

# Changes in the Tropical Cyclone Genesis Potential Index over the Western North Pacific in the SRES A2 Scenario

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## ABSTRACT

The Tropical Cyclone Genesis Potential Index (GPI) was employed to investigate possible impacts of global warming on tropical cyclone genesis over the western North Pacific (WNP). The outputs of 20th century climate simulation by eighteen GCMs were used to evaluate the models' ability to reproduce tropical cyclone genesis via the GPI. The GCMs were found in general to reasonably reproduce the observed spatial distribution of genesis. Some of the models also showed ability in capturing observed temporal variation. Based on the evaluation, the models (CGCM3.1-T47 and IPSL-CM4) found to perform best when reproducing both spatial and temporal features were chosen to project future GPI. Results show that both of these models project an upward trend of the GPI under the SRES A2 scenario, however the rate of increase differs between them.

**Key words:** Genesis Potential Index, tropical cyclone, western North Pacific, global warming, SRES A2

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## 1. Introduction

Tropical cyclones are a type of natural disaster, bringing violent weather such as very strong winds, heavy thunderstorms, and torrential rain. When a tropical cyclone affects China, it will usually have originated from the western North Pacific (WNP), the most active area for these phenomena. The combined effects of increasing population, increasing urbanization, and the occurrence of tropical cyclones have caused a marked rise in human and economic damage to many coastal areas. Therefore, it is of great interest and societal importance to understand how tropical cyclones are affected by climate change.

A series of studies have investigated tropical cyclone and climate change connections from an observational perspective (Chan and Liu, 2004; Emanuel, 2005; Webster et al., 2005; Fan, 2007a, b; Shepherd and Knutson, 2007; Zhou and Cui, 2008; Zhou et al., 2008; Chen, 2009). However, due to a lack of long-term and reliable data, some of the results from these analyses have proven to be controversial.

Meanwhile, many studies have used climate models to study the issue. There are two main techniques for diagnosing tropical cyclone activity in climate models. The first is to detect the location and track of individual tropical-cyclone-like vortices in a model's output (Haarsma et al., 1993; Bengtsson et

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al., 1995; Walsh and Watterson, 1997; Camargo and Zebiak, 2002; Chauvin et al., 2006; Oouchi et al., 2006; Bengtsson et al., 2007). Usually, a series of dynamical and thermodynamical criteria are settled based on observed climatology. A simulated tropical cyclone is defined if the relevant variables exceed the threshold. For most current GCMs, the resolution is not sufficient to capture the dynamics of tropical cyclones. Therefore, in some studies, downscaling has been used as an approach to obtain reasonable results (Emanuel et al., 2008; Knutson et al., 2008). The second technique is to provide an estimate of tropical cyclone activity through large-scale environmental factors (Gray, 1979; Ryan et al., 1992; Watterson et al., 1995; Royer et al., 1998; Emanuel and Nolan, 2004). Most state-of-the-art GCMs can provide a reasonable reproduction of large-scale features of past and present climate, although they do not tend to have sufficient resolution to resolve the dynamics in the tropical cyclone. Thus far, a quantitative theory describing how large-scale features affect tropical cyclone activity is still lacking, while empirical methods have been proven to be useful approaches in some studies (Camargo et al., 2007a, b; Caron and Jones, 2008).

Gray (1979) developed an empirical tropical cyclone genesis index which can present a reasonable description of the seasonal and spatial variation of tropical cyclone genesis. However, it has been pointed out in a number of other works that the index may be not appropriate for climate change studies, since a specific threshold for thermodynamic conditions according to present climate is used (Ryan et al., 1992; Royer et al., 1998). Royer et al. (1998) improved the index by replacing the SST threshold with convective potential, which can avoid the use of parameters that might not be suitable to future climate. Caron and Jones (2008) evaluated both the original and modified index using ERA-40 data and found that both indices can obtain a reasonable global number and spatial distribution of implied tropical cyclones compared to observations. The authors also estimated the index using outputs from the World Climate Research Programme's (WCRP) Coupled Model Intercomparison Project Phase 3 (CMIP3) dataset. The modified index in a nine-model ensemble showed an increase in all the scenarios over the WNP.

Emanuel and Nolan (2004) developed another empirical index, the Genesis Potential Index (GPI), to relate tropical cyclone genesis to several large-scale environmental factors. This index has similar factors to those in Gray's index, such as wind shear and mid-tropospheric relative humidity, but with a large difference in the thermodynamic variable. The GPI uses potential intensity, which depends on the air-sea thermo-

dynamic disequilibrium and the difference between the SST and the temperature at the level of neutral buoyancy for an adiabatically lifted boundary layer parcel. Since the parameters that might be specific to present climate are avoided in developing the index, the GPI is suitable to climate change studies. Indeed, the index has been applied to reanalysis and output from climate models, with results showing that it can replicate observed seasonal variations and the location of genesis in several basins, and that there is an increase of the GPI in general over the WNP under global warming circumstance (Camargo et al., 2007a, b; Vecchi and Soden, 2007; Gualdi et al., 2008).

In this study, with a focus on the WNP ( $0^{\circ}$ – $40^{\circ}$ N,  $100^{\circ}$ – $180^{\circ}$ E), the GPI was used to diagnose tropical cyclone genesis in WCRP-CMIP3 GCMs, and further to investigate the impact of global warming on tropical cyclone genesis. Before using the index to project future tropical cyclone genesis, the ability of the GPI itself and the GCMs to reproduce the observed spatial and temporal variation was evaluated by ERA-40 reanalysis dataset and outputs from the GCMs. The models with the best performance could then be chosen to project future GPI.

