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CHARACTERISTICS OF TROPICAL CYCLONES IMPACTING A NUCLEAR POWER PLANT IN SOUTHERN FUJIAN AND ESTIMATE OF MINIMUM CENTRAL PRESSURE

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Abstract: Based on tropical cyclone (TC) data for the period 1949 to 2008 and following the Gumbe－I method, Pearson-Ⅲ method and determinacy method, this article estimates the possible minimum central pressure of TCs affecting southern Fujian where a nuclear power will be located. Results show that the observed minimum central pressure of TCs agrees well with the results determined with the methods above and there is little difference between them (the minimum central pressure is 867.4 hPa and 868.1 hPa, respectively, in a 1,000-yr return period). Established with the theory of atmospheric dynamics, the determinacy method yields a result of 867.28 hPa/1000 years, only a little smaller than the result of the probability method. Because of randomicity in parameter adjustment with the Pearson-Ⅲ method whereas the determinacy method is theoretically solid and its estimates are the smallest of the three methods, it is therefore reasonable, for security and conservative concerns, to adopt the result determined with the determinacy method as the possible maximum intensity of TC (with the central pressure being 867.28 hPa in a 1,000-yr return period).

Key words: southern Fujian area; tropical cyclones; climate characteristics; possible minimum central pressure; probability method; determinacy method

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1 INTRODUCTION

Fujian's southern coast is high in the frequency of tropical cyclones (hereinafter referred to as TCs) and experiences serious disasters. A designed benchmark of TCs is an important parameter for nuclear power engineering and the lowest estimated possible central pressure of TCs is the key benchmark in the design process. The so-called “possible largest TC” refers to one that is hypothetically stable, which is determined based on the value of maximum sustained winds for a specific coastal region with the combination of selected meteorological parameters[1]. The first step to decide the TC benchmark is to estimate the lowest central pressure P_0, and then with P_0 and relevant parameters, to determine the possible maximum wind speed in the TC. So it is clear that the minimum central pressure is the key for the maximum possible TC benchmark design during a feasibility study for nuclear power plants. The TC is the result of air-sea interaction[2]. Lin et al.[3] studied the relationship between the TC activity and Pacific sea surface temperature (SST). The studies from Huang et al.[4, 5] showed that the TC activities have close relationship with the Pacific Meridional Model (PMM) of coupled ocean-atmosphere and the central North Pacific SST anomalies, which affect the large-scale TC-related climatic conditions in the Pacific. Zhang[6], Yu et al.[7], Lei et al.[8], Ma et al.[9] have done lots of research on the relationship between the intensity of TCs and the climate change, with some pointing out that the climate anomalies led to the reduction of the frequency of TCs but the increase in intensity. Li et al.[10] characterized the statistical feature of the TCs landing on China and pointed out that in different coastal areas (excluding islands) the intensity of TCs landing on China attenuates mainly within 12 hours after landing, and the stronger the landing TC, the

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more severe the attenuation. Wang et al.[11] showed that the time between July and September is critical for the occurrence of TCs moving to the north, especially in July and August which are a peak occurrence period, while in the time between January and April as well as December no TCs go north. Wang et al.[12] carried out statistical analysis of the features of the TCs in the South China Sea (SCS) and the Northwest Pacific that are with center wind speed ≥17.2 m/s in 1949–2005, and demonstrated that the TCs landing on China mostly take place from July to September and the most frequent landing area is the south coast of China.

With regard to the P_0 calculation, theories of certainty and probability, clearly stipulated in the Nuclear Security Guidelines[1] (hereinafter referred to as "Guidelines"), are used in this study to estimate the local minimum pressure of the TC center on a once-in-1,000-yr chance. The statistic methods of Pearson-III distribution and Bell distribution are commonly used to estimate the extreme value[13]. Chen et al.[14] gave a rather detailed description of several extreme-value distributions in meteorological applications. With the Gumbe extreme value distribution method, Zhou et al.[15] estimated the possible maximum TC intensity for a nuclear power plant in Hongyanhe, Liaoning and obtained some credible and conservative results. With the Poisson distribution, Yang[16] also analyzed the disasters caused by coastal TCs in China. The determinacy method is based on the principles of atmospheric dynamics[1]. Some research results showed that the TCs in western Pacific tend to enhance. The sensitivity of atmospheric conditions was tested by Cai[17] with the determinacy method, with the results showing that the possible lowest TC central pressure has a positive linear relationship with the geopotential height of TC's upper boundary (100 hPa) but a negative linear relationship with the air temperature of TC's upper boundary or SST, with a slow response to the values taken for the geopotential height and SST but a rapid response to that of air temperature. Meanwhile, with this method, Cai[17] calculated the maximum possible TC in the northern coastal areas of Zhejiang, concluding that the determinacy method—because of sufficient theoretical support and reliable data base—derives reasonable and safe design values and compensates the shortage of the probability theory.

