Hurricanes and Climate Change

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Editors

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Cover illustration: Frequency and intensity of hurricanes at lifetime maximum intensity over the North Atlantic. The color scale is linear from 1 (blue) to 15 (yellow) indicating the number of hurricanes reaching lifetime maximum (first time only) within the hexagon. The value inside the hexagon is the maximum intensity (m/s) of all lifetime maximum values in the bin. The analysis is done on a Mollweide projection so that the hexagons have equal area. Data source: U.S. National Hurricane Center best-track, 1943-2008.

Cover design: deblik

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Preface

Hurricanes are among nature's most destructive agents. Widespread interest surrounds the possibility that they might even get more damaging in the future. Some policy makers consider it a call to action. Financial want to know when and by how much. And scientists are certainly challenged by the range and interactions of the processes involved. This book, arising from the Second International Summit on Hurricanes and Climate Change (31 May through 5 June 2009 in Corfu, Greece), contains new research since the First Summit (2007 in Crete) on topics related to hurricanes and climate change. Chapters are grouped into studies using global climate models and those taking empirical and statistical approaches. The latter include investigations of basin-wide and regional tropical cyclone activity.

The book opens with a review of progress on an international project to compare global climate models on their ability to generate tropical cyclones. Chapter 2 highlights predictions of tropical cyclone activity under global warming using a cloud-resolving climate model. Chapter 5 discusses the potential insights of considering tropical cyclone activity as critical phenomenon. Chapter 6 highlights the importance of sea-surface temperature in driving the amount of monetary losses from hurricanes (but not the frequency of loss events) affecting the United States. This is important as most of the literature on this subject, including that written by some of the insurance companies, has failed to do a credible job with this issue. We know greater monetary losses occur with stronger hurricanes. We know hurricanes can become more intense when they are over warmer waters. So we expect the probability of a large loss to be higher when the oceans warm. Interestingly, results show that when sunspots are few there is a higher probability of at least one loss event.

The intriguing finding of a solar signal in hurricane activity is taken up in more detail in Chapter 7. Statistical evidence of a linkage between the solar cycle and major hurricanes over the eastern North Pacific and hurricanes along the U.S. coast is presented. These results are particular salient given that the sun may be going through an extended period of inactivity. The record of coastal hurricanes is sometimes invoked as evidence that climate change plays no significant role in modulating hurricane activity. But other factors could mitigate against a climate signal in these hurricanes. For instance, evidence presented in Chapter 10 is consistent with the hypothesis that hurricanes near land may be increasingly affected by continental aerosols. Also, modeling studies show increasing carbon dioxide causes the stratosphere to cool leading to a faster jet stream and a tendency for more frequent positive phases of the North Atlantic Oscillation. It is well known that a positive North Atlantic Oscillation tends to steer the hurricanes away from the United States.

Return periods of high winds from hurricanes in the vicinity of Florida are estimated in Chapter 11. Historically the state was affected by hurricane winds of 60 m s^{-1} once every 2 years, but there is evidence that the strongest hurricanes may be getting stronger in this part of the world as well. Chapter 13 provides a methodology for producing a track-relative climatology. This is a novel way to examine hurricane activity, and it is applied toward understanding the risk of high winds to Eglin Air Force Base in northern Florida.

Although much has been written on hurricanes and climate change, the chapters in this volume represent some of the more interesting and innovative new research on this important topic. The Summit, which had participants from 17 different countries, was sponsored by Aegean Conferences, the Risk Prediction Initiative, and Climatek. Plans are underway to hold the Third International Summit on the island of Rhodes in the summer of 2011.

Tallahassee, Florida
April 2010

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Chapter 1
The Tropical Cyclone Climate Model Intercomparison Project

Kevin Walsh, Sally Lavender, Hiroyuki Murakami, Enrico Scoccimarro, Louis-Phillipe Caron, and Malek Ghantous

Abstract In this chapter, a review is given of progress to date on an intercomparison project designed to compare and evaluate the ability of climate models to generate tropical cyclones, the Tropical Cyclone climate Model Intercomparison Project (TC-MIP). Like other intercomparison projects, this project aims to evaluate climate models using common metrics in order to make suggestions regarding future development of such models. A brief summary is given of the current ability of these models and some initial conclusions are made. Coarser-resolution climate models appear to have difficulty simulating tropical formation in the Atlantic basin, but simply increasing the resolution of such models does not necessarily lead to improved simulations in this region. The choice of convective scheme is also important in determining the tropical cyclone formation rate. There appears to be little relationship between the simulated details of the large-scale climate and model tropical cyclone formation rates, and possible reasons are given for this. Recent fine-resolution models have shown considerable improvement in their simulation of both global and Atlantic tropical cyclone formation, leading to the possibility that such models could be used for detection and attribution studies of the causes of observed changes in tropical cyclone formation rate, particularly in the Atlantic basin.

Keywords Tropical cyclone · Climate model · Global warming · Intercomparison

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1 Introduction

The possible effect of climate change on tropical cyclones remains one of the most controversial topics in modern meteorology. Opinions on this issue range from flat denial that there could be any effect to predictions of large increases in tropical cyclone incidence and intensity that are already detectable in the observed record. A range of techniques have been used to make inferences about this topic, ranging from purely statistical analyses to sophisticated fine-resolution models to fundamental theories of atmospheric behaviour.

Some years ago, the debate about the effects of climate change on overall global warming went through the same stage as the current controversy about its effects on tropical cyclones. In both topics, initial theoretical work established that such an effect was consistent with our understanding of atmospheric physics – for tropical cyclones and climate change, this was the work of Emanuel (1987). For global climate change, this was followed by a period of model development and experimentation, accompanied by argument over both the existence and the magnitude of the possible climate change signal. This debate is now essentially over: there are few serious climate scientists who still believe that there is no significant global effect. Numerous detection and attribution studies have shown that the observed twentieth and early twenty-first century warming is consistent with climate model predictions based on the observed increases in greenhouse gas concentration in the atmosphere (Hegerl et al. 2007). These same climate models project even larger changes later this century (IPCC 2007).

