WRF Model Application to Analyze Factors Affecting Tropical Cyclone Forecasting in the Gulf of Thailand

Porpattama Hammachukiattikul

Mathematics Program, Faculty of Science and Technology, Phuket Rajabhat University, Phuket, Thailand
Corresponding author. E-mail address: porpattama@pkru.ac.th

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Abstract

This paper studies the factors affecting tropical cyclones forecasting in the Gulf of Thailand. The Weather Research and Forecasting (WRF) model is used for the simulation of tropical cyclones. The most interesting case is the formation of Typhoon Gay (8929) on 31 October 1989, which caused extensive losses in lives and property. A 30-year reanalysis dataset from the European Center for Medium-Range Weather Forecasts (ECMWF) and the National Centers for Environmental Prediction (NCEP) indicates that cold surges during the northeastern monsoon played an important role in the formation and WRF model simulation of Typhoon Gay. The results showed that Typhoon Gay had a lower intensity than that calculated from using tropical cyclone wind observations. A Rankin vortex initialization (i.e., a TC bogus technique) was applied for the adjustment of *u-v* winds in the tropical cyclone by defining parameters in the tropical cyclone (e.g., a radius of 350 km and a wind speed of 186 kt), which provided strong wind speeds. The three experiment cases are 1) changes in *u-v* wind at 1 level (925 hPa), 2) changes in *u-v* wind at 3 levels (925, 850, and 500 hPa), and 3) changes in *u-v* wind at 6 levels (1000, 925, 850, 700, 600, and 500 hPa). This paper compares these results with those for maximum wind speed from the Regional Specialized Meteorological Center (RSMC), which were calculated at 6 *u-v* wind adjustment levels given maximum wind speeds similar to those in the RSMC data. From this analysis, the influence of cold surges from northeast monsoons during the formation and intensification of tropical cyclones in the Gulf of Thailand was determined.

Keywords: Tropical Cyclone, WRF Model, Winter Monsoon Cold Surge, Forecast, the Gulf of Thailand

Introduction

Tropical cyclones are severe weather events that typically last about 60 hours, usually cause significant damage, with heavy rain and disastrous wind speeds, causing severe flooding, resulting in agricultural damage, environmental damage, and loss of life. The eye of a tropical cyclone is characteristically quiet and calm, surrounded by an intense circular storm, with low pressure counterclockwise circulation in the northern hemisphere and clockwise circulation in the southern hemisphere. Cyclones form over warm tropical waters, with the wind speed near the ocean surface exceeding 17 m/s. The magnitudes of maximum wind speed report by the World Meteorological as tropical depression (63 km/hr.), tropical storm (63 km/hr. - 88 km/hr.), severe tropical storm (89 km/hr. - 118 km/hr.), and typhoon (118 km/hr.). The circulation of tropical cyclone is arisen from coriolis force and pressure gradient force. The origin of tropical cyclone is from equatorial area. Tropical cyclone's life time is six days. The tropical cyclone process contains 4 steps as formation state, immature state, mature stage, and decaying stage. In the winter season, tropical cyclones forming in the Pacific Ocean move across the South China Sea and the Gulf of Thailand, and across the south of Thailand. Over the last 63 years (1951-2013), 191 tropical cyclones were made landfall in Thailand, and 13 tropical storms and 1 typhoon is Typhoon Gay occurring on November 4, 1989 was made landfall in the southern region of Thailand during the winter season.

There are two main monsoon seasons relevant to Thailand. The summer monsoon originates in the west of Thailand in the Indian Ocean, and brings heaviest rain, whereas the winter monsoon season originates in the Pacific Ocean and South China Sea, and usually brings less rainfall and tropical cyclone. These changes in the monsoonal wind direction from the summer to the winter season, with the differences in rainfall, are due to temperature differences between the oceans, and the continental temperature, together with the influence of the Himalayas in preventing much of the monsoonal wind and moisture from the cold continental interior reaching the coast in the winter monsoonal season. One characteristic of the winter monsoon is cold surges, which produce severe storms, flooding, high waves and tropical cyclone formation.

In winter monsoon, northeasterly wind from the South China Sea starts to increase and flow into 5 °S or Thailand area. The characteristic of South China Sea is a low inversion, while high pressure of Siberian and Turkestan. The origin cold air surge to northwest of India and occur frequency in the period from November to December. Over the Indian Ocean, the surges are associated with the characteristic of tropical cyclone. Tropical cyclone occurs over the South China Sea during the northeasterly surge event, high intensity of vortices over the South China Sea. The enchantment of the horizontal gradient of zonal wind by the northeasterly surge appears over the Indian Ocean in November.

