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Analysing present, past and future tropical cyclone activity as inferred from an ensemble of Coupled Global Climate Models

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ABSTRACT

Using the Yearly Genesis Parameter (YGP) and the Convective-YGP (CYGP), the main large-scale climatic fields controlling tropical cyclone (TC) formation are analysed and used to infer the number of TCs in a given basin using ERA40 reanalyses for the period 1983–2002. Both indices show a reasonable global number and spatial distribution of implied TCs compared to observations.

Using the same approach, we evaluate TC activity in the last 20-yr period of the 20th century in an ensemble of nine Coupled Global Climate Model simulations submitted to the IPCC AR4. We extend this analysis backwards in time, through the 20th century, and find the ensemble derived CYGP suggests no trend in inferred TC numbers while the YGP, after applying a correction to compensate for its oversensitivity to sea surface temperature, suggests a small upward trend. Both indices give a fair geographical distribution of cyclogenesis. Finally, we assess future TC trends using three emission scenarios. Using the CYGP, which appears the most robust index for application to climate change, a small increase is predicted in the northwestern Pacific in the A1B and A2 scenarios.

1. Introduction

The active 2005 hurricane season likely contributed to the growing awareness of the general population and policy makers towards climate change and its possible consequences. Ironically, no consensus exists within the scientific community regarding the variety of possible changes in tropical cyclone (TC) activity (e.g. length of TC season, geographical distribution of TCs, maximum TC intensity, etc.) that might ensue in response to increasing levels of CO_2. The fourth assessment report of the IPCC (Meehl et al., 2003) suggests an increase in mean wind and precipitation intensity of TCs, but whether or not this trend can already be observed, as claimed by Emanuel (2005) and Webster et al. (2005), or if this apparent trend is just a result of decreasing quality of the observed data sets as one goes backwards in time (Klotzbach, 2006) or to varying measurement techniques (Wu et al., 2006) remains an open question. However, when it comes to TC frequency, no particular consensus has yet emerged from the various model simulations and whether or not the global frequency of TCs will remain at current levels, increase or decrease in the future remains highly uncertain.

Two techniques have commonly been used to diagnose the number of TCs in Global Climate Models (GCMs). The first technique consists of locating and tracking what have been coined tropical cyclone-like vortices (TCLVs) (Walsh and Watterson, 1997). GCM resolutions are too coarse to resolve real TCs and instead reproduce systems reminiscent of TCs (known as TCLVs), but with some distinct characteristics. Specifically, simulated TCLVs do not reproduce important features of the TC, such as the eye structure. Many studies, using both Global and Regional Climate Models, have relied on this technique to estimate future TC activity by comparing the simulated number, intensity and paths of TCLVs in current and future climate conditions, often with contradictory results (Haarsma et al., 1993; Bengtsson et al., 1996; Sugi et al., 2002; McDonald et al., 2003; Chauvin et al., 2006; Oouchi et al., 2006; Bengtsson et al., 2007b). Latest results using this technique seem to point towards an overall reduction in the number of cyclones, but an increase in the number of intense storms. However, these simulations rely on systems that are reminiscent of TCs but not necessarily representative of them: the structure of the TCLVs cannot be considered genuinely close to reality. The 17 ms^{-1} threshold limit normally used to define the existence of a TC has to be

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lowered in these simulations in order to detect an adequate number of TCLVs. It then becomes somewhat arbitrary to fix a wind speed criterion for detection of a 'TC'.[1] Hence, while studies based on this technique might be suggestive of a likely response of TCLVs to increases in GHGs, they are likely to remain not entirely convincing until the models used adequately reproduce systems more closely reminiscent of observed TCs.

The second technique used to estimate future TC frequency provides an estimate of tropical storm activity through the use of a genesis parameter, dependent on seasonal mean large-scale fields which are known to play a role in controlling TC genesis (Gray, 1975). Developed empirically, these indices allow a quantification of the influence of large-scale fields on TC activity and reproduce with some accuracy the observed number, seasonal and geographical distribution of TCs for the present climate. This method may be better suited to TC analysis in low resolution GCMs that might be expected to simulate, with some level of accuracy, the large-scale climate controls on TC activity rather than the TCs themselves. This contention rests on the premises that there exists a deterministic large-scale control on TC activity which remains valid in future climate conditions and, furthermore, that CGCMs accurately simulate both the present-day large-scale tropical climate and future changes in key large-scale quantities in response to increasing levels of GHGs. One major drawback of this approach is that it can only give an estimate of TC numbers and cannot address the issue of changes in TC intensity.

To the authors knowledge, Ryan et al. (1992) were the first to use a genesis index with climate model output to estimate future TC activity in a greenhouse gas enhanced atmosphere. They used the genesis index developed in Gray (1975), the Seasonal Genesis Parameter (SGP) and, through comparing the SGP for simulated present and future climate conditions, derived a large increase in implied TC numbers in both hemispheres. This they deemed to be an overestimate of the probable real future TC trend due to the oversensitivity of the index to ocean surface temperature. This conclusion was shared by Royer et al. (1998) when they applied a similar analysis to a different climate model, which led to the development of a new index, the Convective SGP (CSGP), which retains some of the parameters of the SGP but replaces the ones considered to be unreliable in future climate conditions (the difference between these two indices is discussed in Section 2). Using this new index, Royer et al. predicted a decrease in the number of TCs in the Southern Hemisphere (SH) and a small increase in the Northern Hemisphere (NH), the largest increase being located in the western North Pacific (WN Pac). McDonald et al. (2003), using the same index found a more complex pattern of changes, including a region of decreasing activity in the WN Pac. They also found that the pattern of change given by the CYGP was similar to the pattern found by tracking individual TCs. This last conclusion was shared by Chauvin et al. (2006), when comparing possible TC activity changes over the Northern Atlantic. All of these studies relied on one single CGCM or a single atmospheric GCM run with prescribed ocean surface temperatures for present and future climate conditions. Recently, Camargo et al. (2007) analysed the predictive skill of another index, the Genesis Potential Index (GPI), developed by Emanuel and Nolan (2004), for current climate conditions using 5 atmospheric GCMs forced by observed SSTs. The relationship between the GPI and the number of TCs was found to be model and resolution dependent.

In this study, we attempt to estimate the possible change in the number of TCs in future climates by comparing the CSGP and the SGP, to which we have applied a first-order correction, in an ensemble of model simulations prepared for the IPCC fourth assessment report (AR4) and originating from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project, phase 3 (CMIP3). In Section 2, we describe both indices, while in Section 3 we evaluate these indices by using the ECMWF 40 yr reanalysis data (ERA40, Uppala et al., 2005) and comparing the implied number of TCs from the ERA40 SGP and CSGP with the number of observed cyclones for the same period (1983–2002). We also discuss the dangers inherent in using reanalysis data in attempting to detect a trend in the evolution of these indices and implied trends in TC occurrence. In Section 4, we introduce the models used in this study and compare the simulated present-day SGP and CSGP for the CGCM ensemble to the reanalysis data and observed TC occurrences over a similar period. We then look at the CGCM simulated time evolution of the SGP and CSGP for the period 1861–2000 and discuss a possible correction to the SGP. Finally, in Section 5, we compare the indices and implied TC numbers for future climate conditions under three different CO_2 equivalent emission scenarios.

2. Methodology

The SGP is the product of a dynamic potential and a thermal potential, each of which rely on three parameters. Together, these six components summarize the main large-scale dynamic and thermodynamic variables believed to control TC activity on seasonal timescales.

$$\mathrm{SGP} = \underbrace{(|f| \times I_\zeta \times I_{WS})}_{\text{Dynamic potential}} \times \underbrace{(E \times I_\theta \times I_{RH})}_{\text{Thermal potential}},$$

where the dynamic potential is defined such that

(1) $f = 2\Omega \sin\phi$ is the Coriolis parameter at a given latitude (ϕ is the latitude and Ω the angular velocity of the Earth) in $10^{-5}\,\mathrm{s}^{-1}$.

(2) $I_\zeta = \zeta \frac{f}{|f|} + 5$ with ζ being the relative vorticity at 925 hPa in $10^{-6}\,\mathrm{s}^{-1}$ and $|\,|$ denotes an absolute value.

[1]For additional information's on the arbitrariness of TC detection in Coupled Global Climate Models (CGCMs), see recent article by Walsh et al. (2007).

(3) $I_{WS} = (|\frac{\delta V}{\delta P}| + 3)^{-1}$ is the inverse of the vertical shear of the horizontal wind (V) between pressure (P) levels 950 hPa and 200 hPa, in m s^{-1}/750 hPa.[2]

The thermal potential is defined as

(4) $E = \int_0^{60} \rho_w c_w (T - 26)\, \mathrm{d}z$ measures the thermal energy of the ocean between the surface and 60 m depth (ρ_w and c_w are the density and specific heat capacity of sea water), in 10^3 cal cm^{-2}.[3]

(5) $I_\theta = (\frac{\delta \theta_e}{\delta P} + 5)$ is the moist static stability defined as the vertical gradient of the equivalent potential temperature θ_e between the surface and 500 hPa, in K/500 hPa.

(6) $I_{RH} = Max(\frac{RH-40}{30}, 1)$, where RH is the average relative humidity in percent between 500 hPa and 700 hPa (i.e. a measure of the mid-tropospheric humidity).

If any of the components of the SGP is less than or equal to zero, the SGP is set to zero. The SGP is usually divided between the boreal winter (JFM), spring (AMJ), summer (JAS) and fall (OND) and is found to be a good predictor of the number of cyclones formed in a 5° × 5° latitude–longitude grid for a given 20-yr period. The Yearly Genesis Parameter (YGP) is calculated as the sum of the four SGPs and can be used to derive the annual average number of TCs over the same 5° × 5° box for a given 20-yr period.

In its original form, Gray (1975) set the threshold for deep convection at 26° C. However, we will here use a threshold of 26.3° C when evaluating the SGP/YGP in current climate conditions. This is done to address a recurrent criticism of the YGP which is its reliance on the constant value of 26° C as the threshold for TC formation. It is argued that with increasing temperatures in the tropics, the vertical lapse rate will adjust such that the warmer atmosphere will experience a shift in atmospheric stability, resulting in an increase in the threshold SST required to support deep convection. To a first order, one might expect the threshold SST for TC development to follow the mean surface warming over the tropical ocean. This implicitly assumes convection acts to maintain a relatively constant vertical lapse rate as the surface warms. Here, we attempt a type of first order correction based on this hypothesis by increasing Gray's original threshold.

