

A forecasting approach of tropical cyclone genesis based on thresholds of multi-physical parameters and its verification using ECMWF model data

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सार – हालांकि काफी अध्ययनों ने साबित किया है कि उष्णकटिबंधीय चक्रवात (टीसी) के मार्ग और तीव्रता का पूर्वानुमान संख्यात्मक मौसम पूर्वानुमान (NWP) मॉडल से प्राप्त जानकारी पर बहुत अधिक निर्भर करता है, कुछ शोधों से पता चला है कि पश्चिमी उत्तरी प्रशांत महासागर (WNP) बेसिन में NWP मॉडल उष्णकटिबंधीय चक्रवात की उत्पत्ति का कितना अच्छा पूर्वानुमान लगाते हैं। NWP मॉडल द्वारा WNP बेसिन में उष्णकटिबंधीय चक्रवात उत्पत्ति पूर्वानुमान की विशेषताओं को समझने के लिए, यह अध्ययन ऐतिहासिक आंकड़े का उपयोग करते हुए उष्णकटिबंधीय चक्रवात के बनने की पहचान हेतु मापदंड का एक सेट प्राप्त करता है तथा 2013 और 2015 के बीच ECMWF मॉडल आंकड़े के आधार पर इसे सत्यापित करता है - परिणाम बताते हैं कि प्रभाव सीमा मानदंड के आधार पर अपनाए गए प्रतिशतता मूल्यों का एल्गोरिदम के प्रदर्शन पर महत्वपूर्ण प्रभाव पड़ता है। एक विशिष्ट अंतराल पर प्रभाव सीमा का उचित समायोजन प्रभावी रूप से टीसी की उत्पत्ति के पूर्वानुमान को बेहतर बना सकता है। उदाहरण के लिए, WNP बेसिन में पूर्वानुमान परिणाम 850 hPa स्तर पर सापेक्षिक भ्रमिलता छोटे परिवर्तनों के लिए सबसे अधिक संवेदनशील हैं। अनुकूलतम प्रभाव सीमा संयोजन योजना के पूर्वानुमान परीक्षण के परिणाम बताते हैं कि इसके प्रदर्शन का काल 24 से 48 घंटे के बीच होता है और उष्णकटिबंधीय चक्रवात के बनने के 12-72 घंटे पहले हिट दर से संबंधित होता है। 24 घंटे से कम के लीड समय के लिए, हिट दर मूल रूप से थोड़ी कमी के साथ उच्च स्तर पर 0.7 से ऊपर रखी गई थी। उसके बाद, प्रदर्शन 48 घंटे से आगे स्थिर होने से पहले तेजी से गिरता है। इसके अलावा, ईसीएमडब्ल्यूएफ मॉडल में उष्णकटिबंधीय चक्रवात की उत्पत्ति के पूर्वानुमान का प्रदर्शन साल-दर-साल और विभिन्न डब्ल्यूएनपी क्षेत्रों में भी भिन्न भिन्न रहा है। यह दक्षिण चीन सागर (SCS) की तुलना में फिलीपींस के पूर्व में बेहतर प्रदर्शन करता है। दूसरी ओर, उच्च गलत चेतावनी (FA) दर दक्षिण चीन सागर के मध्य भागों में फिलीपींस और पश्चिमी उत्तरी प्रशांत महासागर (WNP) के मध्य भाग के आसपास के जल क्षेत्र में पाए जाते हैं। ECMWF के प्रदर्शन में विभिन्न बेसिनों में महत्वपूर्ण विसंगति भी देखी जा सकती है। एक उष्णकटिबंधीय चक्रवात की उत्पत्ति से पहले 24 घंटों के भीतर अटलांटिक बेसिन के लिए दिए गए पूर्वानुमान, पश्चिमी उत्तरी प्रशांत महासागर (WNP) बेसिन के लिए पूर्वानुमान से बेहतर होता है।

ABSTRACT. While considerable studies have proved that the track and intensity forecasts of tropical cyclone (TC) relied heavily on output from numerical weather prediction (NWP) model, few researches investigated how well NWP models forecast TC genesis in the western North Pacific (WNP) basin. In order to understand the characteristics of TC genesis forecast in WNP basin by NWP models, this study derives a set of criteria to identify the formation of TC using historical data and verifies it based on ECMWF model data between 2013 and 2015. The results show that the percentile values adopted as the criteria thresholds have a significant impact on the performance of algorithm based on the criteria. A reasonable adjustment of threshold in a specific interval can effectively improve the TC genesis prediction. For example, in the WNP basin the forecast results are most sensitive to small changes in the relative vorticity on the 850 hPa level. The results of forecast test of the optimal threshold combination scheme indicate that the turning point of performance lies between 24 and 48 hours with regard to the hit rate in the 12-72 hours prior to the formation of TC. For lead time less than 24 hours, the hit rate was basically maintained at a high level above 0.7 with a small decrease. After that, the performance drops sharply before stabilizing beyond 48 hours. In addition, the performance of the TC genesis prediction in ECMWF model varies significantly from year to year and also in different WNP regions. It performs better to the east of the Philippines than over the South China Sea (SCS). On the other hand, high false alarm (FA) rates are found in the central parts of the SCS up to the waters around the Philippines and the central part of the WNP. The

significant discrepancy in ECMWF's performance can also be observed between different basins. Within the 24 hours before the genesis of a TC, the forecasts for the WNP basin verify better than those for the Atlantic basin.

Key words – Tropical cyclone, Genesis forecast criteria, Verification, NWP model product.

1. Introduction

The western North Pacific (WNP) is the most active area of tropical cyclones in the world. On average, about 33 TCs are generated here each year, accounting for about one-third of global total. More than 80% of them would eventually develop from tropical depression into tropical storms or above (Frank and Young, 2007; Feng *et al.*, 2012; Oropeza and Raga, 2015). Under the influence of weather systems such as subtropical ridge and monsoon trough, most of the TCs forming in the WNP would make landfall over China, Japan, the Philippines, Vietnam, and Korean Peninsula, bringing severe economic loss and high casualties to the regions. Operational TC forecasts mainly rely on outputs from NWP models. However, each model has its unique characteristics, strengths and weaknesses in capturing the genesis and intensification of TCs.