Weather modeling integrates the fields of mathematics, computing, and atmospheric sciences. The Weather Research and Forecast (WRF) model applies these three scientific areas to weather forecasting. This research uses the WRF model to study the factors affecting tropical cyclone development in the Gulf of Thailand, which include latent heat and sensible heat (over areas below 5 °S), low pressure, weak vertical wind shear, and upper level divergence (Montgomery & Farrell, 1993) studied the physical mechanisms inside and outside of tropical cyclones, including potential vorticity (PV) disturbances at high and low levels. A related theory on the relationship between atmospheric and oceanic factors was proposed by Emanuel (1986), who studied energy transfer from the ocean into the atmosphere. Brett (2010) developed sensitivity experiments using numerical weather prediction (NWP) modeling to define a responsive function, which would analyze perturbation of model. Hsiao et al (2010) changed the initial positions of tropical cyclones in the WRF model, which resulted in the observation data being more suitable for model's results. Huang and Guan (2012) studied the development of tropical cyclones over the South China Sea late in the tropical cyclone season and found that a longer monsoon time causes tropical cyclones to be stronger. Vissa, Satyanarayana, and Kumar (2013) found that relationship between the presences of peak cold surge with the presence of Typhoon Peipah in the South China Sea. For the winter monsoons, cold surge from the high latitudes create a relatively greater amount of clouds over tropical areas and the mid-latitude regions. The cold surge could affect large-scale circulation, including typhoons and tropical depressions. However, Wu, Yang, Wang, and Fong (2005) analyzed observation data to study the start times for monsoons over the South China Sea and found that latent heat release during cloud formation and tropical cyclone over the Bay of Bengal. Chang (2003) indicated that the Typhoon Vamei formation is associated with an interaction of strong cold surge that created the high vortices. Wongsaming and Exell (2011) found condition of a strong high-pressure area which is associated with cold surges during the winter monsoon. The forecasting of cold surges in Thailand revealed that the wind speed increased by at least 2.6 m/s, the mean sea level pressure increased by at least 1.8 hPa, the surface temperature increased by at least 1.7 °C and the dew point temperature increased by at least 2.1 °C during these events. The main objective of the present study is to investigate the influence of cold surges during the northeast monsoon on the formation and intensification of tropical cyclones over the Gulf of Thailand.

Methods and Materials

Rankin Vortex Initialization (Bogussing)

The tropical cyclone (TC) lifetime over the oceans where observational data are lacking and special effect should to taken into the initialize WRF model. Ranking vortex initialization (i.e. a bogussing method) is designed to significantly enhance initial tropical cyclone data (e.g., strength and a good position). Generally, vortex bogussing is generated the tropical cyclone like vortex that can be inserted into the numerical initial condition of WRF model. Vortex bogussing assumes the initial position, central sea level pressure, maximum tangential wind speed, and radius at the maximum tangential wind during a tropical cyclone. The tangential wind velocity is calculated as follows

$$c = c_m \frac{r}{R_m} \qquad for \quad r \leq R_m \tag{1}$$

$$c = c_m \left(\frac{r}{R_m} \right)^{-\alpha} \qquad for \quad r > R_m \tag{2}$$

where c_m represents the maximum tangential wind velocity, R_m represents the radius of maximum wind speed, and c represents the tangential wind velocity, which depends on the radius of the cyclone (r)

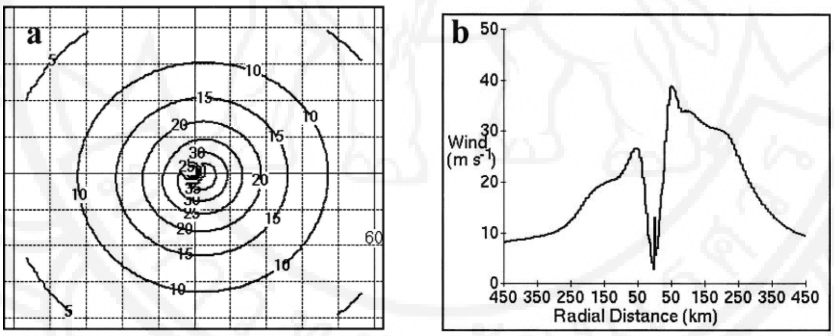


Figure 1 Relationship between wind speed and the radius of maximum wind speed

α is a constant between 0.5-1.0, which is set at $\alpha = 0.6$ in this research, and the tangential wind is calculated from the wind direction along both the x-axis(u) and the y-axis (v).

$$u = c\cos\theta \tag{3}$$

$$v = c\sin\theta \tag{4}$$

where θ represents the angle of the wind from the north.

The geopotential height can be determined from $z = gh$; if g represents gravity, and h represents height, then

$$\frac{\partial z}{\partial r} = fc + \frac{c^2}{r} \tag{5}$$

Replace (1) and (2) into (5) and integrate both sides of equations. The results are as follow

$$\int dz = \left(fc_m + \frac{c_m^2}{R_m} \right) \int \frac{r}{R_m} dr \qquad ; r \le R_m \tag{6}$$

$$\int dz = fc_m \int \left(\frac{r}{R_m} \right)^{-\alpha} dr + c_m^2 \int \frac{r^{-1-2\alpha}}{R_m^{-2\alpha}} dr \qquad ; r > R_m \cdot \tag{7}$$

Z is relative to r; hence,

$$z(r) = \frac{c_m}{2}\left(fR_m + c_m \right) \left(\frac{r}{R_m} \right)^2 + c_1 \qquad ; r \le R_m \tag{8}$$

$$z(r) = \frac{fR_m c_m}{1-\alpha} \left(\frac{r}{R_m} \right)^{1-\alpha} - \frac{c_m^2}{2\alpha} \left(\frac{r}{R_m} \right)^{-2\alpha} + c_2 \qquad ; r > R_m \cdot \tag{9}$$