Warming trends in the ocean vary greatly between individual basins, as shown by Casey et al. (2001), but choosing different temperature changes for different regions of the globe would be impractical here. Instead, based on Bindoff et al. (2007), we use a mean linear trend of 0.1° C/decade for all the tropics, resulting in an increase of 0.3° C between the period used in Gray's original work when the YGP was developed (1952–1971) and current conditions (1983–2002 for ERA40 and 1981–2000 for CGCMs). Based on our earlier discussion regarding the atmospheric lapse rate adjustment to SST changes, this leads to an increase in the SST threshold in the YGP from 26 to 26.3° C. This new value of 26.3° C will be used as the new threshold for current climate conditions and will serve as a reference when defining past and future thresholds which will be adjusted around this reference value based on specific (model and observed) SST trends. Henceforth, this tropical SST dependent YGP will be referred to as the *adjusted YGP*.

By comparison, the Convective SGP (CSGP) replaces the thermal potential of the SGP by a convective potential defined as

$$\text{convective potential} = k \times P_c \tag{1}$$

where P_C is the seasonal mean convective precipitation, in mm day^{-1} computed by a given model. As opposed to Royer et al. (1998), we do not apply an a priori threshold criteria for the convective precipitation. However, if the number of TCs predicted is less than 0.5 per 20-yr period, we set the CSGP to 0. The convective potential is also set to 0 over land regions. The CSGPs can also be summed over all seasons to give a CYGP. This index was developed with the goal of predicting future TC activity, hence the proportionality constant is determined empirically such that the total, global number of TCs predicted by the CYGP for a given (present-day) period be the same as that from the YGP. The advantage of this index lies in the fact that the convective precipitation integrates in an internally consistent manner, with respect to each model, the vertical atmospheric response to changes in SST, atmospheric stability and humidity whereas the SGP does not. It is worth mentioning that two recent studies (McDonald et al., 2003; Chauvin et al., 2006) have found good agreements between the actual TC activity generated by their GCM and this index. Also, it should be emphasized that this potential is best suited for low resolution GCMs, since convective precipitation is a model artefact resulting from coarse model resolution and the need to parametrize convection and therefore separately simulate convective and large-scale precipitation. Any significant increase in resolution should ideally see a gradual transfer of simulated convective precipitation into the large-scale component. This technique we believe is applicable to the resolution of present day (IPCC AR4) CGCMs and is likely to remain so until GCMs are running at resolutions significantly better than ∼1°.

We aim to evaluate both indices by comparing the implied number of TCs from each index using ERA40 simulated values for the 20-yr period 1983 to 2002. In doing this, we are implicitly assuming that the global reanalysis accurately represents the components of the SGP and CSGP at the 5° × 5° scale. We then compare CGCM simulated TC values for the 20-yr period 1981 to 2000 to the observed number of TCs and those derived from the reanalysis. 1983–2002 represents the last 20-yr period of data available from the ERA40 reanalysis and was deemed the most accurate with respect to the assimilation of satellite data

[2]Due to data availability, we use the 925 hPa level instead of the original 950 hPa for both the vorticity and the wind shear.

[3]Because only the SSTs were available for the reanalysis and for some CGCMs simulations, it was assumed that the ocean temperature to depth 60 m was that of the surface temperature. Royer et al. (1998) estimated that this led to an overestimation of the thermal content of the Atlantic by up to 50% and in the Indian and Pacific Ocean by up to 20–30%.

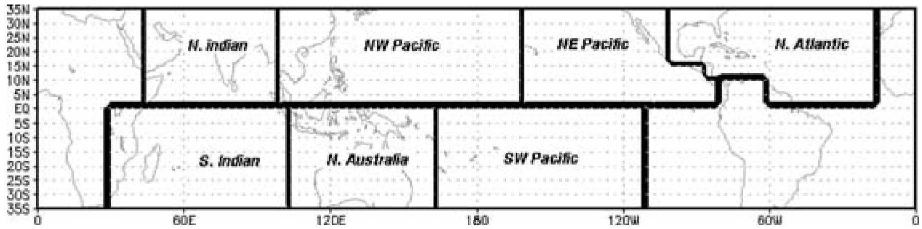

Fig. 1. Geographical location of the different basins.

over the tropical oceans. The 1981–2000 period in the model simulations corresponds to the last 20-yr period of the 'Climate of the 20th Century' scenario. We deemed these two periods to be sufficiently similar to each be classed as 'present climate conditions'.

Observations were taken from the Joint Typhoon Warning Center (JTWC) best track data set for the SH, WN Pac and Northern Indian Ocean and from the National Hurricane Center (NHC) best track data set for the Northern Atlantic and northeast Pacific (NE Pac) (Fig. 1 shows the different basins). A storm was considered a TC at the location and the time for which the surface sustained winds were first measured to be higher or equal to 17 m s^{-1}. Each TC was considered only once, even if it lost its tropical storm status for a short period and regained it later. The exceptions to this rule are the few TCs originating from the Atlantic which weaken to a depression over North/Central America only to revert to TC status once they reach the warm waters of the NE Pac.

3. Evaluation of the YGP and CYGP using ERA40 reanalyses

Figure 2b and c compare the YGP and CYGP implied TC activity derived from the ERA40 reanalysis data, to observed numbers for the period 1983–2002 (Fig. 2a). This is done to give an indication of the implied TC numbers we might expect from the YGP and CYGP using the best available large-scale meteorological data. Depending on the quality of the reanalysed large-scale tropical meteorology, this exercise can be considered a partial evaluation of the ability of the YGP and CYGP indices to infer TC statistics. As summarized in Table 1, the observed global mean number of TCs per year during the 1983–2002 period is 86.1 with an annual standard deviation over the 20-yr period of 7.3 cyclones. The ERA40 YGP predicts an average of 75 TCs per year for the same period. Most regions of cyclogenesis are well reproduced by the ERA40 YGP, even if there appears to be an overall overestimate in the SH and an underestimate in the NH. This shift in TC formation from the NH to the SH originates mostly from an underestimate of TC activity in the NE Pac and the Northern Atlantic and an overestimate in the southwest Pacific (SW Pac), as can be seen from Table 2, which details the observed and analysis derived TC statistics by basin for the 1983–2002 period. There is also unusual activity in the Red Sea and in both Hemispheres TC formation is predicted slightly closer to the Equator than currently observed. It is interesting to note that these results show some striking similarities with that of Bengtsson et al. (2007a) who have tracked individual cyclones in ERA40 reanalysis in the NH.

In the original study by Gray (1975) discrepancies between observations and YGP predictions were not as pronounced as they are with ERA40: no TCs were predicted in the Red Sea or on the Equator and TCs in the NE Pac and NW Pac were closer to what was observed. Lowering the SST threshold in the YGP back to the original value used by Gray (1975), that is, 26° C, in the evaluation of the YGP with ERA40 increases the mean annual frequency of TCs to 83, closer to current observations, but does not improve the geographical distribution: if the activity in the NW Pac region now approaches current level, the SW Pac region now overestimates TC activity and the NE Pac still does not capture the high density cyclogenesis present in that basin (not shown). Whether these differences between Gray's (1975) original predictions and ERA40's are due to deficiencies in the reanalysis data compared to the observational data used by Gray we are unable to evaluate at this time.

For the CYGP, we calculate the constant k of the convective parameter so that the total number of cyclones for the 1983–2002 period is the same for both methods, that is, 75 TCs per year. This leads to a value of $k = 0.1379$, which lies between the respective values found using GCM derived YGP and convective precipitation by Royer et al. (1998) and McDonald et al. (2003), namely 0.145 and 0.1159.

This index gives a distribution comparable to the YGP, but we see a shift in activity between the different basins: TC activity is reduced in the NW Pac and around Northern Australia but is increased in the NE Pac, N Atlantic and Southern Indian Ocean. Interestingly, the CYGP predicts a low level of activity off the coast of Brazil where Hurricane Catarina struck in 2004 (McTaggart-Cowan et al., 2006) and in the gulf of Guinea close to where a strong tropical depression/weak tropical storm formed in mid-April 1991 (McAdie and Rappaport, 2003). However, most noticeable is the inability of the index to predict TC formation in the NE Pac close to the coast. Similarly in the NW Pacific basin, TC activity is predicted to occur further East in the central Pacific, leading to unrealistically high activity in that region. Finally, the CYGP removes the unusual activity predicted in the Red Sea, fails to predict TCs in the Arabian Sea and maintains

