Effects of the outer size on tropical cyclone track forecasts

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Abstract
The track forecast of a tropical cyclone (TC) located near the neutral point of a split subtropical high pressure system under the influence of a nearby trough is difficult and can lead to a large forecast spread among different global numerical weather prediction models. Three TCs with large forecast spread under such an environmental flow pattern have been identified: Hagupit (2008), Lupit (2009) and Nida (2009). Simulations using a bogus vortex of different radii of 15 m s$^{-1}$ (R15) with the same environmental flow for each TC case are conducted to study the effect of TC size on the forecast track of the TC. With a nearby strong monsoon trough, a TC with a smaller R15 merges with the cyclonic circulation within the trough leading to a larger outer circulation. After removing the symmetric component of the TC from the total wind field, an extensive cyclonic asymmetric gyre is found and its circulation steers the TC to move more westward. The TC thus shifts northward within the neutral point. With a weak monsoon trough further away from the TC, a TC with larger R15 interacts with the monsoon trough, causing the TC to move more westward. With the presence of a westerly trough, a TC with larger R15 and outer circulation interacts with the trough such that the TC moves more northeastward. The importance of a correct representation of TC size in a numerical weather prediction model in predicting the TC track is discussed.

KEYWORDS
ensemble, monsoon trough, numerical weather prediction, size, track, tropical cyclone

1 INTRODUCTION

Tropical cyclone (TC) track forecast errors of different operational warning centres have substantially decreased in the past decade (Peng et al., 2017; Yamaguchi et al., 2017). The adoption of the consensus of TC forecasts from different centres generally gives a more accurate prediction than just using the forecasts of each model because the random errors and biases of individual models tend to offset one another (Goerss, 2000; Goerss et al., 2004; Elsberry, 2007, 2014). However, Yamaguchi et al. (2017) pointed out that, even though the forecasts have improved on average in the past decade, there are still many cases when the track forecasts are extremely large.

In the summer season, the monsoon trough and strong southwesterly flow penetrate to the western North Pacific basin and therefore affect TC tracks. Several studies have documented the interaction of TCs with nearby tropical systems especially the monsoon gyre. Idealized simulations were conducted by Carr and Elsberry (1995).
to study the track changes of TCs with different intensities and location relative to a monsoon gyre. The TC first rotates around the gyre cyclonically and then suddenly decelerates after merging with the monsoon gyre and subsequently turns north. Liang and Wu (2015) further pointed out that a TC can turn sharply northward if the TC merges with the monsoon gyre, or moves westward or turns northward without a sharp turn if no merging occurs. They also showed that a TC with a stronger outer circulation has a smaller turning angle. Chen et al. (2009) showed that a meridional vorticity tendency dipole associated with a monsoon trough would drive the TC northward during strong monsoon conditions. In contrast, associated with a monsoon trough would drive the TC northward during strong monsoon conditions. In contrast, during weak monsoon conditions, the steering from the enhanced trade easterlies leads to a northwestward motion of the TC. Wu et al. (2011) suggested that strengthened synoptic-scale southwesterly flow shifts the TC north and northwestward. A smaller cyclonic circulation, such as the remnant circulation of a TC, a tropical disturbance or the upper-tropospheric circulation of a mid-latitude system, can also lead to changes of the TC track. Carr and Elsberry (2000) pointed out that a TC would have a cyclonic turning when the TC apparently merges with an adjacent cyclonic circulation and subsequently becomes larger in size. Ge et al. (2018) pointed out that a TC would have a sharp north turn due to the cancelling of the TC vorticity advection by that of the monsoon gyre with a domination of the beta drift when a TC is initially placed on the eastern side of a deeper monsoon gyre in an idealized simulation.

The presence of a subtropical anticyclone together with a tropical system makes the TC movement more complicated. The flow patterns governing the straight westward-moving or recurving TC have been studied by a composite wind circulation and a probabilistic clustering method (Harr and Elsberry, 1991, 1995a; 1995b; Camargo et al. 2007). The anomalously strong subtropical ridge and the anomalous low-level cyclonic shear associated with an enhanced monsoon trough lead to a straight westward-moving TC. The recurving track of a TC is attributed to the anomalously strong equatorial westerlies associated with an anomalous cross-equatorial flow and a weaker subtropical ridge with a weak point. The extents of the subtropical high (SH) and the high pressure over China are also a major reason for the large forecast errors of TC tracks (e.g. Qian et al., 2013, Wu et al., 2013, Shi et al., 2014, Yang et al., 2018).

