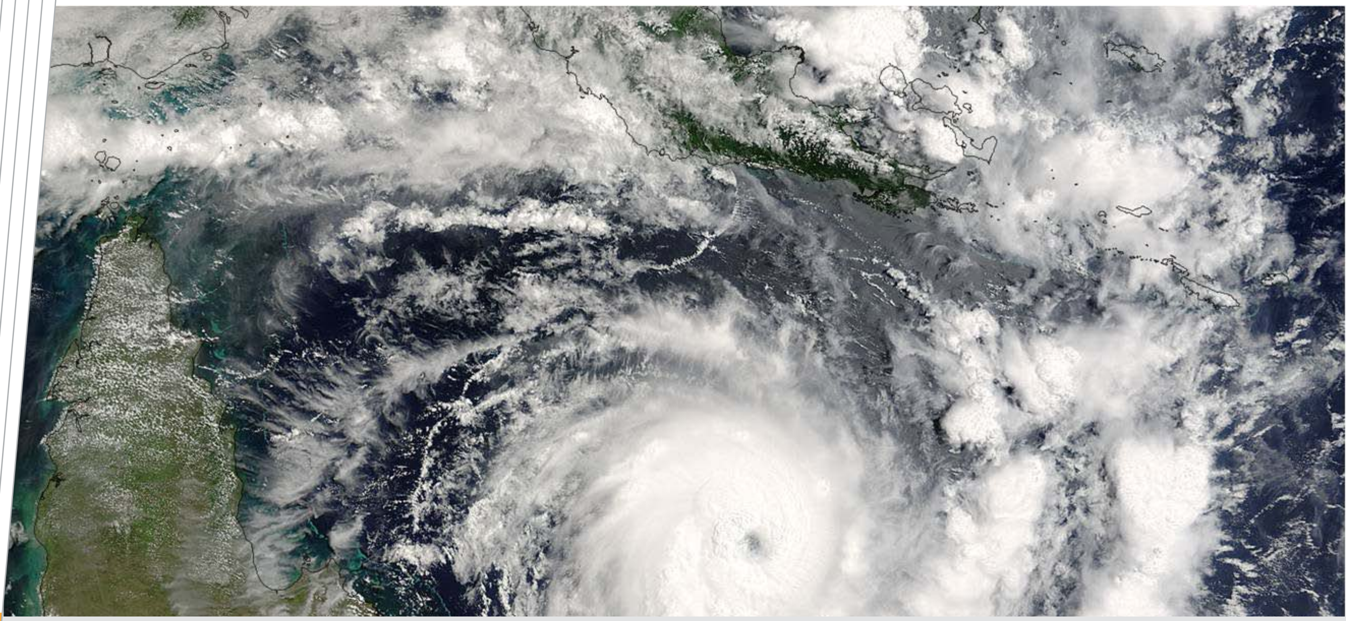

The impact of climate change on the climatology of tropical cyclones in the Australian region

Climate Adaptation Flagship Working Paper #11

Helping Australia Adapt to a Changing Climate

Deborah Abbs

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Image on Cover: MODIS image of TC Ingrid on 5 January 2005. Sourced from NASA Visible Earth http://visibleearth.nasa.gov/view.php?id=72726

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ABSTRACT

This report presents results from CSIRO's Conformal Cubic Atmospheric Model (CCAM). An analysis of outputs from CCAM downscaled to 65 km grid spacing with NCEP reanalyses shows that the model is able to simulate the spatial characteristics of tropical cyclone (TC) occurrence in the Australian region and that the configuration used for these simulations is able to differentiate between El Niño and La Niña events. However, the modeled frequencies are less than observed with, on average, approximately 60% of the observed number of TCs simulated by CCAM. The underestimate in TC occurrence is most likely due to the relatively coarse grid spacing used in this study.

Climate change projections using this modelling system show a strong tendency for a decrease in TC numbers in the Australian region, especially in the region of current preferred occurrence. On average, for the period 2051-2090 relative to 1971-2000, the simulations show an approximately 50% decrease in occurrence for the Australian region, a small decrease (0.3 days) in the duration of a given TC and a southward movement of 100 km in the genesis and decay regions. On average, the southward movement in decay region is greater off the Queensland coast than off the coast of Western Australia. Five of the seven simulations show statistically significant decreases in TC occurrence.

A method to apply these projections to specific locations is developed and used to illustrate the importance of using a risk assessment approach when using these projections in the development of management and planning frameworks. Further downscaling of a sample of individual TCs shows a distinct shift towards deeper pressures and a flattening of the maximum wind speed distribution with a larger percentage of TCs producing high wind speeds in the 2070 climate than either the 1980 or 2030 climates.

The findings described above are consistent with findings for Southern Hemisphere TC changes from recently published international studies.

1. INTRODUCTION

Tropical cyclones are amongst the world's most destructive and costly natural hazards; thus accurate estimates of future changes in their frequency, intensity and location would be of great value. Tropical cyclones are low pressure systems that form over warm tropical waters and have well defined wind circulations of at least gale force strength (sustained winds of 63 km/h or greater with gusts in excess of 90 km/h).

Formation of tropical cyclones generally occurs within a band between 5° and 25° from the Equator. Table 1 of Nguyen and Walsh (2001) shows that 99.2% of observed tropical cyclone formation in the south-west Pacific Ocean occurs equatorward of 25°S, while only 1.2% of storms form equatorward of 5°S. The climatology of TCs in the Australian region (Figure 1) is based on the southern hemisphere TC archive constructed in the National Climate Centre of the Bureau of Meteorology. The archive currently consists of cyclone best track data for the TC seasons from 1969/70 to 2005/06. The number of occurrences of cyclones in each 2° x 2° square was first calculated and then interpolated to finer resolution and a line-smoothing algorithm applied during the contouring process.