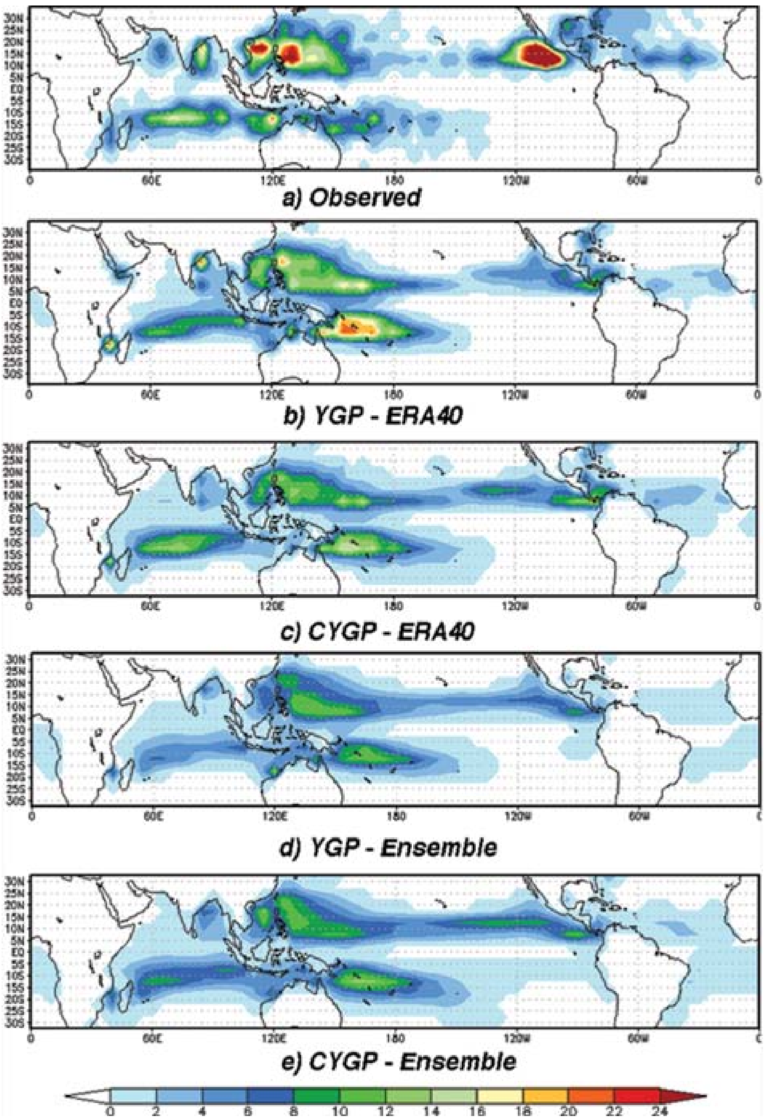

Fig. 2. Geographical distribution of TCs observed (a) and predicted with the adjusted YGP (b) and CYGP (c) in ERA40 reanalysis data, for the 1983–2002 period. Also, the predicted geographical distribution of TCs using the adjusted YGP (d) and CYGP (e) in an ensemble of nine CGCMs for the period 1981–2000. The units are TCs per 20 yr per 5° latitude–longitude.

Table 1. Mean annual global number of TCs detected and predicted at end of the 20th century and percentage of TCs occurring in the northern and Southern Hemisphere. The figure following the ± sign gives the standard deviation of the observed annual value over the 20-yr period

	Mean number of TC/year	%NH/%SH
Observations (1983–2002)	86.1 ± 7.3	69.1/30.9
ERA40 YGP (1983–2002)	75	57/43
ERA40 CYGP (1983–2002)	75	56/44
First Ensemble YGP (1981–2000)	58	58/42
First Ensemble CYGP (1981–2000)	75	55/45
Second Ensemble YGP (1981–2000)	43	47/53
Second Ensemble CYGP (1981–2000)	102	45/55

Table 2. Mean annual number of TCs per basin at the end of the 20th century. The figure following the ± sign gives the standard deviation of the observed annual values over the 20-yr period

	N Ind	NW Pac	NE Pac	N Atl	S Ind	N Aus	SW Pac
Observations (1983–2002)	4.8 ± 2.2	27.9 ± 4.0	16.5 ± 4.2	10.2 ± 3.7	11.9 ± 2.5	9.0 ± 3.0	5.8 ± 3.6
ERA40 YGP (1983–2002)	3.1	26.5	6.4	3.8	9.5	12.1	9.6
ERA40 CYGP (1983–2002)	2.2	21.7	9.2	6.3	12.8	8.6	8.9
Ensemble YGP (1981–2000)	1.9	20.6	8.1	1.4	6.7	8.2	7.4
Ensemble CYGP (1981–2000)	3.1	22.5	11.2	2.7	11.2	9.1	10.3

TC activity too close to the Equator. Again, this result shows good agreement with that of Bengtsson et al. (2007a).

Both indices reproduce the seasonality of TC formation with reasonable accuracy (not shown). By comparing individual seasons, it is seen that the unrealistically high TC activity in the SH is mainly due to an overestimate of activity during the JFM season, although both parameters incorrectly predict some low level TC activity in the JAS (winter) season in this hemisphere.

It is tempting to try to detect a trend in TC activity using the ERA40 reanalysis data for the period 1958–2002. However, applying the SGP or CSGP technique to the recent past using ERA40 data, the number of TCs decreases in an unrealistic manner in all basins. Deriving the YGP for the period 1963–1982 from ERA40 data, we find the mean annual number of cyclones predicted drops to 46. Although there is some uncertainty in cyclone archives, such a large decrease in TC formation (≈50%) is completely at odds with accepted trends in the global number of TCs over the recent past, which suggest a relatively constant global TC number over the past 40 yr, notwithstanding variations between individual basins (Webster et al., 2005).

The main factor responsible for this sharp reduction appears to be a significant reduction in the integrated water vapour content of the ERA40 atmosphere in the 1963–1982 period relative to the 1983–2002 era, leading to a large reduction in the humidity based parameters in the ERA40 YGP. Bengtsson et al. (2004) showed that this trend in IWV in ERA40 primarily arises from changes in observational coverage, in particular an increase in satellite coverage in the latter period, contributing to a moistening of the ERA40 atmosphere through increased data assimilation, rather than a real IWV trend. We can estimate the impact of such a dry bias on the YGP index by substituting the 1963–1982 relative humidity and specific humidity (used to calculate equivalent potential temperature) values for those of the 1983–2002 period and repeating the YGP calculations for the 1983–2002 period, with the new values and all other parameters unchanged. Doing so reduces the YGP from 75 TCs per year to 54 TCs per year. The remaining difference can be explained by a warming trend present in the lower troposphere in the reanalysis data. Again, according to Bengtsson et al. (2004), a large portion of this warming is caused by increased observational coverage in the latter time period. Substituting the surface temperatures (both atmosphere and ocean) of 1963–1982 into the 1983–2002 period further reduces the (1983–2002) YGP to 47 TCs per year. The drier and colder atmosphere of the 1963–1982 period is also reflected in the reduction of convective precipitation and in the CYGP: substituting the 1963–1982 ERA40 convective precipitation in the 1983–2002 CYGP reduces the mean annual number of TCs from 75 TCs per year down to 63 TCs per year. We therefore conclude that the majority of any trend in implied TC frequency through the ERA40 period is mainly an artefact of changing observational coverage.

The SGP and CSGP obtained from the ERA40 reanalyses for the 1983–2002 period produce reasonably accurate estimates of the global mean TC activity, as well as the geographical and seasonal distribution lending some credence to the YGP and CYGP indices in evaluating CGCM simulated TC statistics. ERA40 will subsequently be used in conjunction with observations for comparison when the same analysis is performed on an ensemble of CGCMs for a similar time period.

4. Evaluation of the YGP and CYGP in an ensemble of CGCMs for the climate of the 20th century

4.1. *Seasonal/yearly genesis parameter*

Nine CGCMs from the CMIP3 multimodel dataset were chosen to build an ensemble from which to evaluate the SGP and CSGP indices. The models were selected based on van Ulden and Oldenborgh's (2006) analysis of the quality of the simulated 20th century mean sea level pressure (MSLP) variability. Of particular interest was the mean spatial correlation and mean explained spatial variance of the MSLP over the whole globe and over the tropics specifically (30° N–30° S).[4] Where data was available, we were guided by these two criteria, which partially defines the quality of the simulated large-scale atmospheric variability in a given CGCM, in selecting the best performing models.

This pre-selection of ensemble members might indeed underestimate the level of uncertainty in future TC trend, but probably

[4] Also, some CGCMs had to be discarded due to data unavailability at the time this study was performed.

Table 3. CGCMs included in this study; first and second ensemble

CMIP3 I.D.	Short name	Country	Atmospheric resolution	Reference
BCCR-BCM2.0	BCCR2	Norway	$T63$, $L31$	Furevik et al. (2003)
CGCM3.1 (T63)	CGCM3.1	Canada	$T63$, $L31$	Flato (2005)
CSIRO-Mk3.5	CSIRO3.5	Australia	$T63$, $L18$	Gordon et al. (2002)
ECHAM5/MPI-OM	ECHAM5	Germany	$T63$, $L31$	Jungclaus et al. (2006)
GFDL-CM2.0	GFDL2.0	USA	$2.5^\circ \times 2.5^\circ$, $L24$	Delworth et al. (2006)
GFDL-CM2.1	GFDL2.1	USA	$2.5^\circ \times 2.5^\circ$, $L24$	Delworth et al. (2006)
MIROC3.2 (hires)	MIROC	Japan	$T106$, $L56$	K-1 model developers (2004)
MRI-CGCM2.3.2	MRI	Japan	$T42$, $L30$	Yukimoto et al. (2002)
UKMO-HadGEM1	HadGEM	UK	$1.875^\circ \times 1.25^\circ$, $L38$	Johns et al. (2007)
GISS-EH	Gisseh	USA	$5^\circ \times 4^\circ$, $L24$	Schmidt et al. (2006)
IPSL-CM4	IPSL4	France	$2.5^\circ \times 3.75^\circ$, $L19$	Marti et al. (2007)
PCM	PCM	USA	$T42$, $L18$	Washington et al. (2000)

Table 4. Total number of simulations used for each scenarios

Model name	Scenario 20c3m (Climate of the 20th century)	Scenario B1 550 ppm stabilisation	Scenario A1B 720 ppm stabilisation	Scenario A2 850 ppm stabilisation
BCCR2	1	1	1	1
CGCM3.1	1	1	1	0
CSIRO3.5	1	1	1	1
ECHAM5	3	2	2	2
GFDL-CM2.0	3	1	1	1
GFDL-CM2.1	3	1	1	1
MIROC	1	1	1	0
MRI	3	2	3	2
HadGEM	2	0	1	1
Total	18	10	12	9

increases the reliability of the results by filtering out CGCMs that do not reproduce adequately the global and tropical large-scale circulation. The CGCMs retained are listed in Table 3, along with the number of simulations produced for each GHG scenario listed in Table 4. The YGP/CYGP for a given model is defined as the mean of an ensemble of integrations, for that model, for a given emission scenario or present-day control integration (i.e. only 1 YGP/CYGP value for a given model, for a given emission scenario, contributes to the multimodel ensemble).