The height of the air pressure system can be used to calculate the constants c_1 and c_2; then,

$$z(r) = z(R) - \left(\frac{fR_m c_m}{2(1-\alpha)} \left\{ 2\left(\frac{R}{R_m} \right)^{1-\alpha} - (1+\alpha) - (1-\alpha)\left(\frac{r}{R_m} \right)^2 \right\} \right) \left(-\frac{c_m^2}{2\alpha} \left\{ \left(\frac{R}{R_m} \right)^{-2\alpha} - (1+\alpha) + \alpha \left(\frac{r}{R_m} \right)^2 \right\} \right) \qquad ; r \le R \tag{10}$$

$$z(r) = z(R) - \left[\frac{fR_m c_m}{(1-\alpha)} \left\{ \left(\frac{R}{R_m} \right)^{1-\alpha} - \left(\frac{r}{R_m} \right)^{1-\alpha} \right\} - \frac{c_m^2}{2\alpha} \left\{ \left(\frac{R}{R_m} \right)^{-2\alpha} - \left(\frac{r}{R_m} \right)^{2\alpha} \right\} \right] ; r > R \cdot \tag{11}$$

Data

Initial data for tropical cyclone modeling can be acquired and downloaded from the National Center for Environmental Prediction (NCEP) and the European Centre for Medium-Range Weather Forecasts (ECMWF) such ERA-Interim. The NCEP data have a 1 x 1° spatial resolution and a 6-hour temporal resolution, and the ECMWF data have a 2.5 x 2.5° spatial resolution and a 6-hour temporal resolution. Twenty-year tropical cyclone data on those that influence southern Thailand are shown in Figures 2-3. In this research, Typhoon Gay is selected because it caused substantial damage in southern Thailand (Table 1, which was collected from the Joint Typhoon Warning Center (JTWC)

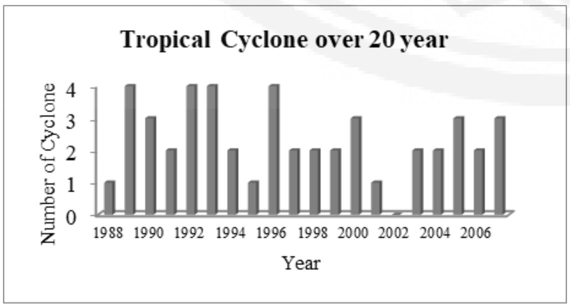


Figure 2 Tropical data from 1988-2007

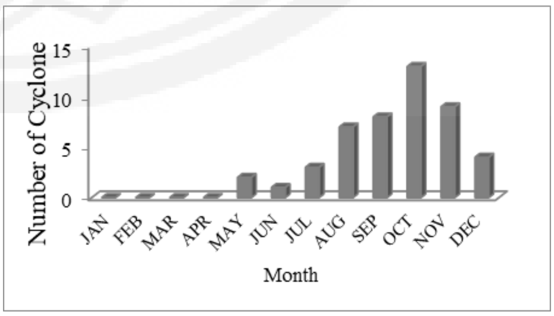


Figure 3 Monthly tropical data over 20 years

Table 1 Observation data for Typhoon Gay (1989)

Name	Year	Month	Day	Hour (UTC)	Latitude	Longitude	Wind (kt)	P_{center}
	1989	11	2	03	8.0	102.3	0	1002
	1989	11	2	06	8.1	102.1	35	998
	1989	11	2	12	8.2	101.9	40	994
	1989	11	2	18	8.4	101.8	40	994
	1989	11	3	00	8.7	101.6	45	992
Gay	1989	11	3	06	9.0	101.4	45	990
	1989	11	3	12	9.7	101.1	55	980
	1989	11	3	18	10.1	100.8	60	975
	1989	11	4	00	10.3	100.3	65	970
	1989	11	4	06	10.6	99.8	75	960
	1989	11	4	12	10.8	99.0	65	970
	1989	11	4	18	11.3	97.5	60	975

Study Area

The study area consists of 2 domains covering Thailand. The first domain has 99,000 points, and the second domain has 320,000 points, which are shown in Figure 4.

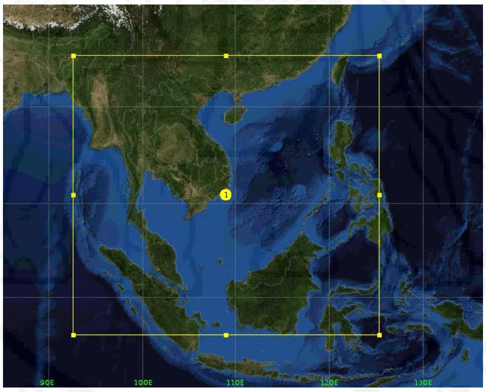


Figure 4 Study Area

Northeast wind

Northeasterly winds cause cold surges to travel from northern Thailand to the Gulf of Thailand, which causes the humidity is travel over southern Thailand from November to December. However, this experiment defines the northeast wind direction from 22.5° to 67.5°, as shown in Figure 5.

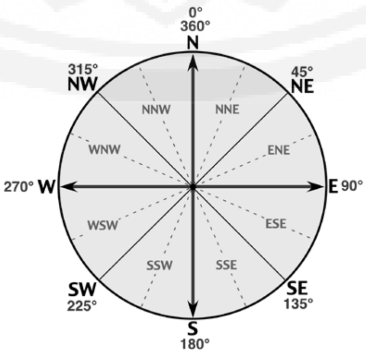


Figure 5 Wind direction (http://www.physicalgeography.net/fundamentals/7n.html)

Northeast Wind Adjustment

Optimization of the wind speed to increase the strong northeast wind speed is defined by the following equation $U_{new} = aU_{model}$, where U_{new} represents the improved wind speed, and U_{model} represents the wind speed from the WRF model. Then, the wind components in the *x* and *y* directions (u_{new}, v_{new}) show that

$$u_{new} = a_1 u_{model} \quad (12)$$

$$v_{new} = a_2 v_{model} \quad (13)$$

where the constants are a_1=2.33 and a_2=2.44

Table 2 Description of experimental cases.