The interaction of TC size with the environmental flow also affects TC track forecasts. Carr and Elsberry (1995) found that the β-induced Rossby dispersion of the outer circulation of a TC induces a trailing anticyclone to the east and southeast of the TC, leading to the northward turn of the TC. Carr and Elsberry (1997) further pointed out that, the larger the outer circulation of the TC, the larger and stronger is the trailing anticyclone. Bender et al. (2017) examined the forecast track performance by modifying the gale wind radii of the vortex based on a combination of satellite and short-term model forecasts. They showed that the forecast error for recurring storms is reduced but it is worsened for westward-moving storms with slow bias. Kunii (2015) pointed out that a better assimilation of TC radius data leads to improved TC track forecasts.

Tang et al. (2019) pointed out that the influence of the monsoon trough on a TC located near the neutral point between the SH and the high pressure system over China would lead to a large forecast spread by different global numerical weather prediction (NWP) models. An accurate prediction of the TC characteristics, the monsoon trough and the subtropical anticyclone are important for TC track forecasts. The objective of this study was therefore to study the interaction among these factors and the TC track especially for a TC with large forecast spread by different global NWP models and located near the weak/neutral point of the high pressure belt where the influence of all these factors is comparable.

The data and methodology are described in Section 2. Results are presented in Section 3 and the discussion and conclusion are given in Section 3.3.4.

2 | DATA AND METHODOLOGY

2.1 | Data and selection of cases

A dataset created by the Working Group on Numerical Experimentation (Yamaguchi et al., 2017) containing the forecast tracks of TCs from the global models of 11 NWP centres was used in conjunction with the best-track data from the Regional Specialized Meteorology Center Tokyo—Typhoon Center to identify cases in the western North Pacific with large track forecast errors. The non-perturbed (control) prediction of the global ensembles data from the International Grand Global Ensemble (the former name is the Observing System Research and Predictability Experiment [Parsons et al., 2017] Interactive Grand Global Ensemble [Bougeault et al., 2010; Swinbank et al., 2016]) was used in the present study to analyse the large-scale atmospheric patterns that influence TC motion. The National Centers for Environmental Prediction Final Analysis (NCEP FNL analysis) was used as the “truth” for comparison with the predicted fields of different global models and the Weather Research and Forecasting (WRF) model simulations (see Section 2.2). The FNL analysis is considered to be one of the most accurate global synoptic analysis products.
because it incorporates all available real-time and delayed observational data (more detailed descriptions about the FNL analysis dataset are available at https://rda.ucar.edu/datasets/ds083.2/#!description).

TC cases with large forecast spread (defined as the average distances of all model forecast members from the ensemble mean larger than the 75th percentile of the annual distribution) were chosen. Such large forecast spread has to persist for at least 2 days (i.e. four forecast cycles) so that the causes of the track forecast error are prominent enough rather than some instability of the models or defects of the initial conditions. An additional condition that the TC apparently passes near the neutral/weak point, defined as the minimum wind speed between the broken subtropical high pressure belt, was applied to filter the cases further. TC Hagupit (2008), Lupit (2009) and Nida (2009) were selected to be studied in this work.

2.2 | WRF simulations

In order to study the effect of TC size on its forecast track, simulations using the WRF model version 3.7.1 were conducted with the same environmental conditions and physics for each TC case. A triply two-way nested domain with 27, 9, 3 km grid size and 33 σ levels with a model top of 50 hPa was used. The grid points for each domain were 570 × 367, 553 × 553 and 379 × 379 respectively. The outermost fixed domain was the same for the different TC cases covering 15 °S to 75 °N and 60 °E to 160 °W while the inner domains were vortex-following movable nests, with the intermediate domain and the innermost domain focusing mostly on the western North Pacific and the TC core respectively. Topography was from the US Geological Survey database with 10 min, 2 min and 30 s resolutions for the outer to innermost domains respectively.

The physics options used in the simulations included the WRF Single-Moment 3-class microphysics scheme, the Rapid Radiative Transfer Model for general circulation models for long and short wave radiation, the fifth-generation Pennsylvania State University–National Center for Atmospheric Research (PSU–NCAR) Mesoscale Model (MM5) Similarity Surface Layer Scheme, the Noah Land Surface Model land surface scheme, the Yonsei University Planetary Boundary Layer scheme and the Kain–Fritsch cumulus parameterization scheme. Cumulus parameterization is only turned on for the outermost domain. The Global Forecast System (GFS) analysis data were used as the initial environmental and boundary conditions.