It is still a great challenge for NWP models to provide an accurate forecast of TC genesis, because of the scientific hypotheses behind tropical cyclogenesis remain actively debated. Starting from Riehl (1950), many theories like CISK (the conditional instability of the second kind) (Ooyama, 1964; Charney and Eliassen, 1964), WISHE (wind-induced surface heat exchange), (Emanuel, 1986) "top down" (Ritchie and Holland, 1997; Simpson *et al.*, 1997), "bottom up" (Enagonio and Montgomery, 2001), VHTs (vortical hot towers) (Hendricks *et al.*, 2004) and "pouch" (Dunkerton *et al.*, 2009; Wang *et al.*, 2012; Wang, 2014) proposed by many researchers, aimed at the understanding of TC genesis. However, the theories could not completely explain how cumulus convection organizes, or a tropical weak disturbance develops into a large-scale TC with organized deep convection and a closed surface wind circulation pattern about a well-defined center (Rajasree *et al.*, 2016).

Limited by theoretical studies, grid distances and calculation speeds, it is difficult for numerical models to perfectly describe the generation process of tropical cyclones (Buendía *et al.*, 2007; Nath *et al.*, 2015). With different parameterization schemes and initial fields, there are variations in skill and characteristics of TC forecasts between different models. While considerable researches have focused on the forecast skills of NWP models about track and intensity forecast after formation of TC (Majumdar and Finocchio, 2008; Snyder *et al.*, 2010; Choudhury and Das, 2017; Emanuel, 2017; Jun *et al.*, 2017), there have been only a few concerns about the skill of TC genesis in NWP models, especially in the WNP.

A clear definition of a model-generated TC is a major key to evaluating the performance of TC genesis forecast by NWP models. Although the theory of tropical cyclogenesis is controversial, the conditions of tropical cyclone generation are widely accepted. In the late 1940s, Palmén (1948) and Riehl (1948) proposed that TC generation needs to meet certain environmental conditions. Gray (1968) then conducted a systematic climatological study of the genesis and development of TCs worldwide, and pointed out that the frequency of TC occurrence is related to six factors. Based on climatological factors discussed in Gray (1968), Tory and Frank (2010) proposed five necessary conditions for TC genesis: Sea surface temperature higher than 26.5 °C with a mixing layer of about 50 m; A relatively deep layer of conditional instability; An increasing positive vorticity at low levels; Large-scale ascent, a humid mid-troposphere with organized deep convection, and weak to moderate vertical wind shear.

On the basis of TC genesis climatology, previous studies (Bengtsson *et al.*, 1995; Vitart and Anderson, 2001; Oouchi *et al.*, 2006) referred to thresholds of winds at 10m or at 850 hPa level, relative vorticity at 850 hPa, average temperature of low to mid-tropospheric levels (700-300 hPa) obtained in NWP models to define a model generated TC. Based on this notion, Tory *et al.* (2013) replaced the relative vorticity by absolute vorticity and added Okubo-Weiss parameter and environmental parameters to identify genesis in NWP models. Majumdar and Torn (2014) further improved Tory's formalism and set three thresholds to estimate TC genesis location: (i) layer-averaged 700-850 hPa relative vorticity computed over a disk of radius 200 km; (ii) 200-850 hPa thickness difference computed over a disk of radius 200 km; (iii) the local minimum of mean sea level pressure (MSLP) within 5° in latitude or longitude. The values of the above parameters were collected at the time when a TC formed and thresholds can be obtained using different quantile of the collected samples. Halperin *et al.* (2013) summarized the results of previous studies (Cheung and Elsberry, 2002; Marchok, 2002) and proposed a detailed criteria of model fields that must be met for at least 24 consecutive hours, including a relative minimum in MSLP with at least one closed isobar and 850 hPa relative vorticity, 250-850 hPa thickness and wind speed at 925 hPa near the relative minimum in MSLP exceeding thresholds that derived from a certain percentiles based on historical samples. Halperin *et al.* (2013) evaluated TC genesis forecast in North Atlantic

