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Verification of Downscaling Framework for Interannual Variation of Tropical Cyclone in Western North Pacific

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Abstract

The downscaling framework, which is originally proposed by Emanuel et al. (2008), is modified to improve the interannual variation of the tropical cyclone features in Western North Pacific (WNP). The original framework, which utilizes axisymmetric model driven using monthly mean atmosphere and ocean variables, well reproduced interannual variation of tropical cyclone indices over North Atlantic while there is room for further improvement over WNP.

The modified treatment of relative vorticity plays an essential role for improving interannual variation of genesis counts and power dissipation index in WNP. In this update, we introduced probability of cyclogenesis special to WNP which is a priori calculated using monthly mean 850-hPa level relative vorticity and best track. The result suggests that the monthly mean relative vorticity represents a potential of characteristic initiating disturbance in WNP such as monsoon trough and intraseasonal variation. Another experiment shows increased influence of vertical wind shear in middle troposphere improves the distribution of tropical cyclogenesis in WNP while it slightly deteriorates the interannual variation of genesis count.

1. Introduction

Tropical cyclone is among the most destructive meteorological phenomena that cause tremendous damages to human society including infrastructure, agriculture, transportation, and so on. Predicting the genesis, track, and intensity of tropical cyclones, however, is still one of the most challenging issues in the atmospheric sciences (Knutson et al. 2010). Therefore, it is essential to learn key factors controlling the location and number of tropical cyclogenesis for investigating the impacts of climate change on behavior of tropical cyclones.

Interannual variation and genesis frequency of tropical cyclone have been intensively studied through many different approaches, such as statistical analysis (e.g., Chan 1985), global and regional models (e.g. Zhao et al. 2009; Knutson et al. 2007), and through the diagnosis of large-scale atmospheric parameters (e.g., Gray 1975; Emanuel and Nolan 2004). In particular, regional model enables to reproduce interannual variation of the tropical cyclone number in the North Atlantic (Knutson et al. 2007). Dynamical downscaling, however, requires huge computational resource to perform high resolution simulation using three-dimensional atmospheric model.

Emanuel et al. (2006, 2008) recently developed a new downscale framework that is able to simulate tropical cyclone behaviors including genesis counts, intensities, and tracks in spite of surprisingly low computer cost. In this method, formation and development of tropical cyclone is calculated by theory-based

axisymmetric model (Emanuel et al. 2004) driven using ambient meteorological variables obtained from the reanalysis data or general circulation models. Simulated interannual variation of annual tropical cyclone number is highly correlated with that observed ($r = 0.69$) in North Atlantic during 1980 and 2006 which is comparable skill to that by dynamical downscaling using a regional model ($r = 0.73$) during the identical period (Emanuel et al. 2008; Knutson et al. 2007). In Western North Pacific (WNP), however, there is essentially no correlation between observed and simulated interannual variation of tropical cyclone number. Therefore, it is necessary to clarify a reason for such a different ability between North Atlantic and WNP by the Emanuel's downscaling framework and to pursue alternative ways toward better performance of the tropical cyclone behaviors in WNP.

The purpose of this study is to modify the downscaling framework proposed by Emanuel et al. (2008) in order to improve the performance of interannual variation of tropical cyclone features in WNP. We speculate that the treatment of two environmental atmospheric parameters in the downscaling framework, namely vertical wind shear and lower tropospheric relative vorticity, may be responsible for the different ability between North Atlantic and WNP. These parameters do not explicitly appear in the governing equation of the axisymmetric model though vertical wind shear effect is parameterized, and the relative vorticity is used for determining the probability of genesis, as those mentioned in Section 2.2. Therefore, the sensitivity to the two parameters with regard to interannual variation of the tropical cyclone in WNP is investigated.

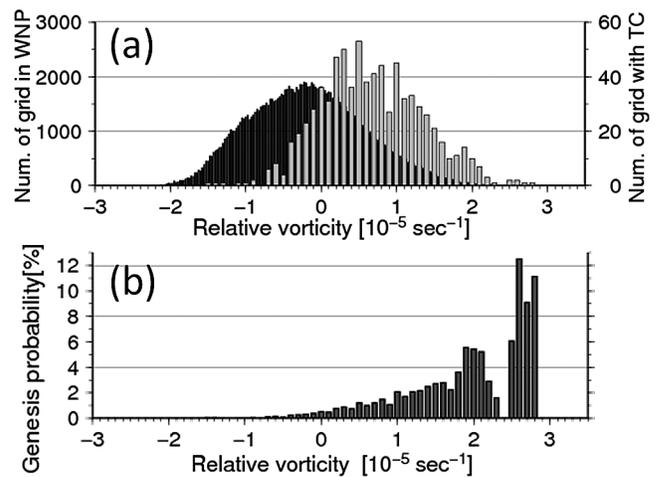


Fig. 1. (a) Frequencies of monthly mean 850-hPa relative vorticity during 1979 and 2008 for available 2.5 degree grids in WNP domain (black) and for grids with tropical cyclone genesis (gray), i.e., the first grid where any grades of tropical disturbance is recorded in the best track. (b) Relationship between probability of tropical cyclone genesis and the monthly mean relative vorticity. The probability is computed as the percentage of gray bar against the black bar in (a).