Case	01	02	03	04	05	06
Descriptions	Control	Bogussing	Control & Bogussing - 1 level (E01)	Northeast *u-v* wind adjustment - 1 level (NE)	Northeast *u-v* wind adjustment - 3 levels (NE01)	Northeast *u-v* wind adjustment - 6 levels (6LEV)

Table 3 Constant parameters for tropical cyclone modeling

Year	Name	Pressure (mb)	Max. Wind (kt)	TC Max. Radius (km)
1989	Gay	989	186	350

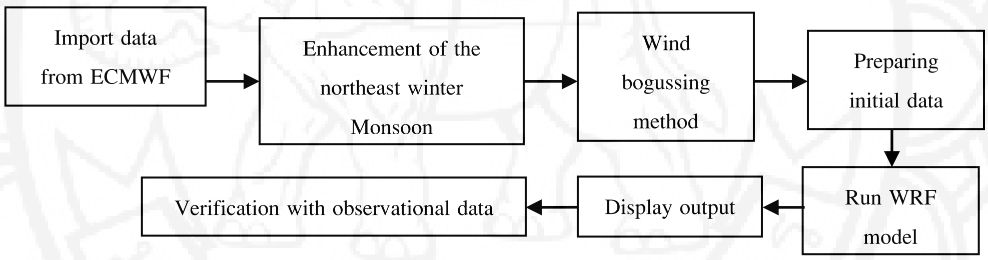


Figure 6 Experimental process

The constant parameters used in the Rankin vortex initialization method (from the Joint Typhoon Warning Center (JTWC) are shown in Table 3. Figure 6 shows the process for each experimental case.

Results and Discussion

Monthly wind speeds and 2 m temperature from the ECMWF and NCEP data were analyzed at 200 hPa and 850 hPa for 1989. Figure 7 (a) illustrates the average 30-year wind speeds from the ECMWF data (green) using average wind data from November 1989 (Red), and Figure 7 (b) illustrates NCEP winds using wind data from November 1989. The NCEP data provides stronger wind speeds than the ECMWF data. Therefore, the simulation selected the ECMWF data because it is suitable for enhanced wind speeds.

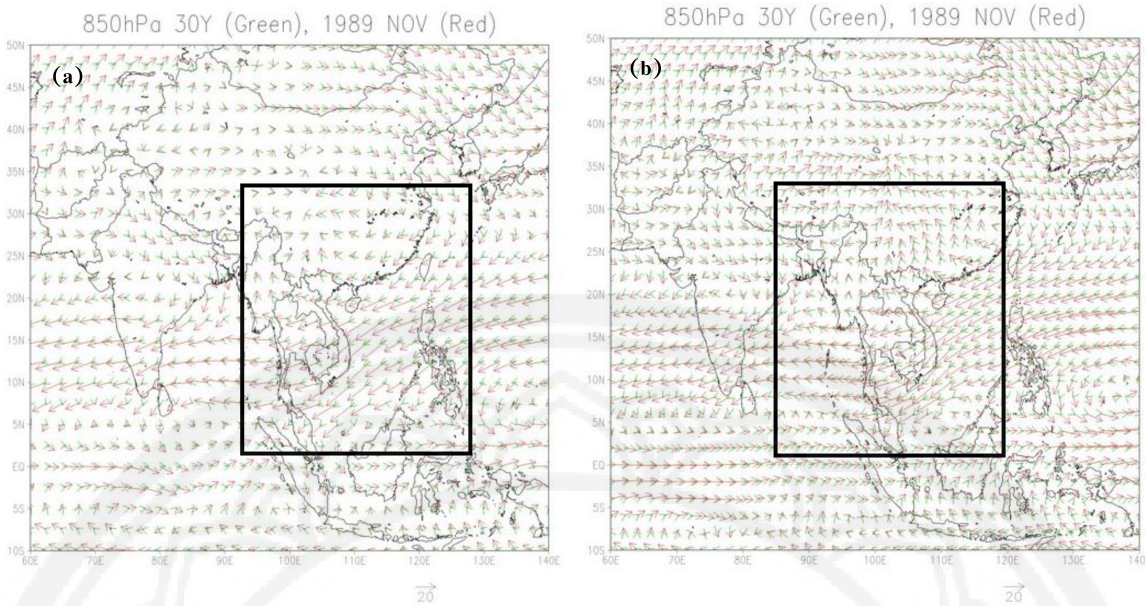


Figure 7 Average 30-year winds (green) using wind data from November 1989 (red). (a) ECMWF data (b) NCEP data

Table 4 Maximum wind speeds.

Name	Experimental Cases	Observed Maximum Wind Speed (m/s)	Maximum Wind Speed from the Model (m/s)	Absolute error (m/s)
GAY	Control	41.51	40.25	1.26
	Bogussing 1 level	44.14	43.46	0.68
	NE	45.22	46.12	0.90
	NE01	50.74	52.34	1.60
	6LEV	55.63	57.41	1.78

Table 4 shows that the resulting enhanced northeast wind speeds at 6 levels are the strongest because the simulation intensified depending on the cold surge during the winter monsoon. The other cases show that improving many level provide the stronger maximum wind speed. Figure 8 shows the 2 m temperature; the black color represents the temperature at approximately 270 K (-3.15 °C). The temperature in October is greater than that in other months. This is because Typhoon Gay began its formation in October.