2 DATA AND METHODS

Based on scientific data, such as 1949–2008 *Typhoon Yearbook and Tropical Cyclone Yearbook* compiled by the Shanghai Institute of Typhoon, *Meteorological Disasters in China (Fujian Volume)*, and the *Fujian Climate Impact Assessment Report: 2001-2008*, and according to the requirements of the Guidelines, the TC assessment area for nuclear power plants should cover areas 300 to 400 km from where the plants are located. Here in our work, TCs that have been within a 400-km radius around a nuclear power plant in southern Fujian from 1949 to 2008 (hereafter referred to as the assessment area, which is marked as a circle in Figure 1), and are ever stronger than tropical depression inside the assessment area[15] are investigated.

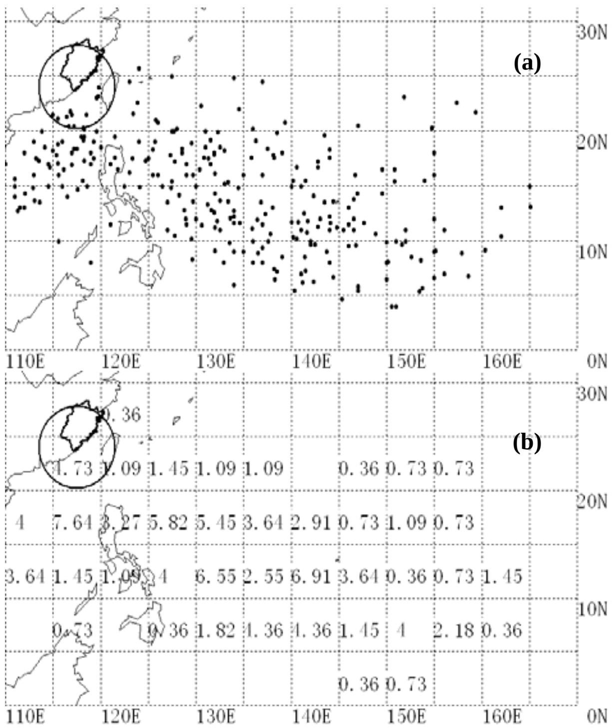

Figure 1. Sources of TCs affecting the assessment area (a) and their frequency distribution (b) in 1949-2008.

The probability method and determinacy method are used in this paper to calculate the possible TC minimum central pressure. Meanwhile the Gumbe and Pearson-III method is applied as the probability method.

2.1 *Extreme value from Gumbe- Ⅰ method*

The Bell probability distribution function is presented as follows[13]:

$$p(x) = \exp\{-\exp[-(x-\alpha)/\beta]\}$$

The return period is

$$L = \frac{1}{p(x)}$$

where x is the variable of distribution, $p(x)$ the probability in which x is not exceeded, α the location parameter, and β the level parameter.

2.2 *Pearson - Ⅲ method*

The density distribution function of Pearson - Ⅲ is presented as follows[13]:

$$y = P(x) = \frac{\beta_\alpha}{\Gamma(\alpha)}(x-a_0)^{\alpha-1}e^{-\beta(x-a_0)}$$

By appropriate conversion, α, β, and a_0 can be represented with three statistical parameters of $\bar{x}$, C_s and C_v,

$$\alpha = \frac{4}{c_s^2}\ ;\quad \beta = \frac{2}{mc_v c_s} = \frac{2}{\sigma c_s}\ ;\quad a_0 = \bar{x}(1-\frac{2c_v}{c_s}),$$

where $\bar{x}$ is the mean, C_s the coefficient of skew, and C_v the coefficient of variation, and α depends on the coefficient of skew. Thus the curve shape can be determined under certain preconditions of α, and β depends mainly on the standard deviation of data series σ, because it determines the scale of the variable value (dispersion).

