis locations (circles) are noted (e.g., poleward movement in R2, R3, R4 and R6-West under RCP8.5; see also Kossin et al. 2014; Moon et al. 2015). For the mean trajectory, there seems to be no clear deviation between the current and future climate simulations, although one exception appears to be the trajectory of R6-West. This trajectory appears to shift from west-southwest in the current-climate to more southwestward in the future-climate, potentially shifting mean TC landfall positions farther south over the eastern coast of Australia (see also Fig. 5, bottom-right panel).

Furthermore, projected changes in TC numbers are also compared for the eastward and westward trajectories defined earlier (for regions R3–R7; Table 3). The significant decrease of TC numbers in the central South Indian (R3) was found to more heavily reduce the eastward tracks (-65%) than the westward tracks (-39%). The decrease in TC numbers over northern Australia (R5) was found to reduce the westward track numbers by 33%, yet the number of eastward tracks was found to increase by 6% (although the change in the latter was not considered statistically significant). Westward TC tracks in the Coral Sea region (R6) were found to increase by 16%, with region-wide numbers offset by an accompanying decrease in eastward numbers (-13%). Farther into the South Pacific (R7), projected decreases in TC numbers were more evenly spread across the different track types (Table 3). For completeness, projected changes in the mean TC track lifetimes were also examined (Table 4) but no major changes (> 1 -day) were noted.

c. Track density change

The prior sections have separately given detailed analyses of the two aspects of TC track density changes between the current- and future- climate model simulations. Here, we combine these two aspects into a single measure called “TC activity” that can collectively

explain changes in TC track density under the RCP8.5 scenario. TC activity is measured by accumulating the number of unique TCs either forming or entering a $2.5^\circ \times 2.5^\circ$ grid box over the entire SH basin for both current- and future-climate simulations using the 12-M ensemble of CMIP5 models (Fig. 8). TC activity is found to decrease significantly (up to 3 TCs per decade) throughout the South Indian basin extending through to 135°E (i.e. including R1–R4, and R5-West) in the future-climate. The decrease in TC activity is most concentrated centrally in the basin (R3) and occur over the open ocean. However, the coastal communities of east Africa, Madagascar and western Australian region are likely to experience a similar decrease in activity ($\sim 1\text{--}2$ per decade). Overall, these decreases are likely from the significant decreases in TC numbers over those regions (Section 3a) rather than projected changes in track directions that showed little deviation (Section 3b).

East of 135°E , projected changes in TC activity are comparatively smaller in magnitude (mostly within ± 1 TC per decade). Notably, the small patch of increased TC activity alongside the eastern coast of Australia is supported by significant agreement between individual models of the 12-M ensemble (not shown). TC activity here is influenced by the number and mean trajectory of TCs in the R5-East and R6-West sub-clusters. In R6-West, TC numbers were found to slightly increase in magnitude for both the 12-M and 5-M ensembles (Table 3). The mean trajectory of R6-West was also found to move more favourably into this patch of increased density (Fig. 7). However, the combination of these effects only amounts to a very small increase in the coastal TC activity (~ 1 per twenty years). It is beyond the scope of this study to determine whether this increase is related to the poleward or other shifts in track density due to climate change as it may require complicated downscaling techniques (e.g., Walsh and Katzfey 2000; Emanuel 2013). East of the dateline (R7), TC activity was generally found to decrease (~ 1 per decade) and is attributed to

decreasing TC numbers in this region as also noted in several other previous studies (e.g., Tory et al. 2013c).

4. Changes in the Large-scale Environment

As seen earlier, substantial changes in TC activity between the current-climate simulation and future-climate RCP8.5 simulation were attributed to changes in TC numbers rather than tracks. Therefore, the large-scale environmental parameters associated with TC formation are empirically analysed here to better understand these projected changes. TC formation is controlled by a set of dynamic and thermodynamic environmental parameters (e.g., Gray 1975; Tory and Frank 2010), noting that not all of these parameters may be relevant on climate time-scales.