Because the vortex contained in the large-scale GFS analysis is too weak compared with the best-track intensity, a modified Rankine bogus vortex from the WRF intrinsic TC bogussing scheme was inserted in the domain. The tangential wind profile of the modified Rankine bogus vortex is governed by the following equation:

\[
V_T = V_{\text{max}} \left( \frac{r}{r_{\text{max}}} \right) \quad \text{for } r < r_{\text{max}}
\]

\[
V_T = V_{\text{max}} \left( \frac{r}{r_{\text{max}}} \right)^{\alpha} \left( 1 - \frac{r - r_{\text{max}}}{R_{\text{tc}} - r_{\text{max}}} \right) \quad \text{for } r \geq r_{\text{max}}
\]

where \( V_T, V_{\text{max}}, r_{\text{max}}, R_{\text{tc}}, r \) and \( \alpha \) are the tangential wind, maximum wind speed, radius of maximum wind, radius of the TC (defined where the azimuthal average of the relative vorticity of the TC is equal to zero), radius from the TC centre and wind profile modifier, respectively. As \( r_{\text{max}} \) is not included in the best-track data, the radius of 50 km in the Japan Meteorological Agency (JMA) best-track data was used as the approximate value of \( r_{\text{max}} \) if this value was available; otherwise, \( r_{\text{max}} \) was chosen as 50 km. The wind profile modifier (\( \alpha \)) is a factor modifying the shape of the tangential wind profile to fit the radius of 15 m s\(^{-1}\) wind (R15) to the JMA best-track (radius of 30 km wind) data and the desired value in different simulations (to be specified in the following sections for different TC cases).

Bogus vortices with different values of R15 specified using the modified WRF intrinsic TC bogussing scheme were spun up for 36 hr under the environmental conditions 36 hr prior to the initial time (\( t - 36 \) hr). The spun-up vortices with all the TC-related variables (including total wind field, pressure variables etc.) within the radius of the TC (defined as the radius where the azimuthal average 850 hPa relative vorticity equal to zero) were then inserted into the environmental conditions at the initial time (\( t = 0 \) hr) with the original vortex in the environment being removed by the WRF intrinsic TC removing scheme.

3 | RESULTS

3.1 | TC Nida (2009)

3.1.1 | Overview of Nida

TC Nida formed over the western North Pacific at 1800 UTC November 21, 2009 (hereafter, the date/time will be simplified to yymmddhh, where yy is the year, mm is the month, dd is the day and hh is the hour, i.e. 09112118) and generally moved northwest (black line in Figure 1a). According to the JMA best-track data, the minimum sea level pressure of the TC dropped to 950 hPa with values of R15 of around 310 and 240 km at the northeastern and
The southwestern parts of the TC respectively at 09112500. The TC became almost stationary from 09112800 to 09113000 as the TC was located in the neutral point between a split subtropical high pressure system. TC Nida then moved westward due to the northward shift of the SH by a tropical disturbance southwest of TC Nida (not shown). TC Nida eventually recurved at 09120300 and dissipated.

### 3.1.2 | Forecast of global models

At 09112500, a strong monsoon trough is located west of TC Nida with minimum sea level pressure ~1,006 hPa (Figure 2a) and its circulation combines with the outer circulation of TC Nida. The track forecasts of different models for TC Nida are spread widely (Figure 1a). Some models (e.g. European Centre for Medium-Range Weather Forecasts [ECMWF], Meteorological Service of Canada, Environment and Climate Change Canada [ECCC]) predict a recurving track while the others (e.g. UK Met Office [UKMO], NCEP) predict the TC moving west to southwestward after around 72 forecast hours (+72 hr).