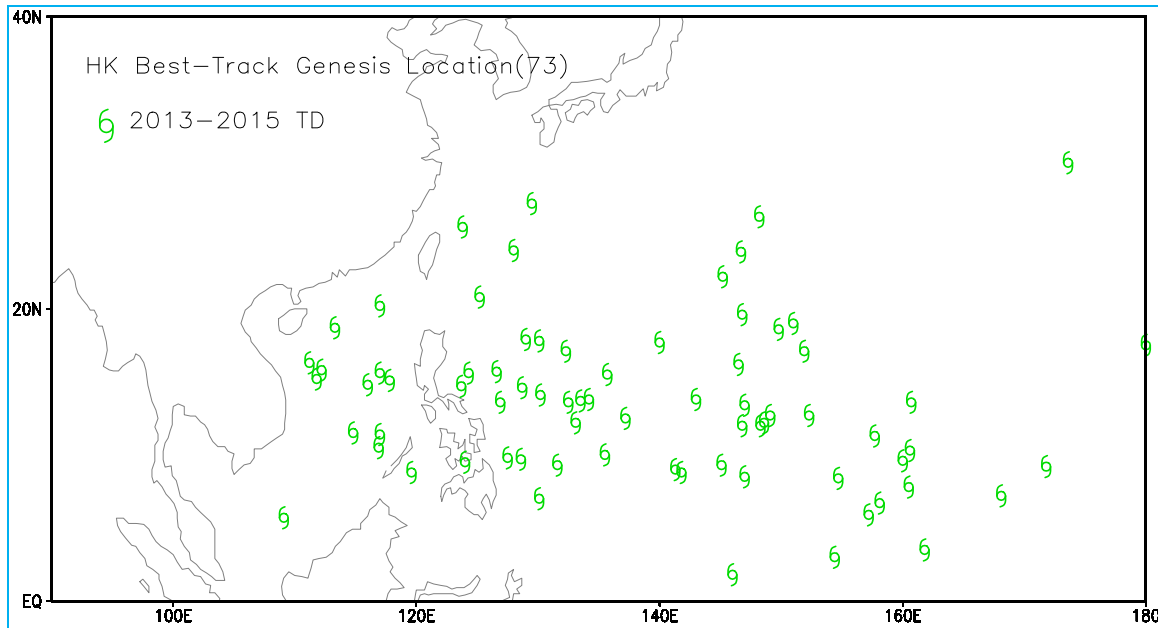


Fig. 1. TC genesis positions between 2013 and 2015 extracting from the HKO TC BT data

TABLE 1
ECMWF analysis field between 2013 and 2015

Year	Period (month/day)	Number of samples	TC cases missing*
2013	1/31-11/30	33	Super Typhoon Danas (1324)
2014	1/1-10/31	19	Tropical Storm Hagibis (1407), Typhoon Vongfong (1419)
2015	1/1-9/30	18	Super Typhoon Soudelor (1513)

*Data are not available

from several global models. In particular, the hit rate of ECMWF exceeded 60% for 6-18 hours of forecasts.

Being one of the most severe weather, TC genesis forecast is essential for disaster prevention and mitigation, longer lead time is thus required to mitigate the potential risks timely. A correct assessment of TC genesis forecasts from NWP models could improve the usefulness of model products, and hence improve TC forecasts. This in turn provides a longer lead time for disaster mitigation and reduces the damages brought by TCs. This study uses multi-thresholds to define TC formation (Bengtsson *et al.*, 1982; Walsh *et al.*, 2007) and evaluates the performance of TC genesis forecast in the WNP provided by ECMWF deterministic model, which is widely used in Asian countries. It also investigates method to verify TC genesis

forecast from NWP models and provides insights of future objective TC genesis forecasts.

2. Data and analysis methods

2.1. Data

Large sample size is required to evaluate the skill of a NWP model. Since there are only 4 cases during 2013-2015 in which the initial state is tropical storm (TS) designated by HKO, this study evaluates cases of tropical depression genesis, and the forecast performance of TS genesis was not discussed separately. The following three types of data were provided by the Hong Kong Observatory (HKO):

- (i) Analysis field of ECMWF deterministic model during 2013-2015, with a spatial resolution of $0.125^\circ \times 0.125^\circ$. Data integrity is shown in Table 1;
- (ii) 12-168 hours forecast field of ECMWF deterministic model during 2013-2015, with a spatial resolution of $0.125^\circ \times 0.125^\circ$. Data integrity is shown in Table 2;
- (iii) TC best track (BT) data of the HKO (Fig. 1).

Thresholds were determined based on ECMWF analysis fields while ECMWF forecast fields were used in the verification of TC genesis. TC BT data of HKO

TABLE 2
ECMWF forecast field between 2013 and 2015

Year	Period (month/day)	Number of samples	TC cases missing*
2013	1/31-11/30	31	Severe Tropical Storm Sonamu (1301), Super Typhoon Danas (1324) and Typhoon Nari (1325)
2014	1/1-10/31	13	Tropical Storm Lingling (1402), Tropical Storm Faxai (1403), Tropical Storm Peipah (1404), Tropical Storm Hagibis (1407), Severe Tropical Storm Nakri (1412), Severe Tropical Storm Fengshen (1414) and Typhoon Vongfong (1419)
2015	1/1-9/30	17	Tropical Storm Bavi (1503) and Super Typhoon Soudelor (1513)

*Data are not available

provided the time and location of TC genesis for samples extraction and verification.

2.2. TC genesis criteria

Based on the criteria proposed in Halperin *et al.* (2013) and integrating definition in Cheung and Elsberry (2002) and Walsh *et al.* (2007), the definition of TC genesis in NWP forecast fields in the central and western North Pacific are proposed as follows:

- (i) a relative minimum in MSLP with at least one closed isobar at a 2 hPa interval;
- (ii) a relative maximum in 850 hPa relative vorticity greater than the historical threshold within 2.5° of the MSLP minimum;
- (iii) a maximum in 250-850 hPa thickness (differences in gph) greater than the historical threshold within 2.5° of the MSLP minimum;
- (iv) wind speed at 925 hPa must exceed the historical threshold at any one point within 5° of the MSLP minimum;
- (v) criteria (i) - (iv) must be met for at least 24 consecutive forecast hours.

Since TC is a cyclonic disturbance with a warm-hearted structure and a closed circulation around a local minimum of sea level pressure, we strive to use variables that fully comply with this definition and satisfy the above principles. Criteria (i) - (iii) were mainly based on the results from previous studies (Cheung and Elsberry, 2002; Walsh *et al.*, 2007). Criteria (i), (ii) and (iv) (the closed

isobar at a 2 hPa interval, relative maximum of relative vorticity and wind speed exceeding historical thresholds) proposed by Halperin *et al.* (2013) can exclude most of the weak low pressure systems commonly found in the equatorial area over 10° S~10° N and in the vicinity of the inter-tropical convergence zone (ITCZ). It can also eliminate relative MSLP minima that are not cyclones, but merely broad areas of relatively low pressure between two high pressure systems. Criterion (iii) is designed to measure the amplitude of the vortex warm core. Based on the difference of climatological characteristic statistic (Cheung and Elsberry, 2002), criterion (iii) can exclude extratropical cyclones and reduce FA rate as the 250-850 hPa thickness fields are much smaller than TCs. There could be short-term increase in convective activity of tropical cloud cluster due to diurnal cycle, but eventually the cluster could not develop into a tropical depression that the FA can be excluded by the criterion (v).

