A Simple Trajectory Model for Climatological Study of Tropical Cyclones

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ABSTRACT

The establishment of a tropical cyclone (TC) trajectory model that can represent the basic physics and is practically advantageous considering both accuracy and computational cost is essential to the climatological studies of various global TC activities. In this study, a simple deterministic model is proposed based on a newly developed semiempirical formula for the beta drift under known conditions of the environmental steering flow. To verify the proposed model, all historical TC tracks in the western North Pacific and the North Atlantic Ocean basins during the period 1979–2018 are simulated and statistically compared with the relevant results derived from observed data. The proposed model is shown to well capture the spatial distribution patterns of the TC occurrence frequency in the two ocean basins. Prevailing TC tracks as well as the latitudinal distribution of the landfall TC number in the western North Pacific Ocean basin are also shown to agree better with the results derived from observed data, as compared to the existing models that took different strategies to include the effect of the beta drift. It is then concluded that the present model is advantageous in terms of not only the accuracy but also the capacity to accommodate the varying climate. It is thus believed that the proposed TC trajectory model has the potential to be used for assessing possible impacts of climate change on tropical cyclone activities.

1. Introduction

Tropical cyclones (TCs), which may cause strong winds, torrential rainfall, and storm surges in coastal areas, are among the most devastating natural phenomena in the world (Pielke et al. 2008; Park et al. 2014; Walsh et al. 2019). In recent years, a public concern is whether global warming has a major impact on TC activities, including the variability of TC occurrence frequency in a particular ocean basin, the migration of the geographical locations at which TCs experience their lifetime-maximum intensities, the future trend of landfall possibility along a particular coast, and so on. As a result, a significant number of studies have been carried out to investigate the climatological variability of TC tracks. In the literature, these studies generally fall into two categories: whether climate change to date has already had a detectable effect on TC tracks and how

climate change might affect TC tracks in the future (Yin 2005; Kossin et al. 2010, 2016; Walsh et al. 2019).

Various methods have been developed to depict TC tracks. In general, these methods can be distinguished between mesoscale atmosphere–ocean coupled methods and global atmospheric circulation methods. The global atmospheric circulation methods can be further classified as having a direct approach, a deterministic approach, or a statistical approach. The mesoscale atmosphere–ocean coupled methods are theoretically rigorous (Zhang and Emanuel 2016; Chen et al. 2018), but they cannot be applied to climatological studies at present time due to their critical requirement on computer resources. The direct approach with a global atmospheric circulation model is to identify TC-like vortices in the output of a general circulation model (GCM) (Murakami and Wang 2010; Walsh et al. 2019). Previous studies based on the direct approach have yielded results with uncertain accuracies, indicating the deficiency of low-resolution GCMs in resolving actual TCs (Murakami et al. 2011; Yokoi et al. 2013). More recently, Tory et al. (2013a,b,c) proposed a direct approach using the so-called Okubo–Weiss–Zeta method (Provenzale 1999) for TC detection.

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This approach yields reasonable results from both fine- and coarse-resolution GCMs (Chand et al. 2017; Bell et al. 2018, 2019), but it is still reported to be problematic for TC tracks in coastal regions (Tory et al. 2013b). The statistical approach integrated into a GCM (Emanuel et al. 2006; Hall and Jewson 2007) is totally or partially based on the statistical properties of TC parameters derived from historical observations (Emanuel 2000; Yu et al. 2016). TC tracks obtained with this approach are synthetic and meaningful only from the statistical point of view. The most critical problem in the statistical approach is probably a possible lack of consistency for the statistical properties of parameters due to changing climate. The deterministic approach integrated into a GCM has significant advantages as compared to both the direct approach and the statistical approach, and is the major concern of this study.