Carr and Elsberry (1995, 1997) and Tang et al. (2019) pointed out that the TC track is sensitive to the outer wind structure of a TC (see Section 1). Figure 3a shows the TC size difference, defined as the azimuthal average of 850 hPa relative vorticity equal to zero (hereafter “V0 size” for simplicity and for clear distinction from the wind-defined TC sizes) of the TC between the FNL data and that in different NWP models. The V0 size is over-predicted by the UKMO, NCEP and Bureau of Meteorology, Australia (BOM) models, all of which also predict the TC turning west after around 72 forecast hours (see Figure 1a). On the other hand, the models with a northward movement or recurving track (e.g. ECMWF, ECCC and Korea Meteorological Administration (KMA)) under-predict the V0 size (Figure 3a). The mechanism of the V0 size leading to differences in the forecast track will be discussed in Section 3.1.3.

### 3.1.3 | WRF model simulations

In order to study the effect of V0 size of the TC on its track, TCs with three different R15 values were spun up for 36 hr (see Section 2 for the details of the spin-up processes): the best-track R15 size (BTS), 1.5 times BTS and twice BTS, denoted BTS-Ni, 1.5BTS-Ni and 2BTS-Ni respectively (the symbol Ni represents TC Nida; a similar abbreviation is used for other TC cases in the following sections). The BTS-Ni TC first moves northwestward similar to the best track but turns westward after around 72 forecast hours (+F72 hr) (see Figure 1b). The 1.5BTS-Ni and 2BTS-Ni TC have a similar track to that observed at first and turn northward after 48 forecast hours (+F48 hr).

After the spin-up processes, the V0 sizes of the smallest to largest BTS TC are around 1,000, 800 and 680 km respectively. The BTS-Ni experiment has the largest over-prediction of V0 while the 2BTS-Ni experiment has the smallest (and even an under-prediction) (Figure 3b). In other words, the TC with a smaller R15 actually has a larger V0 size. After subtracting the symmetric (i.e. azimuthal wavenumber 0) component of the TC from the total wind field, a cyclonic gyre (hereafter cyclonic asymmetric gyre for clear distinction from any cyclonic circulations in the total wind field) is found to the southwest of the BTS-Ni TC (Figure 4a). Even though
this gyre is masked by the TC circulation, it distorts the circulation of the TC, making it more extensive on the southwestern but more restricted on the northeastern side of the TC (Figure 4b). The BTS-Ni TC is not large enough to capture the cyclonic circulation (the capture process in the Fujiwhara effect; Lander and Holland, 1993). Instead, the cyclonic circulation “connects with” the TC to form an extensive cyclonic circulation. However, the 2BTS-Ni TC is large enough to capture the cyclonic gyre such that the gyre merges with the TC leading to a distorted circulation on the southwestern side of the TC (Figure 4d). The V0 size of the BTS-Ni TC (small R15) is therefore larger than that of the 2BTS-Ni TC (large R15).

The circulation of the cyclonic asymmetric gyre dominates within the core of the BTS-Ni TC (Figure 4a). The TC is thus advected northwestward and then westward leading to a westward movement after around 72 forecast hours (+F72 hr). As the TC gains less in latitude, the high pressure over the south of China extends eastward and further advects the TC westward (not shown). However, as the cyclonic asymmetric gyre is captured by the 2BTS-Ni TC (Figure 4d, similar to the observed situation [not shown but close to that forecast from NCEP – see Figure 4f]), it is weakened and its circulation is less extensive than that in the BTS-Ni TC. The circulation of the cyclonic asymmetric gyre does not completely embed the TC core (Figure 4c; compare with BTS-Ni TC in Figure 4a). Instead, the TC is situated between the circulation associated with the cyclonic gyre and the SH to move northward (similar to the observed [not shown]).

Similarly, the circulation of the global-model-predicted TC with westward-moving track is extensive on
FIGURE 4  Left panel: 300–850 hPa averaged total wind minus the symmetric component of the tropical cyclone (TC) Nida (2009). Right panel: total wind. The wind field of the forecast of (a), (b) best-track R15 size (BTS)-Ni, (c), (d) 2BTS-Ni and (e), (f) National Centers for Environmental Prediction (NCEP) model at 48 forecast hours with initial time 09112500 (valid time 09112700). The TC symbol in the left panel indicates the TC location. Shadings show the wind speed in m s⁻¹. The green and blue circles in the right panel indicate the R15 and V0 size of the TC respectively.
the southwestern side of the TC (Figure 4e; only NCEP is shown). A cyclonic asymmetric gyre is found to the southwest of the TC after removing the symmetric component of the TC (Figure 4f). The circulation associated with the cyclonic gyre dominates within the TC core and thus advects the TC westward. On the other hand, the global-model-predicted TCs with northward-moving/recurving track are not embedded by the circulation associated with the cyclonic asymmetric gyre (not shown but similar to Figure 4c). The TC is thus advected by the SH to move north to northeastward.