In contrast, for tropical cyclones and climate change, the debate continues. There are fundamental reasons why this is so. Most climate data consists of daily records, whereas tropical cyclones are considerably rarer events. Unlike the global climate record of (for example) land-based screen temperature, there is considerable controversy about the consistency of the tropical cyclone record, due to significant changes in observing systems over several decades (Kossin et al. 2007). Unlike the land-based temperature record, the main tropical cyclone records, the best track data, were never intended to be used as climate data sets. As a result, little attention was paid to ensuring that the techniques used to construct them were consistent from year to year. The other issue limiting scientific conclusions from this debate is that until very recently, climate model simulations of the observed distribution of tropical cyclone extreme wind speeds were poor (e.g. Walsh 2008). This is also in contrast to the quality of the simulation of global average temperature: since this is considerably easier to simulate, its quality has always been better (IPCC 2007). One of the crucial steps in the debate on the causes of the observed increase in global average temperature over the past century or so was the development of an ability to simulate that increase and the relative contributions of the various climate forcings (aerosols, solar radiance, greenhouse gas concentrations) to observed climate change (e.g. Stott et al. 2001). Thus the causes of global climate change were able to be identified, through the process of detection and attribution.

Recent improvements in climate model simulations of tropical cyclones have the same potential to resolve arguments about the causes of observed trends in tropical cyclone characteristics, provided of course that there is agreement on the magnitude and direction of observed trends. Leaving aside the question of observed trends for the moment, this article focuses on recent developments in tropical cyclone climate models.

2 Tropical Cyclones as Simulated by Climate Models

2.1 Current-Climate Simulation

A recent review of the quality of tropical cyclone simulation in climate models is contained in Walsh (2008). In a nutshell, this paper concluded that the simulation of tropical cyclone formation and tracks by the best climate models is reasonable. In contrast, the simulation of tropical cyclone intensity distributions is inadequate, largely as a result of coarse resolution. While the simulation of tropical cyclone formation and tracks does not depend so much on model resolution as intensity does, there is still considerable room for improvement in climate model simulations of these variables. This is important as there have been observed trends in tropical cyclone formation that are less controversial than trends in observed wind speeds (e.g. Kossin et al. 2007). Thus climate models used for attribution studies need the best possible simulation of these trends that can be obtained.

Recent climate models have continued to demonstrate improvement in their ability to simulate tropical cyclones. In particular, Knutson et al. (2008) employ a regional climate model of 18 km resolution to demonstrate an excellent ability to simulate the year-to-year variations of tropical cyclone formation in the Atlantic basin, when forced with NCEP reanalyses. This model uses a form of internal nudging to ensure that the larger scale features of the regional model solution in the interior of the domain remain similar to the large-scale forcing outside of the domain. The regional climate model study of Semmler et al. (2008) employed a resolution of 28 km over an Atlantic domain, giving a good simulation of both the mean and the interannual variability of tropical cyclone formation in this basin. No internal nudging was used in this model simulation.

Global model simulations have also been improving. Bengtsson et al. (2007) used the ECHAM5 atmosphere-only model, run with observed interannually-varying sea surface temperatures, to generate large numbers of simulated tropical cyclones, although numbers were lower than observed in the Atlantic basin. Gualdi et al. (2008) used a T106 (about 125 km resolution) version of the SINTEX-G coupled ocean-atmosphere model and examined the tropical cyclone climatology. This model employs the mass flux convection scheme of Nordeng (1994), as adapted from the previous work of Tiedtke (1989). Numbers of tropical cyclones generated globally were less than observed but still good in the Atlantic region. The statistical-deterministic model of Emanuel et al. (2008) also generates reasonable numbers of storms in the Atlantic and has a good representation of the interannual variability of storm formation. The global 50 km resolution model of Zhao et al. (2010) used observed SSTs as a lower boundary condition, running four realisations of the period 1981–2005. The model produced realistic simulations of the observed trends in tropical cyclone frequency over that period of time, including the upward trend in numbers in the Atlantic basin. While correlations between simulated and observed interannual variation were good in the Atlantic, they were not as good in other tropical cyclone formation basins, with the Indian Ocean displaying a poor relationship. In all of these simulations, however, the simulated distribution of tropical cyclone intensity remains inadequate, with much fewer high-intensity storms simulated than observed.

As model resolution increases and experience is gained in constructing the best model formulation required to generate tropical cyclones, the simulation of tropical cyclone climatology will improve. But high-resolution global model runs remain very expensive, so most climate simulations during the next few years will continue to be of coarser resolution (100–200 km). It would be best if the climate model that is used for prediction of future global or regional temperature and precipitation also had a reasonable climatology of tropical cyclone formation, as this would demonstrate that the model is performing well at most spatial and time scales. Nevertheless, one issue that was identified by Walsh et al. (2007) was that many climate model studies of tropical cyclones had been performed to date but that almost all of them used different criteria to define a model-generated tropical cyclone. One way to circumvent this issue would be to define a simulated tropical cyclone in the same way that observed tropical cyclones are defined: by simply counting all of the storms that had 10 m wind speeds in excess of $17.5\,\mathrm{ms}^{-1}$ and had the warm core structure of tropical cyclones, similar to the method used by Zhao et al. (2010) for their 50 km resolution global model simulations. Even so, this is a very severe test for a climate model of coarser resolution, indeed an unfair test as it compares a model of limited resolution with reality, which has effectively unlimited resolution. Climate models are usually validated by comparing their performance against observations that have been degraded to a resolution similar to that of the model. Walsh et al. (2007) proposed the same process for tropical cyclone simulation: to degrade data from weak, observed tropical cyclones to the resolution of the climate model and determine what are their maximum wind speeds at that resolution. Additionally, this serves as a way of comparing the results of climate models running at slightly different resolutions. In this way, the native ability of the model to generate tropical cyclones is assessed in a resolution-appropriate fashion.

This was the philosophy behind the proposed Tropical Cyclone climate Model Intercomparison Project (TC-MIP).[1] Like all intercomparison projects, this project proposes and defines common metrics for the assessment of climate models of tropical cyclones (e.g. Camargo et al. 2007; Yokoi et al. 2009). Ideally, at this stage in the intercomparison project, it would be best if there were numerous recent high-resolution global model experiments that could all be analysed using consistent methodologies. Such model output does not yet exist, but the proposed CMIP5 archive may eventually provide such a resource. In the meantime, building on similar previous projects, we reanalyse the CMIP3 model output and some recent high-resolution climate models, using common metrics for all models, including two separate detection routines.