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2. Data and method

2.1 Forcing and verification data

Three-dimensional atmospheric data (temperature, zonal and meridional winds, and relative humidity) provided by NCEP-NCAR reanalysis (Kalnay et al. 1996) and monthly mean sea surface temperature provided by the Extended Reconstructed SST (ERSSTv2; Smith and Reynolds 2004) are used to initialize and to drive the model. Standard deviation of daily mean wind speed is calculated for each month in order to determine travel speed of the modeled cyclone, detail of which is addressed in Section 2.2. Targeting period of this study is from 1979 through 2008 in order to prevent using pre-satellite period. All grades (tropical depression, tropical storm, severe tropical storm, typhoon, and extra-tropical cyclone) defined in the Japan Meteorological Agency's best track data are employed as a verification data for simulated tropical cyclone features.

2.2 Methodology for simulating tropical cyclones

This study basically follows the downscaling framework developed by Emanuel et al. (2008) except for the influence of low-level vorticity and steering wind calculation. Intensity of individual tropical cyclone is calculated by an axisymmetric model (Emanuel et al. 2004). As a forcing due to the environmental condition, the model uses monthly-mean atmosphere and ocean variables where modeled tropical cyclone is located. The variables are updated every 6 hours as the location of the modeled tropical cyclone changes. Simulation of each tropical cyclone is subdivided into three steps, that is, genesis seeding, development, and track. We repeat the following procedures for monthly basis during the studied period (1979–2008).

a. Genesis

Tropical cyclone seeds, which have maximum surface wind speed of 15 m sec^{-1} , are initially distributed on every 2.5° grid over WNP (100°E – 180°E and 0°N – 30°N) where monthly mean relative vorticity at 850 hPa level is positive and monthly mean potential intensity (V_{pot} ; Bister and Emanuel 1998) is greater than 40 m sec^{-1} as in Emanuel et al. (2008).

Emanuel et al. (2008) introduced “vorticity weighting”, in which the probability of genesis is determined by the product of Coriolis parameter and 850-hPa relative vorticity in order to account the potential of initial disturbances. We follow this treatment but with observation-based weighting ratio to determine a number of seed (N) in each 2.5° grid box. Figure 1 illustrates the frequency of the relative vorticity over the WNP domain. The histogram of monthly mean relative vorticity at 850 hPa is centered near weakly negative while it is likely to shift positively when samples are taken from grid points where tropical cyclone is generated in the corresponding month. It is evident that the genesis probability in WNP is well explained by simple function of the monthly mean relative vorticity (Fig. 1b). Based on the relationship in Fig. 1b, we determined a number of seed as

$$N = \min\{1 + 2.5 \times \xi \times 10^5, 5\}, \quad (1)$$

where ξ is the monthly mean relative vorticity. We already confirmed the relationship in Fig. 1b does not largely differ in case vorticity around the tropical cyclone are removed although upper tail of the histogram, i.e., $\xi > 2.4 \times 10^{-5} \text{ sec}^{-1}$, is evidently direct outcome of cyclones' vorticity. Thus, we set the limitation for seeding number in Eq. 1, which is consistent with a statistical analysis by Tippett et al. (2011) who found the dependence of vorticity to genesis probability becomes saturate when vorticity exceeds threshold value.

It is obvious that the number of seeds assumed in this study is much larger than observed tropical cyclone number in order to cover any possible area of cyclone genesis. Therefore, we will mainly focus on the relative variations of tropical cyclone in time and space rather than pursuing the absolute number.