## 2. Method and data

The definition of the GPI is as follows:

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

where  $\eta$  is the absolute vorticity at 850 hPa ( $\text{s}^{-1}$ ),  $H$  is the relative humidity at 600 hPa (%),  $V_{\text{pot}}$  is the potential intensity ( $\text{m s}^{-1}$ ), and  $V_{\text{shear}}$  is the magnitude of the vertical wind shear between 850 hPa and 200 hPa ( $\text{m s}^{-1}$ ). The technique used to calculate potential intensity was a generalization of that described in Emanuel (1995) to take into account dissipative heating (Bister and Emanuel, 1998), in addition to sea surface temperature, sea level pressure, and atmospheric temperature and mixing ratio, at various pressure levels. More detailed information about the index can be found in Emanuel and Nolan (2004) and Camargo et al. (2007a, b).

In this paper, the observed GPI was calculated from the ERA-40 reanalysis dataset (Uppala et al., 2005) and the second Hadley Centre Sea Surface Temperature (HadSST2) dataset (Rayner et al., 2006). The observed cyclone genesis events, taken from the Joint Typhoon Warning Center (JTWC) best track dataset, were used to estimate the GPI's ability at de-

**Table 1.** Selected model features. Partly extracted from Randall et al. (2007) (Table 8.1).

Model ID, Year	Atmosphere Top, Resolution, References	Ocean Resolution, Z Coordinate, Top BC References	Coupling Flux Adjustments, References
BCCR-BCM2.0, 2005	top=10 hPa, T63 ( $1.9^\circ \times 1.9^\circ$ ) L31, (Déqué et al., 1994)	$(0.5^\circ - 1.5^\circ) \times 1.5^\circ$ L35, density, free surface, (Bleck et al., 1992)	no adjustments, (Furevik et al., 2003)
CCSM3, 2005	top=2.2 hPa, T85 ( $1.4^\circ \times 1.4^\circ$ ) L26, (Collins et al., 2004)	$(0.3^\circ - 1^\circ) \times 1^\circ$ L40, depth, free surface, (Smith and Gent, 2002)	no adjustments, (Collins et al., 2006)
CGCM3.1(T47), 2005	top=1 hPa, T47 ( $\sim 2.8^\circ \times 2.8^\circ$ ) L31, (McFarlane et al., 1992; Flato, 2005)	$1.9^\circ \times 1.9^\circ$ L29, depth, rigid lid, (Pacanowski et al., 1993)	heat, freshwater, (Flato, 2005)
CNRM-CM3, 2004	top=0.05 hPa, T63 ( $\sim 1.9^\circ \times 1.9^\circ$ ) L45, (Déqué et al., 1994)	$(0.5^\circ - 2^\circ) \times 2^\circ$ L31, depth, rigid lid, (Madec et al., 1998)	no adjustments, (Terray et al., 1998)
CSIRO-MK3.0, 2001	top=4.5 hPa, T63 ( $\sim 1.9^\circ \times 1.9^\circ$ ) L18, (Gordon et al., 2002)	$(0.8^\circ \times 1.9^\circ)$ L31, depth, rigid lid, (Gordon et al., 2002)	no adjustments, (Gordon et al., 2002)
CSIRO-MK3.5, 2006	top=4.5 hPa, T63 ( $\sim 1.9^\circ \times 1.9^\circ$ ) L18, (Gordon et al., 2002)	$(0.8^\circ \times 1.9^\circ)$ L31, depth, rigid lid, (Gordon et al., 2002)	no adjustments, (Gordon et al., 2002)
ECHAM5/MPI-OM, 2005	top=10 hPa, T63 ( $\sim 1.9^\circ \times 1.9^\circ$ ) L31, (Roeckner et al., 2003)	$(1.5^\circ \times 1.5^\circ)$ L40, depth, free surface, (Marsland et al., 2003)	no adjustments, (Jungclaus et al., 2005)
GFDL-CM2.0, 2005	top=3 hPa, $2.0^\circ \times 2.5^\circ$ L24, (GFDL GAMDT, 2004)	$(0.3^\circ - 1.0^\circ) \times 1.0^\circ$ , depth, free surface, (Gnanadesikan et al., 2004)	no adjustments, (Delworth et al., 2006)
GFDL-CM2.1, 2005	top=3 hPa, $(2.0^\circ \times 2.5^\circ)$ L24, with semi-Lagrangian transports (GFDL GAMDT, 2004)	$(0.3^\circ - 1.0^\circ) \times 1.0^\circ$ , depth, free surface,	no adjustments, (Delworth et al., 2006)
GISS-ER, 2004	top=0.1 hPa, $(4^\circ \times 5^\circ)$ L20, (Schmidt et al., 2006)	$(4^\circ \times 5^\circ)$ L13, mass/area, free surface, (Russell et al., 1995)	no adjustments, (Schmidt et al., 2006)
INGV-SXG, 2005	top=10 hPa, T106 ( $\sim 1.125^\circ \times 1.125^\circ$ ) L19, (Roeckner et al., 1996)	$(0.5^\circ - 2^\circ) \times 2^\circ$ L31, depth, free surface, (Madec et al., 1999)	no adjustment, (Valcke et al., 2000)
INM-CM3.0, 2004	top=10 hPa, $(4^\circ \times 5^\circ)$ L21, (Alxeev et al., 1998; Galín et al., 2003)	$(2^\circ \times 2.5^\circ)$ L33, sigma, rigid lid, (Diansky et al., 2002)	regional freshwater, (Diansky and Volodin, 2002; Volodin and Diansky, 2004)
IPSL-CM4, 2005	top=4 hPa, $(2.5^\circ \times 3.75^\circ)$ L19, (Hourdin et al., 2006)	$(2^\circ \times 2^\circ)$ L31, depth, free surface, (Madec et al., 1998)	no adjustments, (Marti et al., 2005)
MIROC3.2(medres), 2004	Top=30 km, T42 ( $\sim 2.8^\circ \times 2.8^\circ$ ) L20, (K-1 Model Developers, 2004)	$(0.5^\circ - 1.4^\circ) \times 1.4^\circ$ L43, sigma/depth, free surface (K-1 Model Developers, 2004)	no adjustments, (K-1 Model Developers, 2004)
MRI-CGCM2.3.2, 2003	top=0.4 hPa, T42 ( $\sim 2.8^\circ \times 2.8^\circ$ ) L30, (Shibata et al., 1999)	$(0.5^\circ - 2.0^\circ) \times 2.5^\circ$ L23, depth, rigid lid, (Yukimoto et al., 2001)	heat, freshwater, momentum ( $12^\circ\text{S} - 12^\circ\text{N}$ ) (Yukimoto et al., 2001; Yukimoto and Noda, 2003)

