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Study on the Atmospheric Diffusion of Airborne Radionuclide under LOCA of Offshore Floating Nuclear Power Plants Based on CALPUFF

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Abstract: Studying the migration and diffusion of radionuclides plays an important role in emergency decision making and accident mitigation of floating nuclear power plants. Based on the CALPUFF model, this paper simulates the spatial distribution and concentration distribution of airborne radionuclides ¹³¹I diffusion under the conditions of sailing and power supply under LOCA (Loss-of-Coolant Accident) of the floating nuclear power plant, and the influence of four meteorological parameters, namely wind speed, cloudiness, temperature and air pressure, on the migration was analyzed using sensitivity analysis. The results show that the wind direction affects the diffusion direction of ¹³¹I, and the concentration of ¹³¹I decreases with the increase in the diffusion distance; under the same conditions, the radionuclides diffuses farther and the affected area is larger under the sailing condition. Wind speed is the dominant factor affecting the diffusion of radionuclides, followed by the cloud amount parameter, temperature parameter, and air pressure parameter. The research results can provide theoretical support for emergency responses to nuclear accidents in offshore floating nuclear power plants.



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Keywords: floating nuclear power plant; migration regularity; Lagrange model (CALPUFF); sensitivity analysis

1. Introduction

The offshore floating nuclear power station is the product of the combination of ship engineering and nuclear engineering, which refers to the construction of a mobile nuclear power station using floating platforms (such as ships) [1]; it is a small modular reactor that has the advantages of excellent mobility and versatility, although it may produce more chemically and physically active waste at the back end of the nuclear fuel cycle compared to large reactors of equivalent volume [2,3]. Floating nuclear power plants are the key to future international development and an important technology reliance for human expansion of offshore resources, and the development of nuclear energy is an important decision and policy for China in terms of paving the way for sustainable development. Unlike floating nuclear power plants, which are moored and operated at sea, land-based nuclear power plants are built on the coast or inland and cannot be moved once they are built, and the operating environments of the two are different. However, the restrictive space of the ship and the uncertainty of the marine environment bring great operational risks to the offshore floating nuclear power plants, which will pose a serious threat to the marine environment and personnel safety in case of radionuclides leakage accidents. The migration of radionuclides in the atmosphere has attracted much attention in the fields of nuclear accident emergency response and emergency response to emergencies. Numerical simulation is a powerful tool to study the underlying physics of atmospheric

transport and to reasonably quantify and analyze the environmental impact of radioactive dispersion [4]. Although nuclear emergency detection technology has developed many advanced detection technologies [5], in order to prevent and mitigate the consequences of an accident in an offshore floating nuclear power plant, it is particularly important to study the dispersion pattern of radionuclides under LOCA (Loss-of-Coolant Accident) in an offshore floating nuclear power plant.

After the Chernobyl accident, the numerical model of atmospheric dispersion of various radionuclides started to become the focus of research in the field of nuclear safety. Domestic and foreign scholars have carried out some studies on the migration patterns of radionuclides in severe accidents of ship's reactors, focusing on the close-range or closed environments, respectively. Zou et al. [6] used computational fluid dynamics to simulate the diffusion of airborne radionuclides under the combined conditions of platform position, wind direction, and breach direction (north–south–west–east) within two kilometers after a breach accident in a floating nuclear power plant. Zhao et al. [7] used computational fluid dynamics to study the diffusion of radionuclides in the cabin after a severe accident of a large breach in the marine reactor, and obtained the time node for the leakage of radionuclides to adjacent cabins and containment. A large number of scholars regard ^{131}I as the main impact nuclide of nuclear accidents, and put forward that the release rate of ^{131}I was 1×10^{16} Bq/s in the famous Fukushima nuclear accident [8]. Victor Minenko [9] found that the activity concentrations of ^{131}I and other radionuclides in Belarusian milk during the first month after Chernobyl were linked to an increase in thyroid cancer in Belarusian children and adolescents as a result of inhaling excess ^{131}I . Wang et al. [10] adopted the law of atmospheric diffusion within the 20 km area of the wharf ^{131}I after the small power reactor was broken. Huang [11], based on CFD, studied the law of airborne radionuclide diffusion under the water loss accident of a floating nuclear power station, and calculated the release rate of ^{131}I with the severe accident procedure. Some scholars have proposed the tools and methods to estimate the concentration of nuclear fission products, such as ^{131}I and other source terms [12,13].