The deterministic approach integrated into a GCM often requires a careful consideration of the fundamental physics for TC motion (Wu and Wang 2004; Wu et al. 2005; Emanuel et al. 2006; Colbert et al. 2013, 2015; Lin and Emanuel 2016). With this approach, TC tracks must then be jointly determined by the large-scale environmental steering flow and the beta drift (Carr and Elsberry 1990; Wang et al. 1998; Chan 2005). The environmental steering flow plays a central role in driving the TC forward, while the beta drift represents a major deviation of the TC motion from the environmental steering flow. Compared with the statistical approach, TC tracks obtained with the deterministic approach may simulate actual events and have no problem in principle to include the effects of climate change (Wu and Wang 2004; Wu et al. 2005; Colbert et al. 2013, 2015; Lin and Emanuel 2016). Compared with the direct approach, the deterministic approach does not require to resolve the motion of vortices. The TC tracks obtained are then less dependent on the resolution of the GCM and, therefore, more reliable (Lin and Emanuel 2016).

The environmental steering flow is defined as the large-scale motion of the atmosphere around the TC, averaged both vertically and horizontally (Chan and Gray 1982), which may be conveniently obtained from the observed data (Chan and Gray 1982; Chu et al. 2012; Colbert and Soden 2012). Formulation of the beta drift, on the other hand, does not seem to be easy (Wu and Wang 2004; Emanuel et al. 2006; Zhao et al. 2009; Colbert and Soden 2012; Colbert et al. 2015). Wu and Wang (2004) adopted the mean beta drift velocity derived from the observed data. Emanuel et al. (2006) assumed the beta drift velocity to be a constant vector over a regional ocean. Note that Wu and Wang's (2004) beta drift velocity cannot be simply given by a formula. Based on the study of Wu and Wang (2004), Zhao et al. (2009)

proposed an empirical relation between the mean beta drift and the large-scale environmental flow. Empirical relations between the magnitude of the beta drift velocity and the angle of the TC track were also suggested (Colbert and Soden 2012; Colbert et al. 2015). Note that the physical mechanism behind the beta drift was ignored in all these studies.

Fiorino and Elsberry (1989) provided a comprehensive explanation on the beta drift. The underlying physics was then further clarified by Chan (2005). According to these authors, the beta drift velocity depends not only on the size and intensity but also on the inner structure of the cyclone. Basically, it was realized that the nonlinear interaction between the cyclone and the meridional gradient of the Coriolis parameter is the primary mechanism for the beta drift. There are also studies indicating that the nonuniformity of the environmental flow certainly affects the beta drift (Wu and Emanuel 1993; Williams and Chan 1994; Wang and Li 1995; Li and Wang 1996). The large-scale horizontal shear in the environmental flow seems to be a key factor in determining the TC motion in most cases (Chan 2005). This point was further confirmed by a statistical study of the influence of large-scale environmental flows on the climatological characteristics of the beta drift (Zhao et al. 2009). In addition, the kinetic energy transferred into the structured inner core of the cyclone was also identified to be proportional to the horizontal shear in the environmental flow (Li and Wang 1996). There were also arguments about the effect of the vertical shear in the environmental flow (Wu and Emanuel 1993), but it is certainly less important to the beta drift than the effect of the horizontal shear (Chan 2005).

Existing models for TC tracks including the effect of the beta drift (Wu and Wang 2004; Emanuel et al. 2006; Zhao et al. 2009; Colbert and Soden 2012; Colbert et al. 2015; Chen et al. 2018) are either too sophisticated to be practically used in climatological studies or not accurate enough. The main objective of the present study is to establish a climatologically effective TC trajectory model that is simple enough to be readily applicable in a GCM but can correctly include the effect of the beta drift given the large-scale environmental flow condition. A brief verification of the proposed model is also provided.

2. A simple TC trajectory model

a. Beta drift

According to Fiorino and Elsberry (1989) and Chan (2005), the nonlinear interaction between a mesoscale TC circulation and the meridional gradient of the Coriolis

parameter leads to a pair of counterrotating gyres (i.e., the beta gyres) within the core of the TC. The cyclonic gyre is located at the southwest and anticyclonic gyre at the northeast within a TC in the Northern Hemisphere. At the same time, there is a near-uniform ventilation flow between the two gyres, or across the TC center, which is thus directed to the northwest in the Northern Hemisphere. It has been demonstrated that this ventilation flow associated with the beta gyres somehow plays a dominant role in determining the beta drift velocity. It is then of special interest to find a general expression for this ventilation flow velocity so that a formula for the beta drift velocity can be obtained.