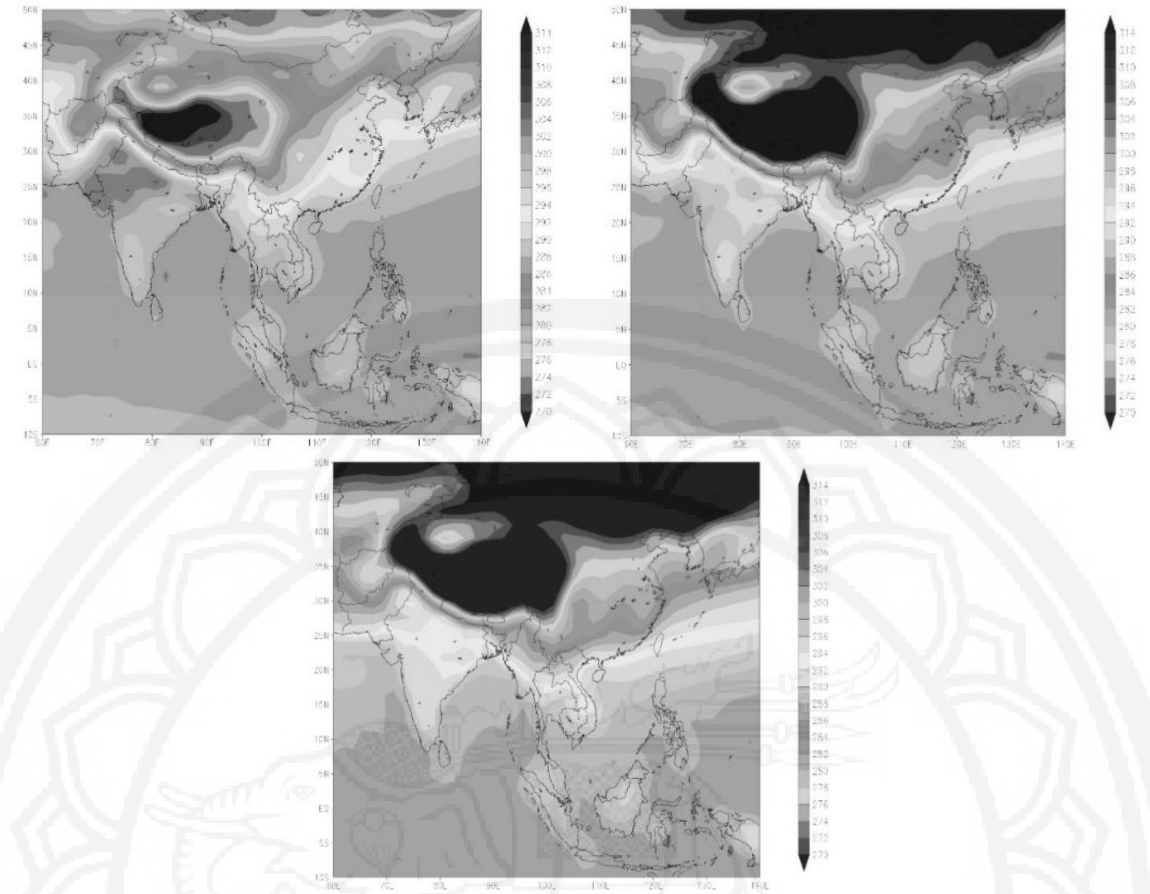


Figure 8 Surface temperature in October, November, and December of 1989

The air pressure and wind speed at each level at 00 UTC in December 1989 were analyzed. The high pressure over China propagated over Thailand (i.e., a cold surge), which caused two cold surges on 1st and 2nd, and 14th to 16th of December 1989. It was found that as the temperature decreased, a strong northeast wind developed over the South China Sea and the Gulf of Thailand, as shown in Figure 9.