**Table 1.** Continued.

Model ID, Vintage	Atmosphere Top Resolution References	Ocean Resolution Z Coord, Top BC References	Coupling Flux Adjustments References
PCM, 1998	top = 2.2 hPa, T42 ( $\sim 2.8^\circ \times 2.8^\circ$ ) L26, (Kiehl et al., 1998)	$0.5^\circ\text{--}0.7^\circ \times 1.1^\circ$ L40, depth, free surface, (Maltrud et al., 1998)	no adjustments, (Washington et al., 2000)
UKMO-HadCM3, 1997	top=5 hPa, $2.5^\circ \times 3.75^\circ$ L19, (Pope et al., 2000)	$1.25^\circ \times 1.25^\circ$ L20, depth, rigid lid, (Gordon et al., 2000)	no adjustments, (Gordon et al., 2000)
UKMO-HadGEM1, 2004	top=39.2 km, $\sim 1.3^\circ \times 1.9^\circ$ L38, (Martin et al., 2004)	$(0.3^\circ\text{--}1.0^\circ) \times 1.0^\circ$ L40, depth, free surface, (Roberts, 2004)	no adjustments, (Johns et al., 2006)

scribing the spatial and temporal features of cyclone genesis.

The output of “20th Century Climate in Coupled Models” (20C3M), a pilot project of CMIP, was used to estimate the ability of the GCMs to reproduce tropical cyclone genesis via the GPI. This project collects data from 20th century simulations from coupled ocean–atmosphere GCMs, driven by prescribed forcings such as increases in the atmospheric concentration of anthropogenic greenhouse gases and aerosols. The levels of these forcings are based on historical observations or reconstructions. The simulation started typically in the late 19th century and finished at the end of 20th century.

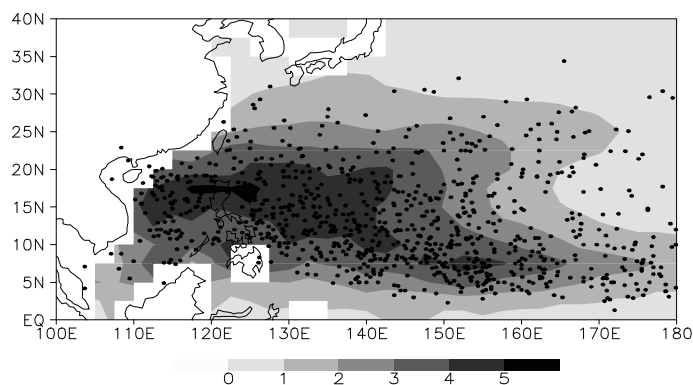
Forcings in the experiment employed in this study, as future climate realization under a background of global warming, were based on the A2 storyline in the IPCC’s Special Report on Emissions Scenarios (SRES) (Nakicenovic et al., 2000). Eighteen models were used: BCCR-BCM2.0, CCSM3, CGCM3.1-T47, CNRM-CM3, CSIRO-Mk3.0, CSIRO-Mk3.5, GFDL-CM2.0, GFDL-CM2.1, GISS-ER, INGV-SXG, INM-CM3.0, IPSL-CM4, MIROC3.2-M, MPI, MRI-CGCM2.3.2,

PCM, UKMO-HadCM3, and UKMO-HadGEM1. Table 1 lists the features of all these selected models. All the outputs of the models were taken from the WCRP-CMIP3 multi-model dataset (Meehl et al., 2007), and more detailed information about the models and experiments are available from [http://www-pcmdi.llnl.gov/ipcc/about\\_ipcc.php](http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php). Only one realization was selected from each of the model outputs.

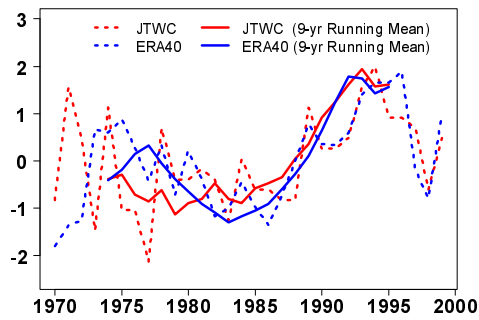
### 3. The GPI in the ERA-40 reanalysis

In this section, we describe how the JTWC best track data was used to validate the performance of the GPI in describing tropical cyclone genesis over the WNP. Different from previous studies which have used NCEP–NCAR reanalysis data (Camargo et al., 2007a, b), here, the ERA-40 reanalysis dataset was employed. Bearing in mind the quality of the observation dataset before the 1970s (Emanuel, 2005), and that the 20C3M simulations in some models end at 1999, the evaluation analysis period in this study was confined to 1970–1999.