2.3 *Determinacy method*

Based on atmospheric thermodynamics and fluid dynamics and with the atmospheric statics equation, the determinacy method calculates the sea level pressure (P_0) of the TC[1, 14]. Specifically,

Atmospheric statics equation: $\mathrm{d}\,p = \rho g\,\mathrm{d}\,z$,

State equation: $p = pRT$,

Thickness equation: $\Delta \mathrm{h} = 29.289\overline{\mathrm{T}}_\mathrm{v}\ln\frac{P_1}{P_U}$,

Average virtual temperature equation: $\overline{T_v} = \overline{T}(1+0.608\overline{m})$, and

Average specific humidity: $\overline{m} = 0.622\overline{E}/(\overline{P}-\overline{E})$.

Here is what the symbols and units stand for. p: pressure (hPa); z: height (gpm); ρ: air density (kg/m^3); g: gravity acceleration (cm/s^2); T: temperature (k); R: gas constant (J / (g • k)); Δh: thickness (gpm); P_l: specific layer pressure from the lower layer (hPa); P_u: specific layer pressure from the upper layer (hPa); $\overline{T_v}$: average virtual temperature (k); $\overline{m}$: average specific humidity (g/kg); $\overline{E}$: average vapor pressure (hPa).

The key process in the P_0 calculation is setting five parameters, i.e., the tropopause height, tropopause temperature, SST, distributions of vertical temperature and humidity in the TC eye. Specific steps are shown as follows. First, the thickness of individual standard isobaric layers is to be determined, thererfore the average temperature for each of the layers must be obtained. According to the assumption for the vertical distribution temperature right over the TC eye and with the help of the temperature-logarithmic pressure (T-ln$P$), the temperature from each of the isobaric layers from 100 to 850 hPa is computed. The average temperature between the layers is also calculated. The average temperature between 850 hPa and the sea surface is the mean between the 850 hPa temperature and SST. Then, the virtual temperature of every layer over the TC eye is determined based on the vertical distribution of humidity. Lastly, the thickness equation is applied to calculate the thickness between the layers above 850 hPa.

By subtracting the 100 hPa height from the total thickness from 100 to 850 hPa, we obtained the isobaric height for 850 hPa. Then the virtual temperature between 850 hPa and sea level is used, with the help of the thickness formula, to calculate the sea-level pressure P_0.

3 STATISTICAL CHARACTERISTICS OF THE TCS AFFECTING ASSESSMENT AREA

Located in the southern coast of Fujian which is frequently affected by TC[2, 15], the nuclear power plant is a typical coastal nuclear power plant. Based on the requirements of the Guidelines, a total of 273 TC samples meet the conditions for statistical study in the assessment area.

3.1 *Intensity and sources of TCs*

3.1.1 SOURCES OF TCS

Figure 1 shows that the TCs affecting the assessment area originate from 5 to 30°N, 110 to 165°E in the ocean, preferably concentrated at 10 to 20°N, 110 to 150°E in the SCS and the Philippine Sea.

3.1.2 INTENSITY OF TCS

Table 1 shows that in all the 273 TCs affecting the assessment area, the highest frequency ever reached in the entire lifecycle is with super-typhoons, followed, in turn, by severe tropical storms, typhoons, and severe typhoons; the least frequency is with tropical depressions and tropical storms. Once inside the assessment area, the TC is weakened to some extent due to surface friction. Typhoons and severe tropical storms are the TCs that have the highest number of occurrence, followed by severe typhoons, tropical depressions and tropical storms, with super-typhoons having the minimum of all. For the classification of TC intensity, see reference [18].

3.2 *Characteristics of TC frequency distribution*

In 1949–2008 (59 years), the average number of TCs landing on or affecting the nuclear plant site is 4.6, where the total number of TCs landing on the assessment area is 183, or 3.1 per year; the total number of TCs affecting the assessment area is 90, or 1.5 per year. Moreover, there is a significant variation of inter-annual frequency (not shown). The 1950s to early 1970s is a period of more TCs and then the late 1990s is a period of less TCs, while the present time shows an increasing trend. The most frequency of TC is in 1961 (13) and the least is in 1989 (1).