To describe the evolution of the beta gyres, we consider the conservation of kinetic energy within the gyres following Wang and Li (1995):

$$\frac{dE}{dt} = F, \quad (1)$$

where E represents the domain-integrated kinetic energy within the beta gyres while F is the net energy flux to the developing gyres; d/dt denotes the rate of change observed when following the advection of the beta gyres.

Based on a numerical study of Li and Wang (1996), the rate of kinetic energy transferred to the beta gyres from the environmental flow is proportional to the horizontal shear of the environmental flow ($\partial V/\partial x + \partial U/\partial y$), that is,

$$F = \frac{1}{2} \left(\frac{\partial V}{\partial x} + \frac{\partial U}{\partial y} \right) (-\sin 2\alpha) E, \quad (2)$$

where U and V denote the zonal (x) and meridional (y) components of the environmental flow, respectively; α is the azimuthal angle of the beta gyres, that is, the azimuthal angle of the anticyclonic gyre center measured counterclockwise from due north, and $\sin 2\alpha < 0$ when the anticyclonic gyre is located in the northeast quadrant in the Northern Hemisphere. Thus, a positive horizontal shear allows the environmental flow to feed kinetic energy to the beta gyres so that the beta drift is accelerated, and vice versa. As a support to Eq. (2), it is known that the rate of the kinetic energy transferred to the beta gyres from the environmental flow is nearly independent on the TC intensity and structure (Li and Wang 1996).

Substituting Eq. (2) into Eq. (1) and completing the integration under the assumption that the environmental flow is quasi-steady, we have

$$E = E_0 \exp \left[a_0 \left(\frac{\partial V}{\partial x} + \frac{\partial U}{\partial y} \right) (t - t_0) \right], \quad (3)$$

where E_0 is the kinetic energy possessed by the beta gyres at $t = t_0$ and a_0 is a dimensionless constant.

By Eq. (3) it is possible to estimate the representative circumferential velocity of the beta gyres within a characteristic time interval τ :

$$W = W_0 \exp \left[a_\tau \left(\frac{\partial V}{\partial x} + \frac{\partial U}{\partial y} \right) \tau \right], \quad (4)$$

where W is the representative circumferential velocity of the beta gyres; W_0 and a_τ are constants to be determined. The ventilation flow associated with the beta gyres is expected to have a velocity with magnitude proportional to W . Including the effect of omitted factors, the beta drift velocity may then be expressed as

$$\mathbf{u}_\beta = \mathbf{u}_1 + \mathbf{u}_2 \exp \left[a_\tau \left(\frac{\partial V}{\partial x} + \frac{\partial U}{\partial y} \right) \tau \right], \quad (5)$$

where $\mathbf{u}_\beta$ is the beta drift velocity; $\mathbf{u}_1$ is introduced to represent the omitted effect of those factors that cannot be represented by the horizontal shear in the environmental flow, such as the intensity and the inner structure of the TC as well as the vertical nonuniformity and the horizontal acceleration of the steering flow; and $|\mathbf{u}_2| = W_0$.

To determine the constants in Eq. (5) we may have to rely on the statistical information on TCs in a particular ocean basin. Over the western North Pacific basin, the mean beta drift velocity—that is, the averaged vectorial difference between TC advection velocity and the large-scale steering flow velocity, based on the records of TC events observed from 1965 to 2007—has an orientation of 320° and a magnitude of 3.3 m s^{-1} according to Zhao et al. (2009). Chen and Duan (2018) found that the mean beta drift velocity over the western North Pacific basin has an orientation of 310° and a magnitude of 2.9 m s^{-1} , based on the observed data for TCs during 1949–2014. In addition, a numerical study of Fiorino and Elsberry (1989) showed that the orientation of the ventilation flow between the beta gyres in the Northern Hemisphere may rotate by about 45° from initially northward to finally northwest, and the direction of the ventilation flow remains stationary once the beta gyres are eventually formed. These studies all suggest that the mean beta drift velocity possesses a directional angle of about 315° and a magnitude between 1.0 and 4.0 m s^{-1} , although some discrepancies do exist due to variations in the period of study. Therefore, we adopt the following expressions for the zonal and meridional velocity components of the beta drift over the western North Pacific basin:

$$u_\beta = -W_\beta \left\{ 1 + \exp \left[\gamma \left(\frac{\partial U}{\partial y} + \frac{\partial V}{\partial x} \right) \right] \right\}, \quad (6)$$

$$v_\beta = W_\beta \left\{ 1 + \exp \left[\gamma \left(\frac{\partial U}{\partial y} + \frac{\partial V}{\partial x} \right) \right] \right\}, \quad (7)$$

FIG. 1. Computational flowchart for a TC track.

where $W_\beta = 1.0 \text{ m s}^{-1}$ and $\gamma = 2000\text{s}$. In Eqs. (6) and (7), the magnitudes of u_β and v_β are the same but their signs are different because previous studies suggested that the beta drift has a directional angle of about 315° . The value of γ is determined so that the magnitude of the beta drift velocity mostly falls into the range between 1.0 and 4.0 m s^{-1} as the observed horizontal shears in the environmental flows around all TCs occurred over the western North Pacific basin during the period 1979–2018 are substituted.

It is worthwhile to mention that a TC trajectory model with the beta drift velocity expressed by Eqs. (6) and (7) must not be expected to accurately depict the motion of an actual TC event. The model is applicable only in climatological studies of TC tracks. This is not only because the model is simple and many small-scale meteorological factors that affect the motion of a TC are omitted but also because the parameters in the model are statistically calibrated with observed data.

b. Computational method for TC tracks

In climatological studies, a TC is often treated as a point vortex that moves from its genesis position. The track of the TC can then be determined by connecting the discretized positions of the moving TC center solved from the following difference equations:

$$x_{n+1} = x_n + (U + u_\beta)\Delta t, \quad (8)$$

$$y_{n+1} = y_n + (V + v_\beta)\Delta t, \quad (9)$$

where x and y are the zonal and meridional coordinates of the TC center, respectively; the subscript n indicates a value at $t = t_0 + n\Delta t$ while t_0 is the time when the TC is initially generated; Δt is the time step and $\Delta t = 6 \text{ h}$ is widely adopted in practical studies of TC tracks.

It is now clear that a TC track can be uniquely determined once the environmental steering flow velocity components U and V are available over the lifetime of the TC event. The environmental steering flow in this study is defined as the flow averaged both in the horizontal plane and in the vertical direction. Horizontally, it is averaged over a 5° – 7.5° radial band from the TC center (Chan and Gray 1982). Vertically, a deep-layer mean (Holland 1984; Deng et al. 2010; Colbert and Soden 2012) is taken considering the wind field at levels of 850, 500, and 200 hPa. Historical information of the horizontal wind field can be obtained at a $2.5^\circ \times 2.5^\circ$ resolution and a 6-h interval from the reanalysis data of the National Centers for Environmental Prediction and National Center for Atmosphere Research (NCEP–NCAR) (Kalnay et al. 1996). It may be worthwhile to mention that, when applied to a climatological study of TC tracks, the model yields a slightly worse but still very good results when the monthly mean wind data are used in place of the instantaneous data.

The computational algorithm for obtaining a TC track can be summarized in Fig. 1. The major steps include

FIG. 2. TC occurrence frequency obtained from (a) the observed data, (b) the computed results, and (c) the difference between (a) and (b) with the proposed TC trajectory model in the western North Pacific Ocean basin during the period 1979–2018.

(i) setting the genesis position and time as the initial conditions of a computational step; (ii) reading the horizontal winds at the known time step and at levels of 850, 500, and 200 hPa from the reanalysis data; (iii) computing the environmental steering flow; (iv) computing the horizontal shear of the environmental flow; (v) computing the beta drift velocity; (vi) renewing the position of the TC center; and (vii) repeating (ii) to (vi) until the TC moves out of the domain of interest or up to 10 days.