The climatology of observed cyclone genesis and



**Fig. 1.** Observed GPI climatology estimated by ERA-40 (shaded) and tropical cyclone genesis events (black dots) during 1970–1999.



**Fig. 2.** Interannual and interdecadal (9-yr running mean) variation of the GPI and tropical cyclone genesis in the JTWC best track dataset. All time series are normalized. The GPI was averaged over ( $0^{\circ}$ – $40^{\circ}$ N,  $100^{\circ}$ – $180^{\circ}$ E).

the GPI over the WNP is displayed in Fig. 1. The climatological GPI was the composite of monthly mean GPI calculated from reanalysis data. The results show most of the tropical cyclones occurring over a zone between  $5^{\circ}$ – $30^{\circ}$ N, with a maximum centre over the region  $10^{\circ}$ – $20^{\circ}$ N,  $110^{\circ}$ – $160^{\circ}$ E. The distribution of the GPI shows a similar spatial pattern, with a relatively high GPI located over the middle of the tropical WNP, indicating that GPI can depict well the spatial distribution of observed tropical cyclone occurrence.

Figure 2 displays the interannual and interdecadal variation (9-yr running mean) of observed tropical cyclone genesis and area mean GPI over the WNP. As can be seen, the interannual variability of the GPI and observed tropical cyclone genesis show similar features. The correlation coefficient between them is 0.45, which is significant at the 95% confidence level. On the interdecadal timescale, the GPI exhibits a better performance, with the correlation coefficient up to 0.90. This indicates that the GPI can also reasonably infer the temporal characteristics of tropical cyclone genesis.

Therefore, in the following analysis, the GPI was chosen as a proxy index to investigate the ability of the climate models to simulate the WNP cyclone genesis, and further to project changes in WNP cyclone genesis under a background of global warming.

#### 4. The GPI in the 20C3M experiment

Confidence in the projection of future climate by models depends mainly on their ability to reproduce past and present climate. Therefore, the outputs of 20C3M simulations by eighteen GCMs from the WCRP-CMIP3 multi-model dataset were used to evaluate the performance of the models at describing present cyclone genesis. Since the resolution of the models are not identical, the model fields were inter-

polated to the same resolution as the ERA-40 dataset.

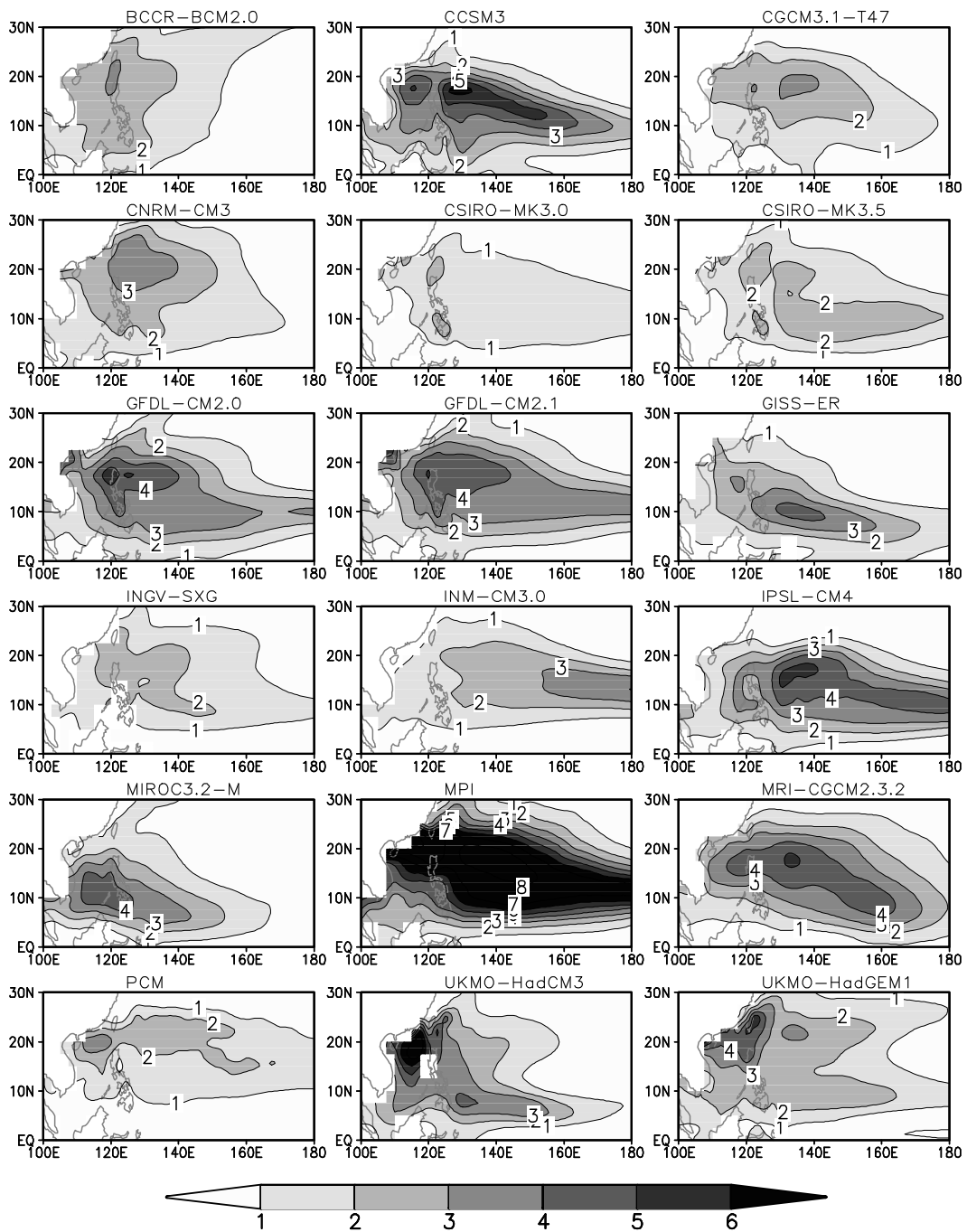
Figure 3 shows the climatology of the GPI in all eighteen GCMs during 1970–1999. For the spatial structure, most of the models could generally reproduce the distribution of tropical cyclone genesis over the WNP, as shown in Fig. 1. However, there are systematic biases in some of the models. For example, the maximum center in CNRM-CM3 and PCM shows a northward shift, and in INM-CM3 an eastward shift, as compared to the most active genesis area shown in Fig. 1. In addition, all of the models more or less underestimated the GPI compared to that estimated from the ERA-40 reanalysis data, except for the MPI model.