The dynamic parameters evaluated include relative vorticity at 850 hPa, environmental vertical wind shear between 850 and 200 hPa and low-level convergence at 850 hPa. The only thermodynamic parameter evaluated is mid-level relative humidity at 700 hPa. Values of large-scale fields (such as U and V components of winds at respective levels) needed to compute these parameters are taken during the peak of the SH TC season (i.e. December to February), and then composited over all models in consideration to form multi-model ensembles for the current- and future-climate simulations (Figs 9 and 10).

To a large extent, all large-scale environmental parameters exhibit less favourable future conditions for TC development in the South Indian Ocean (west of 130°E; regions R1-R4) where models project a strong reduction in climatological numbers between the current- and future-climate (Fig. 3). Cyclonic relative vorticity is reduced in the main genesis zone (~8 – 15°S), particularly evident in R1 around Madagascar, and appears to be the main factor inhibiting TC development here in the future climate (Fig. 9a; Fig. 10a). Reduced mid-level

relative humidity (Fig. 9c; Fig. 10c), as well as reduced low-level convergence (Fig. 9d), are also consistent with a reduction in TC numbers.

In R5 north of Australia ($\sim 130 - 155^\circ\text{E}$), we see a slight enhancement of cyclonic vorticity (Fig. 9a; Fig. 10a), particularly near the east Australian coast ($\sim 140^\circ\text{E}$, 12°S). While these conditions should favour development of TCs, we suspect that projected decline in the number of TCs in this region is strongly modulated by substantially reduced low-level convergence (Fig. 9d) and to a lesser extent by relative humidity (Fig. 10c). In the two South Pacific regions (R6 and R7; $155^\circ\text{E} - 135^\circ\text{W}$), increased environmental vertical wind shear (Fig. 9b), and to a lesser extent reduced low-level relative vorticity and convergence (Fig. 9a and Fig. 9d), appear to be the main factors inhibiting TC formation.

5. Discussion and Summary

A comprehensive study was undertaken in the SH to examine the likely projected changes in TC track densities due to anthropogenic greenhouse warming. Climate model simulations from the CMIP5 experiments were used to assess changes in TC track densities between the current (1970–2000) and future-climates (2070–2100). Two multi-model ensembles were used, a 12-model (12-M) and a 5-model (5-M) version, with the latter only containing models that met more strict criteria such as model independence.

Unlike previous climate projection studies for the SH basins, we have objectively created seven regions (R1–R7) based on cluster analysis where each region is characteristically distinct in terms of mean genesis location and track shapes. After robust statistical assessment and validation of TC numbers and tracks for each region using observed records from the IBTrACS database, CMIP5 simulations from the current-climate were compared with those from the future-climate (under representative concentration pathway 8.5; RCP8.5) to examine the influence of increasing atmospheric greenhouse gas

concentrations on regional-scale TC characteristics in the SH basins. The major findings of this work are summarised as follows.

- Compared to observations, CMIP5 models can realistically simulate regional TC numbers and tracks reasonably well in the SH.
- TC track density is projected to decrease ($\sim 1\text{--}3$ per decade) by the late twenty-first century for coastal communities situated in the South Indian Ocean and Western Australia. This was attributed to a significant decrease in TC numbers west of 130°E ($\sim 18\text{--}42\%$; R1–R4) due to changes in environmental parameters such as reduced relative humidity, relative vorticity and convergence.
- TC track density change over eastern Australia and the Coral Sea was found to be fairly minor (within ± 1 TC per decade). Notably, poleward of 20°S on the eastern Australian coast, there was significant agreement between models of a small increase in track density (~ 1 per twenty years). This could be potentially due to an increase in the number of Coral Sea storms tracking westward (R6-West), increased lifetime of R5-East storms, or change in mean trajectory of R6-West storms.
- Over the South Pacific (R7), a decrease in TC track density was found (~ 1 per decade). This was attributed to a significant decrease in TC numbers ($\sim 15\%$), consistent with increased environmental vertical wind shear, and to a lesser extent, reduced low-level cyclonic vorticity and convergence.
- Projected changes in the mean lifetime of TC tracks in each region were also examined but no indication of any major change (> 1 day) between current- and future-climate simulations were established.