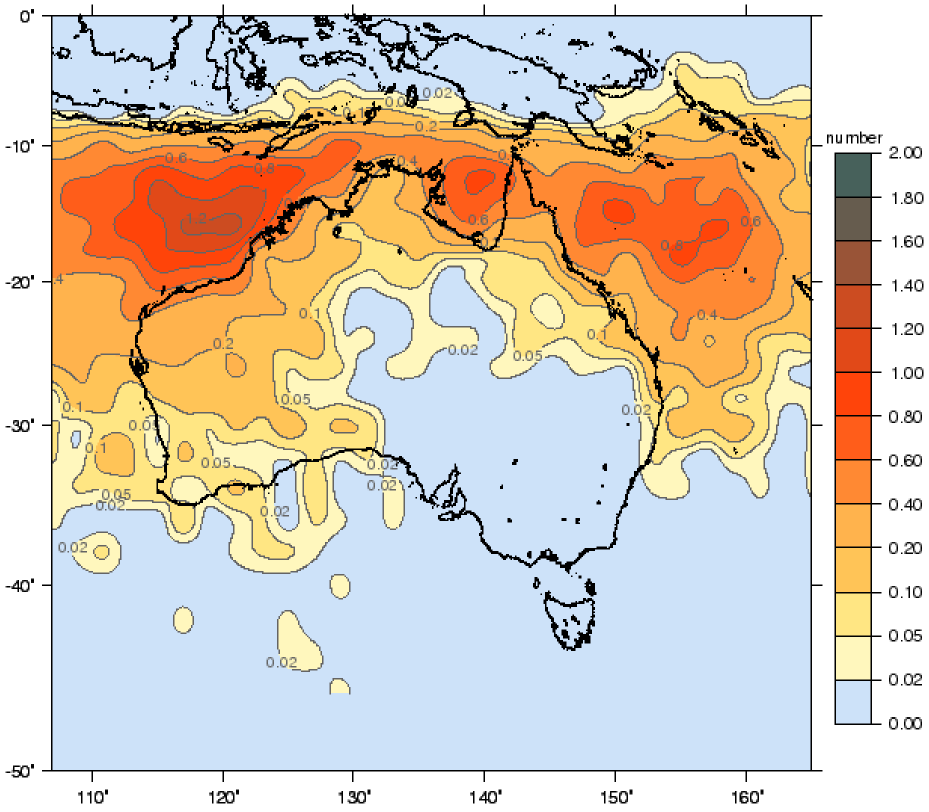


Figure 1: Average annual distribution of TCs in the Australian region. Occurrence is expressed as the number of cyclones per year within a 2x2 degree grid cell. Figure based on data from the Bureau of Meteorology Best Track dataset.

The climatology can be characterised by a preferred region of occurrence between latitudes 10 and 20°S with maxima occurring off the Queensland and Western Australian coastlines and in the Gulf of Carpentaria. It includes all systems that at some time during their lifetime were defined as a tropical cyclone and thus includes TCs that have decayed into rain depressions and are below TC intensity. The weaker systems are included as it is impossible to differentiate between these systems and TCs in the pre-1984 era as intensity information is missing from the dataset for the earlier period.

Throughout the world, tropical cyclone activity and intensity are variable on the intra-seasonal, inter-annual, inter-decadal and multi-decadal timescales. Australian region tropical cyclone numbers are correlated with indices of the El Niño Southern Oscillation (ENSO) from the central and eastern equatorial Pacific, indicating a remote effect on tropical cyclone numbers. Tropical cyclone activity is lower in the Australian region during El Niño events, while La-Niña events typically produce the opposite conditions (Nicholls, 1979, 1984, 1985; Kuleshov 2003, Kuleshov *et al.* 2008, Ramsey *et al.* 2008). In the Australian region (see Figure 2) the strongest correlations are with August - October sea surface temperatures (SST) (Ramsey *et al.* 2008).

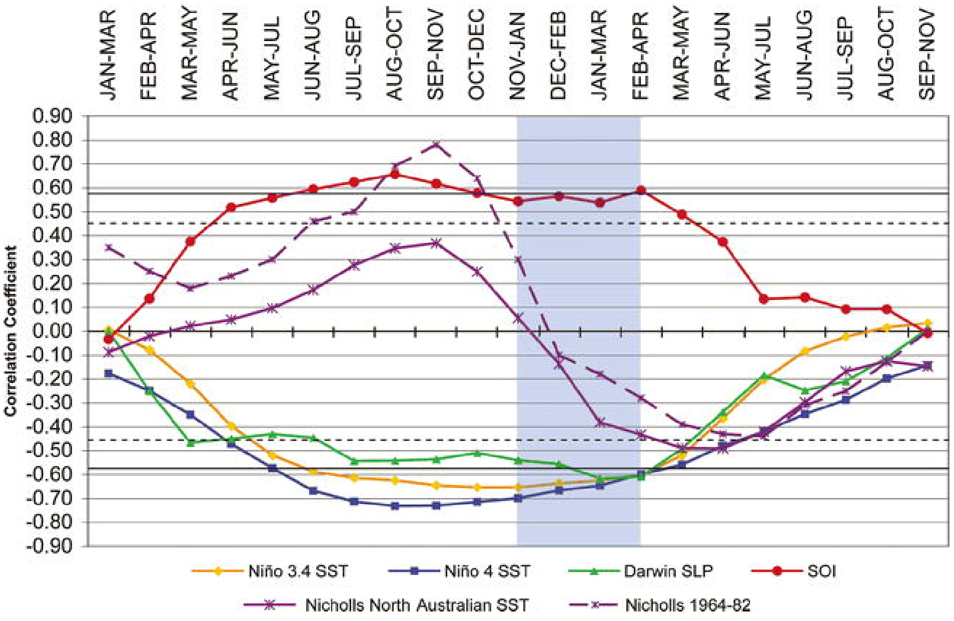


Figure 2: Annual cycles of correlation for 1970–2005 between number of November–April TCs in the Australian region and various ENSO-related parameters (Niño-3.4 SST, Niño-4 SST, Darwin SLP, SOI), and Nicholls north Australian SST, for running 3-month periods starting with January–March preceding the TC season and ending with September–November following the TC season. Purple dashed line gives the correlations obtained by Nicholls (1984) for his north Australian SST region for 1964–82. Correlations for 1970–2005 with larger magnitude than the thick dashed (solid) line are significant at the 5% (1%) level according to a two-sided *t* test (Wilks 1995, 121–122). Core of November–April TC season is shaded in light blue. Source: Ramsey *et al.* (2008).