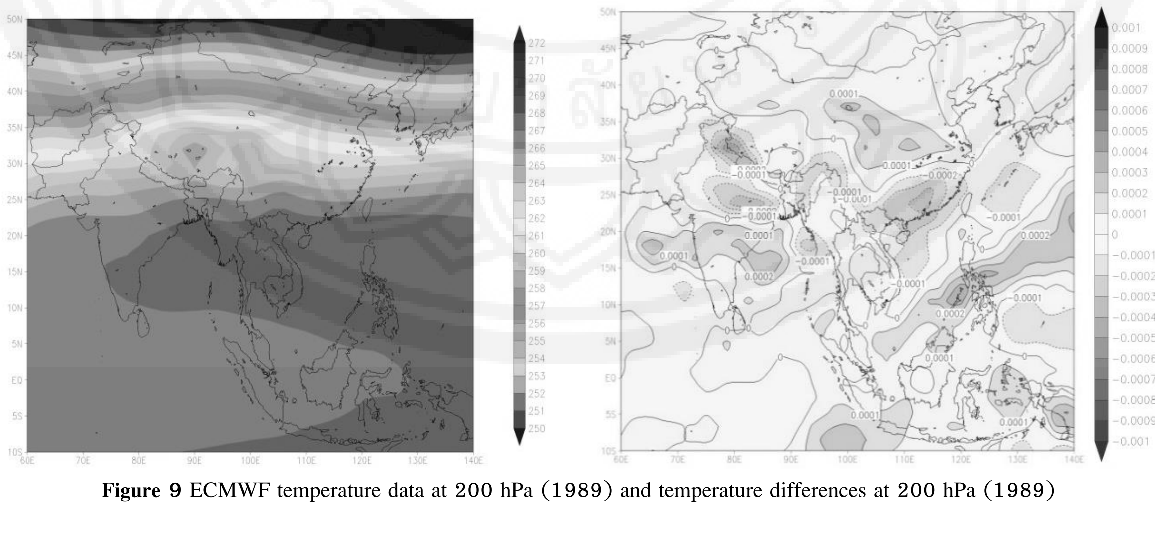


Figure 9 ECMWF temperature data at 200 hPa (1989) and temperature differences at 200 hPa (1989)

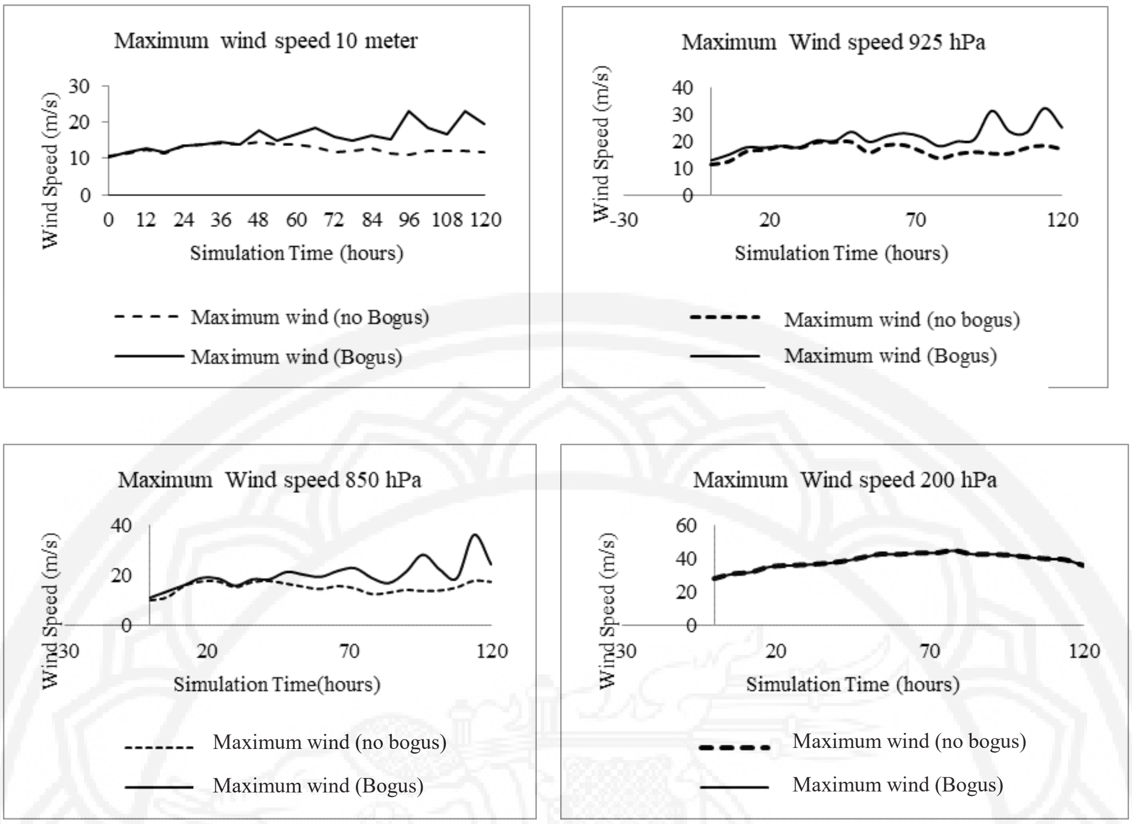
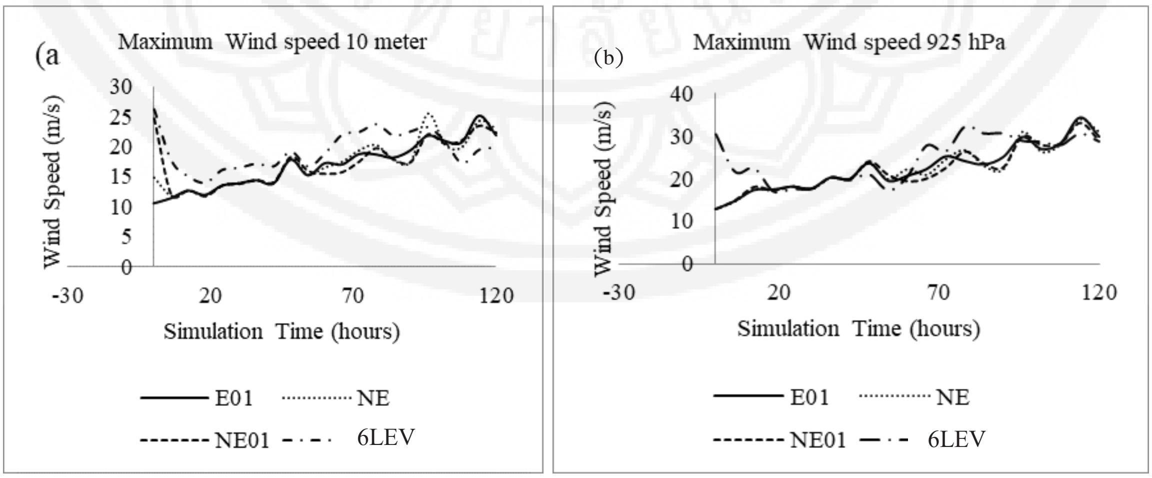