Overall, the projections of annual TC numbers given by this study are consistent with fine-resolution (60 km) model experiments performed by Murakami et al. (2012) as they also showed a more confident reduction in TC numbers over the South Indian Ocean than the South Pacific (as per their Fig. 4). Using slightly coarser resolution model experiments, Rathmann et al. (2014) also showed similar results, emphasising that the significant decrease of TCs in the South Indian Ocean under RCP8.5 was consistent with more frequent early twentieth century (1900–1930) TCs. Similar to the present study, Sugi et al. (2014) attributed a less favourable large-scale environment to the widespread reduction of TC numbers in the South Indian Ocean. Our result of no major changes in TC track lifetimes was consistent with the results of Knutson et al. (2010) but in contrast to Rathmann et al. (2014) who projected TC lifetimes in the SP basin (i.e. in our R5–R7 regions) to decrease by 19%.

Future areas of scientific interest suggested by this study include: (1) the extent at which projected changes are modulated by ENSO, (2) quantitative assessment of the drivers of eastward and westward tracks in the regions R3–R6 with respect to natural modes such as monsoonal waves and ENSO, and (3) further investigation into the causes of a slight increase in TC activity poleward of 20°S on the eastern Australian coast.

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Appendices

A. Robustness of multi-model ensembles

We test the robustness of the 12-M ensemble results as it may be argued that some key assumptions may be violated on the following grounds.

- (1) Model independence: presence of same-family members in the ensemble.
- (2) Model biases: models simulating TCs where they are not observed in the real-world (e.g. eastern South Pacific).
- (3) Model reliability: ensuring models correctly simulate SH TC formation and track climatology patterns.
- (4) Sensitivity: exclusion of short-lived TCs (<48-hrs) in the analysis.

We first address point (4) by repeating the 12-M analysis of Section 3a with short-lived (<48-hr) TCs included. It is found out of the 84 trials (12 models with 7 regions each) there are only two models that indicate changes of sign from a reduction in TC numbers to an increase (BCC-CSM1.1m changed from -1% decrease to +4% increase in R2; while CNRM-CM5 changed from a -17% decrease to a 2% increase in R3). Similarly, two other regions changed sign from an increase in TC numbers to a decrease in two other models. Overall, there is no change in the 95% significance of the sign tests for each region. Confidence intervals of percentage change in TCs are also similar as the previous analysis (not shown).

To address points (1) - (3), we assess each model subject to the following criteria.

- i. Detected model TCs should be within $\pm 50\%$ of observed climatology [$0^\circ - 225^\circ\text{E}$]

- ii. Less than 5% of a model's TCs should form in the eastern South Pacific (between $[230^{\circ} - 300^{\circ}\text{E}]$)⁴
- iii. Spatial density correlations between model TC tracks and observed climatology should be above 0.85.
- iv. Cluster analysis should produce similar clusters to the observed climatology (as in Fig. 2a).

In order to properly address these concerns (i. – iv.), a decision was made to create a new ensemble that only contains the models that best meet the above criteria. Knutti et al. (2013) derived a 'family tree' of CMIP5 models, documenting their similarities and highlighting how code sharing between institutions is behind some interdependency. Here, only one model from each family (e.g., Table A1) is allowed to be part of the new ensemble, to ensure independence is retained. Results for each model (Fig. A1; Table A1; Table A2) show that the models ACCESS1.0, CCSM4, MIROC5, BCC-CSM1.1M and CSIRO-MK3.6 meet all four criteria, and are therefore first-choice members of the new ensemble. The B-tier includes ACCESS1.3 and HadGEM2-ES but as they share common characteristics with ACCESS1.0, these are not included in the ensemble. The three GFDL models all have similar errors from the criteria assessed, with GFDL-ESM2m managing the best score of "C". However, given that the emphasis of this ensemble is on track-related performance, errant steering in the South Pacific makes this model unsatisfactory to include. Therefore, only the five A-tier models are used to form the 5-model ensemble (5-M).