Table 1. Characteristics of intensity of TCs affecting the assessment area in 1949–2008.

TC intensity	Through TC life cycle		Into the assessment area	
	Frequency	Frequencies /%	Frequency	Frequencies /%
Tropical depression	22	8.1	36	13.2
Tropical Storm	25	9.2	33	12.1
Severe Tropical Storm	59	21.6	68	24.9
Typhoon	56	20.5	84	30.8
Severe Typhoon	45	16.5	39	14.3
Super-Typhoon	66	24.2	13	4.8
Total	273	100	273	100

The time when most TCs affect the assessment area is August, followed in turn by September and July. The TCs that occur from July to September take up 76.6% of the total. On the time scale of ten days, the occurring TC (Figure 2) is mainly distributed between middle July and late September, with late July, early August, late August and early September being the periods of most concentrated TC influence on the assessment area. The earliest typhoon that affects the assessment area happens in early April (1967), the latest early December (2004), the earliest typhoon that makes landfall on the assessment area takes place in early May (1999), and the latest early November (1954).

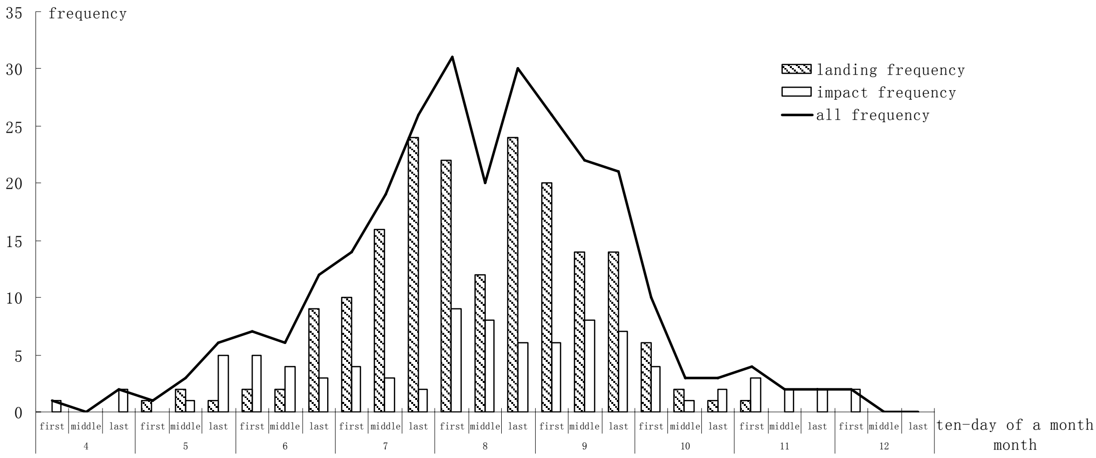

Figure 2. Distribution of TC frequency landing on and affecting the assessment area in 1949–2008.

3.3 *Characteristics of path and landing locations*

The paths in which the TCs land on the assessment area can be divided into two categories (Figure 3); one is direct landing on the assessment area, 110 samples in all (Figure 3a), and the other is landing on the assessment area again after initial landing on Taiwan Island (Figure 3b), 73 samples in all. At the same time, the paths in which the TCs affect the assessment area can also be divided into two categories; one is turning to the northeast after landing on Taiwan Island, 63 samples in all (not shown), and the other is the western path, 27 samples in all (not shown). As can be seen from Table 2, for the TCs landing on the assessment area, most of them (as many as 92 samples) first land on the coast of Guangdong east of the Pearl River estuary, or 50.3% of the total, followed by those landing on the northern and central coast of Fujian, 69 in all, taking up 37.7%. However, the frequency of the TCs directly landing on the southern coast of Fujian (specifically the coast of Xiamen, Zhangzhou and Quanzhou) is relatively low, only 22 samples, or as much as 12%.