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[1] www.earthsci.unimelb.edu.au/∼kwalsh/tcmip_index.html

3 Model Description

The CMIP3 climate model archive (www-pcmdi.llnl.gov) was established to enable further analysis of output produced for the IPCC Fourth Assessment Report (IPCC 2007). The simulations analysed here are the climate of the twentieth century experiments (20c3 m), for the model years 1980–1999. In these runs, coupled ocean-atmosphere models are forced with the observed increase in greenhouse gas concentrations over the twentieth century. The models analysed (Table 1) have

Table 1 List of models analysed from CMIP3 archive. Resolution is in degrees

No.	Model	Institution	Resolution
1	BCCR-BCM2.0	Bjerknes Centre for Climate Research	2.8 × 2.8
2	CGCM3.1(T47)	Canadian Centre for Climate Modelling & Analysis	3.75 × 3.75
3	CGCM3.1(T63)	Canadian Centre for Climate Modelling & Analysis	2.8× 2.8
4	CNRM-CM3	Météo-France/Centre National de Recherches Météorologiques	2.8 × 2.8
5	CSIRO-Mk3.0	CSIRO Atmospheric Research	1.9 × 1.9
6	CSIRO-Mk3.5	CSIRO Atmospheric Research	1.9 × 1.9
7	GFDL-CM2.0	US Department of Commerce/NOAA/Geophysical Fluid Dynamics Laboratory	2.5 × 2.0
8	GFDL-CM2.1	US Department of Commerce/NOAA/Geophysical Fluid Dynamics Laboratory	2.5 × 2.0
9	GISS-AOM	NASA/Goddard Institute for Space Studies	4.0 × 3.0
10	GISS-EH	NASA/Goddard Institute for Space Studies	5.0 × 4.0
11	GISS-ER	NASA/Goddard Institute for Space Studies	5.0 × 4.0
12	FGOALS-g1.0	LASG/Institute of Atmospheric Physics	2.8 × 3.0
13	INM-CM3.0	Institute for Numerical Mathematics	5.0 × 4.0
14	IPSL-CM4	Institut Pierre Simon Laplace	3.75 × 2.5
15	MIROC3.2(hires)	University of Tokyo, National Institute for Environmental Studies, and JAMSTEC	1.1 × 1.1
16	MIROC3.2(medres)	University of Tokyo, National Institute for Environmental Studies, and JAMSTEC	2.8 × 2.8
17	ECHAM5/MPI-OM	Max Planck Institute for Meteorology	1.9 × 1.9
18	MRI-CGCM2.3.2	Meteorological Research Institute	2.8 × 2.8
19	NCAR-CCSM3	National Center for Atmospheric Research	1.4 × 1.4
20	NCAR-PCM1	National Center for Atmospheric Research	2.8 × 2.8
21	UKMO-HadCM3	Hadley Centre for Climate Prediction and Research/Met Office	3.75 × 2.5
22	UKMO-HadGEM1	Hadley Centre for Climate Prediction and Research/Met Office	1.9 × 1.25

a range of resolutions, from 1° × 1° to 5° × 4°. While none of these models have resolutions that are genuinely suitable for the generation of intense tropical cyclones, the techniques developed as part of this project for examining the interrelationships between model formulation, model large-scale climate and model generation of tropical cyclones are directly applicable to similar comparisons of the results of high-resolution models.

Two recent high-resolution models have been analysed using the TC-MIP common metrics. The MRI/JMA 20-km global mesh model (Mizuta et al. 2006) is run using a timeslice method for model years 1979–2003. The model is hydrostatic, with 60 vertical levels, uses a semi-Lagrangian time integration scheme and a prognostic Arakawa-Schubert cumulus convection scheme (Randall and Pan 1993). The CMCC-INGV model is a fully coupled general circulation model without flux adjustments using a T159 (about 80 Km) atmospheric component (Roeckner et al. 2003). The parameterization of convection is based on the mass flux concept (Tiedtke 1989), modified following Nordeng (1994). The global ocean model used is a 2° resolution global ocean model (Madec et al. 1998) with a meridional refinement near the equator, to 0.5°. The CMCC-INGV data used in this work are obtained running the model over the period 1970–1999 using twentieth century (20C3 M) atmospheric forcings as specified by the IPCC (http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php).

4 Methodology

4.1 Large-Scale Climate Variables

One of the primary goals of the intercomparison project is to identify relationships between simulated large-scale climate variables and simulated tropical cyclone formation. As part of the TC-MIP project, the following climate variables are examined, as they have been shown in previous observational studies to influence tropical cyclone formation and characteristics (e.g. intensity, size):

- Mean sea level pressure
- Precipitation
- Convective precipitation
- Sea surface temperature
- Maximum potential intensity
- Genesis potential index
- Relative humidity
- Wind shear
- Surface latent heat flux

The definition of most of these variables is self-explanatory, but explanation is needed of some of them. Convective precipitation is the model's estimate of that portion of the precipitation that is convective rather than stratiform. Numerous observations had shown that the presence of persistent deep convection is a prerequisite for tropical cyclone formation (e.g. McBride 1995). It is recognized, though, that the quality of model simulation of this quantity varies greatly between models, as it is determined by the model's convective parameterisation. Maximum potential intensity (potential maximum wind speed and potential minimum pressure) is based on based the formulation of Bister and Emanuel (1998). The genesis potential index (GP) is that of Emanuel and Nolan (2004):

$$GPI = \left|10^5\,\eta\right|^{3/2}\left(\frac{\mathrm{H}}{50}\right)^3\left(\frac{V_{pot}}{70}\right)^3\left(1+0.1\,\mathrm{V}_{shear}\right)^{-2}$$

where η is the absolute vorticity at 850 hPa in s^{-1}, H is the relative humidity at 700 hPa in percent, V_{pot} is the potential maximum wind speed in metres per second and V_{shear} is the magnitude of the vertical wind shear between 850 and 200 hPa, also in metres per second.

Not all of these variables will be discussed in this chapter, as a full analysis of the interrelationships has yet to be performed. This chapter will focus on the relationship between the genesis potential and model-generated tropical cyclone formation, as the GP includes several of the large-scale variables analysed.