Some scholars also use the CALPUFF (California Puff Model) model for research. It is an unsteady three-dimensional Lagrangian puff transport model which can fully consider the hourly and spatial changes of wind and stability. Scire et al. recommend CALPUFF for diffusion simulations ranging from tens of meters to 300 km [14]; it is suitable for complex topographic conditions and aqueous environments, for dispersion simulation of inert pollutants and changes in pollutants according to linear removal and linear chemical transformation mechanisms [15]. It is also widely used in the field of radionuclide diffusion [16–19]. DarioGaiotti [20] used the CALMET/CALPUFF modeling system to simulate the cumulative deposition of ^{137}Cs in the Chernobyl nuclear accident, and the results showed that the CALMET/CALPUFF system can reproduce the large-scale characteristics of the ^{137}Cs measured. Based on the Lagrangian particle-tracking model, Ouyang [21] studied the influence of sea surface absorption at different launch heights on the ocean atmosphere diffusion after a severe nuclear accident of a power ship, and established a simulation model of radionuclide atmospheric diffusion over the ocean. Periañez et al. [22] used the CALPUFF model to simulate the diffusion of radionuclides in the Indian Ocean after a hypothetical accident in a nuclear power plant along the coast of the North Indian Ocean under the meteorological conditions of winter monsoon and summer monsoon. The results showed that there is no difference in the distribution of radionuclides in the two seasons. Seasonal variability in the distribution of radionuclides was not very significant during the period as expected in the opposite circulation scenario. Li et al. [23] used the CALPUFF numerical model developed on the basis of the Lagrangian model to drive NCEP to reanalyze the meteorological data, and conducted source term evaluation and numerical simulation research on the Fukushima radionuclide leakage accident. The results showed that the CALPUFF simulation and the actual monitoring values are consistent, and the two are consistent at key time points. However, studies on

the mesoscale range of radionuclide dispersion in the atmosphere after a serious accident in offshore floating nuclear power plants are limited.

This paper selects the 50 km × 50 km range and real-time meteorological data in the part of the East China Sea connected to Haiyan County, Zhejiang province, China, based on the CALPUFF model to study the spatial distribution and concentration distribution of radionuclide dispersion under the navigation and power supply conditions of an offshore floating nuclear power plant loss of water accident, and to decipher the importance of four meteorological parameters, namely wind speed, cloudiness, temperature and air pressure, on the atmospheric migration of airborne radionuclides, so as to provide a reference for the emergency response to nuclear accidents in floating nuclear power plants.

2. Calculation Method

2.1. Calculation Model

In this paper, the CALPUFF model is used to simulate the dispersion trajectory and distribution of the airborne radionuclide ^{131}I in a hypothetical scenario of a breach accident at an offshore floating nuclear power plant. The model uses a terrain-following coordinate system and can simulate the trajectory distribution of contaminants formed with time and space by splitting the smoke mass function [24], which is mainly modeled using three modules, CALMET, CALPUFF and CALPOST. The CALMET module is a meteorological model which can generate a wind field and a temperature field in an hourly three-dimensional grid area. Before CALMET simulation, geographical data (geo.dat), meteorological data (surf.dat) and upper air data (up.dat) should be prepared. Geographical data need a terrain elevation data preprocessing module (TERREL), land use data preprocessing module (CTGPROC), and a geographical data synthesis module (MAKEGEO). The CALPUFF module is an unsteady three-dimensional Lagrange smoke transport model. The CALMET module is used to generate wind field and temperature field files to transport smoke emissions from pollution sources and simulate diffusion and transformation process. The CALPOST module processes the output file of the CALPUFF module to generate the required concentration file for post-processing [14].