Interannual variation of the GPI in the eighteen GCMs is shown in Fig. 4. It can be seen that most of the models were poor at reproducing interannual variation of tropical cyclone genesis. Only CGCM3.1-T47 and IPSL-CM4 obtained a reasonable result. The year-to-year variation of the GPI in these two models was significantly correlated to that in observed data at the 95% confidence level. As shown in Fig. 5, some models showed much better performance on the interdecadal timescale, such as CGCM3.1-T47, CSIRO-Mk3.5, GFDL-CM2.1, INGV-SXG, IPSL-CM4, MRI-CGCM2.3.2, and UKMO-HadGEM1. The interdecadal variation in these models and that in the observed data was significantly correlated at the 95% confidence level. Among them, CGCM3.1-T47 and IPSL-CM4 showed the best performance. The interdecadal variation in these two models fitted observed results very well, with correlation coefficients of 0.91 and 0.88, respectively.

Taking into account spatial distribution, and interannual and interdecadal variation, two of the eighteen models, CGCM3.1-T47 and IPSL-CM4, showed the best performance. In order to reduce the uncertainty in projection, we therefore chose these two models to project future GPI under SRES A2.

#### 5. The GPI in the SRES A2 experiment

Figure 6 shows projected changes in the GPI during the 21st century in the SRES A2 experiment, relative to the 1980–1999 climatology in the 20C3M experiment. The results suggest that there might be a higher GPI over most of the WNP in the middle period of the 21st century (2041–2060) in CGCM3.1-T47. The largest increase would be over the area  $10^{\circ}$ – $20^{\circ}$ N, with the rate of increase being above 15%. The change projected to occur in the late 21st century (2081–2100) is similar to that in middle period of the 21st century, but with a larger increment. The change projected by IPSL-CM4 shows similar features. However, a de-