4.2 Detection of Tropical Cyclones in Model Output

Two detection methods are used for the identification of tropical cyclones in the climate model output. The CSIRO detection scheme (Walsh et al. 2007) defines a low-level wind speed threshold for tropical cyclone identification that is resolution-dependent. The resolution-dependent thresholds are derived from the maximum 10 m winds seen in high-resolution analyses of weak tropical cyclones that are degraded to various coarser resolutions. In this way, the output of a coarser-resolution model is compared with reality degraded to the same resolution. For models of horizontal resolution finer than about 30 km, the detection threshold becomes the same as the observed definition: 17.5 m s^{-1} wind speeds at a height of 10 m. At a climate model resolution of 200 km, the threshold becomes about 13 m s^{-1}. The advantage of this scheme is that enables the results of climate models of different resolutions to be compared. A disadvantage is that it does not account for the non-linear interaction inherent in climate models between resolution and storm development.

In addition, the detection scheme of Camargo and Zebiak (2002) was employed. In this scheme, joint probability distribution functions of quantities important for tropical cyclone detection, such as low-level vorticity, are constructed for each tropical cyclone formation basin. Based on these probability distributions, tropical cyclones are declared to be those lows that have values of these quantities in excess of a pre-defined statistical threshold. The advantage of this scheme is that it partially corrects for model biases and thus gives a better indication of the pattern of model formation in regions where storms might be weak, while still giving an indication of

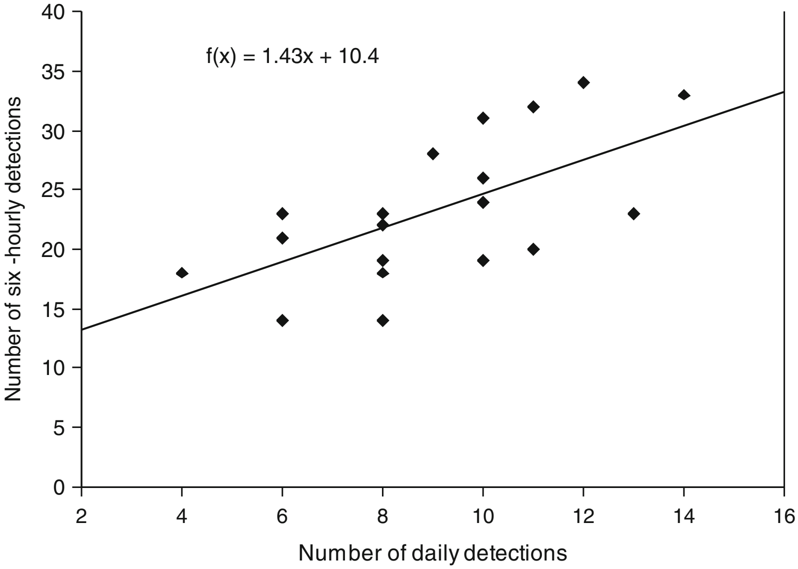

Fig. 1 Comparison of number of detections from four-times daily NCEP-2 reanalyses versus detectionsfrom the same data daily averaged. Only one detection per individual storm track is made

the differences in formation rates between basins. A disadvantage is that because the thresholds vary between basins and between models, it becomes harder to compare model results using this scheme.

One issue that needs to be addressed for this type of scheme is that the CMIP3 archive consists almost entirely of daily-average data rather than instantaneous fields. This causes tropical cyclones in the models to be smeared over an area rather than detected at a specific location. For example, Fig. 1 shows a comparison between detection of storms using the CSIRO detection scheme for four times daily instantaneous NCEP-2 reanalyses versus the same data daily averaged. Only one count per individual storm track is made so that a direct comparison can be made between formation rates in the two datasets. It is clear that applying the CSIRO detection scheme to daily average data results, as expected, in a considerable undercount of detections. Thus as an approximate correction for this effect, we multiply detected numbers of storms in the daily-average data using the CSIRO detection scheme by a factor of 2.5, commensurate with the relationship shown in Fig. 1. This approximate factor has been chosen because the linear relationship shown in Fig. 1 cannot be used precisely, as it implies that zero daily detections must be accompanied by roughly ten 6-h detections, which is unphysical.

5 Results

5.1 CMIP3 Model Output

5.1.1 Large-Scale Fields: Emanuel Genesis Parameter

Figure 2 shows a compilation of genesis parameter results, for January–March (Fig. 2a) and July–September (Fig. 2b), with models arranged down the page from highest to lowest resolution. For January–March (Fig. 1a), almost all models display higher GP than derived from the NCEP-2 reanalysis (top figure). Further analysis of the reasons for this systematic model bias indicate that almost all models have higher 700 hPa relative humidity values than observed in a broad band across the regions close to the location of the monsoonal trough. Since the GP is related to the cube of the relative humidity, this largely explains the overestimate in almost every model of the NCEP-based GP.

The reasons for this bias are unclear at this time. The representation of the boundary-layer physics in a model with relatively coarse vertical resolution is necessarily fairly crude, and it is possible that this leads to an excessive vertical transport of moisture in these models, particularly in the tropics. Alternatively, there may be a systematic dry bias in the NCEP-2 reanalysis over the monsoon trough regions. Trenberth (2005) note that the precipitable water content in the NCEP-2 reanalysis over the tropics is dry compared with the ERA-40 reanalysis, and also dry compared with RSS SSM/I data. In general, the spatial pattern of the GP produced by the higher-resolution models is mostly superior to that produced by the lower-resolution models. Calculations of GP using the ERA-40 given a much better agreement with model-simulated GP (not shown).

Figure 2b shows similar results for July–September. Once again, the GP shows general higher values than those derived from the NCEP reanalysis.