Other large scale patterns affecting TC occurrence in the region are the 40-60-day Madden-Julian Oscillation (MJO) (Hall *et al*. 2001) and the Inter-decadal Pacific Oscillation (IPO) (Grant and Walsh 2001).

More recently, evidence has emerged that the relative frequency of very strong tropical cyclones may be increasing in some regions (Emanuel 2005; Webster *et al.* 2005; Hoyos *et al.* 2006; IPCC 2007). However, these findings have generated significant controversy within the scientific community due to concerns with the quality of the historical tropical cyclone data on which these studies relied (McBride *et al*. 2006; Curry *et al*. 2006). Analysis of the Australian tropical cyclone database indicates substantial increases in detected tropical cyclone numbers with the advent of weather radar in the late 1950s, although there have been apparent decreases in numbers since the 1970s, largely due to an increase in El Niños (Kuleshov *et al*. 2008). Harper and Callaghan (2006) reviewed the Western Australian tropical cyclone database for 1968-2001. That review uncovered an artificial bias towards underestimating TC intensities. After they removed inconsistencies and biases, trends remained in the data. For example, there still remain trends in the number of intense storms, with some increase since 1980. In the 15-year period 1974-1988, 29% of all storms were Saffir-Simpson category 3 or 4 storms, while in the 10-year period 1989-1998, 41% of all storms were of these categories, an increase of 42%. This compares with an increase of 203% in the original tropical cyclone database. Elsner *et al.* (2008) found that the strongest tropical cyclones are getting stronger, particularly over the North Atlantic and Indian oceans.

There is substantial evidence that the large-scale environment in which TCs form and evolve is changing as a result of global warming. Theory and models are used to provide information on possible future changes in tropical cyclone activity. The theories include potential intensity theories as well as empirical indices that attempt to relate tropical cyclone frequency to large-scale environmental conditions. The models range from global climate models (with a grid spacing of 200 to 500 km) to finer resolution regional models (with a grid spacing of 20 to 70 km). In the models, the TCs are located and tracked using objective techniques such as those described by Walsh *et al.* (2004) and Oouchi (2006). Global climate models (GCMs) generally have a grid spacing that is larger than the typical scale of tropical cyclones, so the modelled cyclones tend to be wider and less windy than observed tropical cyclones. Finer resolution studies (Walsh *et al.* 2004) are frequently used to investigate possible changes in TC climate over a region of interest, although Oouchi *et al*. (2006) have presented the results from a GCM with a grid spacing of 20km and Zhao *et al*. (2009) have presented the results from a GCM with a grid spacing of 50 km.

Projected changes in tropical cyclones are subject to the sources of uncertainty inherent in climate change projections. These include the future climate-forcing scenario (e.g. greenhouse gas and aerosol emissions), model dynamics and physics, errors in the modelled tropical cyclone climatology, regional changes in environmental conditions and climate drivers such as ENSO. Consequently there is large uncertainty in projected TC changes. In recent years, there has been a growing number of studies using results from medium and high resolution GCMs. The results from these studies are summarised by Knutson *et al*. (2006) and IPCC (2007) and indicate a consistent tendency for fewer tropical cyclones globally in a warmer climate. Results for the Southern Hemisphere and Australian region are discussed below. However, there are significant regional variations in the direction of the changes and these vary between models. Substantial disagreement remains between climate models concerning future changes in TC intensity, although the finest resolution models show evidence of an increase in TC intensity in a warmer world. The fourth assessment report of the United Nations Intergovernmental Panel on Climate Change (IPCC 2007) considered that it is likely that storm intensity will continue to increase through the 21st century, and declared it more likely than not that there has been some human contribution to the increases in tropical cyclone intensity, although this contribution may be very small compared to natural variability.

2. MODEL AND METHODOLOGY

2.1 The CCAM Model

The model used in this study is the CSIRO Conformal-Cubic Atmospheric Model (CCAM) of McGregor and Dix (2001). CCAM is a global model that uses a stretched grid, formed by projecting the panels of a cube onto the surface of the Earth. The cube is then stretched so that the area of interest is simulated using a finer resolution, while the remainder of the globe is simulated with increasingly coarser resolution away from the region of interest. This is a very efficient way of obtaining fine resolution over a small region. It also avoids problems associated with fixed boundaries which are typically encountered in regional climate models.

In the simulations considered herein, the region of interest lies over the Australia region and has a grid spacing of approximately 65 km. Two sets of simulations are considered; (1) an ensemble of 15 climate simulations nested in NCEP reanalyses and (2) an ensemble of 11 simulations nested in GCMs sourced from the IPCC CMIP3 archive. The NCEP reanalyses provide a dataset of globally gridded atmospheric values that are in dynamic balance (i.e. the thermodynamic and kinematic fields are internally consistent) and, importantly, provides a method to “gap fill” both spatially and temporally. For simplicity, within this report the outputs from the NCEP reanalyses are considered to be “observations” and thus the reanalysis-based results are used to determine whether or not the model can reproduce the spatial occurrence and inter-annual variability of TCs in the region. A good representation of these characteristics provides some confidence in the suitability of the modelling system for providing projections of changes in TC activity.

Archived outputs from CCAM are used to detect and track tropical cyclone-like vortices (TCLVs) which are subsequently analysed to identify possible changes in their frequency and intensity. The 12-hourly output fields were interpolated to a 0.5° × 0.5° grid (about 50 km grid spacing) covering the domain 90°E-160°W and 10°N-60°S. The variables used in the detection scheme are: the wind speed at 10 metres above the ground, mean sea level pressure; and the horizontal components of the wind and the temperature in the atmosphere at 800 hPa, 750 hPa, 500 hPa and 300 hPa.