We first evaluate the original YGP, with a fixed SST threshold of 26° C as suggested by Gray (1975) for the nine models and the ensemble mean YGP for the scenario 20c3m (climate of the 20th century), running from 1861 to 2000. This period is broken down into seven 20-yr periods and the YGPs are calculated for each respective 20-yr block. Figure 3 gives the mean annual number of TCs per 20-yr period for each model and the ensemble mean using the YGP. Besides the mean annual number of cyclones being too low and the large differences between individual GCMs, an upward trend common to all models can be seen. Records of TCs preceding the 1940s are scarce, but there does not seem to be any strong evidence to support such an upward trend in cyclogenesis over the last 140 yr. In fact, these upward trends seem to confirm that at least part of the increase in TC formation detected by Ryan et al. (1992) and Royer et al. (1998) was due to weaknesses in the YGP itself.

To compensate for this trend, we now apply the correction suggested in Section 2. We first increase the current period (1981–2000) SST threshold required for TC formation to 26.3° C and then, for each preceding 20-yr period (or subsequent 20-yr period in future climate scenario), we average the surface temperature over the tropical oceans (30°S–30°N) for each model individually and compare it to the average 20 yr value of the reference period (1983–2002) for the same model. We then shift the threshold temperature for TC formation by this SST difference and recalculate the YGP for each 20-yr period using this new SST threshold. This procedure is done separately for each

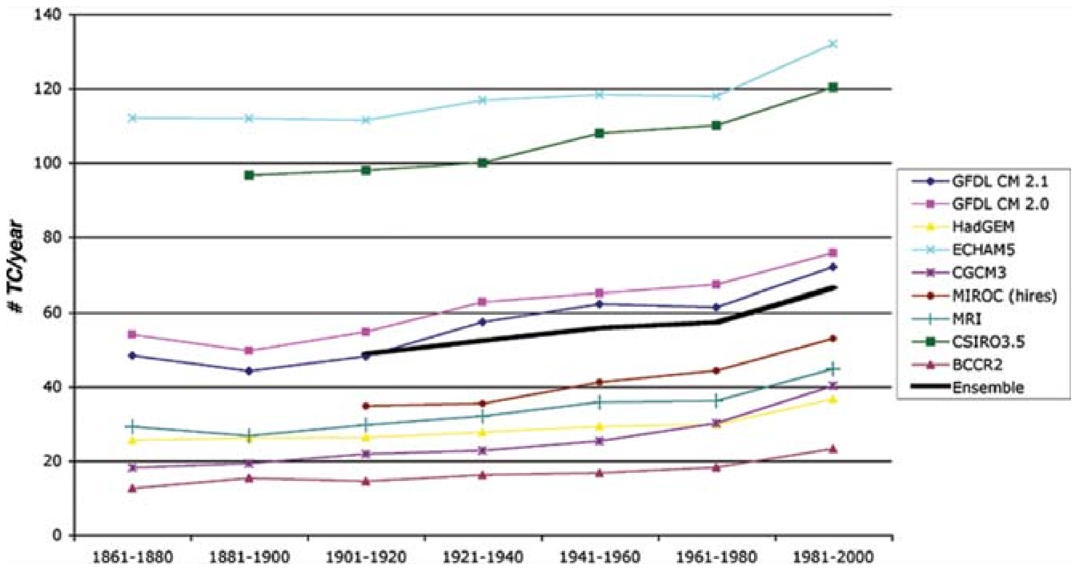

Fig. 3. Time-series of the mean global annual number of TCs based on the original YGP in nine CGCMs for the period 1861–2000 in the 20c3m scenario.

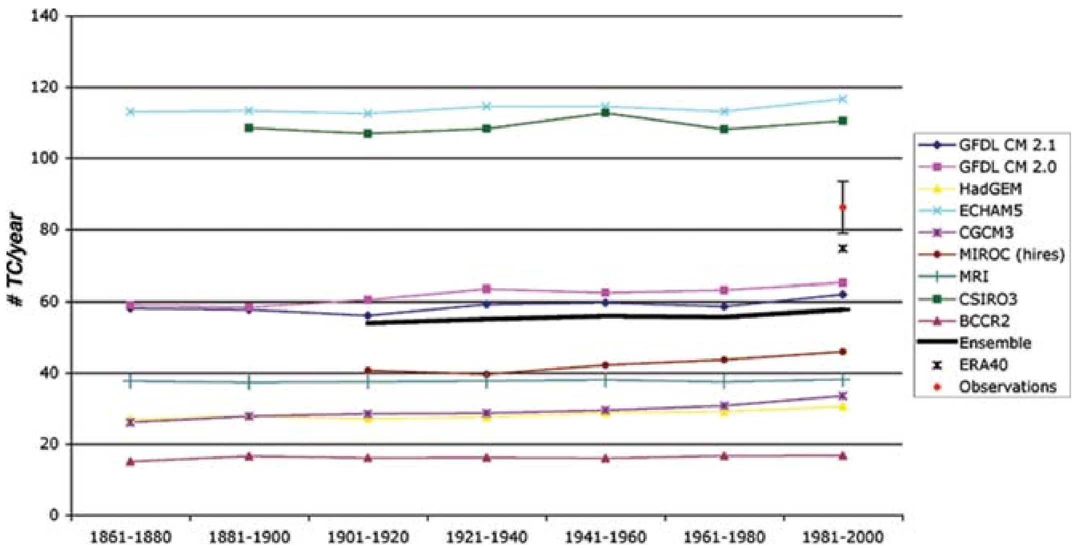

Fig. 4. Time-series of the mean global annual number of TCs based on the adjusted YGP in nine CGCMs for the period 1861–2000 in the 20c3m scenario. Also shown is the mean global annual number of TCs observed and derived from the adjusted YGP using ERA40 reanalysis for the period 1983–2002.

simulation. The changes in the threshold value between 1861–1880 and 1981–2000 are relatively small for all models and vary between 0.98° C for CGCM3.1 to 0.27° C for ECHAM5. The resulting mean annual TC number using this adjusted YGP per 20-yr period is given in Fig. 4. The upward trend over the past century is greatly reduced but is still apparent. To investigate the cause of this trend, Table 5 presents an estimate, for each season, of the change in the individual parameters of the SGP over the 20th century. This is presented in the form of a ratio 1981–2000: 1901–1920. The ocean thermal energy term does not contribute to the leftover trend, but the thermal potential is still responsible for it. This might be an indication that at least one other parameter requires some adjustment.

Comparing the geographical distribution of the adjusted YGP for the 1983–2002 period from the ERA40 reanalysis to the ensemble mean of the last 20-yr period of the 20c3m simulation, 1981–2000 (Fig. 2d), we see that most main cyclogenesis areas depicted in the reanalysis are also present in the CGCM ensemble, although at a systematically lower intensity. Besides a general decrease in the number of TCs, TC formation in the CGCM ensemble mean is largely absent from the Gulf of Mexico and the Northern Atlantic, which seems primarily due to lower

Table 5. Seasonal ratio of 1981–2000 to 1901–1920 for the parameters and potentials of the adjusted YGP

	I_{RH}	I_{θ}	E	Thermal potential	I_{ζ}	I_{WS}	Dynamic potential
JFM	1.04	1.04	0.97	1.05	1.01	1.01	1.01
AMJ	1.03	1.05	0.96	1.02	1.00	1.01	1.00
JAS	1.01	1.05	0.98	1.03	1.08	1.02	1.03
OND	1.01	1.05	0.99	1.04	1.00	1.02	1.00

mid-tropospheric humidity in the ensemble compared to ERA40. Also, some unrealistic activity is predicted in the Southern Atlantic and off the coasts of South America. The activity in the Southern Atlantic arises because the mid-tropospheric humidity of the ensemble in that region is too high and passes the threshold of 40% required for TC development, whilst the activity off the west coast of South America (Eastern Pacific) is due to an excess of ocean thermal energy during the JFM season, possibly due to a lack of stratocumulus clouds leading to a positive bias in surface short wave flux and a positive SST bias. Equally, a failure to accurately simulate ocean upwelling in the Eastern Pacific could lead to a similar positive SST bias. The ensemble YGP also predicts unrealistic TC formation in the Central Pacific. It should be noted that by tracking individual cyclones in ECHAM5, Bengtsson et al. (2007a) also detected TC formation in the latter region.

As in the reanalysis, the CGCM ensemble mean adjusted SGP gives a relatively accurate seasonal distribution of TCs for both JFM and JAS (not shown). Comparing the zonal mean distribution of TCs between the CGCM ensemble, reanalysis and observations (Fig. 5) clearly shows that both the ensemble and the reanalysis underestimate TC formation in the NH during JAS. In contrast, ERA40 overestimates TC formation in the SH during JFM while the ensemble underestimates it. Comparing both the thermal and dynamic potentials for the period 1983–2002 (Fig. 6) for JFM shows that the 10°S–15°S band is where both potentials are larger in ERA40 than the ensemble while the higher level of activity in ERA40 during JAS is caused by a larger thermal potential across the Northern tropics (Fig. 6). Nevertheless, the CGCM ensemble components of the SGP show striking similarity to those in the reanalysis.

Because the index depends on climatological large-scale fields, we might expect that many simulations performed using the same model would return similar indices with a relatively small spread in the predicted number of cyclones. This turns out to be the case, as we can see from Table 6, where the mean annual number of cyclones predicted by each model for the period 1981–2000 is given along with the standard deviation when the number of simulations was greater than 1. We observe a similar pattern whether we look at individual basins, seasons or different 20-yr periods. This suggest that a large number of simulations from one model does not increase greatly the robustness of findings related to the YGP, at least at the basin scale.