CALMET is a meteorological field module that in order to better track the terrain changes, adopts terrain tracking coordinates, as shown in Equation (1), and calculates wind speed on the basis of terrain tracking coordinates, as shown in Equation (2).

$$Z = z - h_t \quad (1)$$

$$W = w - u \frac{\partial h_t}{\partial x} - v \frac{\partial h_t}{\partial y} \quad (2)$$

where Z is the vertical coordinate varying with the terrain, z is the original vertical coordinate of the Cartesian coordinate system, and h_t is the terrain height. W is the wind speed in the changing coordinate, and w is the vertical wind speed in the Cartesian coordinate. u and v are horizontal wind speed components, corresponding to the x and y directions, respectively. The wind speed of each grid is generated using the data of observation stations, as shown in Equation (3).

$$(u, v)_2 = \frac{\frac{(u, v)_1}{R^2} + \sum_k \frac{(u_{obs}, v_{obs})_k}{R_k^2}}{\frac{1}{R^2} + \sum_k \frac{1}{R_k^2}} \quad (3)$$

where $(u_{obs}, v_{obs})_k$ is observation speed of ground station k , $(u, v)_1$ is the first-step wind speed at the grid point, $(u, v)_2$ is the second-step wind speed at the grid point, R_k is distance from observation station K to grid point, and R is the weighted parameter of the user-specified first-step wind field.

CALPUFF takes the three-dimensional wind field and meteorological field obtained by the CALMET meteorological module as initial boundary conditions, and calculates the trajectory change of the release source through the transport and diffusion simulation in

the module. In the CALPUFF mode, the receptor point concentration equation of a puff at a certain point is as follows:

$$C = \frac{Q}{2\pi\sigma_x\sigma_y} g \exp[-d_a^2/(2\sigma_x^2)] \exp[-d_c^2/(2\sigma_y^2)] \quad (4)$$

$$g = \frac{2}{\sigma_z\sqrt{2\pi}} \sum_{n=-\infty}^{\infty} \exp[-(H_e + 2nh)^2/(2\sigma_z^2)] \quad (5)$$

where C is the ground concentration, Q is the source strength, σ_x , σ_y and σ_z are the diffusion coefficient, d_a is the downwind distance, d_c is transverse distance, h is the height of the mixing layer, H_e is the effective height of the ground from the center point of the puff, and g is the vertical component in the Gaussian equation used to solve the problem of multiple reflections between the mixed layer and the ground.

2.2. Study Area and Object

The power supply phase of a floating nuclear power plant at sea is generally fixed near the power supply target, while the construction, commissioning, refueling, maintenance and decommissioning phases take place at different locations, during which fuel needs to be transported periodically by sea. The area of this study includes the part of the East China Sea connected to Haiyan County, Zhejiang Province, China, with a range of 50 km × 50 km. Two scenarios of power supply and navigation were studied with a loss of water accident at an offshore floating nuclear power plant, using the spread of radionuclide ^{131}I leakage as the study object. The sailing speed of the Russian academician Lomonosov of 2.5 m/s was used as the operating speed under the sailing scenario of this study, and the release rate of ^{131}I was assumed to be 6.0×10^3 Bq/s [11], with a constant speed of continuous discharge for 5 h. The exit velocity of radionuclide ^{131}I was set to 10 m/s, the discharge height of the source was 10 m, and the flue gas exit temperature was 300 K. Under the sailing conditions, the floating nuclear power plant at sea moves in a straight line along the latitude, with a constant speed of 2.5 m/s for 5 h. The UTM (universal transverse mercator grid system) coordinates of the emission source are (300.380, 3378.249).

To compare the radionuclide diffusion after the floating nuclear power plant rupture accident under navigation conditions and power supply conditions, the parameters under power supply conditions are set as follows: The release source is also set at UTM coordinate (300.380, 3378.249), and the release source is stationary at this position for 5 h. Other conditions are consistent with the input conditions under sailing conditions.