5.1.2 Comparison Between Results of Two Detection Schemes

Figure 3 shows a comparison between the two detection schemes. Tropical cyclone formation for the months January–March, from the IBtracs best track data (Knapp et al. 2009) (top), and from the CSIRO Mk3.5 model output for the CSIRO detection scheme (middle) and basin-dependent detection scheme. The best track data shows the well-known pattern of observed tropical cyclone in the Southern Hemisphere summer months: maximum formation occurs in regions off the northeast and northwest coasts of Australia and east of Madagascar. The CSIRO detection scheme shows that the CSIRO Mk 3.5 model appears to be simulating about the correct number of formations, although the pattern of formation has some deficiencies: there is little formation in the eastern South Pacific region, for instance. Comparing these detections to those determined using the basin-dependent detection scheme, the patterns are similar. A small amount of formation that is not observed is indicated

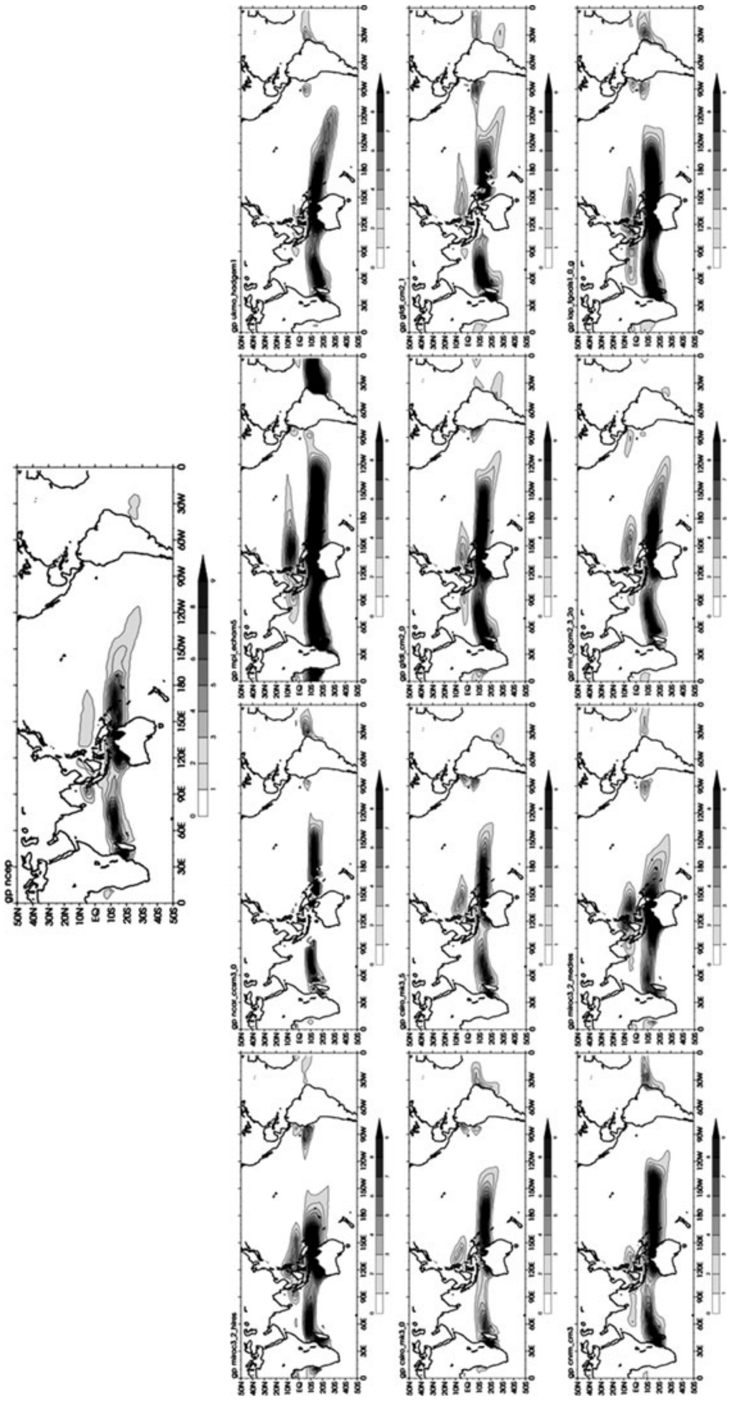

Fig. 2a Emanuel genesis parameter fields for higher-resolution CMIP3 models, January–March. Formation rate is per 2.5° × 2.5° grid box per 20 years