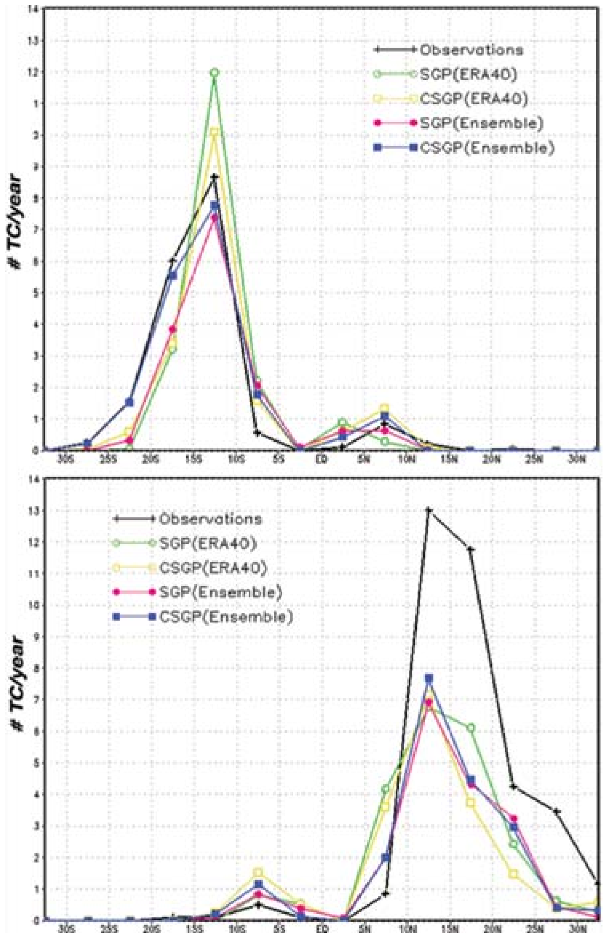

Fig. 5. Mean annual latitudinal distribution of observed and predicted TCs for JFM (a) and JAS (b). Observations and ERA40 reanalysis cover the period 1983–2002; the ensemble covers the period 1981–2000.

In comparison, the large spread of simulated YGP between the individual models is more significant and adding or subtracting a model from the ensemble would have a much greater impact on the index of the ensemble than any of the internal variations obtained from a single model, as can be seen from the standard deviation of the YGP for the ensemble (33 TCs per year). Some of this spread can be attributed to differences in predicted ocean

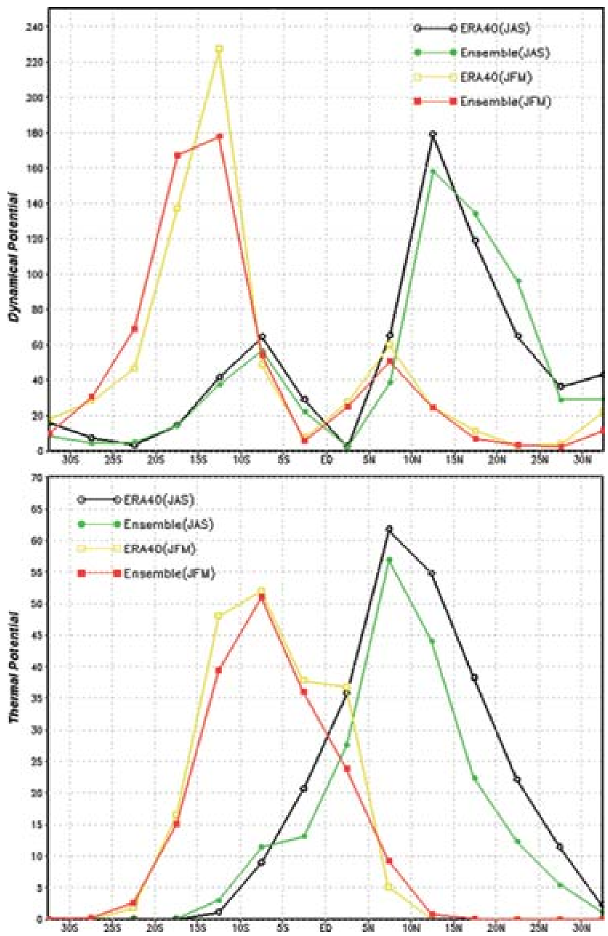

Fig. 6. Zonal sum of the thermal (a) and dynamic (b) potential for ERA40 (1983–2002) and the ensemble (1981–2000) for JFM and JAS.

surface temperature in the tropics. For the period 1981–2000, as much as 2.3° C separates the model with the lowest tropical ocean surface temperature (BCCR2), located at the low end of the YGP spectrum to the warmest model (CSIRO3.5), located at the top end of the YGP spectrum. Also worth mentioning is the relative difference in mid-tropospheric humidity over the tropical ocean between the individual models: more than 18% separates the driest model (MIROC) from the wettest model (ECHAM5) in the regions of cyclogenesis. Three out of the five models predicting lower activity than the ensemble mean (MIROC, HadGEM, CGCM3.1) have a mid-tropospheric relative humidity equal to or lower than 44% in the TC genesis regions while GFDL CM2.0, GFDL CM2.1, CSIRO3.5 and ECHAM5 have a mean value equal to or higher than 50%. For comparison, the mean value of mid-tropospheric humidity in ERA40 is 49%. Given that the humidity in the mid-troposphere is close to 40% in the regions of TC formation for the driest CGCMs, small differences in relative humidity translate into large differences in the YGP. In effect, those CGCMs fail to predict TC formation in many areas due to insufficient moisture in the mid-troposphere.

Table 6. Comparison of the mean annual number of cyclones between the CGCMs and the ensemble using the YGP and CYGP for the period 1981–2000. The figure following the ± sign for individual CGCMs gives the standard deviation across the available simulations made with that specific CGCMs while the figure following the ± sign for the ensemble gives the standard deviation across all the different CGCMs. If no ± sign is present, no ensemble was available for that particular CGCM

Model name	Adjusted YGP	CYGP
BCCR2	16.7	79.0
CGCM3.1	33.4	51.1
CSIRO3.5	110.4	73.5
ECHAM5	116.5 ± 5.8	105.5 ± 0.6
GFDL-CM2.0	65.0 ± 2.6	76.6 ± 0.6
GFDL-CM2.1	61.9 ± 1.7	90.9 ± 0.8
MIROC	45.8	37.0
MRI	38.0 ± 0.3	74.4 ± 0.6
HadGEM	30.4 ± 0.8	88.5 ± 0.7
Ensemble	58 ± 33	75 ± 19

4.2. *Convective Seasonal/yearly genesis parameter*

We now turn our attention to the alternative CSGP/CYGP index. Although it led to an underestimation of TC activity in the NH, we will consider the constant *k* found using ERA40 as an observational based estimate of *k*, linking convective precipitation to mid-tropospheric relative humidity, SST and equivalent potential temperature. Therefore, we use this value in deriving the CSGP for each respective model from eq. (1). This means that we should not expect the annual mean number of cyclones for the individual models to be equal to the values found using the YGP. We evaluate the index for each 20-yr period between 1861 and 2000, the same *k* value is used throughout the entire period implicitly assuming the relationship between convective precipitation and SST, mid-tropospheric RH and equivalent potential temperature are unchanged with time. The geographic distribution of the CYGP for the 1981–2000 period is given in Fig. 2e and the mean annual number of TCs per 20-yr period for 1861–2000 is given in Fig. 7.

Using this index, there appears to be almost no trend in the overall number of cyclones over the course of the past 140 yr (Fig. 7). This seems to support the hypothesis that the index adjusts to match changes in surface temperatures (Royer et al., 1998) and that, if we hope to detect a realistic trends in future TC activity, the CSGP/CYGP seems to be the most appropriate index.

For the 1981–2000 period, the mean annual number of TCs from the CGCM ensemble is 75, the same as estimated with

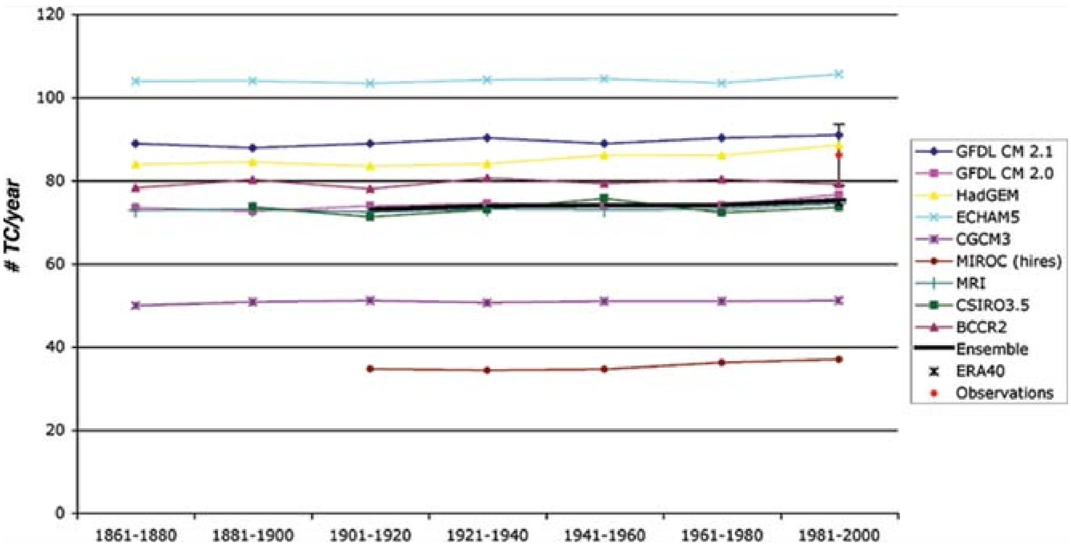

Fig. 7. Time-series of the mean global annual number of TCs based on the CYGP in nine CGCMs for the period 1861–2000 in the 20c3m scenario. Also shown is the mean global annual number of TCs observed and derived from the CYGP using ERA40 reanalysis for the period 1983–2002.

ERA40 (the mean for individual CGCMs is given in Table 6). However, the geographical distribution is somewhat different from the observations and is more similar to the one obtained from the reanalysis, with too high TC formation in the Central Pacific and western South Pacific and some unrealistic activity in the Southern Atlantic and eastern South Pacific. Also, as in previous cases, TC formation is predicted too close to the Equator and underestimated across the NH. Figure 5b clearly shows this underestimate in the NH in both ensemble and reanalysis. Whether this indicates common errors in simulating/analysing the large-scale tropical climate between the global reanalyses and CGCMs or a more systematic weakness in the YGP/CYGP statistic is beyond the scope of this study. Finally, the patterns of the CSGP for the ensemble also follow closely the patterns of CSGP for the reanalysis (not shown).