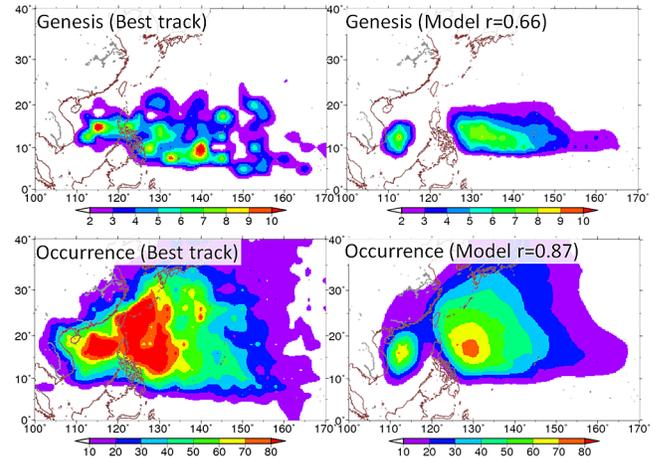


Fig. 2. Geographical distribution of total count of genesis (upper) and occurrence frequency (lower) calculated using 6 hourly cyclone data during 1979 and 2008. Observed pattern in best track is shown on the left while right figures show modeled results. Spatial pattern correlations against the best track are also shown. Correlation coefficients are computed over 100°E – 170°E , 0°N – 30°N for genesis and 100°E – 170°E , 0°N – 40°N for occurrence, respectively. Values from simulation are scaled by factor of 20.

b. Development and track

The intensity evolution for each seed is calculated by the axisymmetric model using monthly mean variables at its location. Only when the maximum wind speed of the seed exceeds 17.2 m sec^{-1} over the duration longer than 48 hours within 9 days of spin-up duration, we assign a tropical cyclogenesis and further movement and development are calculated until the maximum wind speed weakens below 17.2 m sec^{-1} . The moving direction and velocity of each tropical cyclone is assumed to follow a steering wind at its location originally determined by a linear combination of monthly mean wind velocity at 4 layers (850, 700, 500, and 200 hPa) while Emanuel et al. (2006) adopted two layers (850 and 250 hPa). The weighting ratios of the four layers are optimized for WNP with the following constraint; the climatological mean frequency of tropical cyclone occurrence (see also Fig. 2) retains a highest spatial pattern correlation in WNP against the best track. The resultant weighting ratio is 10, 20, 50, and 20% for 850, 700, 500, and 200 hPa, respectively. The influence of β -effect on cyclone track is simply given as the linear function of latitude (Wu and Wang 2004). In order to perform Monte-Carlo simulation, fluctuations for zonal and meridional winds at each 4 layers are given every 6 hours. The fluctuation components are randomly determined from Gaussian distribution using standard deviations of zonal and meridional daily mean winds at each 4 layers for corresponding year and month.

Effect of vertical shear in the middle troposphere, which prevents tropical cyclone to develop, is parameterized and given in the prognostic equation for middle-level entropy as the term, $-\alpha \times |\mathbf{u}_{850\text{hPa}} - \mathbf{u}_{200\text{hPa}}|^2 \times V_{\text{max}}^2 \times (\chi_m - \chi_{m0})$, where $\alpha = 0.005$ is a coefficient for shear influence, \mathbf{u} is monthly mean wind at where the tropical cyclone is located, V_{max} is maximum horizontal wind speed, χ_m is middle layer moist entropy, and χ_{m0} is its environmental value determined by the monthly mean variables (see Emanuel et al. 2004 for more descriptions). Sensitivity to the shear effect (α) on tropical cyclone is also examined and will be discussed in Section 3.2.

3. Result

3.1 Verification of the simulated tropical cyclone in WNP

Figure 2 illustrates annual total genesis count and frequency of occurrence of tropical cyclone during 1979 to 2008. Genesis

location in JMA best track has two centers, one in South China Sea (SCS) and another to the east of the Philippines. Simulated result exhibits two centers at similar locations. The spatial pattern correlation for observed and simulated genesis count is 0.66 over 100°E–170°E and 0°N–30°N domain. The simulated tropical cyclogenesis tends to concentrate in narrow area, and genesis count is relatively less than the observation equatorward of 10°N. The spatial pattern during warm season (May–Oct) also gives high correlation ($r = 0.71$).

Spatial pattern of tropical cyclone occurrence (or track) frequency is well simulated ($r = 0.87$ for 100°E–170°E 0°N–40°N) as well as genesis location with high frequency in SCS and east of the Philippines. Lower frequency along the eastern coast of Eurasia and southern coast of Japan, which indicates the distinction of tropical cyclones after landfall, is also well depicted in the model. Figure 2 supports that the tropical cyclogenesis and its movements are well reproduced by the downscaling framework using monthly mean meteorological variables. This result is consistent with previous works (e.g., Gray 1975; Emanuel and Nolan 2004) which suggest the distribution of tropical cyclogenesis is well explained by the large-scale environmental parameters.