3.1.4 Discussion

Under the influence of a strong nearby monsoon trough (see Figure 2a), a small R15 TC would have a larger V0 size because the TC cannot dominate within the monsoon trough. A TC with over-predicted V0 size has stronger interaction with the monsoon trough such that the TC moves more westward while the reverse occurs for a TC with under-predicted V0 size leading to a more northward track.

3.2 TC Hagupit (2008)

3.2.1 Overview of Hagupit

TC Hagupit formed northwest of Guam at 08091712 and moved westsouthwestward (black line in Figure 5a). The minimum sea level pressure of the TC dropped to 990 hPa with an R15 of around 440 and 260 km in the southwest and northeastern parts of the TC respectively at 08092000 (not shown). It then moved northwestward to the sea east of the Philippines due to the presence of a weak point over the ridge of the SH. The TC then turned westward northeast of Luzon. It eventually made landfall on south China.

3.2.2 Forecast of global models

At 08092000, a monsoon trough extends to the South China Sea with minimum sea level pressure ~1,008 hPa (see Figure 2b). The circulation of the trough apparently does not combine with the circulation of TC Hagupit (compare Figures 2a,b). The forecasts of different models are widely spread (Figure 5a). Some of the models have a similar track to the observed track that turns westward to enter the South China Sea at around 36 forecast hours (see Figure 5a). On the other hand, the models with a straight northwestward or recurving track (e.g. KMA, ECCC and CPTEC) under-predict the V0 size (Figure 6a). These results are similar to the global model results of Nida (2009) (see Section 3.1.2) that TCs with a smaller and larger V0 size move more northward and westward respectively. The mechanism of the V0 size leading to differences in the forecast track will be discussed in Section 3.2.3.

3.2.3 WRF model simulations

Three simulations with different BTS TCs were conducted to study the effect of V0 size of the TC on the forecast track: 0.5 × BTS, BTS and 1.5 × BTS, denoted 0.5BTS-Ha, BTS-Ha and 1.5BTS-Ha TC respectively. The BTS-Ha and 1.5BTS-Ha experiments give a track similar to the JMA best track, i.e. a westward turn over the east of Luzon at around 36 forecast hours (+F36 hr; see

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**Figure 5** As in Figure 1 but for the observed and forecast tracks of TC Hagupit by (a) different global numerical weather prediction models and (b) Weather Research and Forecasting simulations with initial time 08092000.
However, the 0.5BTS-Ha experiment predicts the TC to move more northward and skim over the southern tip of Taiwan. Figure 6b shows that the V0 sizes of the BTS-Ha and 1.5BTS-Ha TCs are well predicted while the 0.5BTS-Ha TC is under-predicted. In other words, a smaller R15 TC has a smaller V0 size, which is opposite to the TC Nida case discussed in Section 3.1.3. The monsoon trough in the Nida case is stronger so that several low pressure systems develop within the trough and interact with TC Nida to form a giant cyclonic circulation (see Figure 4b). However, the monsoon trough in the Hagupit case is weaker and located further away from the TC (Figure 7b). There is no individual low pressure system interacting with the TC such that, unlike the TC Nida case, the V0 size of TC Hagupit does not depend on whether the TC can capture the low pressure system. Instead, the larger the TC, the closer is the outer circulation of the TC to the monsoon trough such that the larger extension is the outer circulation of the TC towards the trough (compare Figures 7b,d for BTS-Ha TC and 0.5BTS-Ha TC respectively). The V0 size of a larger R15 TC is therefore larger.

As the extension of the outer circulation of BTS-Ha TC is larger compared with that of the 0.5BTS-Ha TC, the cyclonic asymmetric gyre on the southwest of the TC (after subtracting the symmetric component of the TC) is more extensive (compare Figures 7a,c). The flow within the BTS-Ha TC core is dominated by the westnorthwestward flow associated with the cyclonic asymmetric gyre but dominated by the northwestward flow associated with both the cyclonic asymmetric gyre and the SH within the 0.5BTS-Ha TC core. 0.5BTS-Ha TC therefore moves more northward.