⁴ Some models produce TCs where they are not observed, particularly in the South Atlantic and eastern South Pacific [east of 135°W]. Storms forming in the eastern South Pacific are more of an issue here as they are nearby to where real TCs are observed to form, creating doubt around the correct simulation of nearby large-scale conditions necessary for TC formation. Therefore, this assessment criteria is put in place to potentially exclude models from the ensemble if more than 5% of a model's TCs form between $[130^{\circ}\text{W}$ and $60^{\circ}\text{W}]$.

B. OWZ Detection and tracking

The OWZ detection system consists of six parameters (Table B1): minimum thresholds of OWZ at the 850- and 500-hPa levels, relative humidity (RH) at the 950- and 700-hPa levels, specific humidity (SpH) at the 950-hPa level and a maximum threshold of vertical wind shear (VWS) between 850- and 200-hPa. The OWZ variable is a low-deformation vorticity parameter used to identify regions favourable for TC formation at the centre of a semi-closed circulation (i.e. a 'marsupial pouch'; Dunkerton et al. 2009), within the lower- to mid-troposphere. More precisely, it is the product of absolute vorticity and the Okubo-Weiss parameter (Okubo 1970; Weiss 1991) normalised by the vertical components of relative vorticity squared such that:

$$OWZ = \text{sgn}(f) \times (\zeta + f) \times \max \left[\frac{\zeta^2 - (E^2 + F^2)}{\zeta^2}, 0 \right] \quad (1)$$

where f is the Coriolis parameter, $\zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$ the vertical component of relative vorticity,

$E = \frac{\partial u}{\partial x} - \frac{\partial v}{\partial y}$ the stretching deformation, and $F = \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}$ the shearing deformation.

The OWZ detection and tracking scheme is concisely summarized in five dot-points below, with further detail accessible in other studies (Tory et al. 2013a; Bell et al. 2018).

- a. Each $1^\circ \times 1^\circ$ grid point is assessed based on the initial threshold values of each OWZ-Detector parameter every 12-hrs.
- b. When at least two neighbouring grid points satisfy the initial thresholds of each OWZ-Detector parameter, these points are considered to represent a single circulation at that point in time.
- c. The circulations from step (b) are linked through time by estimating their position in relation to the circulation's expected position based on an averaged $4^\circ \times 4^\circ$ steering wind at 700-hPa.

- d. Tracks are terminated when no circulation match is found in the next two time-steps within a generous (~350 km) latitude-dependent radius.
- e. The core thresholds are then applied to each storm track, and if they are satisfied for 48-hrs, a TC is declared.

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TABLES

Table 1: The twelve CMIP5 models used in this study. Number of TC detections (>2 day lifetime) between 0°E and 135°W in the Southern Hemisphere for the current-climate (CC, 1970-2000) and future-climate (FC, 2070-2100) under RCP8.5. All models listed form the 12-M ensemble, those in bold form the 5-M ensemble.

Model	Horizontal Resolution	TC Detections		Reference
		CC	FC	
GFDL-ESM2M	2.5°	848	643	Donner et al. 2011
GFDL-CM3	2.5°	812	568	Donner et al. 2011
GFDL-ESM2G	2.5°	784	624	Donner et al. 2011
ACCESS1.0	1.9°	967	599	Bi et al. 2012
ACCESS1.3	1.9°	1078	771	Bi et al. 2012
HadGEM2-ES	1.9°	1150	710	Jones et al. 2011
BCC-CSM1.1	2.8°	588	507	Wu et al. 2014
BCC-CSM1.1M	2.8°	649	703	Wu et al. 2014
CSIRO-Mk3.6	1.9°	980	670	Collier et al. 2011
CNRM-CM5	1.4°	322	301	Voltaire et al. 2012
CCSM4	1.2°	509	439	Gent et al. 2011
MIROC5	1.4°	1038	755	Watanabe et al. 2010