Figure 8 compares the longitudinal distribution of observed TC formation with that predicted from the YGP and CYGP using the reanalysis and the ensemble mean averaged over the latitude band 35 N–35 S. Both show good agreement with observations, but neither of the indices manage to capture the concentrated location of formation in the East Pacific. This problem is not unique to these indices and also occurs when tracking individual cyclones (McDonald et al., 2003; Yoshimura et al., 2006), although when using this technique, there seems to be a

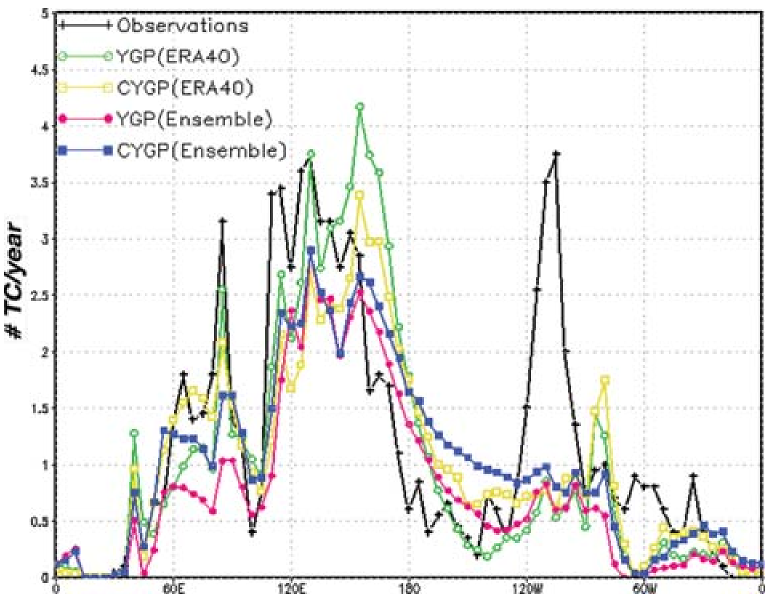

Fig. 8. Mean annual longitudinal distribution of TC cyclogenesis. Observations and ERA40 reanalysis cover the period 1983–2002; the ensemble covers the period 1981–2000.

definite improvement with increasing resolution. It is known that a significant fraction of TC development in the NE Pac occurs through an interaction of Atlantic tropical waves and depressions with Central American orography (Zehnder et al., 1998). Vortex stretching on the downwind (western) side of the Central American mountains can locally increase cyclonic vorticity in an evolving tropical disturbance and potentially be the seed for TC genesis in the East Pacific. This type of local dynamic interaction will not be included in the YGP/CYGP indices that only consider larger scale controls on TC development. The NE Pac is the only region where strong interaction between local orography and TC precursors takes place and seems to suggest the YGP and CYGP indices might not be applicable in this region.

Differences in the CYGP index between individual models again far outweight differences obtained from various simulations of the same model, as can be seen from Table 6. The standard deviation in the mean annual number of TCs is reduced using the CYGP, but is still substantial (25% of the mean annual number of predicted TCs). Except for MIROC, CSIRO3.5 and ECHAM5, all models show an increase in their annual mean number of TCs compared to the YGP, the most dramatic being HadGEM and BCCR2 which increase by a factor ≈3 and 5, respectively. This wide variety of responses may originate from the different convection schemes used in the models, which may each trigger and support deep convection at different ocean temperatures and/or atmospheric stability or humidity values.

In order to justify the choice of the nine CGCMs that we have used, we performed a similar analysis using a smaller ensemble of three CGCMs, each of which were classified as performing poorly based on the analysis of van Ulden and van Oldenborgh (2006). The YGP and CYGP of these three CGCMs (GISSeh, IPSL4, PCM) are displayed in Fig. 9. Both indices suffer from the poorer simulation of large-scale tropical climate variability in these CGCMs: both indices predict a larger number of TCs in the SH than in the NH (see Table 1) and both extend TC activity into the Southeastern Pacific. The YGP of the second ensemble also fails to predict high-level activity in the WN Pac while the CYGP predicts more activity in the Southern Atlantic than in the Northern Atlantic. Hence, as should be expected, both parameters simulate a more accurate distribution of implied TCs when using CGCMs with an accurate representation of large-scale atmospheric variability compared to TC statistics derived using less accurate models. We therefore consider it important that a pre-selection of sufficiently accurate GCMs is made based on performance for the present, observed climate, before an analysis of future TC changes is made. This exercise led to the nine CGCMs used in this study.

5. Future tropical cyclone activity

Having established for the nine member CGCM ensemble that the CYGP and adjusted YGP provide reasonable estimates of the annual number of TCs along with a reasonable depiction of the spatial and seasonal distribution of TCs, we now apply these indices to results originating from a variety of future climate scenarios generated by the same nine CGCMs. In assessing possible future TC activity, we will use three sets of model projections, each based on a different GHG emission scenario for the next 100 yr. In the optimistic scenario, SRES B1, equivalent CO_2 concentrations reach 550 ppm by the year 2100, in the pessimistic scenario SRES A2, 850 ppm and in the intermediate scenario SRES A1B, 720 ppm (Nakićenović and Swart, 2000).

We begin by evaluating time-series of the mean annual number of cyclones per 20 yr for the period 2001–2100 for both indices

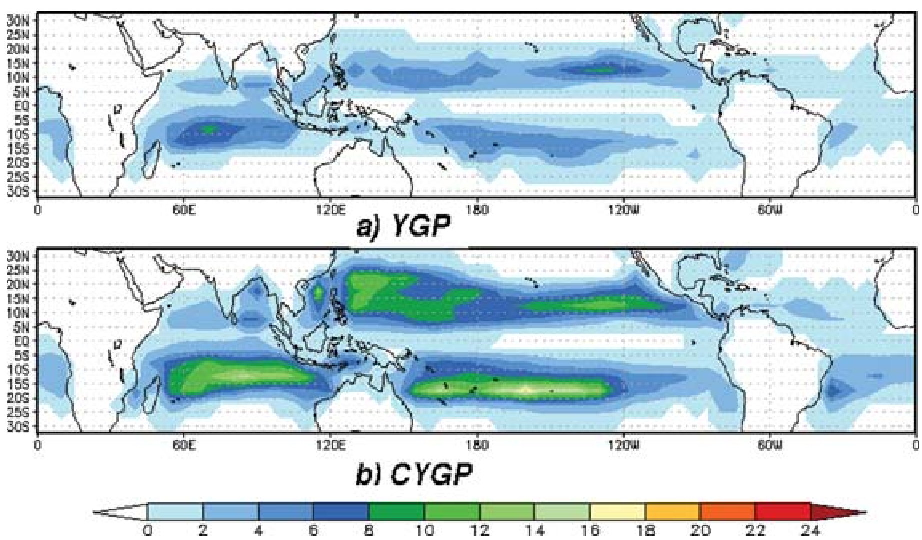

Fig. 9. Predicted geographical distribution of TCs using the adjusted YGP (a) and CYGP (b) in the second CGCMs ensemble for the period 1981–2000. The units are TCs per 20 yr per 5° latitude–longitude.

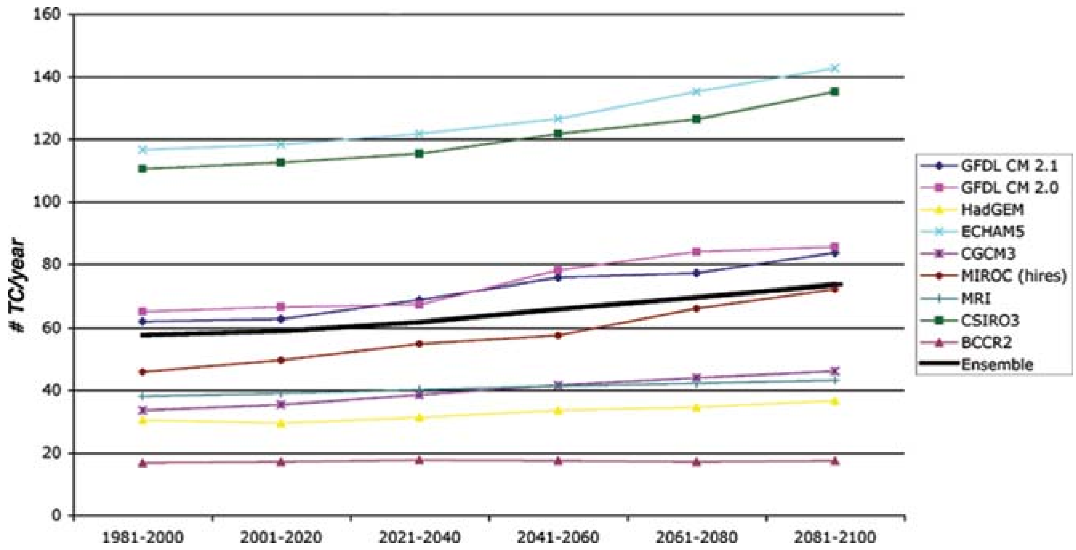

Fig. 10. Time-series of the mean global annual number of TCs based on the adjusted YGP in nine CGCMs for the period 1981–2100 in the SRES A1B scenario.

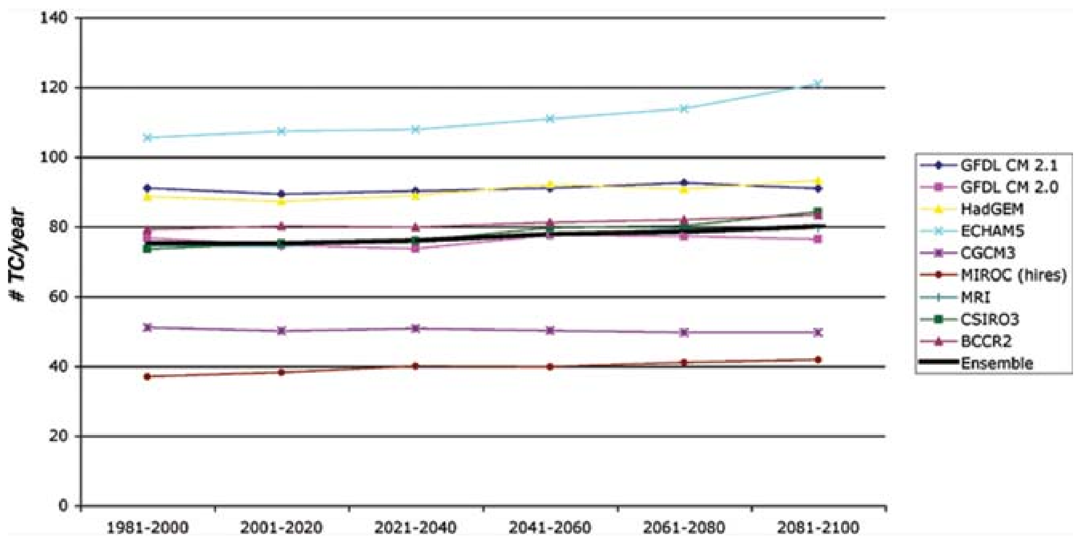

Fig. 11. Time-series of the mean global annual number of TCs based on the CYGP in nine CGCMs for the period 1981–2100 in the SRES A1B scenario.