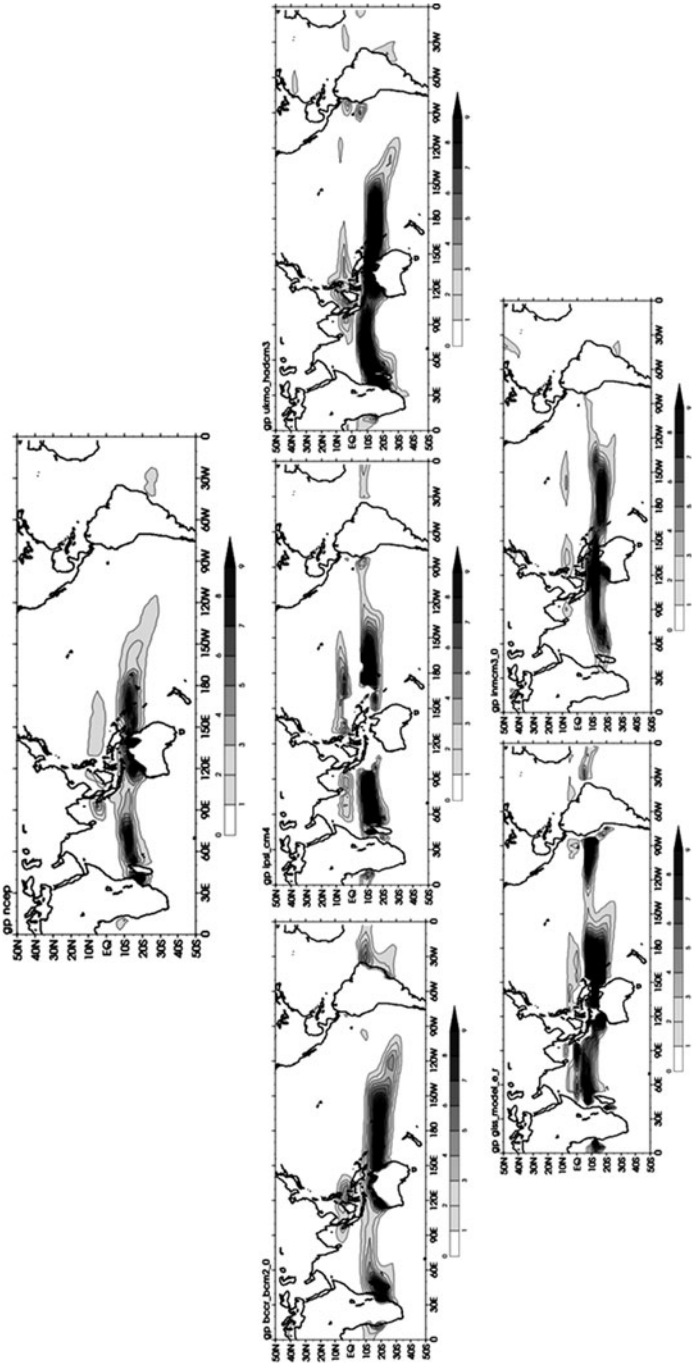

Fig. 2a (continued) For lower-resolution models

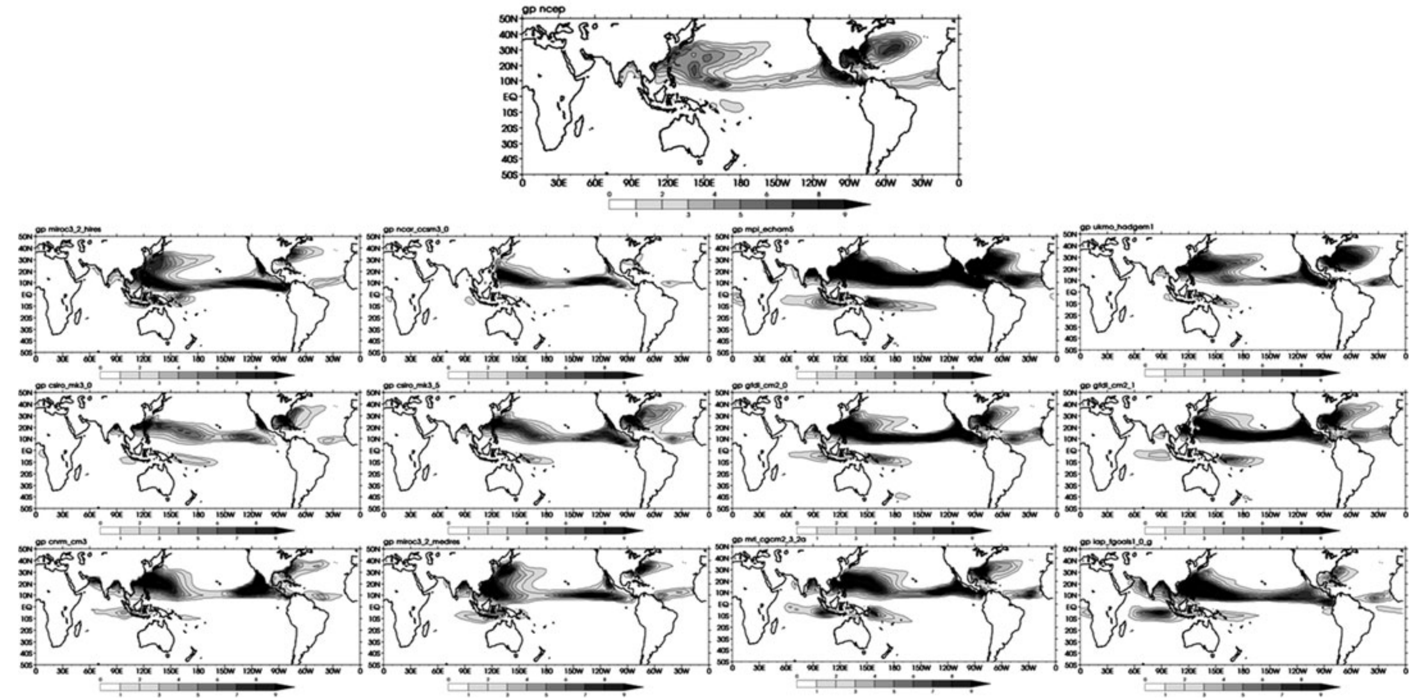

Fig. 2b The same as Fig. 2a for July–September

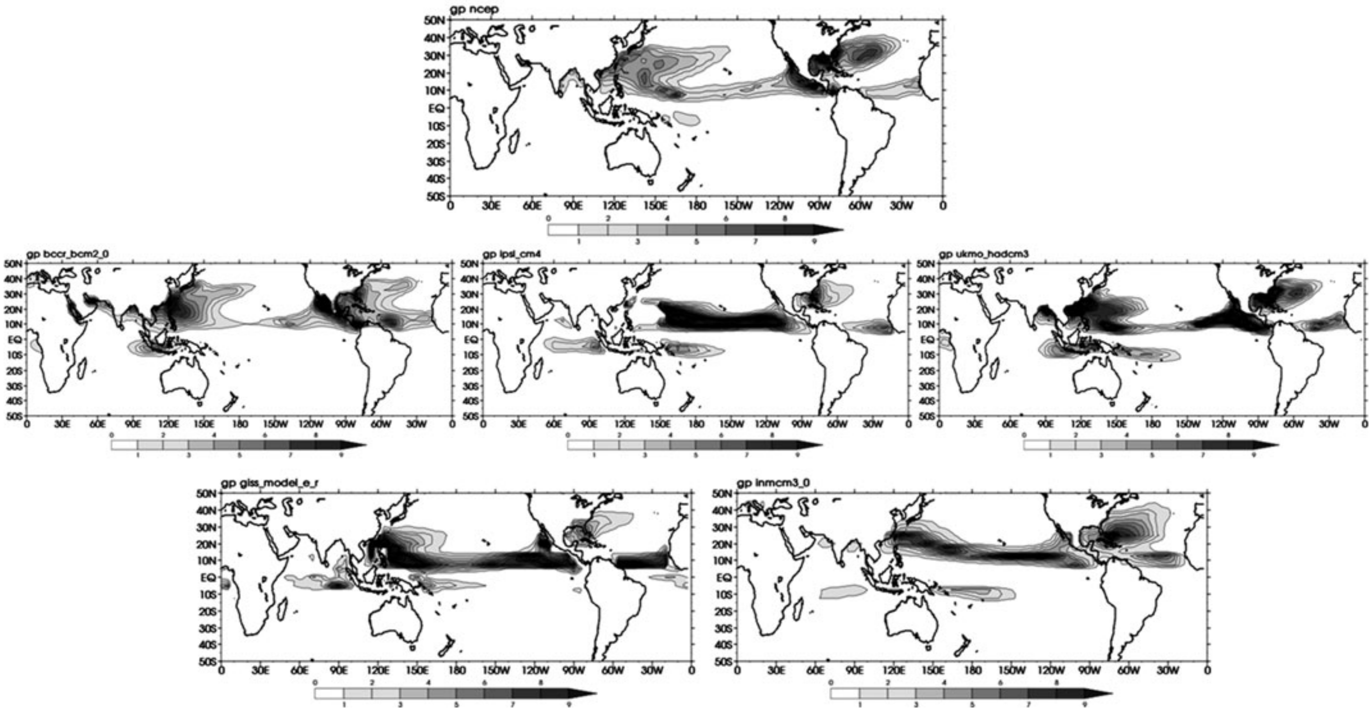

Fig. 2b (continued)

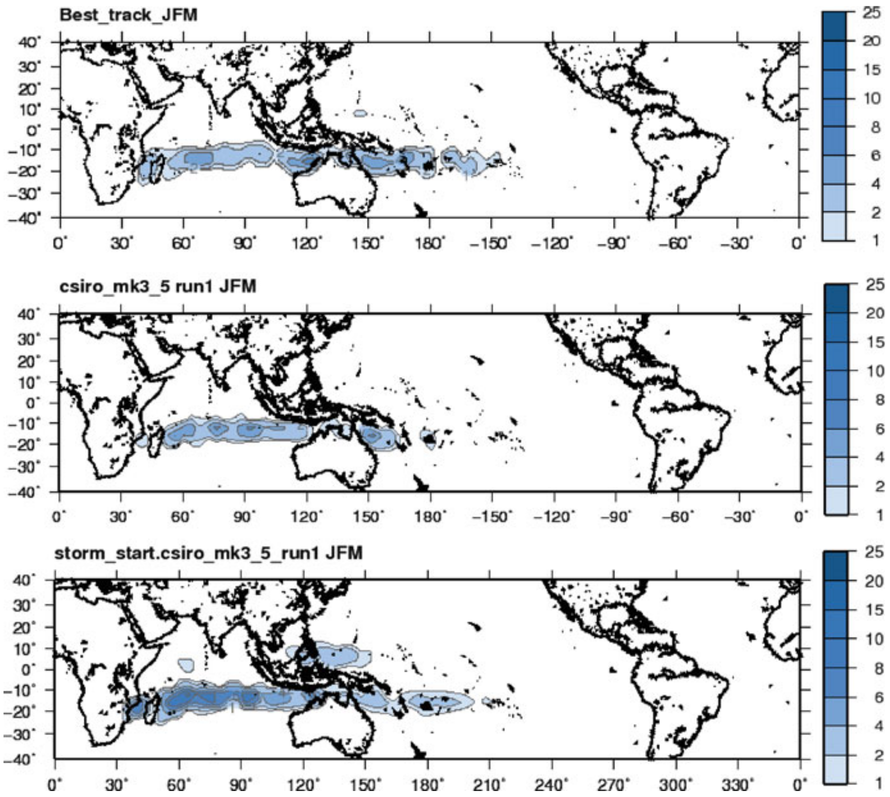

Fig. 3 Global tropical cyclone genesis for JFM from (*top*) IBTracs best track data; and as generated by the CMIP3 CSIRO Mk 3.5 data from (*middle*) the CSIRO detection scheme; and (*bottom*) the basin-dependent detection scheme. Formation rate is per 2.5° × 2.5° grid box per 20 years

in the basin-dependent scheme in the north Indian Ocean. The differences between the results from the two schemes are partly due to the higher sensitivity of the basin-dependent scheme; further analysis of the CSIRO detection results indicates that it also detects some formation in the north Indian Ocean, but at a lower rate.