Table 2: Mean annual TC numbers (and proportion of that region's numbers) in the seven regions observed in IBTrACS (Obs, 1989 – 2013), from model ensemble current climate simulation (CC, 1970 – 2000), and future climate projection (FC, 2070 – 2100) under RCP8.5. Difference between FC and CC model TC numbers (Change). Number of models in agreement on the sign of change in TC occurrences (Sign). Sign and 95% Confidence Interval (CI) values in bold indicate significance at the 95% level. An asterisk (*) indicates one model in that region had the same number of TC occurrences in both current and future climate simulations.

12-model ensemble						95% CI	
Region	Obs	CC	FC	Change	Sign	Lower	Upper
R1	4.2 (20.4%)	6.2 (23.5%)	5.1 (24.3%)	-18%	11/12	-0.30	-0.06
R2	3.2 (15.4%)	3.5 (13.3%)	2.4 (11.3%)	-33%	11/11*	-0.45	-0.21
R3	2.7 (12.9%)	3.1 (11.6%)	1.8 (8.5%)	-42%	12/12	-0.58	-0.26
R4	3.3 (16%)	4.2 (15.8%)	3.3 (15.8%)	-21%	10/12	-0.39	-0.03
R5	1.9 (9.3%)	2.5 (9.7%)	2.2 (10.4%)	-15%	9/12	-0.29	-0.01
R6	2.5 (12%)	2.9 (11%)	2.8 (13.5%)	-3%	9/12	-0.19	0.13
R7	2.9 (13.9%)	3.9 (15%)	3.4 (16.1%)	-15%	10/12	-0.29	-0.01
5-model ensemble						95% CI	
Region	Obs	CC	FC	Change	Sign	Lower	Upper
R1	4.2 (20.4%)	5.9 (22%)	4.9 (23.8%)	-17%	4/5	-0.43	0.08
R2	3.2 (15.4%)	3.7 (13.8%)	2.5 (12.2%)	-33%	4/4*	-0.55	-0.10
R3	2.7 (12.9%)	3.4 (12.7%)	1.8 (8.8%)	-47%	5/5	-0.77	-0.17
R4	3.3 (16%)	4.6 (17.2%)	3.2 (15.7%)	-30%	5/5	-0.53	-0.07
R5	1.9 (9.3%)	3.1 (11.6%)	2.6 (12.7%)	-16%	3/5	-0.34	0.01
R6	2.5 (12%)	2.8 (10.6%)	2.8 (13.7%)	-1%	3/5	-0.34	0.31
R7	2.9 (13.9%)	3.2 (12%)	2.7 (13.1%)	-17%	4/5	-0.38	0.04

Table 3: Mean annual TC numbers in each cluster further split into “westward” and “eastward” trajectories by cluster analysis or otherwise. Information appears as: *Mean annual TC numbers (Frequency percentage for that region)*. Observed in IBTrACS (Obs) and detected in models by the 5-M ensemble (Current Climate, CC; Future Climate, FC). Westward and eastward splits are implied by 2-cluster solutions (see Fig. 4,5,6), except for Region-3* and Region-7 (see Footnote 3). Difference between FC and CC model mean annual TC numbers (Change). Projected changes in mean annual TC counts consistent with 12-M results (increase or decrease) are in bold.