Similarly, the circulation of the global-model-predicted TCs with westward turn (e.g. the prediction of the ECMWF model, not shown but similar to Figure 7b) is more extensive on the southwestern side of the TC than that of the TCs with straight northwestern track (Figure 7f; only the KMA model is shown). The flow within the TC core in the ECMWF model prediction is dominated by the circulation of the cyclonic asymmetric gyre (not shown but similar to Figure 7a) and thus the TC turns westward while both the cyclonic asymmetric gyre and the SH in the KMA model prediction (Figure 7e) and thus the TC do not turn westward.

3.2.4 Discussion

Under the influence of a weak and distant monsoon trough (compared with that in the TC Nida case, see Section 3.1 and Figure 2), TCs with different R15 can dominate differently within the trough such that a TC with larger V0 size (closer to the trough) has a stronger interaction with the trough and the TC moves more westward. On the other hand, a TC with smaller V0 size has small interaction with the trough such that the TC moves less westward and is even steered by other systems to move northward.

3.3 TC Lupit (2009)

3.3.1 Overview of Lupit

TC Lupit formed over the southeast of Guam at 09101412 and moved westward (black solid line in Figure 8a). The minimum sea level pressure of the TC dropped to 975 hPa with R15 being around 330 and 260 km at the northeastern and southwestern parts of the TC respectively at 09101612. It then moved northward with a reversed “S” shaped track due to the influence of the westerly trough and moved westward from 09101900 to 2200. It eventually turned northeastward sharply at 09102300.

3.3.2 Forecast of global models

Only the forecast error in predicting the reversed “S” shaped track is discussed in this study. The forecast of
As in Figure 4 but for TC Hagupit (2008) for 36 forecast hours and initial time 08092000 (valid time 08092112). Upper, middle and bottom panels show the wind field of the forecast of best-track R15 size (BTS)-Ha, 0.5BTS-Ha and the KMA models respectively. The green and blue circles in the right column indicate the R15 and V0 size of the TC respectively.
different models initiated at 09101612 spreads widely (Figure 8a). Some models (e.g. ECMWF, JMA, UKMO) predict a westward-moving track but the others (e.g. KMA, CPTEC) predict a recurving track. Figure 9 shows that the V0 size is over-predicted by the BOM, ECMWF, UKMO and JMA models. All of these models predict a westward-moving track (see Figure 8a). On the other hand, the models with a recurving track (e.g. KMA and CPTEC) under-predict the V0 size (Figure 9a). These results are similar to the global model results of the aforementioned TC cases (see Sections 3.1.2 and 3.2.2) that TCs of smaller and larger V0 size move more northward and westward respectively.

### 3.3.3 WRF model simulations

Three WRF simulations were conducted to simulate the track of TC Lupit: the best-track R15, 0.5 times that of R15 and 2 times that of R15 (denoted BTS-Lu, 0.5BTS-Lu and 2BTS-Lu respectively). The reversed “S” shaped track is well simulated in the BTS-Lu experiment even though the extent of the “S” shape is smaller compared with the observed track (Figure 8b). The subsequent westward movement and sharp northeastward turn are also well predicted. The TC in the 0.5BTS-Lu experiment moves westward without the “S” shaped track while the TC in the 2BTS-Lu experiment meanders northeastward. Figure 9b shows that the V0 size of the 0.5BTS-Lu TC is the smallest while that of the 2BTS-Lu TC is the largest. In other words, a smaller R15 TC has a smaller V0 size, similar to the Hagupit case discussed in Section 3.2.3. It is because the monsoon trough in this case (see Figure 10a for the wind field from the FNL data) is not significant that there is no cyclonic circulation merging with the outer circulation of the TC to form an extensive cyclonic circulation. Moreover, the smaller and larger V0 size of the TC moves more westward and northward respectively (see Figure 8b). The westerly trough is passing north of the TC (Figure 10a). The TC with larger V0 size could interact with the westerly trough because the outer circulation of the TC is closer to the trough. The equatorward flow behind the trough is enhanced by the outer northerly wind associated with the TC such that the trough extends far southward to embed the TC (Figure 10b). The TC therefore moves northeastward. On the other hand, the westerly trough
does not extend southward due to the smaller outer circulation of the TC with smaller V0 size (Figure 10c). The TC is thus located within the neutral point between two high pressure systems. After the trough moves eastward, the split subtropical high pressure belt reconnects (not shown) and thus the TC moves westward.