Figure 3 shows interannual variation of annual total genesis count in WNP. It is obvious that the simulated number and PDI are much larger than that observed because of the assumption in seeding process. Downscaled interannual variation captures observed time series with correlation coefficient of 0.51 ($p = 0.01$) during the studied period, and it is remarkable in the latter period (e.g., $r = 0.73$ during 1993 to 2008) despite there was no correlation for WNP in the original framework from 1980 through 2008 (Emanuel et al. 2008). Additionally, the simulated interannual variation captures some extreme years in tropical cyclone number, that is, maximum in 1994 and minimum in 1998 although some other extremes are missed.

Interannual variation of annual total Power Dissipation Index (PDI) is shown in Fig. 3b. The correlation coefficient is 0.51 ($p = 0.01$) which is slightly higher than Emanuel et al. (2008) ($r = 0.48$) for WNP. Since the PDI is proportional to the product of tropical cyclone number, third power of maximum wind speed, and duration (or lifetime), Fig. 3b indicates the annual integration of tropical cyclone energy over WNP is also reproduced. Since strong tropical cyclone is relatively more in number than that observed (no figure), PDI is overestimated in the model. The result suggests that our Monte-Carlo simulation for cyclone track works fine for WNP domain. As in tropical cyclone number, correlation coefficient for interannual variation of PDI becomes higher in the latter period ($r = 0.67$ during 1993 to 2008).

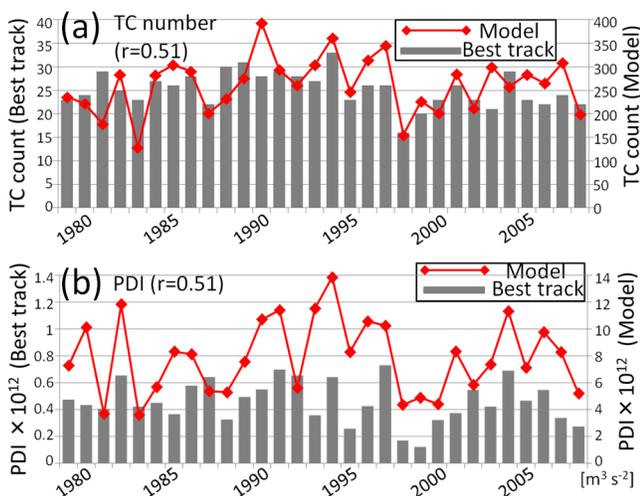


Fig. 3. Interannual variation of (a) annual total number and (b) power dissipation index of tropical cyclone in Western North Pacific in best track (bars and left axis) and simulated results (red solid line and right axis).

Table 1. Correlation coefficients for spatial pattern of annual and warm season (May–Oct.) total cyclogenesis and correlation coefficients for time series of interannual variation of the tropical cyclogenesis count and PDI in WNP against the best track. Interannual variations are evaluated for 1979–2008 period. Correlation for interannual variation during 1993–2008 is also shown.

Run name	Annual genesis location (May–Oct)	Interannual count (after 1993)	Interannual PDI (after 1993)
No weighting	0.66 (0.71)	0.38 (0.51)	0.31 (0.50)
$\alpha = 0.005$ (control)	0.66 (0.71)	0.51 (0.73)	0.51 (0.67)
$\alpha = 0.010$	0.67 (0.71)	0.47 (0.69)	0.49 (0.66)
$\alpha = 0.015$	0.69 (0.73)	0.47 (0.66)	0.49 (0.66)
$\alpha = 0.020$	0.70 (0.74)	0.45 (0.65)	0.49 (0.66)

3.2 Sensitivity experiments

In the previous section, we confirmed an improved performance of interannual variation of tropical cyclone in WNP. Here we investigate the effect of relative vorticity and vertical wind shear for interannual variation of tropical cyclone by means of several sensitivity experiments.

Firstly, impact of relative vorticity is investigated. In our treatment, the number of cyclone seeds is determined using monthly mean 850-hPa relative vorticity as in Eq. 1. In order to investigate the effect of this seeding control, “no-weighting” experiment is conducted in which the number of seed is given as a constant value (i.e., $N = 5$ instead of Eq. 1).

Results in sensitivity experiments are summarized in Table 1. Interannual variations in “no-weighting” run show significantly lower correlation for genesis count ($r = 0.38$) and PDI ($r = 0.31$). Therefore, it is evident that the seeding control using monthly mean relative vorticity has great impact for improving interannual variation of the tropical cyclone features in the current study. On the other hand, spatial pattern of tropical cyclogenesis shows similar performance even without the vorticity weighting.