3. Verification by TC occurrence frequency

To validate the proposed TC trajectory model as well as the formulation for the beta drift velocity, historical TC tracks in a prescribed period may be simulated to yield the TC occurrence frequency in an ocean basin of interest, which may then be compared with the results derived from observed data. The frequency of TC occurrence within a unit area is defined as the mean annual number of TCs generated within or passing through this area. The unit area is taken to be a $5^\circ \times 5^\circ$ grid element in this study. Note that a given TC is counted only once in a particular unit area. To focus on model verification, our attention is especially paid to the TC tracks in the western North Pacific basin (i.e., the ocean basin bounded by 0° – 50° N, 100° E– 180°). The period of study is 40 years from 1979 to 2018, since the TC track data after 1979 are often considered to be more reliable due to availability of satellites for TC observations. Based on the records in International Best Tracks Archive for Climate Stewardship (IBTrACS) dataset v04 (Knapp et al. 2010), there are totally 935 TC events observed in the western North Pacific basin within the period of our study. We compute the tracks for all 935 TC events with the present TC trajectory model. In the computations, the initial time and position of each TC event are specified according to the observed values recorded in IBTrACS dataset v04. The relevant environmental steering flow velocity is derived from the NCEP–NCAR dataset.

As shown in Fig. 2, the computed pattern of the TC occurrence frequency in the western North Pacific Ocean basin is very close to that obtained from the observed data. The correlation coefficient of the two spatial patterns is actually 0.96. In particular, the computed and observed maxima of the TC occurrence frequency almost coincide at 20° N, 125° E. Both observed and computed results show that TCs occur most frequently over the Philippine Sea. The observed and computed high-frequency regions are nearly overlapped, in which the relative error of the local occurrence frequency is less than 10%.

FIG. 3. TC occurrence frequency obtained from (a) the observed data, (b) the computed results, and (c) the difference between (a) and (b) with the proposed TC trajectory model in the North Atlantic Ocean basin during the period 1979–2018.

The proposed TC trajectory model is established based on statistical facts about TC motion over the western North Pacific basin. It is thus not certain if the model is valid globally, even though the physics underlying the formulation is universal. To test the applicability of the model in other ocean basins, the TC occurrence frequency in the North Atlantic Ocean basin is also computed in this study. Based on the IBTrACS dataset v04, there are totally 428 TC events observed in the North Atlantic basin (i.e., the ocean basin bounded by 0°–50°N, 100°–10°W) within the period of our study. The tracks for all 428 TC events are then simulated with the present TC trajectory model. The empirical values for W_β and γ in Eqs. (6) and (7) remain unchanged.

As shown in Fig. 3, the computed pattern of the TC occurrence frequency in the North Atlantic basin is also very close to that obtained from observed data. The correlation coefficient of the two spatial patterns is 0.93. The computed and observed maxima of the TC occurrence frequency almost coincide at 35°N, 70°W. The observed and computed high-frequency regions of TC occurrence are highly similar, in which the relative error of the local occurrence frequency is less than 10%. It is thus clear that the performance of the proposed TC trajectory model in the North Atlantic basin is just as good as its performance in the western North Pacific basin, although the model parameters were calibrated only by statistical data for TCs over the western North Pacific basin. This may imply that the proposed TC trajectory model is generally effective.

4. Verification by prevailing TC tracks

To further validate the TC trajectory model proposed in this study, we try to compare the geometric features of the computed TC tracks with those obtained from observed data. As a reference, results given by existing models, including the mean beta drift model based on observed TC data proposed by Wu and Wang (2004) and the constant vector model proposed by Emanuel et al. (2006), are also presented. To avoid reiteration, we consider only TC tracks in the western North Pacific Ocean basin (i.e., the ocean basin bounded by 5°–20°N, 135°E–180°). Special attention is paid to the prevailing tracks identified by the method of Colbert et al. (2015). According to Colbert et al. (2015), TC tracks in the western North Pacific Ocean basin can be classified into three different types: straight-moving (SM), curved to landfall (CL), and curved to the ocean (CO). Note that TCs of the same type often have similar active season, life cycle, intensity, and landfall impact (Camargo et al. 2007). For example, the SM type may threaten the Philippine Islands and southern China; the CL type may

TABLE 1. TC count by type. The values in parentheses are the differences between observed and computed results.