Region	Obs (1989-2013)	CC (1970-2000)	FC (2070-2100)	Change (FC-CC/CC)
<u>R3</u>				
R3-West*	1.72 (62%)	2.31 (68%)	1.41 (79%)	-39%
R3-East*	1.04 (38%)	1.09 (32%)	0.38 (21%)	-65%
<u>R4</u>				
R4-West	0.68 (18%)	2.20 (48%)	1.65 (51%)	-25%
R4-East	3.00 (82%)	2.41 (52%)	1.57 (49%)	-35%
<u>R5</u>				
R5-West	1.56 (60%)	1.77 (57%)	1.19 (46%)	-33%
R5-East	1.04 (40%)	1.32 (43%)	1.40 (54%)	+6%
<u>R6</u>				
R6-West	0.76 (29%)	1.08 (38%)	1.26 (45%)	+16%
R6-East	1.84 (71%)	1.77 (62%)	1.54 (55%)	-13%
<u>R7</u>				
R7-West	-	1.09 (34%)	0.92 (34%)	-16%
R7-East1	1.51 (42%)	1.24 (39%)	0.99 (38%)	-20%
R7-East2	1.16 (32%)	0.89 (28%)	0.78 (28%)	-12%

Table 4: Mean TC track lifetimes in each region and sub-region as observed in IBTrACS (Obs)

and detected in models by the 5-M ensemble (CC and FC). [†]R5-West observed tracks are often

terminated at or soon after landfall, causing a discrepancy with model tracks.

Region	Obs (1989-2013)	CC (1970-2000)	FC (2070-2100)
<u>R1</u>			
	7.3 days	6.6 days	6.4 days
<u>R2</u>			
	7.5 days	7.6 days	6.7 days
<u>R3</u>			
R3-West*	8.7 days	7.5 days	6.8 days
R3-East*	5.1 days	5.6 days	5.1 days
<u>R4</u>			
R4-West	6.3 days	5.7 days	5.1 days
R4-East	5.3 days	6 days	6 days
<u>R5</u>			
R5-West	4.8 [†] days	8.3 days	8.2 days
R5-East	6.9 days	6.7 days	7.6 days
<u>R6</u>			
R6-West	7.2 days	7.4 days	7.1 days
R6-East	5.8 days	5.4 days	5.2 days
<u>R7</u>			
R7-West	-	5.6 days	5.6 days
R7-East1	3.4 days	5.4 days	5.7 days
R7-East2	3.8 days	4.7 days	4.9 days

FIGURES

Figure 1: Kernel density estimates of the distribution of TC track lifetimes for the observations (blue) and 12 CMIP5 models (orange). (a) all tracks, (b) only tracks that are of at least 48-hr lifetime, and (c) at least 96-hr lifetime.

Figure 2: Kernel density contours enclosing 75% of the TC genesis points of each cluster. Up to 120 TC genesis points are randomly selected from each cluster and displayed on the figure. Mean track trajectory and genesis (grey) for each cluster appear in the centre of the contours. Meridians define the seven genesis study regions (R1-R7) (black dash-dot lines).

Figure 3: (a) Percentage change in mean TC numbers in the CMIP5 models between the current climate simulation (1970-2000) and future climate projection (2070-2100). (b) As in (a) but for the 12-model and 5-model ensembles. Mean changes that are significant at 95% are indicated by an asterisk (*) while changes that have a 95% significant sign agreement of ensemble members are indicated by a plus (+) symbol.

Figure 4: Mean trajectories and individual TC tracks (random sample of up to 100) of observed and model tracks for the single cluster regions R1 and R2.

Figure 5: Mean trajectories and individual TC tracks (random sample of up to 100) of observed and model tracks for the 2-cluster regions (R3–R6). Note tracks in Region-3 are manually split into “west” and “east” tracks (See Footnote 4).

Figure 6: Mean trajectories and individual TC tracks (random sample of up to 100) of observed and model tracks for the 3-cluster region (R7).

Figure 7: Mean trajectories for the current (black) and future (red) climate 5-M ensemble simulations (as in Figs. 4,5,6).

Figure 8: TC activity (a measure of the number of unique TCs either entering or forming within a $2.5^\circ \times 2.5^\circ$ grid-box) for the current- and future-climate 12-M simulations (a,b), projected change in TC activity between these simulations (c) and (d) TC activity observed in the IBTrACS database.