2.3. Method of forecast verification

With reference to the above criteria, this paper will verify TC genesis forecasts over the WNP provided by 12-72 h ECMWF forecast field. Time and locations of TC genesis are extracted from the HKO BT. ECMWF TC genesis forecasts are classified into four different cases (Cheung and Elsberry, 2002):

- (i) Hit rate - the model TC is generated within 24 hours of the BT TC and is located within 5° of the BT genesis location;
- (ii) Early Genesis (EG) - although the model TC is located within 5° of the BT genesis location, it is generated earlier than BT TC by 24-72 hours;
- (iii) Late Genesis (LG) - during the time when the model TC is generated, the BT TC have been generated more than 24 hours ago (but the BT TC genesis time could not be earlier than the model TC by more than 72 hours). At the time of genesis, the model TC is within 5° of the current location of BT TC;
- (iv) FA - genesis of TC is forecast by the model, but TC is neither generated within 24 hours of the BT, nor located within 5° of the genesis location in BT. Or there is no model TC generated within 24 hours of the BT TC genesis. The above two scenarios are both considered as FA.

Both EG and LG belong to incorrect genesis time, and they are grouped under Incorrect Timing (IT) in the later part of this paper. The results of Pasch *et al.* (2006) and Halperin *et al.* (2013) indicated that using ± 12 hours as tolerance will significantly reduce the hit rate of TC

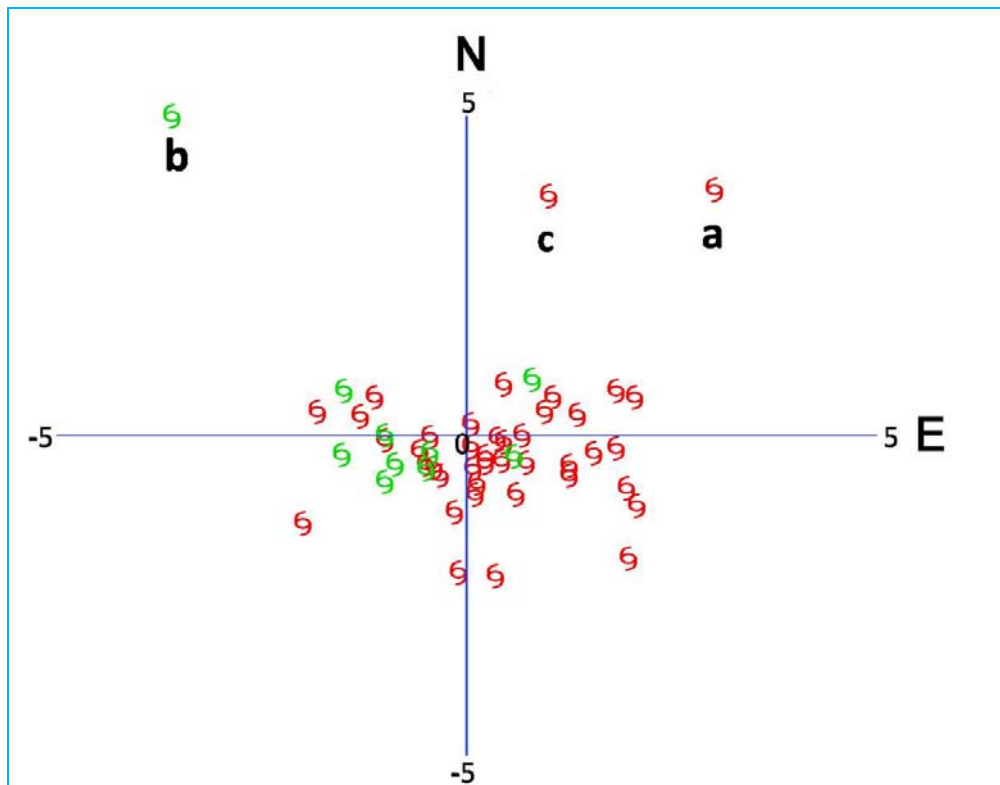


Fig. 2. Positions of relative minimum in MSLP found in ECMWF analysis field and relative to the corresponding BT TC genesis locations, with a grid distance of 5° latitude or longitude. Genesis cases over the seas east of the Philippines (120-180° E) are shown in red while that over the SCS (100-120° E) are shown in green. Symbols a, b and c are explained in the texts

TABLE 3
Statistics of closed isobar criterion

No. of samples	No. of samples not fulfilling closed isobar criterion	TC cases not fulfilling closed isobar criterion
68	2	Super Typhoon Utor (1311), TD1105 (2013)*

* http://www.weather.gov.hk/publica/tc/tc2013/english/track1105_06.htm

genesis forecast comparing with ± 24 hours. Hence, we shall use ± 24 hours as the tolerance.

2.4. Determination of thresholds

With variations in TC genesis characteristics in different basins, definition of parameters and determination of thresholds would also be different. In the following, statistical analysis were carried out based on the above TC genesis criteria, time and location of TC genesis over the WNP between 2013 and 2015 extracting from the HKO BT and 2013-2015 ECMWF deterministic forecast fields.

(i) Retrieved relative minimum in MSLP in ECMWF deterministic forecast fields within 5° of the BT genesis location. It will be included as a sample if there is at least one closed isobar at a 2 hPa interval. Statistics of closed isobar criterion was shown in Table 3.

Although a relative minimum in MSLP in the ECMWF analysis field could be found within 5° of the BT genesis location when Super Typhoon Utor (1311) and TD1105 (2013) formed, there is no closed isobar at 2 hPa interval. Possible reasons could be a relatively earlier and stronger genesis as indicated in the HKO BT, or satellite data near the genesis location not significantly assimilated in ECMWF analysis field.