No. of TCs	Observed	Wu and Wang (2004)	Emanuel et al. (2006)	Present
SM	170	181 (+11)	31 (−139)	150 (−20)
CL	220	129 (−91)	197 (−23)	213 (−7)
CO	104	183 (+79)	264 (+160)	131 (+27)
Not classified	0	1 (+1)	2 (+2)	0
Total	494	494	494	494

make landfall along the eastern coast of China, or the coast of the Korean peninsula and Japan; and the CO type is usually less disastrous because most TCs of this type do not land. Based on the records in IBTrACS dataset v04, there are totally 494 TC events observed in the western North Pacific Ocean basin during the period 1979–2018 that satisfy the definitions of the aforementioned three types, of which 170 TCs belong to the SM type, 220 TCs to the CL type, and 104 TCs to the CO type.

We compute the tracks for all 494 TC events with the mean beta drift model proposed by Wu and Wang (2004), the constant vector model proposed by Emanuel et al. (2006) and the present model, respectively. In the computations, the initial time and position of each TC event are specified following the observed data. The relevant environmental steering flow velocity is derived from the NCEP–NCAR dataset.

The computed TC tracks with each beta drift model are then reclassified into the three different types, respectively, according to the definition of Colbert et al. (2015). Note that a TC track that belongs to one type based on the observed data may fall into another type when it is simulated by a particular trajectory model because the classification of marginal tracks may be changed when the numerical error is not negligible. Shown in Table 1 are the TC numbers of different types as different beta drift models are employed. It is seen that the results computed with the present model are much closer to the observed data. The number of CL-type TCs is evidently underestimated and the number of CO-type TCs correspondingly overestimated with Wu and Wang's (2004) model, whereas the number of SM type is clearly underestimated and the number of CO type overestimated with Emanuel et al.'s (2006) model.

It is necessary to point out that the mean beta drift in Wu and Wang's (2004) model is determined by the vectorial difference between a 40-yr mean of the TC advection velocity and the relevant environmental steering flow velocity over the entire western North Pacific Ocean basin. The direction of the mean beta drift velocity was found to be northwest in general. However, it is locally northeastward near the subtropical high in the middle latitudes. Note that the

subtropical high is usually active for a long time in the Northern Hemisphere. The less emphasized consideration of the effect of the subtropical high in Wu and Wang's (2004) model is probably the major reason for the computational error of the mean beta drift in the middle latitudes, which finally results in a change of some TC tracks of the CL type based on the observed data to the CO type. Other researchers (Zhao et al. 2009) also pointed out this problem when using the mean beta drift given by Wu and Wang (2004).

The beta drift velocity in Emanuel et al.'s (2006) model is assumed to be a constant vector directed to the north over the whole western North Pacific Ocean basin. Since the environmental steering flow is generally westward at the low latitudes and eastward at the middle latitudes, driven by the large-scale summer circulation in this ocean basin, omitting the westward component of the beta drift then leads to an underestimation of the westward component of the TC advection velocity in the low latitudes and an overestimation of the eastward component of the TC advection velocity in the middle latitudes with Emanuel et al.'s (2006) model, which finally causes a significantly reduced number of the westward TC tracks and excessive TC tracks being classified into the CO type.

The prevailing tracks of the three types averaged from the computational results obtained with different beta drift models as well as from the observed data are demonstrated in Fig. 4. The prevailing tracks averaged from the results computed with the present beta drift model are shown to have the best agreement with the relevant ones from the observed data. The prevailing tracks of CL and CO types averaged from the results computed with Wu and Wang's (2004) model are more eastward than the observed ones and the errors further increase at the middle latitudes. As mentioned above, this computational error is probably due to a less emphasized consideration of the effect of the subtropical high. It is also evident that the prevailing track of the SM type obtained with Wu and Wang's (2004) model matches relatively well with the observed one but is still slightly deviated to the southwest. The prevailing tracks of CL and CO types averaged from the results computed with Emanuel et al.'s (2006) model are even more