The second sensitivity experiment aims to investigate the influence of vertical wind shear on the predictability of interannual variation of tropical cyclone features in WNP. The parameter for shear influence ($\alpha = 0.005$ in control experiment) is gradually increased up to 0.020 which is the value Emanuel et al. (2008) used. Genesis location becomes closer to the observed distribution as shear effect increases, for example, $r = 0.70$ and $r = 0.74$ in annual and warm season genesis patterns, respectively when $\alpha = 0.020$ (Table 1). The shear effect strongly restricts genesis distribution since the vertical shear effect tends to limit the tropical cyclogenesis. On the other hand, increase of shear intensity slightly deteriorates the correlation for interannual variation ($r = 0.45$ when $\alpha = 0.020$; Table 1). In summary, vertical shear intensity possesses a contrary sensitivity, that is, stronger shear effect improves the long-term mean genesis pattern while stronger shear effect reduces the performance for genesis number in each year.

The sensitivity experiments reveal that the improvement in interannual variations of tropical cyclone number and PDI are primary due to the seeding number control using a monthly mean relative vorticity. Weakening of vertical wind shear effect also contributes to the improved interannual variations of genesis number and PDI. In the next section, we discuss physical mechanisms for the improvement focusing on the difference between WNP and North Atlantic domain.

4. Discussion

Sensitivity experiments revealed the impact of environmental parameters on interannual variation of genesis number and PDI. Relative vorticity and vertical shear represent dynamical aspect of large-scale environment while other parameters (such as relative humidity and temperature profile) are often used as well

for diagnosing genesis potential of tropical cyclone from the thermodynamic point of view. As mentioned in Section 2.2, the thermodynamic role of environmental atmosphere is incorporated in the axisymmetric model used in the downscaling framework. However, the dynamical effects by relative vorticity and vertical shear need to be given by empirical ways.

In “no-weighting” run, we confirmed that the vorticity weighting, in which the number of seed is given using monthly mean low-level relative vorticity, was crucial on interannual variation of genesis number in WNP. The weighting rate is determined based on observed statistics between relative vorticity and genesis probability. Let us revisit the source of tropical disturbance that relates tropical cyclogenesis in WNP. There are many different processes which relate tropical cyclogenesis in WNP through modulation of large-scale environment, such as intraseasonal variation (Liebmann et al. 1994; Nakazawa 1988), northward extension of ITCZ or monsoon trough (Wang 2006), easterly waves (Li et al. 2003), and so on. Interestingly, some low-frequency phenomena are deeply related to the tropical cyclogenesis in WNP. Especially, recent work by Gao and Li (2011) found intraseasonal variation is likely to initiate multiple typhoons during the active phase. The low-frequency atmospheric variability retains its anomalous relative vorticity after monthly averaging of horizontal winds. This is why tropical cyclogenesis probability (Fig. 1b) shows monotonous relationship against the monthly mean relative vorticity. Therefore, we consider the seeding control using monthly mean vorticity pattern reflects characteristic low-frequency atmospheric phenomena in WNP. On the other hand, in North Atlantic, influence of low-frequency variability like MJO and monsoon trough is less prominent although some influences are recognized (Klotzbach 2010). The interannual variations in tropical cyclone number are more influenced by thermodynamic condition in North Atlantic while it is also influenced by dynamical condition in WNP. The difference in dominant control for tropical cyclogenesis between the two ocean basins gives the contrasting performance in interannual variation of tropical cyclone in the downscaling framework.

5. Conclusion

This study modified a framework for combined dynamical and statistical downscaling method for tropical cyclone, which is originally proposed by Emanuel et al. (2008). The purpose of modification is to improve the performance of interannual variation of tropical cyclone features in WNP. The downscale framework adopts axisymmetric model driven using monthly mean atmosphere and ocean variables obtained from reanalysis data.

A series of sensitivity experiment is conducted to investigate the impacts of low level relative vorticity and vertical wind shear on tropical cyclone number since these parameters do not explicitly appear in the governing equation of the model. The sensitivity test reveals interannual variation of tropical cyclone number and power dissipation index are markedly improved when initial number of cyclone seed is determined by a function of monthly mean relative vorticity in the lower troposphere, in which the weighting ratio is determined by the observed probability in WNP. Another experiment shows that the increased influence of vertical shear in troposphere improves the geographical distribution of tropical cyclone in WNP while it also deteriorates the interannual variation of genesis count.

In WNP, low-frequency atmospheric phenomena, like intraseasonal variation and monsoon trough, have great impact on tropical cyclogenesis. The monthly mean relative vorticity is a rough measure for such phenomena, and number of tropical disturbance is expected to be high under such environment. This is why the seeding control using monthly mean relative vorticity is the main reason for improvement of interannual variation and why the downscaling ability was different between WNP and North Atlantic in the previous study.

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