2.2 TCLV Detection and Tracking Scheme

The TCLV detection and tracking scheme used herein was modified from that of Nguyen and Walsh (2001). The detection criteria are:

1. A vorticity more negative than -10^{-5} s^{-1} (in the Southern Hemisphere);

2. There must be a closed pressure minimum, taken to be the centre of the storm, within 250 km of a point satisfying criterion 1;

3. There must be rotation, defined by wind direction, around the storm centre;

4. The maximum 10m wind speed must be greater than 11.5 ms^{-1};

5. The mean wind speed in the area 500 km × 500 km around the centre of the storm at 850 hPa must be higher than that at 300 hPa;

6. The system must be warm cored. The total of the tropospheric temperature anomalies at 750, 500 and 300 hPa in the centre of the storm must be greater than zero. These anomalies are calculated relative to the mean environmental temperature at each level in the region 750 km east and west and 500 km north and south of the storm centre.

In this study, we focus on the tropical waters in the Australian region, with the region of interest being from 90° to 180°E (the international dateline) and from the equator (0°) to 50°S. Within this domain, tropical cyclogenesis is not allowed poleward of 30°S, however if a TCLV forms within the 0° to 30°S band and tracks poleward, it will continue to register as a cyclone providing that it continues to satisfy the relevant criteria. Once the TCLV has existed for a period of at least 12 hours, criterion 6 (i.e. the requirement for a warm core) is relaxed and the TCLV tracked until it no longer satisfies any of the remaining five criteria. Tracks of less than 24 hours duration are discarded from the final results

The wind speed threshold (criterion 4) used in this study is lower than the grid-spacing based “standard” value suggested by Walsh *et al*. (2007). That study suggests that the threshold wind speed for the detection of the cyclone varies almost linearly with resolution and that the expected wind speed threshold for a simulation with a grid-spacing of 60 km would be approximately 16 ms^{-1}. This wind speed threshold, combined with the other criteria of Nguyen and Walsh (2001), was used to detect TCLVs for several summers but very few storms were detected (less than 10% of the number of cyclones in the observed climatology). A manual examination of the raw model output indicated that a significant number of TCLVs were present in the simulation but undetected as the wind speed threshold of 16 ms^{-1} was too large. Subsequently, a lower threshold of 11.5 ms^{-1} was selected. This value combined with the other criteria retained all observable large-scale tropical systems and virtually eliminated false detections.

3. RESULTS

3.1 Reanalysis-based simulations

The following analysis is based on an ensemble of 15 climate simulations nested in NCEP reanalyses and is used to determine whether or not the model can reproduce the spatial occurrence and inter-annual variability of TCs in the Australian region. The resulting climatology for these simulations is presented in Figure 3 and can be compared with the climatology presented in Figure 1. The results show a good qualitative agreement in the preferred regions of occurrence, with maxima in the Coral Sea, the Gulf of Carpentaria and off the coast of north Western Australia. In all regions, the modeled frequencies are less than observed with, on average, approximately 60% of the observed number of TCs simulated by CCAM. The underestimate in TC occurrence is most likely due to the relatively coarse grid spacing used in this study.

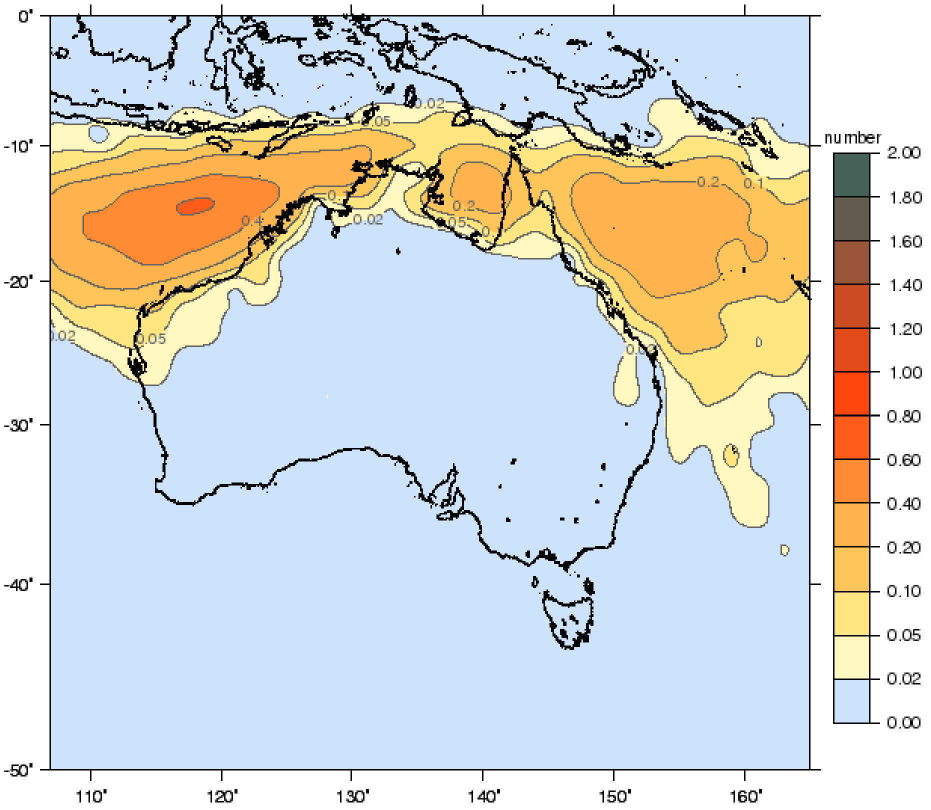


Figure 3: Climatology of TCs based on the ensemble average of 15 simulations nested in NCEP reanalyses. Occurrence is the number of cyclones per year within a 2x2 degree grid.