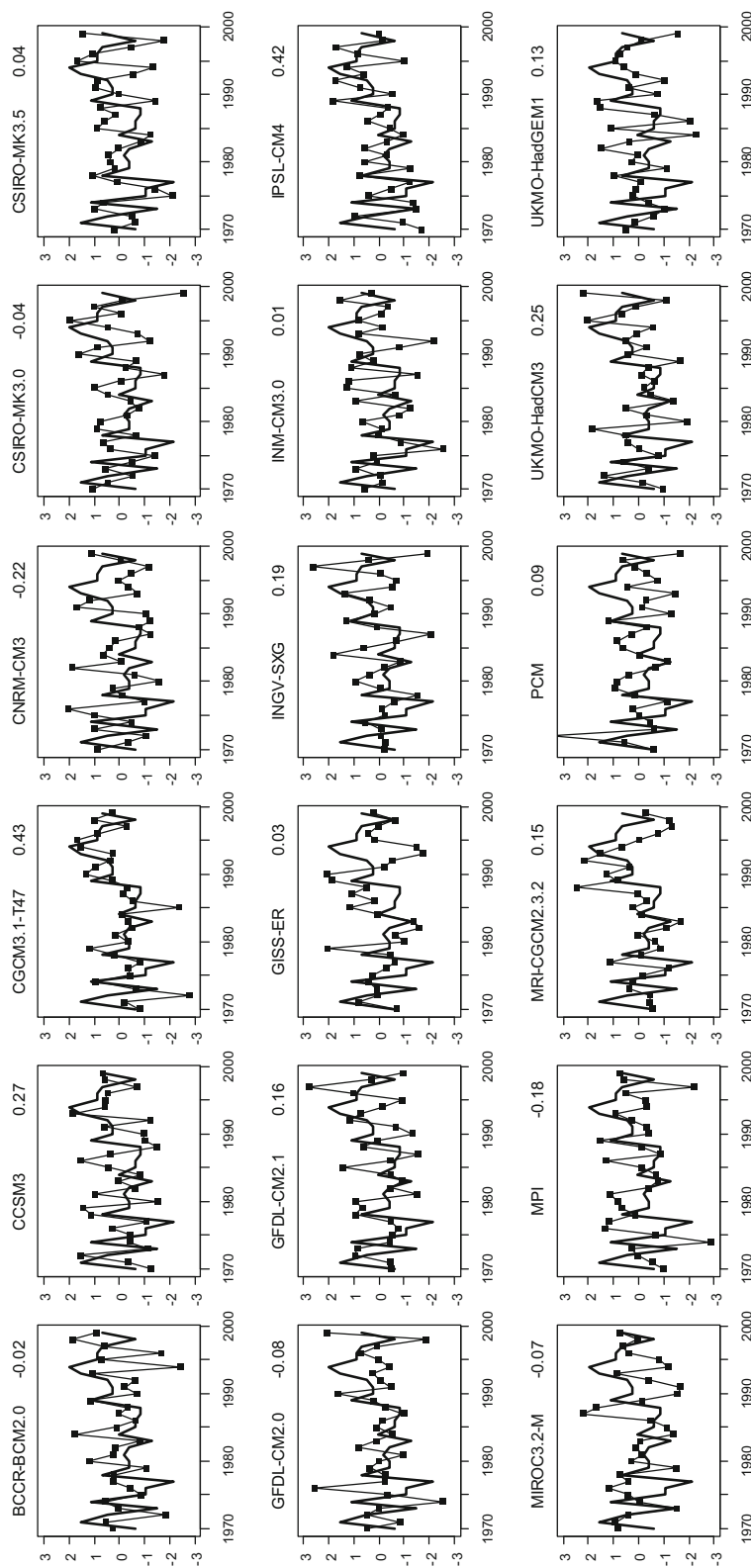


**Fig. 3.** Climatology of the GPI in 18 GCMs during 1970–1999 in the 20C3M simulation.

crease is found over the area south of 10°N, east of 135°E. The decrease is relatively weak and locates in the area south of 5°N in CGCM3.1-T47. These results indicate that there might be more tropical cyclones generated over the area north of 10°N, as inferred by the GPI under a background of global warming. However, there is relatively large uncertainty in projecting changes in the GPI over the area south of 10°N.

Interdecadal and interannual variations of the GPI

in the CGCM3.1-T47 and IPSL\_CM4 models are displayed in Fig. 7. The bold line indicates the 9-yr running mean. The results show an upward trend in both models, but the rate of increase differs between them. In CGCM3.1-T47, the rate of increase during 2041–2060 (2081–2100) is projected to be 13% (20%), compared to 1980–1999 climatology. Meanwhile, in IPSL\_CM4, the rate of increase during 2041–2060 (2081–2100) is predicted to be 7% (9%). These results indi-



**Fig. 4.** Interannual variation of the GPI during 1970–1999 in the 20C3M simulation. The lines with squares indicate outputs from the models, and bold lines show interannual variation of tropical cyclone genesis from the JTWC best track dataset. All time series are normalized. The number on top of each plot is the correlation of two time series. The GPI is averaged over (0°–40°N, 100°–180°E).