However, these results contradict the westward and northward motion of the TC with larger and smaller V0 size, respectively, in the global models. For the westward predicted track (e.g. the UKMO model), the anticyclone on the west of the TC is under-predicted (compare the wind field from the FNL data with that of the UKMO model; Figure 11a,c) such that the circulation of the TC is more extensive on the western side, which gives an over-predicted V0 size (see Figure 9a). After subtracting the symmetric component of the TC from the total wind field, a cyclonic asymmetric gyre is found to the southwest of the TC (Figure 11d). The circulation of the cyclonic asymmetric gyre provides an extra northwestward steering flow to the TC such that the TC moves more westnorthwestward. However, there is no such cyclonic gyre in the FNL data (see Figure 10a). Instead, a weak trough dominates within the neutral point between two high pressure systems, and the TC thus turns slowly northeast.

For the northward-drifting track (e.g. the KMA model), the anticyclone on the west of the TC is well predicted (Figure 11b) such that the TC is trapped in the neutral point between two high pressure systems.
However, as its V0 size is under-predicted, the outer circulation of the TC does not enhance the equatorward flow behind the westerly trough. The trough does not deepen and penetrate into the neutral point and so the TC drifts slowly northward within the neutral point instead of being steered northeastward.

### 3.3.4 Conclusion

In WRF simulations, with a passing westerly trough north of the TC, a TC with larger V0 size has a stronger interaction with the trough such that the TC moves northeastward. However, in global model predictions, a TC with an over- (under-) predicted V0 size moves westward (northward). Such discrepancy is attributed to the under-predicted anticyclone on the west of the TC in the global models such that the circulation of the TC is more extensive on the western side, which gives an over-predicted V0 size. After subtracting the symmetric component of the TC from the total wind field, a cyclonic gyre is found to the southwest of the TC and brings a northwestward flow to steer the TC northwestward.

**FIGURE 11** 250–850 hPa averaged (left panel) total wind and (right panel) total wind minus the symmetric component of the TC Lupit (2009). (a) The National Centers for Environmental Prediction Final Analysis (FNL) data at 09101806. (b) The 42 hr forecast of the KMA model initially at 09101612 with the same valid time as (a). (c), (d) The same as (a), (b) but for the UKMO model. The TC symbol in the left panel indicates the TC location. Shadings show the wind speed in m·s⁻¹. The blue circles in (a)–(c) indicate the V0 size of the TC.
4 | DISCUSSION AND CONCLUSION

During the past few decades, tropical cyclone (TC) track forecast errors of numerical weather prediction (NWP) models have decreased substantially. However, there are still some cases when the forecast tracks of different models diverge to a large extent. Three such cases are studied in this paper, TC Nida (2009), TC Hagupit (2008) and TC Lupit (2009), all of which are located either within or south of the neutral or weak point, defined as the minimum wind speed between the subtropical high and the high pressure near China. Within the neutral point, the steering near the core of the TC is ill-defined. The interaction of asymmetries of the outer wind structure of the TC and the TC size (here defined as the azimuthal average of the 850 hPa relative vorticity equal to zero ["V0 size" for clear distinction from the wind-defined TC sizes]) with the nearby synoptic systems could therefore be important to the track of the TC. In these three TCs, the TC with a larger predicted V0 size generally moved more westward than the observed track while the TC moved more northward for a smaller V0 size.

In order to investigate the effect of TC size (V0 size) solely on the track of the TC, several numerical simulations were conducted using the Weather Research and Forecasting (WRF) model. After the spin-up processes (Section 2), the spun-up vortex was inserted in the environment (from Global Forecast System data) for the forecast of the TC track. The initial environmental conditions for TCs with different sizes were the same for each TC case in order to investigate the contribution of the TC size to the forecast track alone.

The TC inner–outer size relationship is different between the TCs investigated in the present study. TC Nida (2009) with smaller radius of 15 m s\(^{-1}\) wind (R15) has a larger outer circulation (Section 3.1) while the reverse occurs for TC Hagupit (2008) and Lupit (2009) (Sections 3.2 and 3.3 respectively). Moreover, TC Nida (2009) and Hagupit (2008) with larger V0 size move more westward while TC Lupit (2009) moves northward.