Figure 9: Mean kernel density smoothed contours of large-scale TC genesis parameters for the current- and future-climate during the summer months (December-February). For (a) Relative vorticity at 850-hPa where blue (red) shading represents enhanced (suppressed) vorticity in the future climate, (b) environmental vertical wind shear between 250-hPa and 800-hPa where blue (red) shading represents increased (decreased) shear in the future climate, (c) Relative humidity at 700-hPa where red (blue) shading represents increased (decreased) relative humidity, and (d) Low-level convergence where red (blue) shading represents increased (decreased) convergence activity.

Figure 10: Difference in the kernel densities of large-scale TC genesis parameters between the future-climate (FC) and current-climate (CC) 12-M ensembles during the summer months (December-February). (a) Relative vorticity at 850-hPa (R-Vorticity), (b) Environmental vertical wind shear between 250-hPa and 800-hPa, (c) Relative humidity at 700-hPa (R-Humidity), and (d) Low-level convergence (850-hPa).

Supplementary Tables & Figures

Table A1: Criteria assessment of each CMIP5 model. Values in bold indicate that a model has failed to meet a certain criterion. Scores are given based on how well they meet the four criteria with “A” the best performing and “D” the worst. Members chosen for the 5-model ensemble have their scores underlined in the final column. See Table A2 for more information.

Model	C1	C2	C3	C4		Score
Family-1						
GFDL-ESM2M	848	0.03	0.87	N	E4;E5	C
GFDL-CM3	812	0.05	0.90	N	E1;E5	D
GFDL-ESM2G	784	0.01	0.80	N	E1;E4;E5	D
Family-2						
ACCESS1.0	967	0.00	0.86	Y		<u>A</u>
ACCESS1.3	1078	0.00	0.87	N	E4	B
HadGEM2-ES	1150	0.02	0.93	Y		B
Family-3						
BCC-CSM1.1	588	0.09	0.82	N	E2;E3	D
BCC-CSM1.1M	649	0.04	0.91	Y		<u>A</u>
(No family)						
CSIRO-Mk3.6	980	0.00	0.85	Y		<u>A</u>
CNRM-CM5	322	0.05	0.86	N	E3	D
CCSM4	509	0.00	0.93	Y		<u>A</u>
MIROC5	1038	0.00	0.90	Y		<u>A</u>

Table A2: Information for Table A1. “x” represents a value in Table A1 for each model assessed.

Criteria	
C1	+50% observed TC numbers, (364 <x<1092)
C2	% TCs in Eastern South Pacific, (x<0.05)
C3	Spatial correlation with observed, (x>0.85)
C4	Cluster result with observed, [Y=Similar, N=Not similar]
Cluster Error Codes	
E1	Low Latitude (<10°S) cluster in South Indian Ocean
E2	Too many clusters in South Pacific Ocean
E3	No cluster north of Australia
E4	Too many clusters in South Indian Ocean
E5	Westward mean trajectory in South Pacific Ocean

Figure A1: 7-cluster solution for each CMIP5 model in the current climate (1970 – 2000).

Mean TC trajectory and genesis (red line and circle) of a cluster with a kernel density contour enclosing 50% of the genesis points in that cluster (grey dashed). Models in bold indicates similar cluster orientations as the observations.

Table B1: Parameter threshold values for the two stages of the OWZ's TC circulation

detector, subscripts refer to pressure level in hPa.

	OWZ-Detector parameter thresholds					
Criterion	OWZ ₈₅₀	OWZ ₅₀₀	RH ₉₅₀	RH ₇₀₀	VWS ₈₅₀₋₂₀₀	SpH ₉₅₀
Initial	$50 \times 10^{-6} s^{-1}$	$40 \times 10^{-6} s^{-1}$	70%	50%	$25 ms^{-1}$	$10 g kg^{-1}$
Core	$60 \times 10^{-6} s^{-1}$	$50 \times 10^{-6} s^{-1}$	85%	70%	$12.5 ms^{-1}$	$14 g kg^{-1}$