4 CALCULATION OF THE MINIMUM DESIGN PRESSURE AT THE TC CENTER WITH PROBABILITY THEORY

An annual series is constructed by picking a lowest pressure P_0 from the data base of 273 TC samples that enter the assessment area. Then, the Gumbe and Pearson - Ⅲ methods recommended in the Guidelines are used to calculate P_0 for different return periods.

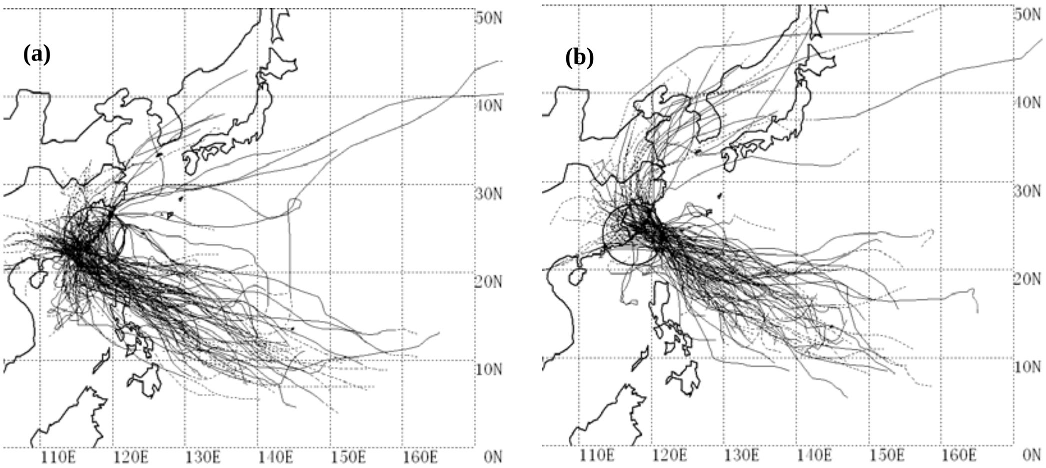

Figure 3. Paths of TCs landing on and affecting the assessment area by (a) direct landing and (b) landing again after landing on Taiwan Island.

Table 2. Location distribution of the TC landing on the assessment area in 1949–2008.

Location	north-central coast of Fujian	southern coast of Fujian	coast of Guangdong east of Pearl River estuary
Samples	69	22	92
Frequency /%	37.7	12	50.3

4.1 *Estimation of year-to-year temporal and spatial distribution of lowest pressure of TCs at sea*

In the offshore waters 400 km around the assessment area, the minimum pressure is 910 hPa, the maximum 980 hPa, and the average 958 hPa, at the TC center, with the standard deviation being 16.8 hPa. Near the TC center, the maximum wind speed is 70 m/s, the minimum 28 m/s, the average 44.8 m/s, with the standard deviation being 9.7 m/s.

The year-to-year spatial distribution of extreme values of TC P_0 over the sea for the assessment area (Figure 4) shows that most of the extreme minimum pressure values at the TC center are located over waters 200 to 400 km from the nuclear power plant. In some years, some TCs strengthen in the offshore area but their intensity is weaker than those that are not strengthened offshore.

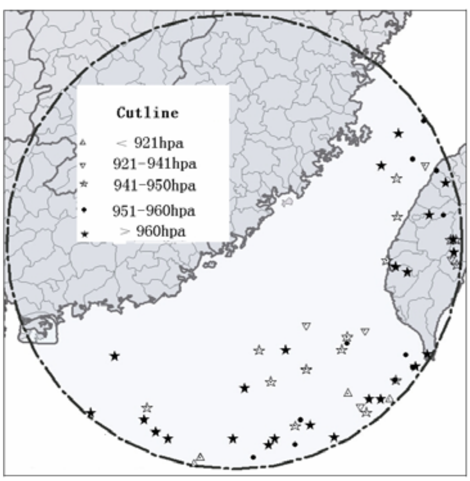

Figure 4. Spatial distribution of annual extreme values of P_0 from over-the-sea TCs affecting the assessment area.

Figure 5 gives the inter-annual curve of extreme minimum pressure at sea, which also shows a gradually enhancing trend in the intensity of TCs affecting the assessment area in recent years[8]. Therefore, the impact of this factor should be included when using the probability theory to calculate the parameters of extreme minimum pressure for different return periods.