Around 97% of the samples fulfilled the closed isobar requirement and the relative minimum in MSLP identified in analysis field is located within 5° of the BT genesis location. 95% of them could be found within 2° (Fig. 2) and the cases of more than 2° were tropical depression Unala (1314) (Symbol a), TD0907 (2014) (Symbol b) (Hong Kong Observatory, 2015) and severe typhoon Krovanh (1519) (Symbol c). This showed that

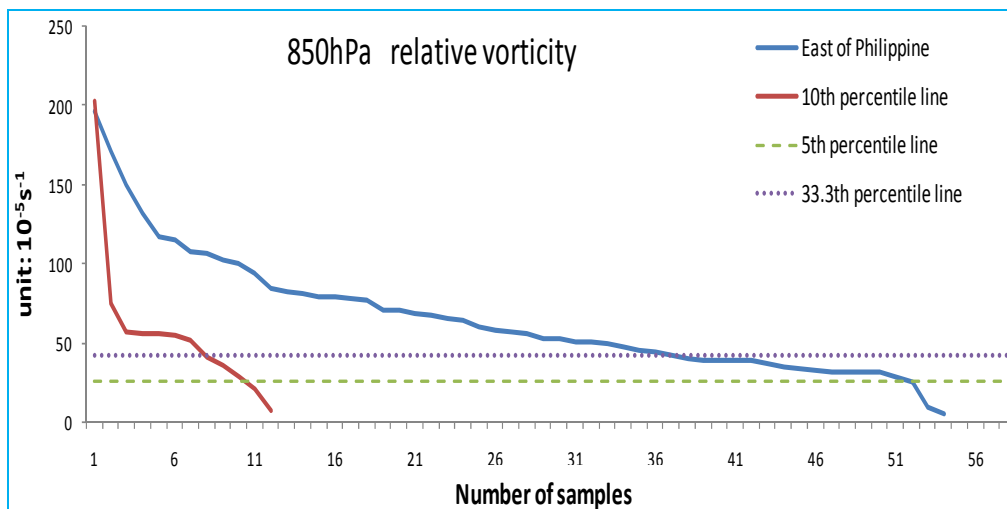


Fig. 3. Distribution of 850 hPa relative maximum in relative vorticity within 2.5° of the MSLP minimum found in ECMWF analysis field. Genesis cases over the seas east of the Philippines are shown in blue while cases over the SCS are shown in red

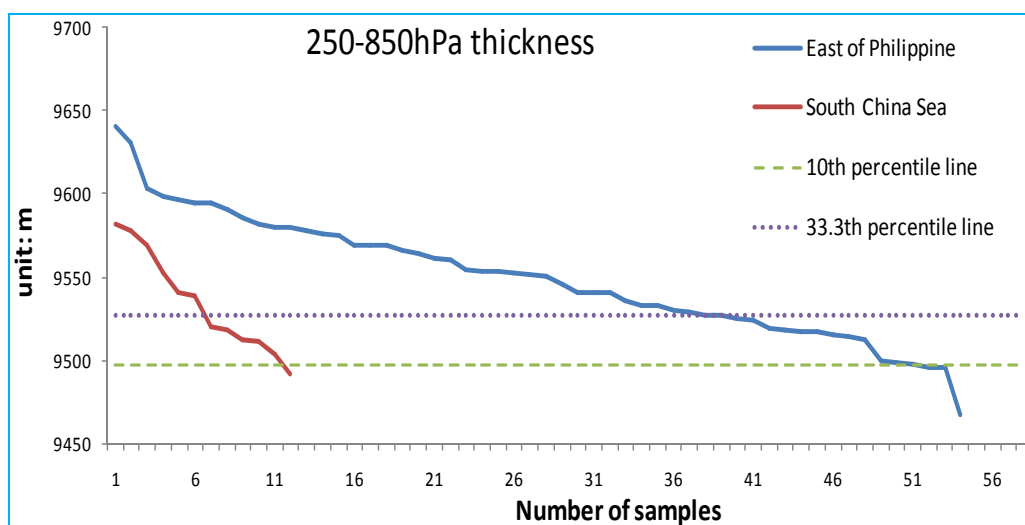


Fig. 4. Same as Fig. 3, but showing maximum 250-850 hPa thickness within 2.5° of the MSLP minimum

ECMWF analysis field could capture most of the TC genesis cases.

(ii) Retrieved relative maximum in 850 hPa relative vorticity within 2.5° of the above MSLP minimum (Fig. 3);

(iii) Retrieved maximum in 250-850 hPa thickness within 2.5° of the above MSLP minimum (Fig. 4);

(iv) Retrieved maximum wind speed at 925 hPa within 5° of the MSLP minimum (Fig. 5).

There were no significant differences in maximum 850 hPa relative vorticity and maximum 250-850 hPa thickness when a TC forms over the seas east of the Philippines and the SCS. However, there were differences in 925 hPa maximum wind speed, with greater wind speed for TCs generated in the seas east of the Philippines than those over the SCS.

Thresholds from analysis fields are determined by finding out the combination of minimum number of parameters for TC genesis, and this can also quantify TC genesis index. The usual way to determine thresholds

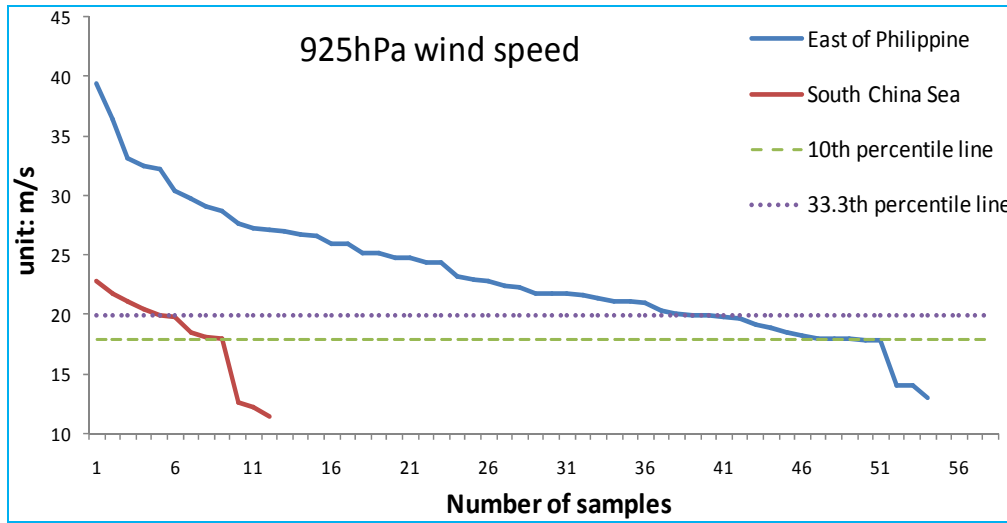


Fig. 5. Same as Fig. 3, but showing maximum 925 hPa wind speed within 5° of the MSLP minimum