5.1.3 PCMDI Model Tropical Cyclone Generation

Results using the CSIRO detection scheme from those higher-resolution PCMDI models that have sufficient daily data to enable tropical cyclone detection are shown in Figs. 4 and 5. In general, results from lower-resolution models tend to be poorer (not shown). Figure 4 shows results for January–March. The same arrangement of models is made as for the GP results of Fig. 1. Comparing Fig. 1 to Figs. 4 and 5, there appears to be little relationship between the GP and the actual rate of model

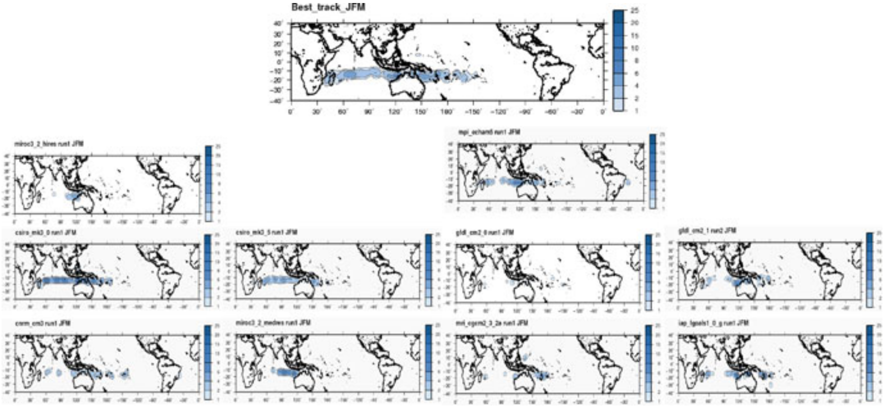

Fig. 4 Detected model tropical cyclone formation rate using the CSIRO detection scheme, for January–March. Units are the same as Fig. 1 (higher resolution models only)