4.2 *Results*

As seen from Figure 6, the TC eye minimum pressure value from both Gumbe-Ⅰ and Pearson-Ⅲ all fits well with real condition, meanwhile the differences between the results calculated for different return periods are not large (Table 3). Because of the random adjustment of parameters with the Pearson-Ⅲ method and for security reasons, the result determined with the Gumbe-Ⅰ method is recommended for the actual design. In other words, the lowest possible pressure near the TC eye, which occurs once in 1,000 years, is 867.44 hPa.

5 ESTIMATION OF MINIMUM DESIGN PRESSURE OF TC CENTER WITH THE DETERMINACY METHOD

5.1 *Determination of parameters*

5.1.1 TROPOPAUSE HEIGHT

A strong and developing TC always maintains a mechanism for high-level divergence and low-level convergence. The vertical extent of a TC system is usually expressed by the height of the tropopause. In view of its large variation, 100 hPa is recommended in the Guidelines to represent the height of the tropopause. In this paper, the data (from 1980 to 2008) from two radiosonde stations nearest to the site of the nuclear power plant are used as the statistics.

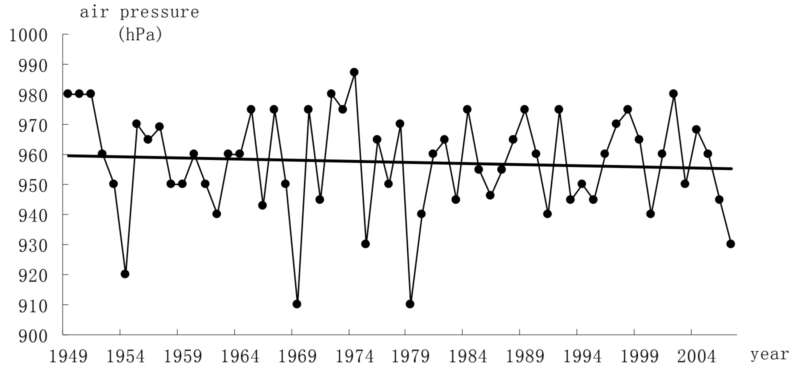

Figure 5. Inter-annual variations of extreme minimum pressure of TCs affecting the marine part of the assessment area.

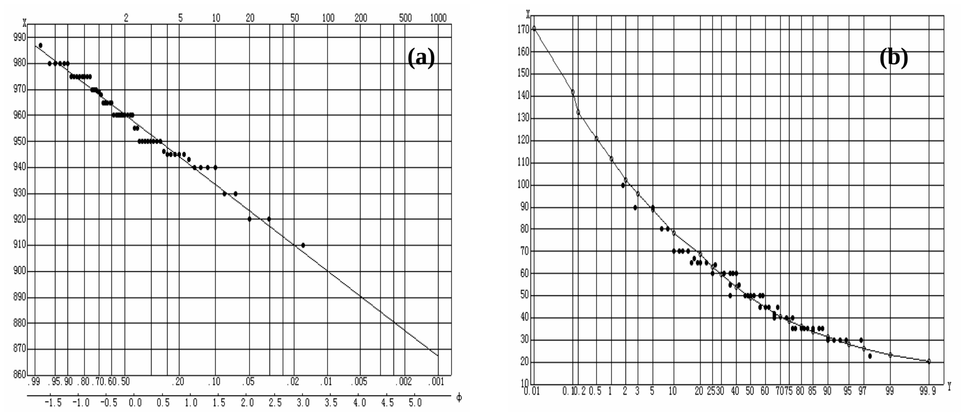

Figure 6. Fitting curves for Gumbe distribution (a) and probability distribution by Pearson-Ⅲ method (b, the vertical axis is the pressure drop) of TC central pressure P_0.

Table 3. Possible minimum central pressure (hPa) of TCs determined with the probability method for different return periods.