TABLE 4

Different combination of percentile chosen based on historical samples. The optimal combination is shown in bold, and the optimal combination over the Atlantic adopted by Halperin *et al.* (2013) is shown in *italics*

Combination	850 hPa relative vorticity	250-850 hPa maximum thickness	925 hPa maximum wind speed
1	0 th percentile (smallest)	0 th percentile (smallest)	0 th percentile (smallest)
2	5 th percentile	5 th percentile	5 th percentile
3	5th percentile	10th percentile	10th percentile
4	10 th percentile	5 th percentile	5 th percentile
5	10 th percentile	10 th percentile	10 th percentile
6	20 th percentile	20 th percentile	20 th percentile
...
<i>Halperin et al. (2013)</i>	<i>33.3th percentile</i>	<i>33.3th percentile</i>	<i>33.3th percentile</i>

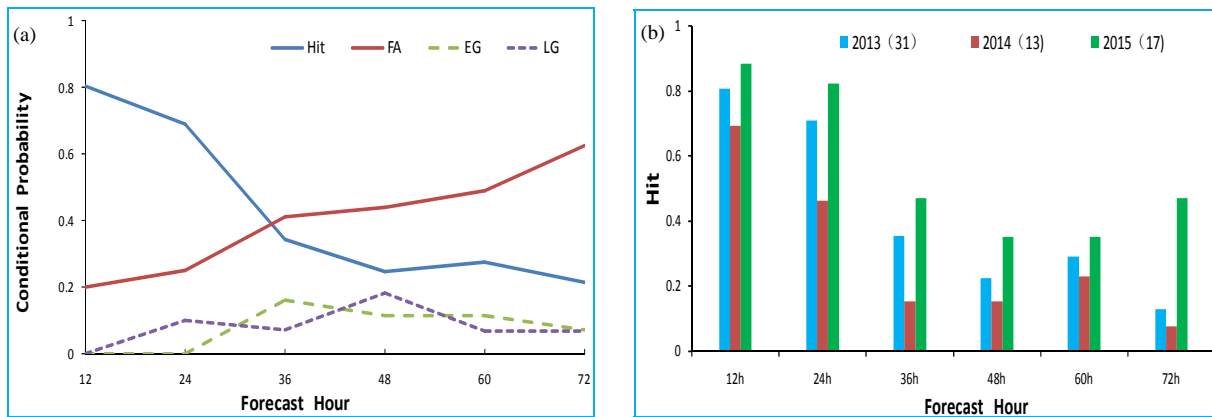
is to pick a certain percentile of historical sequence (from highest to lowest) (Halperin *et al.*, 2013). For example, the threshold that Halperin *et al.* (2013) picked is the 33.3th percentile (the lowest tercile). The percentile picked varies with types and resolution of models, and also geographical area. To better evaluate the skill of model TC genesis forecasts and improve their accuracies, we conducted a series of tests with different combination of thresholds based on criteria (ii) - (iv) as stated in Section 2.3 (detailed results given in Section 3). The optimal combination was the lowest 5th percentile of maximum 850 hPa relative vorticity, lowest 10th percentile of maximum 250-850 hPa thickness and maximum 925 hPa wind speed (shown in bold red in Table 4).

TABLE 5

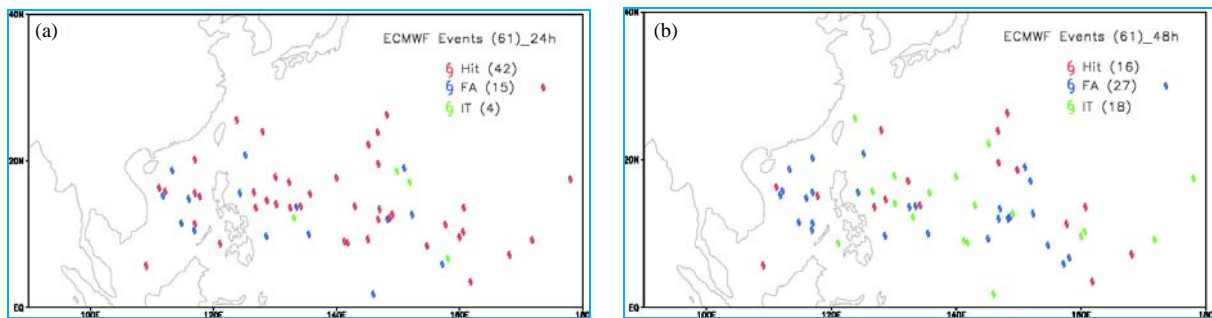
Thresholds obtained from the optimal combination

Basin	850 hPa relative vorticity ($10^{-5} s^{-1}$)	250-850 hPa thickness (m)	925 hPa maximum wind speed (ms^{-1})
WNP	25.8597	9497.5	17.8296
Atlantic	20.286	9473.0	15.43

Table 5 shows the thresholds obtained according to our test results. Comparing with those obtained in Halperin *et al.* (2013) over the Atlantic, their thresholds are significantly lower than ours despite the same



Figs. 6(a&b). Forecast verification of 2013-2015 TC genesis over the WNP using the optimal combination thresholds. (a) Change of hit rate, FA, EG and LG with forecast hours and (b) Change of hit rate in different years



Figs. 7(a&b). Geographical distribution of cases of hit rate, FA and IT (a) 24 hours forecasts prior to TC genesis and (b) 48 hours forecasts prior to TC genesis

ECMWF resolution and higher percentiles chosen. This may be attributed to different number of historical samples and different climatology between the WNP and the Atlantic. Nevertheless, the thresholds obtained in both basins are much higher than tropical oceans. Even for the area with severe tropical cloud cluster activities, their 850 hPa relative vorticity, 250-850 hPa thicknesses and 925 hPa wind speed could not reach the above thresholds. Therefore, miss cases will be rather limited when we use multiple thresholds to predict TC genesis. In this paper, we shall focus on the hit rate, FA, EG and LG of TC genesis.