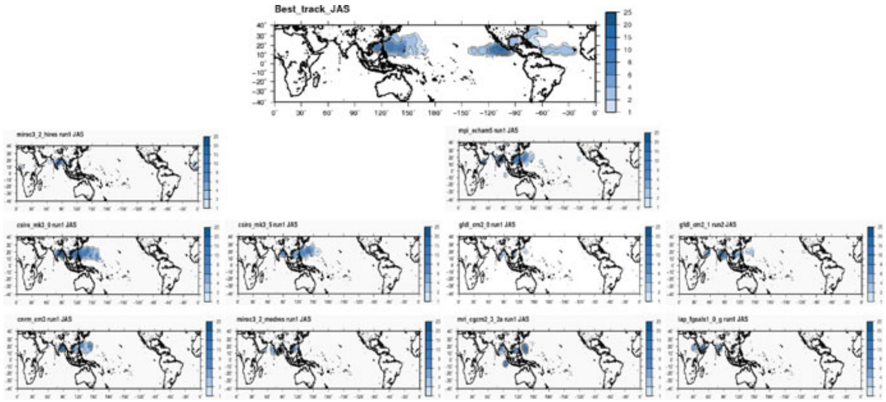

Fig. 5 The same as Fig. 4 but for July–September

formation of storms. For example, the ECHAM5 model (second row, third from the left) has a very large value of GP, but the formation rate is not that high. In contrast, the CSIRO models (third row) have a more realistic GP and a relatively realistic formation rate. Both Camargo et al. (2007) and Yokoi et al. (2009) also found little relationship between the GP and tropical cyclone formation. There are a priori reasons to believe why these relationships might differ from model to model. For instance, models have different representations of horizontal diffusion and diffusive processes that are either explicitly specified in their dynamical formulation or implicit in that formulation – for instance, a model that employs semi-Lagrangian advection has an inherently more diffusive structure than one that uses a more explicit advection scheme. Part of the process of model intercomparison is identifying such model-dependent issues as a way of making recommendations for improvements in model formulation.

The results of Figs. 4 and 5 show that there are substantial differences between the formation rates of cyclones from model to model. There appears to be a slight tendency for lower-resolution models to have lower rates of formation, but this is certainly not systematic: for instance, the MIROC high-resolution model has relatively low rates of cyclone formation despite it being the highest resolution model in the PCMDI suite. A comparison of Figs. 4 and 5 shows that formation rates are consistent from model to model despite the different season: if a model has a larger formation rate in one season than other models, it also has a larger formation rate in the other season.

Some systematic biases are evident in cyclone formation common across most models. For instance, Fig. 5 shows that there is little formation in any model in the Atlantic basin in June–September, even in models like the CSIRO models that have considerable formation in other tropical cyclone basins. The observed formation rate in the Atlantic is consistently lower than in the northeast and northwest Pacific, suggesting that this could be a threshold effect: it can be argued that because the North Atlantic is the only tropical cyclone basin not associated with a monsoon trough, and because the seasonal mean flow has a westerly vertical shear, formation of tropical cyclones is inherently more difficult in the Atlantic (McBride 1995). Thus, in coarse-resolution models, few (or none) are formed. Certainly, finer-resolution models implemented in the Atlantic have little difficulty in generating tropical cyclones (e.g. Knutson et al. 2008), although as discussed later, this is not solely a function of resolution.

6 High-Resolution Global Model Output

Some preliminary results have been obtained from high-resolution model output. The JMA-GSM 20-km global mesh model and the CMCC-INGV 80-km GCM results are shown in Figs. 6 and 7. Both models appear to have a good pattern of cyclone formation compared with observations, although both also have fewer

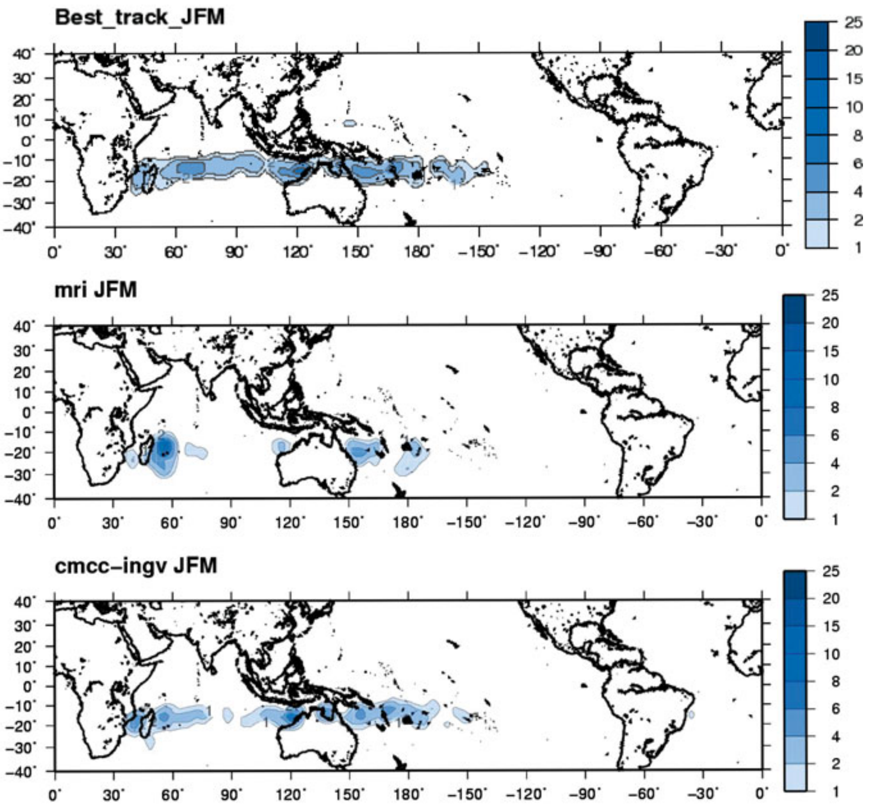

Fig. 6 The same as Fig. 3 for (*top*) the MRI model and (*bottom*) the CMCC-INGV model as described in the text, using the CSIRO detection scheme

than observed tropical cyclone formations. Again, neither model simulates sufficient storm formation in the Atlantic. In the case of the results from the MRI model, it is believed that the specification of the convection scheme in the model is causing the number of tropical cyclones to be less than observed (H. Murakami, 2009, personal communication). For the CMCC-INGV model, the data analysed here are daily average data, which as Fig. 1 shows would lead to an underestimate by at least a factor of 2 on average in the number of detected storms. More recent analysis of the CMCC-INGV model output is shown in Fig. 8, where four-times daily data were analysed. The number of storms generated in the Atlantic basin is considerably larger than in the daily average data, although still less than observed. Numbers in most other basins are good, however.