Table 7. Seasonal ratio of 2081–2100 (SRES A1B) to 1981–2000 for the parameters and potentials of the adjusted YGP

	I_{RH}	I_θ	E	Thermal potential	I_ζ	I_{WS}	Dynamic potential
JFM	1.08	1.23	0.88	1.21	1.00	1.04	1.00
AMJ	1.02	1.26	0.90	1.14	0.93	0.99	0.93
JAS	1.05	1.28	1.01	1.48	1.00	1.03	1.02
OND	1.13	1.26	0.91	1.41	1.03	1.04	1.02

in the SRES A1B scenario. Results using the adjusted YGP are shown in Fig. 10 and using the CYGP, in Fig. 11. The adjusted YGP shows a relatively steep upward trend. From Table 7, the influence of the thermal energy content is greatly reduced compared to previous studies; instead, a large portion of the increase may be attributed to an increase in the moist static stability term. How much of this trend is artificial due to shortcoming of the index itself is unknown. Based on the analysis of results for the

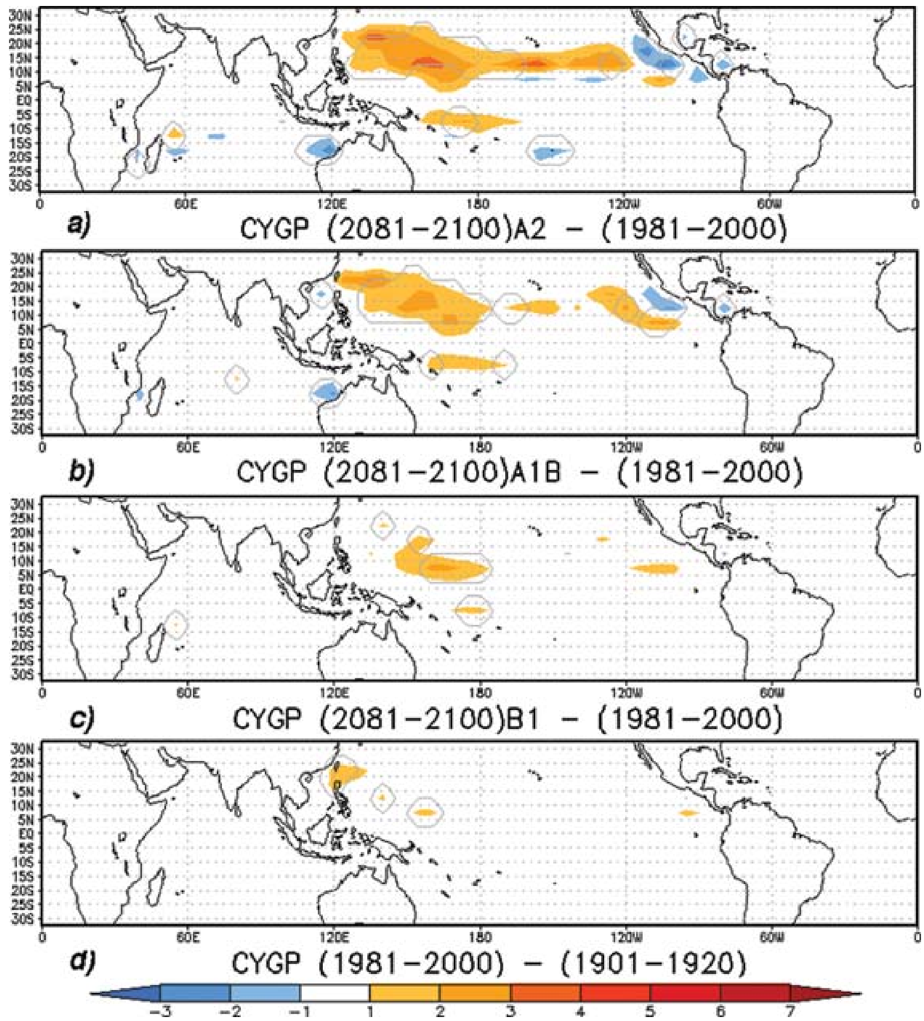

Fig. 12. Geographical change in TCs frequency between the 2081–2100 period in SRES A2 (a), SRES A1B (b), SRES B1 (c) and the 1981–2000 period using the CYGP. For comparison, the difference between the 1981–2000 period and 1901–1920 period using the same index is also shown (d). The grey lines show the areas where a change is predicted by more than 75% of the CGCMs.

period 1861–2000 we contend the CYGP index provides a more accurate representation of past TC activity and therefore feel this index is the most appropriate one to use when considering future trends in TCs. The CYGP shows a small upward trend in the mean annual number of cyclones per 20 yr. The increase between 1981–2000 and 2081–2100 for the ensemble mean is found to be 5 TCs per year, up to an mean annual value of 80 TCs per year. A similar analysis for SRES A2 and SRES B1 gives an increase of 5 TCs per year and 3 TCs per year, respectively. As can be seen in Fig. 11, no global trend common to all CGCMs can be detected since the responses vary between a moderate increase (>10%) (MIROC, ECHAM5, CSIRO3.5), small increase (<10%) (HadGEM, MRI, BCCR2), no trend (GFDL CM2.0, GFDL CM2.1) and a slight decrease (CGCM3.1). However, this global trend can be misleading because all CGCMs do predict changes in locations of cyclogenesis, even if they do not predict a global change. For example, HadGEM predicts a large increase in the WN Pac, compensated by a decrease in the SH, the more pronounced decrease being in the South Indian Ocean.[5] Similarly, GFDL CM 2.0 predicts an increase in activity in the WN Pac compensated by a decrease in the SW Pacific.

Figure 12 shows the geographical distribution of ensemble mean TC changes between 2081–2100 and 1981–2000 for the three emissions scenarios. The ensemble mean increase is not uniformly distributed but mostly concentrated in the WN Pac basin and compensated by a small decrease in the SH. For comparison, the difference between the 1981–2000 climate and the 1901–1920 climate is also shown in Fig. 12d. The mean annual

[5] For comparison, the study performed by McDonald et al. using HadCM found an increase in the South Indian Ocean and both areas of increased and decreased activity in the WN Pac.

Table 8. Percentage changes per basin in the mean annual frequency of TCs between future scenarios (2081–2100) and the 1981–2000 period using the CYGP index. For comparison, the changes over the period 1901–1920 to 1981–2000 are also shown. In bold are the changes larger than the observed annual standard deviation over the 20-yr period (1983–2002)

	Observed number of TCs	Change in SRES A2	Change in SRES A1B	Change in SRES B1	Change in 20c3m
N Indian	4.8 ± 46%	16%	10%	6%	−1%
WN Pacific	27.9 ± 14%	**22%**	**16%**	10%	7%
EN Pacific	16.5 ± 25%	6%	10%	4%	1%
N Atlantic	10.2 ± 36%	−24%	−11%	−4%	−4%
S Indian	11.9 ± 21%	−4%	−1%	1%	3%
N Australia	9.0 ± 33%	−4%	−3%	−1%	−1%
WS Pacific	5.8 ± 62%	5%	3%	4%	4%

change per basin is given in Table 8.[6] The increase in the WN Pacific is even more pronounced in SRES A2 than in SRES A1B but is relatively weak in SRES B1. In both SRES A1B and SRES A2, there appears to be a reduction in TC formation along the coast of Central America in the NE Pac, accompanied by an increase further off the coast. This pattern is also predicted in Bengtsson et al. (2007b), but given that cyclogenesis is poorly represented by our indices in this basin, this result should be taken with caution. Also, there appears to be a small overall reduction of TC formation in the SH. However, this reduction is quite weak and it is questionable if, were it to occur, it could be detected relative to natural interannual variability. Very little change is expected in SRES B1 and no new regions of cyclogenesis are apparent in any of the scenarios. For the scenario where most models were used, SRES A1B, most of the increase in the WN Pac occurs during JAS (53%), while the second largest increase occurs during OND (31%) (not shown) which would result mostly in a more active typhoon season. No significant increase is predicted in the non-typhoon seasons. The increase in TC formation during the summer season in that region is caused by an increase in both convective and dynamic potentials. More specifically, the vorticity term becomes more conducive to TCs, while the wind shear remains at current level (not shown).

6. Conclusion

We have analysed, using ERA40 reanalysis data and what was deemed the more accurate IPCC AR4 models, two parameters believed to accurately represent current TC activity based on large-scale climate controls. Using reanalyses, both the YGP and CYGP manage to capture the major areas of cyclogenesis, although they systematically underestimate TC activity in the NH. By using an ensemble of CGCMs, we see a degradation in the representation of current regions of cyclogenesis and their intensity level, which is caused by the CGCMs failure to adequately simulate large-scale fields used in the evaluation of the indices. By looking at past trends, we deemed the CYGP index to be more robust to changes in climate conditions and have attempted, based on that parameter, to predict future TC activity. With this approach, very little change between current and future TC activity is expected: in only one basin in two out of three scenarios do we detect a change greater than the observed interannual variability of that particular basin.

The weak positive trend for future climate scenarios found in this study is not unlike that of Stowasser (2007) which predicts a slight increase (although no statistically significant) in the number of TCs in the NW Pac in a $6 \times CO_2$ atmosphere. It does contrast sharply however with other studies based on the comparison of the TCLVS which predict an overall reduction in the number of cyclones in the future. In particular, recent papers by Oouchi et al. (2006) and Bengtsson et al. (2007b) predict a reduction in the number of cyclones in the NW Pacific. However, as mentioned earlier, these TCLVs are not TCs and so, any changes in one cannot be absolutely confidently transferred to changes in the other.