FIG. 4. The prevailing tracks of the three TC types averaged from the observed data (black lines) and the computed results with (a) Wu and Wang's (2004) model, (b) Emanuel et al.'s (2006) model, and (c) the present model in the western North Pacific Ocean basin during the period 1979–2018. For the computational results, the green, red, and blue lines represent the SM, CL, and CO types, respectively.

deviated to the east while the prevailing track of the SM type shows a curving trend instead of going straightforwardly to the west. The computational error is likely due to omission of the western component of the beta drift velocity in Emanuel et al.'s (2006) model.

5. Verification by TC landfall

It is certainly important for a trajectory model to accurately catch the landfall location of a TC because the TCs that make landfall often cause catastrophic disasters. In this study, a TC that makes landfall means that

FIG. 5. The distributions of TC landfall number by latitude in the western North Pacific Ocean basin during the period 1979–2018 obtained from the observed data (solid lines) and computed results (dashed lines).

the TC crossed the land–sea boundary from ocean to land at least once. Note that only the first landing is taken into account. To count the number of TCs that make landfall in the present study, we have to rely also on the global relief model of Earth's surface from National Geophysical Data Center that integrates land topography and ocean bathymetry at 0.1° resolution (Amante and Eakins 2009).

It may be interesting to compare the numbers of historically recorded TCs that make landfall to the numbers obtained with the present TC trajectory model. A convincing comparison would certainly provide a valuable verification to the proposed model. For reference, results computed with Wu and Wang's (2004) and Emanuel et al.'s (2006) models are also presented. In the western North Pacific basin, the total number of TC events observed during the period 1979–2018 is 935 as mentioned previously. Among these TCs, the observed landfall rate is 56% with 522 events. In comparison, the computed landfall rate is 59% with 555 events by the present model. It is 53% with 493 events by Wu and Wang's (2004) model, and 38% with 358 events by Emanuel et al.'s (2006) model, respectively. The landfall rate computed with the present model is slightly higher than the observed landfall rate, but the total error is quite acceptable and is at the same level as the result given by Wu and Wang's (2004) model.

Figure 5 shows the distribution of TC landfall number against latitudes. It is evident that the present TC trajectory model can reproduce the observed distribution much better than other models, with a correlation coefficient of 0.97. The maxima in the distribution are also well caught by the present model. In contrary, the number of TC landfalls is obviously underestimated at

22.5° and 35°N and overestimated at 10°–15°N with Wu and Wang's (2004) model, and significantly underestimated at low latitudes with Emanuel et al.'s (2006) model. Note that an accurate representation of the maxima is not trivial because they are closely related to the number of TCs that make landfall at particular coasts (e.g., along the coast of the Philippines, the eastern coast of China, and the coasts of the Korean peninsula and Japan).

6. Concluding remarks

In this study, a simple TC trajectory model was proposed to properly consider the effect of the beta drift given the large-scale environmental flow condition. The horizontal shear in the environmental flow was assumed to be the key variable in a climatologically effective expression for the beta drift. To verify the performance of the proposed trajectory model, all historical TC tracks in the western North Pacific and the North Atlantic Ocean basins during the period 1979–2018 were simulated. The computed patterns of the TC occurrence frequency in the two ocean basins were demonstrated to be very close to those derived from observed data. The prevailing tracks averaged from the results obtained with the present trajectory model were also shown to have the best agreement with the relevant ones derived from observed data in the western North Pacific basin, as compared to the existing models that took different strategies to include the effect of the beta drift. The TC landfall rate as well as the latitudinal distribution of the TC landfall number computed with the proposed model also found the best agreement with those derived from observed data in the western North Pacific Ocean basin, as compared to existing models. It may then be possible to conclude that the proposed trajectory model is advantageous in representing the major climatological properties of TC tracks. It is thus promising to be integrated into a GCM for assessing the possible impact of climate change on TC activities. Note that, when integrated into a GCM, an effective method to initialize TC genesis is necessary.

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