Figure 10 Maximum wind speeds at 10 m, 925 hPa, 850 hPa, and 200 hPa

Comparing the maximum wind speeds between the no bogus and bogus methods at 10 meters shows that the wind forecast using the bogus method was for strong winds at 40 hours and 96 hours (23.07 m/s). Therefore, bogussing at just 1 level is not sufficient; many adjusted levels are shown in Table 2. Figure 11 (a) demonstrates that a 10 ms wind adjusted at 6 levels (6LEV) results in the strongest wind at the beginning of the simulation. The wind speed at three levels (NE01) is less than that at 1 level (NE). After 18 hours, the wind speed fluctuates again, and at 48 hours, the wind speed is approximately 25.5 m/s. The final hour in the 6LEV experiment has the lowest wind speed compared to the other experiments.



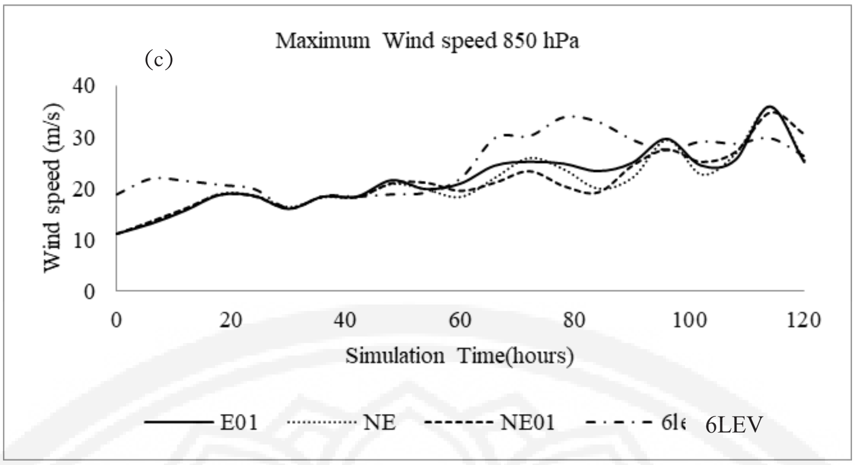


Figure 11 Maximum wind speed at 10 m, 925 hPa, 850 hPa and 200 hPa

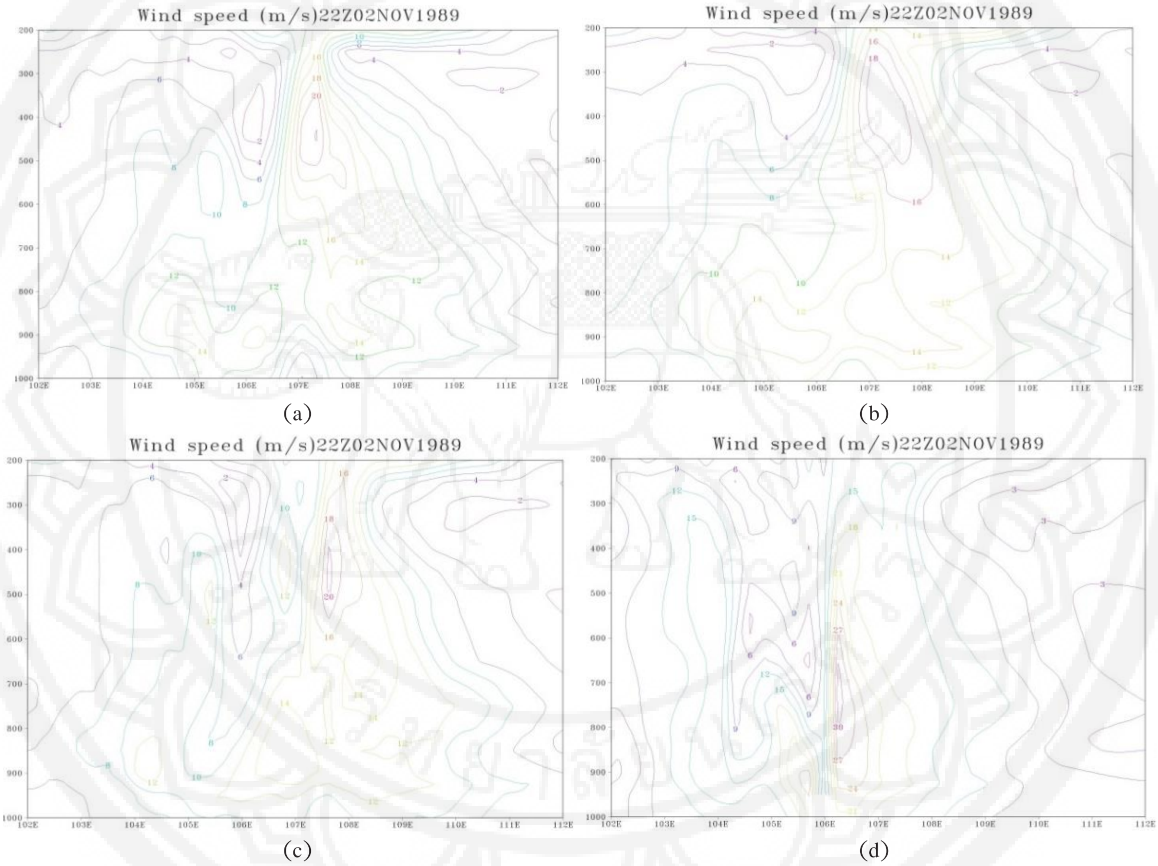


Figure 12 Cross section of the tropical cyclone on November 2, 1989. (a) Control, (b) Rankin vortex initialization, (c) northeast u-v wind adjustment at 3 levels, and (d) northeast u-v wind adjustment at 6 levels

Figure 12 shows the cross sections of the tropical cyclone on November 2, 1989. The x-axis represents the longitude between 102-112 °E, and the y-axis represents the height between 1000–200 hPa. The cross sections indicate the wind speed pattern at each height level. The results show that the 6LEV wind is stronger than that in the other experiments and has a clear pattern. The maximum wind speed is found at 850 hPa (approximately 30 m/s).

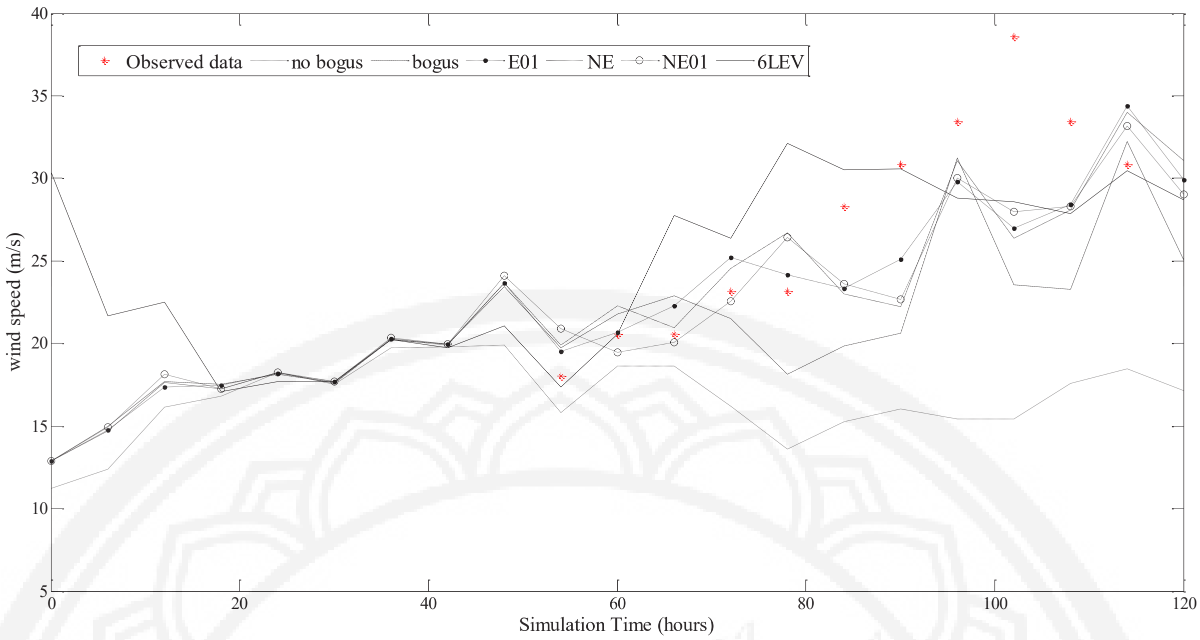


Figure 13 Maximum wind speed at 925 hPa