Return intervals /yr	Gumbe - Ⅰ extreme value	Pearson - Ⅲ (C_v=0.36, C_s=3C_v)
1,000	867.44	868.10
500	877.24	877.04
200	890.37	889.1
100	900.18	898.42
50	909.98	908.02
20	923.28	921.24
10	933.41	931.82
5	944.05	941.32
2	960.17	960.94

In the actual calculation, the 100 hPa height takes the average minimum value of 16,655 gpm in August, which is the minimum geopotential height averaged for the two stations during the proper time of the whole summer for 100 hPa.

5.1.2 Tropopause temperature

Likewise, based on the same statistical results from Table 4, the temperature at the 100-hPa layer is made to represent the temperature of the tropopause, with the value set at –71°C. A little bit more conservative, the assigned value is close to the average maximum temperature at that level for station 1 and station 2, two of the stations nearest to the nuclear power plant site, in summer.

5.1.3 SST

According to the grid data of global average SST and the *Marine Hydrological Atlas* published by the State Oceanic Administration in 1975, the average summer SST is between 28–29°C in the sea around Fujian and Taiwan. For the process of strong warm water in summer, the SST is always higher than the monthly climatological mean, which is why the SST is set at 32°C in this work. Besides, it does occur in routine operation and is supported by a certain range of probability.

Table 4. Height and temperature data at 100 hPa of the radiosonde stations nearest to the nuclear power plant site (Units: height: gpm, temperature: °C).

Location	Station 1			Station 2		
Height	$\overline{H}$	$\overline{H}_{max}$	$\overline{H}_{min}$	$\overline{H}$	$\overline{H}_{max}$	$\overline{H}_{min}$
July	16,767	16,863	16,668	16,764	16,871	16,651
August	16,759	16,856	16,662	16,754	16,863	16,639
temperature	$\overline{T}$	$\overline{T}_{max}$	$\overline{T}_{min}$	$\overline{T}$	$\overline{T}_{max}$	$\overline{T}_{min}$
July	−75.9	−71.4	−80.0	−76.2	−71.7	−80.6
August	−75.6	−71.5	−79.8	−76.2	−71.1	−81.0

5.1.4 VERTICAL DISTRIBUTION OF TEMPERATURE INSIDE THE EYE

In the Guidelines, it is stated that the vertical structure of temperature is assumed to be dry adiabatic above 300 hPa and wet adiabatic below it over the SCS. This work follows this assumption.

5.1.5 VERTICAL DISTRIBUTION OF HUMIDITY OVER THE EYE

According to the Guidelines with regard to the tropical and subtropical sea, the relative humidity is 5% at 100 hPa, 20% at 200 hPa, and 100 % below 300 hPa, for the vertical distribution of humidity over the TC eye in the SCS. Judged from the observational data of a number of strong typhoon cases, this assumption is reasonable.

5.2 *Results*

In Table 5, P_u is the pressure of the upper layer above a specific layer, P_l the pressure of the lower layer below the specific layer, $\overline{T}$ the average temperature of the specific layer, $\overline{T_v}$ the average virtual temperature of the specific layer, $\overline{R}_H$ the average relative humidity, and Δh the height difference between P_u and P_l.

According to the thickness formula Eq. (3), we have

$$P_0 = \exp\left[\Delta h/(29.2898\overline{T}_V) + \ln 850\right]$$
$$= \exp\left[\frac{16655-16472.46}{29.2898\times(273.15+36.46)} + \ln 850\right].$$
$$= 867.28\,\text{hPa}$$

The lowest possible central pressure value based on the determinacy method is 867.28 hPa while the central pressure of the observed strongest typhoon is 910 hPa, or 42.72 hPa lower with the estimate than with the measurement, which is close to the value on a 1,000-year cycle for the following two theories of probability (867.4 hPa for Gumbe-Ⅰ and 868.1 hPa for Pearson-Ⅲ). For safety and conservative concerns, the result of the lowest possible minimum pressure near the TC eye for the nuclear power plant, determined based on the determinacy method, is reasonable.

Table 5. Parameters and relevant values of strongest possible TCs within the assessment area.