The interaction with nearby synoptic systems (e.g., tropical trough and westerly trough) is the crucial factor for these discrepancies. A strong monsoon trough with several lows extends to the southwest of the TC. The TC with smaller R15 cannot dominate within such a monsoon trough. Its outer circulation merges with the trough to form an extensive cyclonic circulation leading to a larger V0 size. The TC therefore moves more westward than is observed. On the other hand, the TC with larger R15 size dominates within the trough and thus moves more northward than is observed. However, the monsoon trough in the case of TC Hagupit is weaker and further away from the TC. A TC with larger R15 has a larger V0 size such that the TC has a stronger interaction with the tropical trough leading to a more westward movement.

If a westerly trough is passing north of the TC, a TC with larger V0 size has a stronger interaction with the trough such that the former moves north to northeastward. Otherwise, a TC with smaller V0 size is still trapped in the neutral point between the split subtropical high pressure system without interaction with the westerly trough.

It is noted that the tracks of the 1.5 times the best-track R15 size (1.5BTS) Nida (-Ni) TC and 2BTS-Ni TC in the TC Nida case are similar because the TC is large enough to dominate within the monsoon trough. Further, a larger V0 size of the TC does not have a significantly larger effect on the interaction with the trough. Similarly, a further smaller V0 size of the TC in the TC Hagupit case does not lead to a recurving track because the TC is already small enough to escape from the influence of the monsoon trough. The recurring track predicted by the global NWP models is probably due to the influence of the large-scale environment flow, which is outside the scope of this study.

Moreover, different sets of TC sizes are studied for different TCs in this work because the R15 size indicated in the best-track data may be erroneous. The 0.5BTS-Ni for the Nida case is not discussed because the BTS TC is already too small and the monsoon trough dominates and merges with the outer circulation of the TC to form an extensive cyclonic circulation leading to the westward turn of the track. A further smaller TC yields a similar result so the 0.5BTS case is not discussed. This shows that the R15 size indicated in the best-track data may have underestimated the actual size of the TC.

Three different flow patterns for a TC located near the neutral point are identified in this study. This does not mean that the track forecast errors are only attributed to these three patterns. Instead, a TC with a different outer size would have a different interaction with different nearby synoptic systems and the importance of correctly representing the outer size of the TC in the NWP model is emphasized. Even though the TCs chosen in this work are from 10 years ago, this does not necessarily mean that the effect of the erroneous model-predicted TC size becomes negligible after the model is upgraded. This study, however, has highlighted the importance of the outer size of a TC on the forecast track especially when the TC is located within or near the neutral or weak point of the subtropical high pressure belt. The strength of the monsoon trough interacting with the outer circulation of the TC is also a crucial factor for the forecast track of a TC. If a TC is located in an environment similar to those discussed in this work, a forecaster may take advantage of the results of this study to pay more attention to the interaction between the TC size and...
the surrounding weather systems in order to reduce the forecast spread. Moreover, better data assimilation and model physics for the outer wind structure of a TC would help to improve the accuracy of the forecast.

The outer size of a TC is not the only factor altering the TC track through the interaction between the TC and the monsoon. The TC track alteration can also be related to other processes such as monsoon-modulated tropical wave propagation (Lau and Lau, 1992; Holland, 1995), local energy accumulation due to the monsoon confluent flow and easterly vertical wind shear enhancing a faster growth and northward propagation of the synoptic wave train to affect the TC movement (Li, 2006), barotropic energy conversion associated with the monsoon trough (Wu et al., 2015), reduction of longitudinal group speed and increase of wave energy leading to an increase in local relative vorticity (Done et al., 2011) and intra-seasonal oscillation (Chen et al., 2018). This study is just to highlight one possible important factor, the outer size, so that forecasters in interpreting the NWP outputs can have a better understanding of the predictions.

ACKNOWLEDGEMENTS

The authors thank the Working Group on Numerical Experimentation and each participating NWP centre for providing the forecast data and the International Grand Global Ensemble for providing the global ensemble dataset, respectively. This project is supported by the Research Grants Council of Hong Kong, General Research Fund (CityU11332816). Dr Yamaguchi is partly supported by the Japan Society for the Promotion of Science KAKENHI Grant 26282111 and 18H01283.

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How to cite this article: Tang CK, Chan JCL, Yamaguchi M. Effects of the outer size on tropical cyclone track forecasts. *Meteorol Appl*. 2020;27: e1888. [https://doi.org/10.1002/met.1888](https://doi.org/10.1002/met.1888)