3. Results and discussion

Owing to the missing data in ECMWF forecast fields (Table 2), there were only 61 cases for verification. The verification results could help better understand the skills of ECMWF model in predicting TC genesis over the WNP and the SCS for various forecast hours and years. This can provide a good reference for operational forecast, and provide a useful reference to developers of NWP models.

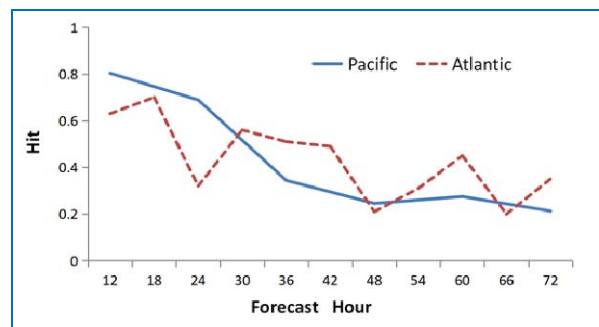
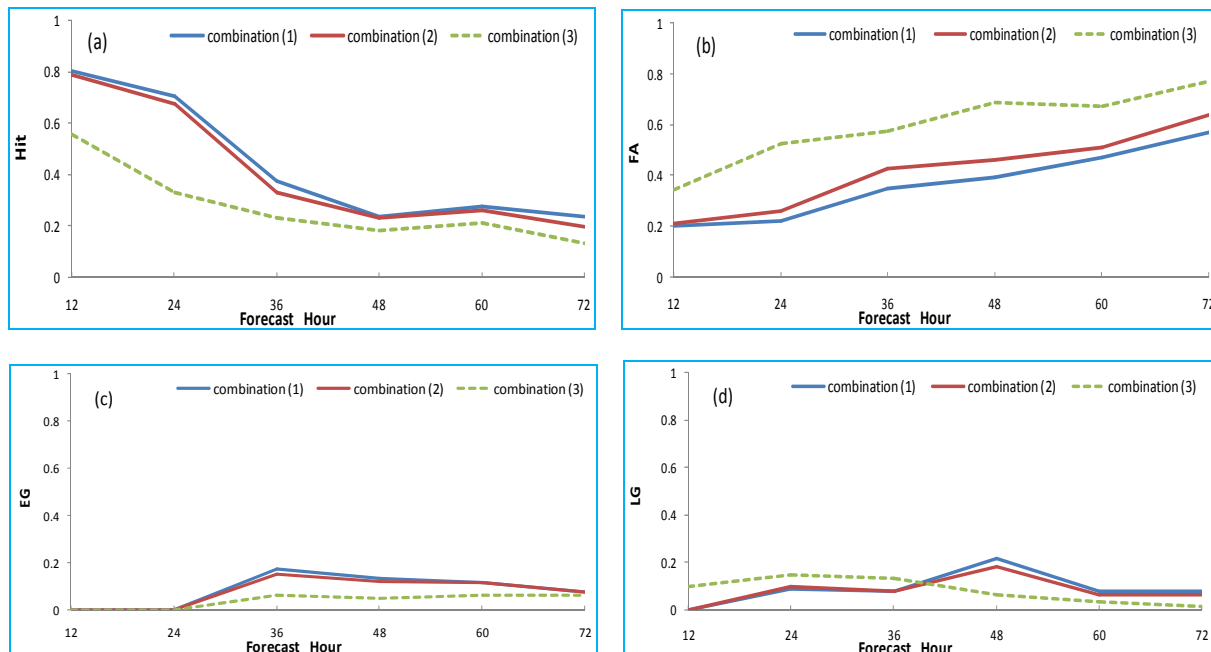


Fig. 8. Change of hit rate with forecast hours in WNP (2013-2015) and Atlantic (2004-2011)

3.1. Optimal scheme of thresholds

Figs. 6(a&b) show the results of the optimal thresholds scheme. Similar to the previous researches, hit rate of genesis drops significantly with forecast period, from 0.8 in 12 hours to 0.24 in 72 hours. In contrast, FA rises gradually with forecast period. There exist three different stages of the drop of hit rate with forecast period



Figs. 9(a-d). Change of (a) hit rate, (b) FA, (c) EG and (d) LG with forecast period using different combination of thresholds

[Fig. 6(a)]: (i) hit rate only drops slightly between 12 and 24 hours and generally keeps above 0.7. This shows that ECMWF's 12 and 24 hour forecasts can reasonably capture more than 70% of TC genesis cases and thus provide an objective guidance to operational TC genesis forecast; (ii) the drop is greatest between 24 and 48 hours, from 0.71 in 24 hours to 0.24 in 48 hours (drop by 2/3). The cyclogenesis forecast skill falls so drastically from 24 hour lead to 48 hour lead, It may be related to the forecast performance of the ECMWF model for tropical cyclones. The ECMWF deterministic prediction system's ability to predict tropical cyclone intensity would drop sharply in the initial stage (0-48 hours) (Hodges and Emerton, 2015); (iii) the drop levels off between 48 and 72 hours. This shows that TC genesis forecast from ECMWF become stable after 48 hours. Surprisingly, EG and LG only change slightly with forecast period, staying within 0.1 and 0.2, contrasting sharply with hit rate and FG.