The ability of the model to simulate the inter-annual variability of TCs occurring in the region has also been examined. The ensemble-average correlation between observed and modelled annual TC numbers is 0.3. While this value is relatively low, it compares favourably with results obtained by Zhao *et al.* (2009) for the South Pacific from their 50 km global climate model simulation. In contrast to the South Pacific results, their modelling system was able skilfully reproduce the inter-annual variability of TCs occurring in the North Atlantic with a correlation of 0.8 for that region. As described earlier, tropical cyclone activity is lower in the Australian region during El Niño events, while La-Niña events typically produce the opposite conditions. The ratio of the number of TCs occurring during El Niño years to that occurring during La Niña years is 0.74 while that obtained from the model ensemble average is 0.64.

These results indicate that, on average, CCAM is able to simulate the spatial characteristics of TC occurrence in the Australian region and that the configuration used for the reanalysis-based simulation is able to differentiate between El Niño and La Niña events.

3.2 Climate change simulations

The climate change projections are from an ensemble of 11 simulations nested in GCMs sourced from the IPCC CMIP3 archive. The simulations considered include climate change forcing using variations of 2 different methods. Five simulations nudge the CCAM atmosphere towards the large scale fields from the host GCM while the remaining six simulations only force CCAM with bias-corrected SSTs from the host model. There are various advantages and disadvantages to both approaches.

- The use of bias-corrected SSTs has the advantage that the cold SST bias in the central equatorial Pacific (characteristic of many GCMs) is not included in these simulations and thus CCAM should develop large scale circulations that are not affected by these biases. The SSTs used in these simulations include the trends and variability characteristic of the host model. This technique also has the advantage that it allows long (140-year) simulations to be conducted. The disadvantage of this technique is that there are suggestions that this method alters the inter-model variability of the projected change in TC occurrence seen between the host models and acts to decrease this variability.
- Simulations nudged towards the large-scale fields from the host model use ‘uncorrected’ SSTs from the host model. They have the disadvantage that the resulting simulations may develop large-scale circulations that are a response to the SST biases of the host model. Another disadvantage is that for simulations nested in CMIP3 models, only 20-year time slice experiments for 2046-2065 and 2081-2100 are possible due to the lack of atmospheric forcing data for other periods. However, these simulations have the advantage that they account for the inter-model variability seen between the host models.

The modelled average annual occurrence of tropical cyclones for the 30-year period corresponding to 1971-2000 is not shown but has a spatial distribution similar to that in Figure 3. The ensemble average projected changes are shown in Figure 4.

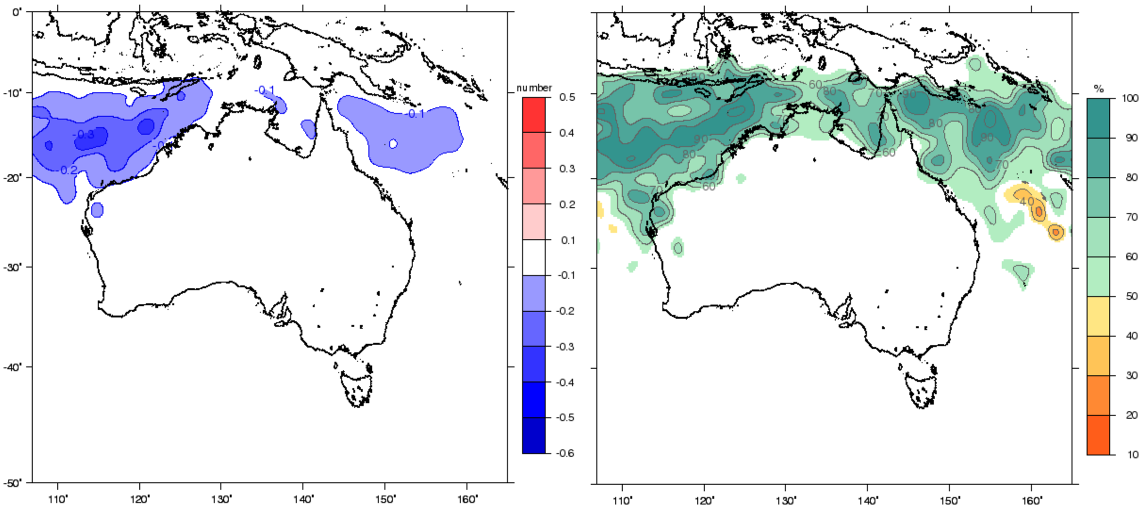


Figure 4: Projected changes in the annual occurrence of TC-like vortices for 2046-2065, relative to 1971-2000, based on the results from 11 climate simulations (left), with blue shading indicating regions of decreased occurrence of events. Inter-model ‘consensus’ for direction of change (right), with green shading indicating regions where more than 50% of simulations project a decrease in TC occurrence.

These results show a strong tendency for a decrease in TC numbers in the Australian region, especially in the region of current preferred occurrence. Further analysis of these simulations has investigated potential changes in the duration, genesis latitude and decay latitude of TCs with selected results for 2051-2090 presented in Table 1. On average, the simulations show an approximately 50% decrease in occurrence for the Australian region, a small decrease (0.3 days) in duration and a southward movement of approximately 1 degree (about 100 km) in both genesis latitude and decay latitude. Occurrence is considered in terms of both TC numbers and TC days. TC number is the actual number of cyclones that occur in the region while TC days accounts for the numbers of days that TC activity occurs within the region and thus better reflects the risk posed by TCs. On average, the southward movement in decay latitude is greater off the Queensland coast than off the coast of Western Australia. Five of the seven simulations show statistically significant (Pr ≥ 0.95) decreases in TC occurrence based on a one-sided Kolmogorov-Smirnov test.