Figure 13 demonstrates the maximum wind speed at 925 hPa, and the red points represent the observational data after 58 hours. The bogus data at 1 level (NE01) and that at 6 levels (6LEV) have similar observational data after 90 hours. Therefore, utilizing the northeast wind at 6 levels is suitable using that observational data.

Conclusion and Suggestion

Factor affecting the development of tropical cyclones in the Gulf of Thailand were analyzed by using the WRF model. First, wind data and 2 m temperature were analyzed at 200 hPa, 850 hPa and compared with wind data over the last 30 years. The results showed that in October of 1989, a stronger than normal wind occurred. High pressure from China propagated over Thailand, which is referred to as a cold surge. However, the northeast *u*-*v* wind is the most important factor in tropical cyclone formation over the Gulf of Thailand. Also, using the WRF model showed that wind speed was a weak factor, which, however gained importance through adjustment using the Rankin vortex initialization method. The results demonstrated that the wind speed was strong at 10 meters, 850 hPa, and 925 hPa. After the change in wind speed, the u and v winds followed a northeast wind direction, which resulted in 3 experiments: 1) 1 changing level at 925 hPa; 2) 3 changing levels at 925 hPa, 850 hPa, and 500 hPa; 3) 6 changing levels at 100 hPa, 925 hPa, 850 hPa, 700 hPa, 600 hPa, and 500 hPa. The experiment found that *u* and *v* winds under the 6 level adjustment scenario were suitable using the observational wind data. A plot of the maximum winds using observational data revealed that the 6-level adjustment winds were good for tropical cyclone formation.

Acknowledgement

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