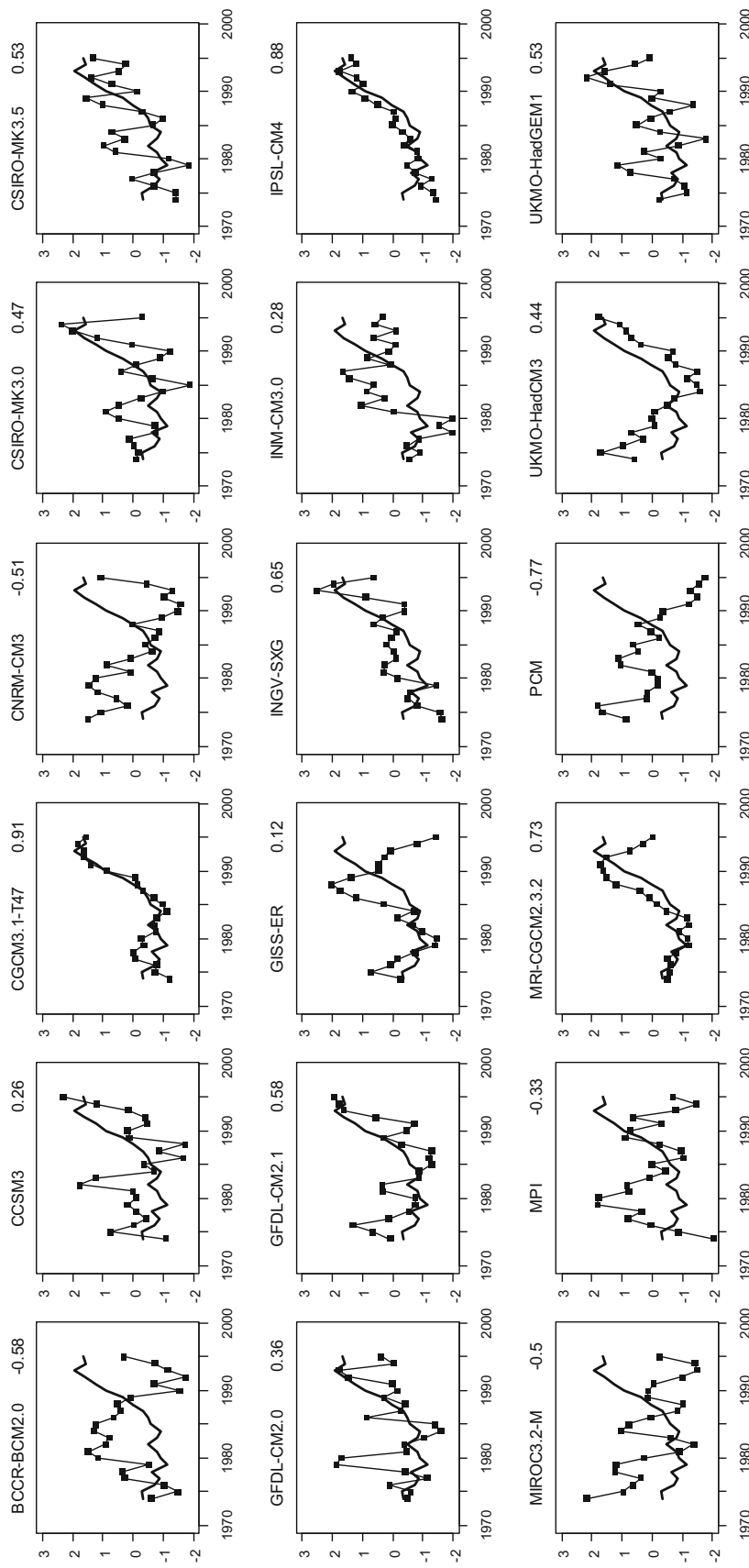
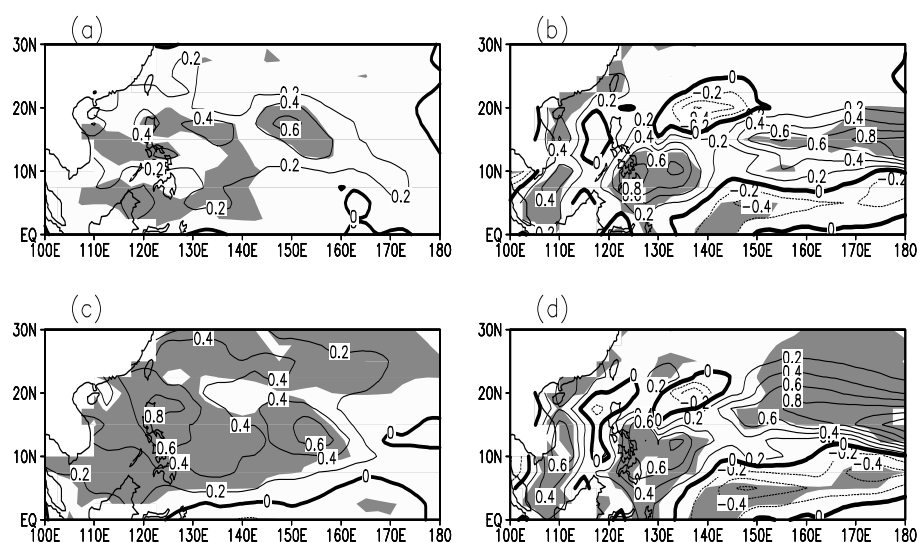
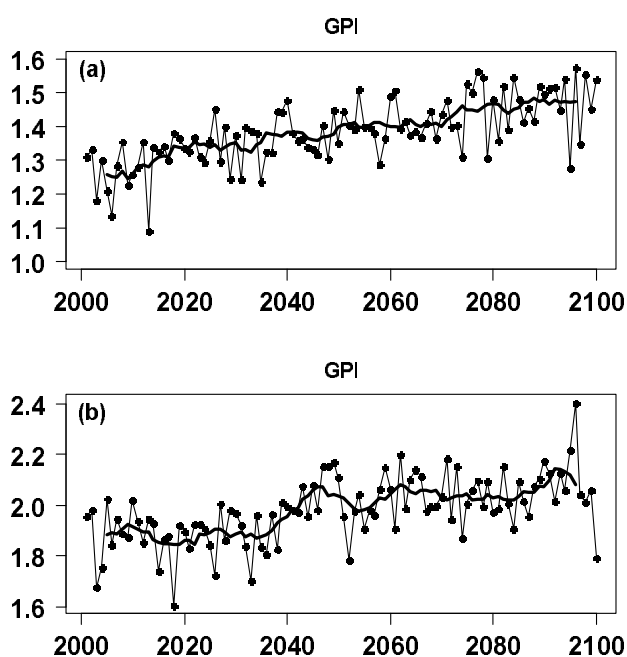


Fig. 5. Same as Fig. 4, but for interdecadal variation.





**Fig. 6.** Spatial distribution of change of the GPI in SRES A2 simulation: (a) Change in 2041–2060 climatology compared to 1980–1999 climatology in the 20C3M experiment in CGCM3.1-T47; (c) change in 2081–2100 climatology; (b) and (d) change in the GPI in IPSL-CM4. Shading denotes changes statistically significant at the 95% confidence level.



**Fig. 7.** Temporal variation of the GPI index during the 21st century in SRES A2 simulation. (a) and (b) show interannual and interdecadal variation of the GPI in CGCM3.1-T47 and IPSL-CM4, respectively. Bold lines indicate interdecadal variation. The GPI is averaged over ( $0^{\circ}$ – $40^{\circ}$ N,  $100^{\circ}$ – $180^{\circ}$ E).

cate that, as inferred by the GPI, tropical cyclone genesis could become more frequent over the WNP on the

whole, but there is large uncertainty in projecting the rate of increase.

Also analyzed were the possible changes in the four components of the GPI. Figures 8 and 9 show the annual mean of the four components [absolute vorticity parameter,  $|10^5\eta|^{3/2}$ ; relative humidity parameter,  $(H/50)^3$ ; potential intensity parameter,  $(V_{\text{pot}}/70)^3$ ; and wind shear parameter,  $(1 + 0.1V_{\text{shear}})^{-2}$ ] averaged over the area ( $0^{\circ}$ – $30^{\circ}$ N,  $100^{\circ}$ – $180^{\circ}$ E) during the 21st century in CGCM3.1-T47 and IPSL-CM4. The percentage change in the relative humidity parameter is projected to be 30% and 8% in the models at the end of the 21st century, while changes in the other parameters are not predicted to be larger than 5%. Therefore, through the above analysis, changes in the GPI are projected to be mainly attributable to changes in relative humidity, as compared to the other three factors.