	Australia				
	Number	*Days*	*Duration (days)*	*Genesis (deg lat)*	*Decay (deg lat)*
ECHAM5	-58%	-59%	-0.4	-1.1	-1.3
GFDL CM2.0	-53%	-55%	-0.3	-0.8	-1.1
GFDL CM2.1	-40%	-52%	-1.0	-1.4	-1.2
MIROC3.2(midres)	-68%	-73%	-0.8	-1.1	-2.0
CSIRO Mk3.5	-39%	-44%	-0.2	-0.5	-0.2
UK HADCM3	-50%	-47%	0.2	-0.7	-1.7
CSIRO Mk3.0	-28%	-23%	0.2	-0.8	-1.9
Ensemble Average	**-48%**	**-50%**	**-0.3**	**-0.9**	**-1.3**

Table 1: Projected changes in total TC numbers, TC days, duration of a given TC, genesis latitude and decay latitude for seven simulations, downscaled using CCAM to 65 km grid spacing, for the period 2051-2090, relative to 1971-2000. Darker blue shading indicates changes in TC numbers that are statistically significant at the 99% level while light blue shading is for changes significant at the 95% level.

3.3 Changes in intensity

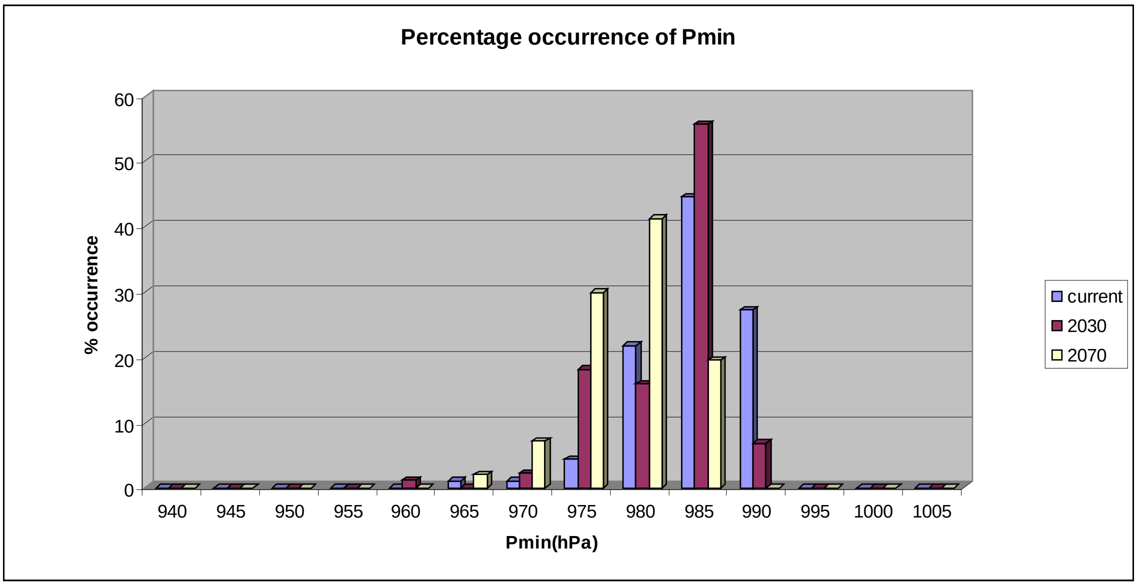
The simulations described above are too coarse for an assessment of changes in TC intensity. Thus a subset of detected TC-like vortices from one CCAM simulation has been further downscaled using the Regional Atmospheric Modelling System (RAMS) to a grid-spacing of 15 km for 40-year time slices centred on 1980, 2030 and 2070. For each time slice 100 events were modelled. While this grid spacing is still inadequate to resolve the fine-scale structure of TCs, the results (2002; McDonald *et al.* 2005; Oouchi *et al.* 2006; Gualdi *et al. 2008;* Zhao *et al.* 2009) is for a decrease in Southern Hemisphere tropical cyclone occurrence late in the 21st Century. In contrast, east Australian-focussed studies by Walsh *et al.* (2004) and Leslie *et al.* (2007) find no change in the mean number of TCs, although it should be noted that the findings from the Leslie *et al.* study are for the period 2000-2050. Most studies project an increase in tropical cyclone intensity.

Figure 5 shows a distinct shift towards deeper pressures and a flattening of the maximum wind speed distribution with a larger percentage of TCs producing wind speeds exceeding 25 m/s in the 2070 climate than either the 1980 or 2030 climates. A larger population of storms needs to be downscaled at higher resolution (e.g. 5 km grid spacing) before quantitative projections of changes in intensity and rainfall can be produced. This is a focus of current downscaling activity.

3.4 Comparison with other studies

A number of global climate modelling studies have appeared in the international literature since 2000 which investigate the impact of climate change on the global occurrence of tropical cyclones. A consistent result from each of these studies (Sugi *et al.* 2002; McDonald *et al.*

2005; Oouchi *et al.* 2006*;* Gualdi *et al. 2008;* Zhao *et al.* 2009*)* is for a decrease in Southern Hemisphere tropical cyclone occurrence late in the 21st Century. In contrast, east Australian-focussed studies by Walsh *et al.* (2004) and Leslie *et al.* (2007) find no change in the mean number of TCs, although it should be noted that the findings from the Leslie *et al.* study are for the period 2000-2050. Most studies project an increase in tropical cyclone intensity.