Similarly, investigating future TC activity by looking at the large-scale fields favourable to TC formation carries its own uncertainties. It should be remembered that, while the CYGP gives reasonable results for present climate conditions, this does not guarantee the followings.

(1) The index will work well in future climate conditions (as the example of the YGP has shown) and, maybe even more importantly.

(2) Current CGCMs correctly simulate future large-scale climate conditions that will occur in the tropics and influence the CYGP implied TC numbers.

It is likely that, until CGCMs significantly increase their resolution to adequately simulate past observed TC statistics,

[6]In order to avoid biases, in the case where no simulation was available for a model for a certain scenario, this model was removed from the ensemble before comparing future and present climate conditions.

variability, intensity and structure, any possible changes in TC activity in response to a changing climate will remain uncertain at best.

7. Acknowledgments

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References

Bengtsson, L., Botzet, M. and Esch, M. 1996. Will greenhouse gas-induced warming over the next 50 years lead to a higher frequency and greater intensity of hurricanes? *Tellus* **48A**, 57–73.

Bengtsson, L., Hagemann, S. and Hodges K. I. 2004. Can climate trends be calculated from reanalysis data? *MPI Report 351*.

Bengtsson, L., Hodges, K. I. and Esch, M. 2007a. Hurricane-type vorticies in a T159 resolution global model: comparisons with observations and reanalyses. *Tellus* **59A**, 396–416.

Bengtsson, L., Hodges, K. I., Keenlyside, N., Kornblueh, L, Luo, J. and Ymagata, T. 2007b. How may tropical cyclones change in a warmer climate? *Tellus* **59A**, 538–560.

Bindoff, N. L., Willebrand, J., Artale, V., Cazenave, A., Gregory, J. and co-authors. 2007. Observations: oceanic climate change and sea level. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, (eds S. Solomon, D. Qin, M., Manning, Z. Chen, M. Marquis and co-editors), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Camargo, S. J., Sobel, A. H., Barnston, A. G. and Emanuel, K. A. 2007. Tropical cyclone genesis potential index in climate models. *Tellus* **59A**, 428–443.

Casey, K. and Cornillon, P. 2001. Global and Regional Sea Surface Temperature Trends. *J. Climate* **14**, 3801–3818.

Chauvin, F., Royer, J.-F. and Déqué, M. 2006. Response of hurricane-type vortices to global warming as simlated by ARPEGE-Climat at high resolution. *Climate Dyn.* **27**, 377–399.

Delworth, T. L., Brocoli, A. J., Rosati, A., Stouffer, R. J., Balaji, V. and co-authors. 2006. GFDL's CM2 global coupled climate models. Part 1: formulation and simulation characteristics. *J. Climate* **9**, 643–674.

Emanuel, K. A. 2005. Increasing destructiveness of tropical cyclones over the past 30 years. *Nature* **326**, 686–688.

Emanuel, K. A. and Nolan, D. 2004. Tropical cyclone activity and global climate. In: *26th Conference on Hurricanes and Tropical Meteorology*, Amer. Meteor. Soc., Miami, FL., 240–241.

Flato, G. M. 2005. The thrid generation coupled global climate model (CGCM3). *www.cccma.ba.ca/modelscgcm2.shtml*

Furevik, T., Bentsen, M., Drange, H., Kvamsto, N. and Sorteberg, A. 2003. Description and evaluation of the Bergen climate model: ARPEGE coupled with MICOM. *Climate Dyn.* **21**, 27–51.

Gray, W. M. 1975. Tropical Cyclone Genesis. *Dept. of Atmospheric Science Paper*, No. 234, Colorado State University, Fort Collins, CO.

Gordon, H. B., Rotstayn, L. D., McGregor, J. L., Dix, M. R. and Kowalczyk, E. A. 2002. The CSIRO Mk3 climate system model. *Tech. Rep. 60, CSIRO Atmospheric Research*, Aspendale.

Haarsma, R. J., Mitchel, J. F. B. and Senior, C. A. 1993. Tropical disturbances in a GCM. *Climate Dyn.* **8**, 247–257.

Johns, T., Durman, C., Banks, H., Roberts, M., McLaren, A. and co-authors. 2004. HadGEM1 - model description and analysis of preliminary experiments for the IPCC Fourth Assesment Report. *Tech. Rep. 55*, U.K. Met Office, Exeter, UK.

Jungclaus, J. H., Keenlyside, N., Botzet, M., Haak, H., Luo, J.-J. and co-authors. 2006. Ocean circulation and tropical variability in the coupled model ECHAM5/MPI-OM. *J. Climate* **19**, 3952–3972.

K-1 model developers. 2004. K-1 couple model (MIROC) description Tech. Rep. 1. *Tech. Rep. 1*, Center for Climate System Research, University of Tokyo, Tokyo.

Klotzbach, P. J. 2006. Trends in global tropical cyclone activity over the past twenty years. *J. Geophys. Res.* **33**, L10805, doi:10.1029/2006GL025881.

Marti, O., Braconnot, P., Bellier, J., Benshila, R., Bony, S. and co-authors. 2005. The new IPSL Climate System Model: IPSL-CM4. *Tech. Rep.*, Institut Pierre Simon Laplace des Sciences de l'Environnement Global, IPSL, Case 101, 4 place Jussieu, Paris, France.

McAdie, C. J. and Rappaport, E. N. 1991. Diagnostic Report of the National Hurricane Center. Vol. 4, No. 1, NOAA, National Hurricane Center, Coral Gables, FL 45 pp.

McDonald, R. E., Bleaken, D. G., Cresswell, D. R., Pope, V. D. and Senior, C. A. 2005. Tropical storms: representation and diagnosis in climate models and the impacts of climate change. *Climate Dyn.* **25**, 19–36.

McTaggart-Cowan, R., Bosart, L. F., Davis, C. A., Atallah, E. H., Gyakum, J. R. and co-authors. 2006. Analysis of Hurricane Catarina (2004). *Mon. Wea. Rev.* **134**(11), 3029–3053.

Meehl, G. A., Stocker, T. F., Collins, W. D., Friedlingstein, P., Gaye, A. T. and co-authors. 2007. The physical science basis. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, (eds S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis and co-editors), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Nakićenović, N. and Swart, R. (eds) 2000. *Special Report on Emissions Scenarios. A Special Report of Working Group III of the Intergovermental Panel on Climate Change*, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 599 pp.

Oouchi, K., Yoshimura, J., Yoshimura, H., Mizuta, R., Kusunoki, S. and co-authors. 2006. Tropical cyclone climatology in a global-warming climate as simulated in a 20 km-Mesh global atmospheric model:

frequency and wind intensity analyses. *J. Meteorol. Soc. Jpn.* **84** (2), 259–276.

Royer, J.-F., Chauvin, F., Timbal, B., Araspin, P. and Grimal, D. 1998. A GCM study of the impact of greenhouse gas increase on the frequency of occurrence of tropical cyclones. *Clim. Change* **38**, 307–343.

Ryan, B. F., Watterson, I. G. and Evans, J. L. 1992. Tropical cyclone frequencies inferred from Gray's yearly genesis parameter: validation of GCM tropical climates. *Geophys. Res. Lett.* **19** (18), 1831–1834.

Schmidt, G. A., Ruedy, R., Hansen, J. E., Aleinov, I., Bell, N. and co-authors. 2006. Present day atmospheric simulations using GISS Model E: comparison to in-situ, satellite and reanalysis data. *J. Climate* **19**, 153–192.

Stowassser, M., Wang, Y. and Hamilton, K. 2007. Tropical cyclone changes in the western north Pacific in global warming scenario. *J. Climate* **20**, 2378–2396.

Sugi, M., Noda, A. and Sato, N. 2002. Influence of global warming on tropical cyclone climatology: an experiment with the JMA global model. *J. Meteor. Soc Jpn.* **80**, 249–272.

Uppala, S. M., Kållberg, P. W., Simmons, A. J., Andrae, U., Da Costa Bechtold, V. and co-authors. 2005. The ERA-40 reanalysis. *Q. J. R. Meteor. Soc.* **131**, 2961–3012.

van Ulden, A. P. and van Oldenborgh G. J. 2006. Large-scale atmospheric circulation biases and changes in global climate model simulations and their importance for climate change in central Europe. *Atmos. Chem. Phys.* **6**, 863–881.

Walsh, K. and Watterson, I. G. 1997. Tropical cyclone-like vortices in a limited area model: comparison with observed climatology. *J. Climate* **10**, 2240–2259.

Walsh, K., Fiorino, M., Landsea, C. W. and McInnis, K. L. 2007. Objectively determined resolution-dependent threshold criteria for the detection of tropical cyclones in climate models and reanalysis. *J. Climate* **20**, 2307–2314.

Washington, W. M., Weatherly, J. W., Meehl, G. A., Semtner, A. J. Jr. Bettge, T. W. and co-authors. 2000. Parallel Climate Model (PCM) control and transient simulations. *Climate Dyn.* **16**, 755–774.

Webster, P. J., Holland, G. J., Curry, J. A. and Chang, H.-R. 2005. Changes in tropical cyclone number and intensity in a warming environment. *Science* **309**, 1844–1846.

Wu, M. C., Yeung, K. H. and Chang, W. L. 2006. Trends in western north Pacific tropical cyclone intensity. *EOS* **87**(48), 537–538.

Yoshimura, J., Sugi, M. and Noda, A. 2006. Influence of greenhouse warming on tropical cyclone frequency. *J. Meteor. Soc. Japan* **84**(2), 405–428.

Yukimoto, S. and Noda, A. 2002. Improvements of the Meteorological Research Institute Global Ocean-atmosphere Coupled GCM (MRI-CGCM2) and its climate sensitivity. *Tech. Rep. 10*, National Institute for Environmental Studies, Japan.

Zehnder, J. A., Powell, D. M. and Ropp, D. L. 2006. The interaction of easterly waves, orography and the intertropical convergence zone in the genesis of eastern Pacific tropical cyclones. *Mon. Wea. Rev.* **127**, 1566–1585.