As seen from the distribution of hit rate in different years [Fig. 6(b)], a significant variation exists in TC genesis forecast performance in different years. This may attribute to the limited number of TCs generated in a year. Also, the difference in the overall strength and structure stability can also contribute to such variation.

The performance of TC genesis forecast also varies in different regions. Even in the WNP, there is a significant variation in forecast performance in different

sea areas [Figs. 7(a&b)]. For example, the hit rate over the seas east of the Philippines (24 h: 70.8%, 48 h: 27.1%) is significantly higher than that over the SCS (24 h: 61.5%, 48 h: 23.1%) and this could be related to thresholds definition. From Section 2.4, 925 hPa wind speed over the SCS when a TC forms was generally smaller than that over the sea east of the Philippines. The NWP model tends to have weak forecast performance for weak TC, which may be the potential reason that the prediction ability of the optimal thresholds scheme is lower in SCS than in the seas east of the Philippines. With the small number of samples, the thresholds defined in this paper are not region specific. Hence, 925 hPa wind speed threshold could be relatively high when a TC formed over the SCS. The verification results also show that among the 13 genesis cases over the SCS, FA was mainly triggered by low 925 hPa wind speed apart from a few case of not fulfilling closed isobar criterion. If there are more samples in the future, we can determine region-specified thresholds and this may improve the hit rate.

For 24 and 48 hours forecasts, EG and LG could only be found in the WNP east of the Philippines and there is no EG and LG over the SCS. It is also worth to note the two regions with the highest FA, one located at the central and northern parts of the SCS to seas near the Philippines (110~130° E, 8~23° N) and another one located at the central part of the WNP (147~160° E, 5~20° N).

The TC genesis criteria proposed in the paper are mainly based on the results from Halperin *et al.* (2013). They applied similar criteria to verify TCs generated in the Atlantic Ocean in ECMWF model during 2004-2011. Comparing the results in the Atlantic Ocean and the WNP, it is discovered that the skill of ECMWF in TC genesis also varies with the basin (Fig. 8). The hit rate over the Atlantic exhibits different characteristics from that over the WNP. After a significant drop between 12 and 24 hours, the hit rate for the Atlantic basin does not drop with the forecast periods between 24-72 hours. Moreover, the forecasts for the WNP appear to perform better than those for the Atlantic. Apart from climatology and number of samples, discrepant data period, forecast field with different time resolution could also be a reason of such discrepancy. As ECMWF has been improved on the physical processes like deep convection, radiation and also the vertical diffusion over the boundary layer since 2007, this would certainly affect the model performance to some extent.

3.2. Analysis using different combination of thresholds

In determining the best thresholds combination, a series of tests have been conducted using combination of different percentiles. Fig. 9 shows three combinations of thresholds.

- (i) 5th percentile of 850 hPa maximum relative vorticity, 10th percentile of maximum 250-850 hPa thickness and 925 hPa maximum wind speed;
- (ii) 10th percentile of 850 hPa maximum relative vorticity, maximum 250-850 hPa thickness and 925 hPa maximum wind speed;
- (iii) 33.3th percentile of 850 hPa maximum relative vorticity, maximum 250-850 hPa thickness and 925 hPa maximum wind speed.

Verification shows that lowering the percentiles would effectively improve the hit rate and decrease FA, but at the same time EG and LG will rise significantly. As a result, it is not preferable to choose a high percentile which means more difficult to generate a model TC.

It is also worth to point out that 850 hPa maximum relative vorticity is the most sensitive one among other parameters. In combination (ii), the performance is not greatly affected when maximum 250-850 hPa thickness and 925 hPa maximum wind speed are set to the 5th percentile. However, when the percentile of 850 hPa maximum vorticity is set to the 5th [combination (i)], there is a significant improvement with the rise of hit rate and

drop in FA in nearly every forecast hours [Figs. 9(a&b)]. Moreover, there is no obvious increase in EG and LG at the same time [Figs. 9(c&d)]. The reason of the high sensitivity of 850 hPa maximum vorticity is a subject for further investigation in the future.

4. Conclusions

This paper sets TC genesis criteria based on previous research results, aiming to assist forecasters to determine the possibility of TC genesis in NWP models. Using the criteria defined, this paper also verified ECMWF TC genesis forecasts for TCs generated over the WNP during 2013-2015.

(i) ECMWF analysis field could capture most of the TC genesis, with the closed isobar criterion being fulfilled. The relative minimum in MSLP was located within 5° of the BT genesis location, and 95% of the cases even lied within 2°.

(ii) Using different percentiles to determinate TC genesis thresholds would significantly affect the results. Larger thresholds would increase FA, while EG would rise when smaller thresholds were used. The forecasts could be improved if reasonable adjustment is made to a particular threshold in a region. A slight adjustment of the relative vorticity at 850 hPa is the most sensitive to the forecast results over the WNP.

(iii) Verification of the optimal thresholds combination showed that 24 hours and 48 hours are the turning points among the forecast between 12 hours and 72 hours prior to the TC generated. The hit rate only drops slightly during the first 24 hours and generally stays above 0.7. Then it drops sharply beyond 24 hours and levels off after 48 hours. A significant variation exists in TC genesis forecast performance in different years. This is attributed to the limited number of TC cases available, the difference in the overall strength and structure stability from one year to another.

(iv) There is a significant variation in TC genesis forecast performance in different sea areas. The forecasts over the seas east of the Philippines are much better than those over the SCS. It is worth to note that the two regions with the highest FA, one located at the central and northern parts of the SCS to seas near the Philippines and another one located at the central part of the WNP. Moreover, the forecasts over the WNP appears to perform better than those for the Atlantic in the first 24 hours and this could be attributed to the different climatology, number of samples and data period in the two studies.

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