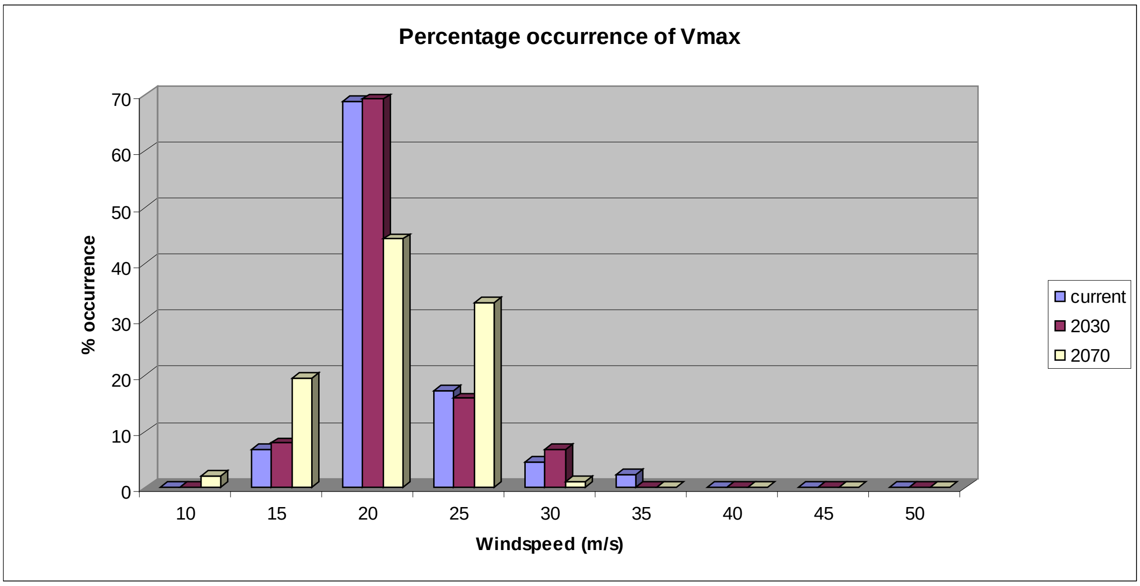


Figure 5: Distribution of modelled (top) minimum pressure and (bottom) maximum wind from the 15 km simulations.

4. APPLICATION OF PROJECTED CHANGES

Developing location-specific projections for changes in TC occurrence is very difficult and ideally probably shouldn't be attempted. In general, different models show quite different projections for changes in TC occurrence at the ocean basin scale so there is high uncertainty. Taking this to the individual site only increases the uncertainty. However, there is an increasing demand for location-specific projections from a variety of stakeholder groups. Engineers require these projections for the planning and design of large infrastructure projects that are expected to have design lifetimes of multiple decades while conservations biologists require these projections as input to framework to assess how climatic processes will affect various animal populations and habitats at a population scale For example, Fuentes and Abbs (2010) used projections based on the simulations reported herein, to assess the possible impact of changes in tropical cyclone occurrence on northern Great Barrier Reef turtle populations.

In an effort to respond to these demands, the following methodology was developed to provide location-specific projections for tropical Australia. Firstly, the TCLV detections that pass within 300 km of each of each site are identified and results collated to provide a measure of TC numbers. Earlier it was shown that on average the modelling system simulates about 60% of the observed number of TCs and so it is necessary to scale the model outputs so that the occurrence of TCs in the modelled climate is the same as reality. To quantify the climatological accuracy of each of the 11 simulations, a scale factor was created for each site that compares the model simulation of past TC activity (1961- 2000) with observations of past TC activity. In analysing the model outputs, it is obvious that some model simulations are better than others and for a particular model some sites are better represented by the model than other sites. It is also possible to use this scale factor to identify which models are performing best for each location. A scale factor of 1 is ideal, meaning that the model simulated accurately the observed frequency of cyclones in the past; a scale value of 0.5 indicates that the model over represents past cyclone occurrence by two times and a scale value of 2 it under represents past cyclone occurrence by half.

Results based on this methodology are tabulated in Table 2 for the observations and the 1961-2000 modelled climate for each of the 11 models for 7 locations in tropical Australia. For model simulations that started in 1971 (the large scale forced simulations) the values have been linearly scaled to account for the shorter time period. Simulation-location pairs with a scale factor greater than 2.5 or less than 0.4 are not considered in the development of projections as it is considered that for these situations the simulation is not accurate at this location. These scale factor thresholds were chosen as it was considered that they were a reasonable compromise between the overall accuracy of the modelling system and values that would dominate in the development of projections.

The results indicate that many of the models (5 out of 11) have difficulty in adequately simulating the TC climate of Darwin, while 2 of the models (large scale forced simulations MIROC3.2-medres and CSIRO Mk3.5) do not perform well along the east coast. Also shown in this table is the representative scale factor which is a measure of the ability of a model to represent the Australian TC climate or the ability of the suite of models to represent the TC climate for a specific location. The representative scale factor is determined by calculating the average of all finite scale factors greater than 1.0. For scale factors less than one, the reciprocal is found before calculating the average – this step was necessary so that “poor-performers” do not cancel each other. The representative scale factor could be used as a "poor man's method" of weighting the simulations although this is not attempted here.

Location-specific projections are provided in Table 3 for 2055 and 2090. The model outputs on which these projections are based are 20-year time slices and so the calculated and scaled occurrences have been doubled to provide projections representative of a forty-year time slice and which are thus comparable with the observations. It is accepted that the use of multiple scaling factors may dominate in some cases but the results serve to illustrate some important considerations, namely:

- The dominant signal is for a decrease in TC occurrence at most Australian locations agreeing with the results presented earlier.
- Some locations, (e.g. Hervey Bay) show a projected increase or no change in TC occurrence in 5 out of 9 of the representative simulations for the 2055 climate and 2 out of 9 simulations for 2090. In some applications (e.g. urban planning, infrastructure development, emergency management) it will be important to recognise that this region may experience an increase in TC occurrence in the future, even though most Australian locations are projected to experience a decrease.