## 6. Summary and discussion

In this study, an empirical index, the GPI, was used as a proxy index to project future tropical cyclone genesis by GCMs. Estimation of the GPI from ERA-40 reanalysis data showed that the GPI can capture the main characteristics of spatial distribution and temporal variation of genesis, as observed in the JTWC best track dataset, indicating that the index could be used to infer tropical cyclone genesis over the WNP. The GPI estimated by the output of the 20C3M simulation showed that the GCMs could generally reproduce

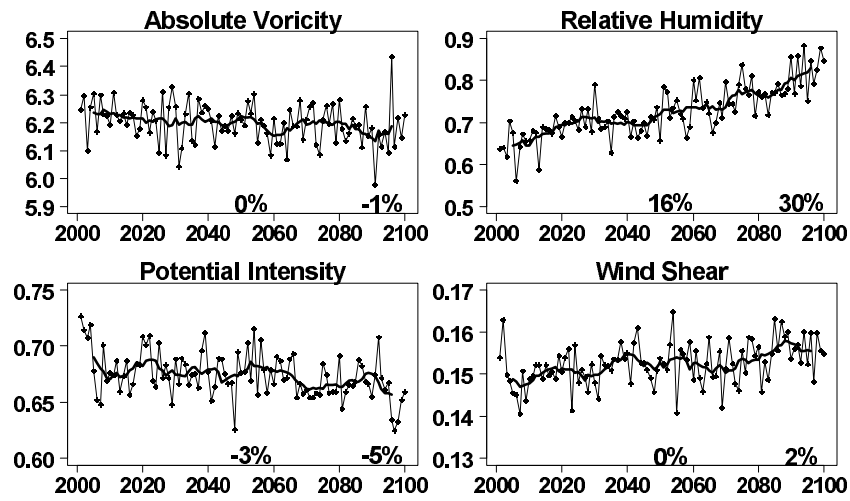


Fig. 8. Temporal variation of absolute vorticity parameter  $(|10^5 \eta|^{3/2})$ , relative humidity parameter  $[(\frac{H}{50})^3]$ , potential intensity parameter  $[(\frac{V_{pot}}{70})^3]$ , and wind shear parameter  $[(1 + 0.1V_{shear})^{-2}]$  in the CGCM3.1-T47 model. Numbers at the bottom of each plot indicate the rate of change during 2040–2059 and 2080–2099, compared to 1980–1999 climatology. All variables are averaged over  $(0^\circ-30^\circ N, 100^\circ-180^\circ E)$ .

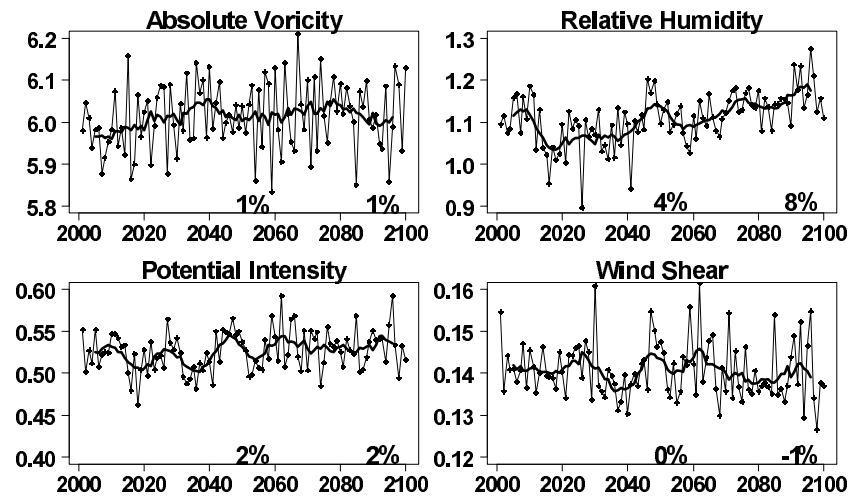


Fig. 9. Same as Fig. 8 but for the IPSL-CM4 model.

the spatial pattern of genesis. Some of the models also showed an ability to capture the temporal variation in observed cyclone genesis. Taking into account the ability of the climate models to simulate both spatial and temporal features, CGCM3.1-T47 and IPSL-CM4, which demonstrated the best performance, were chosen to project changes in cyclone genesis over the WNP under SRES A2. Both of the models predicted an upward trend of the WNP GPI during the 21st century, indicating that there might be more tropical cyclones generated over the WNP in the future. However, the rate of increase in the two models differed,

with CGCM3.1-T47 showing a rate of increase of up to 20% and IPSL-CM4 showing a rate of increase of up to 9% in the late 21st century. This means that there is larger uncertainty in projecting the rate of increase than the sign of change.

The positive trend in the GPI is similar to the work of Caron and Jones (2008). They found that the CYGP (convective yearly genesis potential) index has a positive trend over the WNP under a global warming scenario. The rate of increase in a nine-model ensemble was found to be up to 22% in the late 21st century under SRES A2. Vecchi and Soden (2007) showed

changes in several factors, which were also used in the present study, under SRES A1B by 18 WCRP-CMIP3 GCMs. The multi-model ensemble mean showed that there will be hurricane-favorable conditions over the WNP.

However, Gualdi et al. (2008) used a different approach, detecting simulated tropical cyclones in a high resolution GCM and finding a reduction in tropical cyclones over the WNP when the greenhouse gas concentration doubled and quadrupled. They also calculated the GPI using the same model output and found that the GPI showed some increases over the WNP. Clearly, the results derived from the two approaches do not agree well with each other. As shown in Figs. 8 and 9, relative humidity makes a big contribution to the increase of the GPI over the WNP. However, this factor was not directly employed in the tropical cyclone detecting method in the analysis of Gualdi et al. (2008). This could be one of the potential reasons for the inconsistency in the results, indicating there remains considerable uncertainty in projecting future tropical cyclone activity. This issue needs further exploration.

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