P_U-P_l/hPa	$\overline{T}$/℃	$\overline{T}$v/℃	$\overline{R}$ H/%	Δh/gpm	sum Δh/gpm
100 to 150	−58.58	−58.58	8.75	2 548.34	2 548.34
150 to 200	−36.47	−36.44	16.25	1 994.65	4 542.99
200 to 250	−19.05	−18.71	40.00	1 663.03	6 206.02
250 to 300	−5.41	−4.01	80.00	1 437.31	7 643.33
300 to 350	2.37	4.70	100.00	1 254.56	8 897.89
350 to 400	5.84	8.45	100.00	1 101.42	9 999.32
400 to 450	8.86	11.72	100.00	982.80	10 982.12
450 to 500	11.54	14.63	100.00	888.10	11 870.22
500 to 550	13.94	17.24	100.00	810.69	12 680.91
550 to 600	16.13	19.62	100.00	746.117	13 427.08
600 to 650	18.14	21.81	100.00	691.54	14 118.62
650 to 700	20.0	23.84	100.00	644.67	14 763.29
700 to 750	21.73	25.73	100.00	603.99	15 367.29
750 to 800	23.35	27.5	100.00	568.34	15 935.63
800 to 850	24.87	29.19	100.00	536.84	16 472.46
＞850	32.0	36.46	100.00		

6 CONCLUSION AND DISCUSSION

Based on TC data for the period 1949 to 2008 and following the Gumbe－I method, Pearson-Ⅲ method and determinacy method, this article estimates the possible minimum central pressure of TCs affecting southern Fujian where a nuclear power will be located. The results are shown as follows.

(1) Located in the southeastern Chinese coast, the nuclear power plant is frequently affected by TCs and hit by disasters. There are 4.6 TCs making landfall or exerting influence in the area within 400 km from the site of the nuclear power plant, with 3.1 landfalling TCs and 1.5 affecting TCs annually. The landfall and influence happen mainly in July to September, with high concentration in late July, early August, late August and early September.

(2) The paths on which TCs land on the assessment area can be divided into two categories, one being direct landing and the other being a second landing after an initial landing on Taiwan Island. The paths on which TCs affect the assessment area can also be divided into two categories, one being turning to the northeast after landing on Taiwan and the other being heading westward.

(3) The observed minimum central pressure of TCs agrees well with the results determined with the Gumbe–I method and Pearson-Ⅲ method and there is little difference between them. The results are only a little smaller than that of the probability method. Because the adjustment of parameters is random with the Pearson-Ⅲ method and the Gumbe–I's estimates are just a little smaller than those of the Pearson-Ⅲ method, the Gumbe-Ⅰ method is, for security and conservative concerns, superior over the Pearson-Ⅲ method. The value of minimum central pressure takes 867.4 hPa for a 1,000-year return period.

(4) The determinacy method is theoretically solid and the data sources for calculation are reliable. The estimated result is 867.28 hPa, which is 0.12 hPa lower than the value for the 1,000-year return period determined with the probability theory. It is obvious that the two results are very close. For conservative concerns, it is reasonable and safe to use the result obtained with the determinacy method as the largest minimum pressure around the TC eye that could possibly occur in the area of the nuclear power plant.

(5) It can be seen from Table 6 that P_0 in the area of the nuclear power plant is higher than the others. Climatological averages are shown in Appendix Ⅳ of a study[1] that gives "examples to estimate P_0 with the probability method for the SCS" and decides that the average P_0 in the SCS is 955.5 hPa from 1951 to 1979. Another study for another nuclear power plant at Fuqing, Fujian province, which performs surveys and statistical analysis of TCs and evaluates design benchmarks, has identified 941.6 hPa as an average of P_0 for the same period of time. According to the estimate of this paper, 956.3 hPa is the counterpart over the Fujian waters within 400 km of the nuclear power plant. This value is 0.8 hPa higher than the value for the SCS and 14.7 hPa higher than the Fuqing result. Therefore, compared with the surrounding nuclear power plant, the higher extreme value for a 1,000-year return period is objective and reasonable.

Table 6. Comparisons of extreme values of nuclear power plants in Fujian and surrounding areas in a 1,000-year return period.

Location	Sample collected period/year	Minimum pressure /hPa
South China Sea	1951–1979	853
Fuqing, Fujian	1956–2005	840.7
Daya Bay, Guangdong	1949–1994	845
Qinshan, Zhejiang	(Phase II) 1949–2003	853
nuclear power plant of interest	1949–2008	867.28

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