		Hervey Bay	Mackay	Cairns	Darwin	Broome	Port Hedland	Carnarvon	Rep. scale factor
Observations		22	29	39	52	62	56	27	
Bias-corrected SST simulations	ECHAM 5	12 (1.8)	32 (0.9)	38 (1.0)	18 (2.9)	36 (1.7)	25 (2.2)	17 (1.6)	1.8
	GFDL CM2.0	12 (1.8)	27 (1.1)	33 (1.2)	15 (3.5)	34 (1.8)	31 (1.8)	20 (1.4)	1.8
	GFDL CM2.1	13 (1.7)	27 (1.1)	46 (0.8)	22 (2.4)	26 (2.4)	19 (2.9)	14 (1.9)	1.9
	MIROC3.2 (medres)	15 (1.5)	27 (1.1)	28 (1.4)	18 (2.9)	36 (1.7)	23 (2.4)	20 (1.3)	1.8
	CSIRO Mk3.5	9 (2.4)	29 (1.0)	35 (1.1)	25 (2.1)	32 (1.9)	34 (1.6)	20 (1.4)	1.6
	UK HADCM3	10 (2.2)	30 (1.0)	40 (1.0)	17 (3.1)	39 (1.6)	32 (1.8)	22 (1.2)	1.7
Large scale atmospheric forcing & uncorrected SST	ECHAM5	17 (1.3)	17 (1.7)	22 (1.8)	38 (1.4)	44 (1.4)	66 (0.8)	38 (0.7)	1.5
	GFDL CM2.1	16 (1.4)	53 (0.5)	58 (0.7)	52 (1.0)	86 (0.7)	102 (0.5)	90 (0.3)	1.8
	MIROC3.2 (medres)	4 (5.5)	6 (4.8)	9 (4.3)	5 (10.4)	36 (1.7)	60 (0.9)	53 (0.5)	4.3
	CSIRO Mk3.5	0 (inf)	0 (inf)	8 (4.9)	17 (3.1)	69 (0.9)	109 (0.5)	52 (0.5)	>>2.6
	CSIRO Mk3.0	9 (2.4)	26 (1.1)	48 (0.8)	31 (1.7)	49 (1.3)	38 (1.5)	15 (1.8)	1.6
Representative scale factor		>>2.1	>>1.6	1.9	3.1	1.6	1.9	1.8	

Table 2: Observed and modelled TC numbers for 7 locations in tropical Australia. Shown are numbers of cyclones occurring within 300 km of the location during a 40-year period (1961-2000). For model simulations that started in 1971 (the large scale forced simulations) the values have been scaled to account for the shorter time period. Also shown is the scale factor, in parenthesis, that is used to indicate the accuracy of the model at simulating the late 20th century TC climate. Scale factors greater than 2.5 or less then 0.4 are shown in grey indicating that the models are not accurate at these locations. The representative scale factor is an overall indicator of the ability of the model to represent the Australian TC climate or the ability of the models to represent the TC climate for a specific location.

		Hervey Bay	Mackay	Cairns	Darwin	Broome	Port Hedland	Carnarvon	Rep. scale factor
Observations		22	29	39	52	62	56	27	
Bias-corrected SST simulations	ECHAM 5	26 (7)	22 (4)	21 (4)	23 (6)	41 (7)	45 (22)	13 (25)	1.8
	GFDL CM2.0	11 (4)	17 (13)	24 (12)	21 (7)	11 (7)	11 (18)	8 (11)	1.8
	GFDL CM2.1	10 (24)	19 (21)	27 (14)	43 (28)	52 (43)	65 (47)	27 (19)	1.9
	MIROC3.2 (medres)	9 (3)	4 (2)	8 (3)	23 (0)	31 (28)	78 (39)	43 (22)	1.8
	CSIRO Mk3.5	24 (10)	22 (10)	31 (20)	12 (25)	16 (39)	23 (23)	16 (16)	1.6
	UK HADCM3	22 (18)	23 (6)	16 (12)	31 (18)	19 (25)	11 (14)	7 (7)	1.7
Large scale atmospheric forcing & uncorrected SST	ECHAM5	10 (5)	27 (20)	53 (46)	55 (33)	104 (76)	75 (56)	31 (33)	1.5
	GFDL CM2.1	22 (8)	10 (10)	23 (8)	24 (22)	49 (46)	45 (42)	28 (19)	1.8
	MIROC3.2 (medres)	22 (11)	48 (29)	35 (17)	62 (42)	48 (59)	52 (67)	26 (11)	4.3
	CSIRO Mk3.5	0 (0)	0 (0)	29 (29)	67 (43)	50 (27)	32 (24)	15 (11)	>>2.6
	CSIRO Mk3.0	44 (34)	27 (40)	23 (26)	67 (47)	46 (48)	32 (35)	18 (11)	1.6
Representative scale factor		>>2.1	>>1.6	1.9	3.1	1.6	1.9	1.8	

Table 3: Projections of the number of TCs affecting the indicated locations for the climates of 2055 (2090). The projections are based on 20-year time slices centred on these years and the results scaled to be representative of a 40-year period for comparison with the observations. Results shown in blue indicate a decrease in TC occurrence for the future climate relative to that of the late 20th Century and red results indicate an increase in TC activity for the given location. Results shown in grey indicate that the simulation is not accurate at this location.

5. CONCLUSIONS

This report presents results from an ensemble of 65 km CCAM regional climate model simulations. These results show that the model is able to simulate the spatial characteristics of TC occurrence in the Australian region and that the configuration used for these simulations is able to differentiate between El Niño and La Niña events. However, the modeled frequencies are less than observed with, on average, approximately 60% of the observed number of TCs simulated by CCAM.

Climate change projections using this modelling system show a strong tendency for a decrease in TC numbers in the Australian region, especially in the region of current preferred occurrence. On average, for the period 2051-2090 relative to 1971-2000, the simulations show an approximately 50% decrease in occurrence for the Australian region, a small decrease (0.3 days) in the duration of a given TC and a southward movement of 100 km in the genesis and decay regions. On average, the southward movement in decay region is greater off the Queensland coast than off the coast of Western Australia.

A method to apply these projections to specific locations is developed and used to illustrate the importance of using a risk assessment approach when using these projections in the development of management and planning frameworks. For instance, although the projections show a strong signal of a decrease in TC occurrence for the Australian region, there are some locations in south east Queensland (e.g. Hervey Bay) where approximately 50% of the simulations indicate a possible increase in TC occurrence in the mid-21st Century.

Further downscaling of a sample of individual TCs shows a distinct shift towards deeper pressures and a flattening of the maximum wind speed distribution with a larger percentage of TCs producing high wind speeds in the 2070 climate than either the 1980 or 2030 climates.

The findings described above are consistent with findings for Southern Hemisphere TC changes from recently published international studies.

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