2.3. Main Parameters

2.3.1. Setting of Meteorological Data

According to the data of meteorological monitoring stations in the study area, the annual meteorological data of two ground meteorological stations near the simulation range in 2019 are selected as the ground meteorological data. The simulation time is set from 0:00 on 1 January 2019 to 12:00 on 31 January 2019, and the hourly average concentration distribution of ^{131}I from 0:00 to 5:00 on 1 January 2019 is output in the whole simulation range.

2.3.2. Setting of Original Terrain Elevation Data and Land-Use Data

This study selects the original terrain elevation GEOTIFF format data and the original land-use National Land Cover Dataset 1992 GEOTIFF format data of the research area analyzed with space remote sensing in 2005, with a resolution of 1 km. The ground elevation map of the study area is shown in Figure 1. Most of the ground elevation in the study area is 0 m, followed by elevations ranging from 10 m to 30 m and from 50 m to 60 m, with the highest elevation being that of 210 m. The numbers in the color outline scale in Figure 2 indicate the topographic elevation mapping of the study area, which are the land-use type codes of CALMET: “10” for urban and built-up land, interval “10–20” for urban/built-up

land, “20” for agricultural non-irrigated land, interval “20–30” for agricultural land, “30” for grazing land, interval “30–40” for grassland, “40” for forest land, interval “40–50” for forest land, and interval “50–60” for water bodies. The UTM coordinates of the southwest corner of the simulation range are (275.380, 3343.249), the simulation range area is set to 50 km × 50 km, the grid spacing is set to 0.5 km, the number of grid points in the vertical direction is set to 10, and the vertical layer heights on grid points are set to 0 m, 20 m, 40 m, 80 m, 160 m and 30 m, respectively.

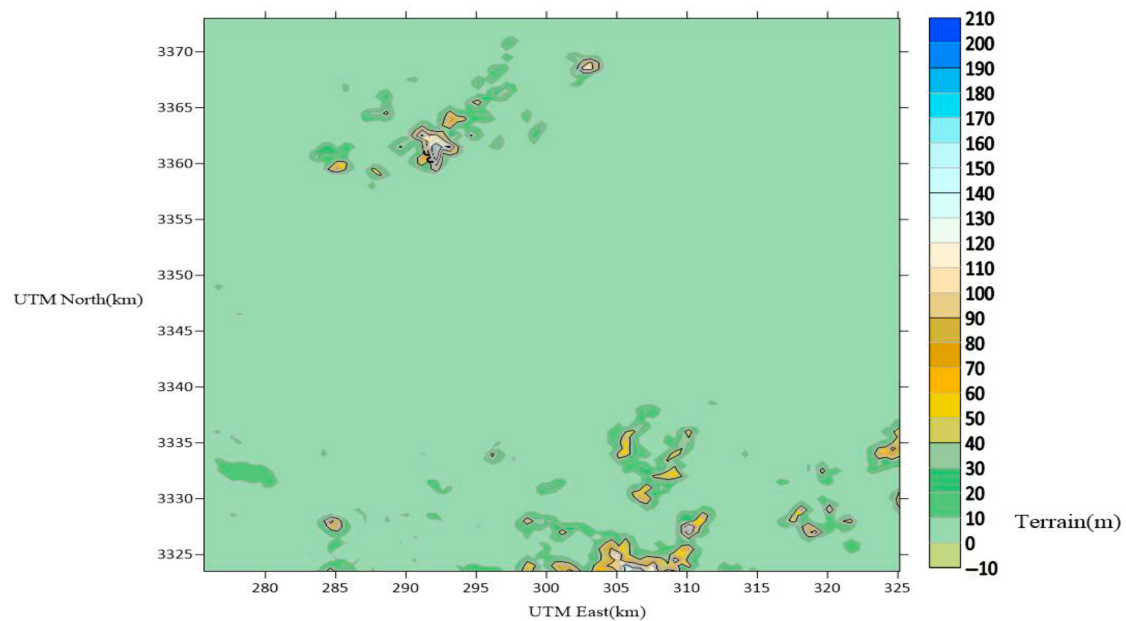


Figure 1. Topographic elevation map of the study area.

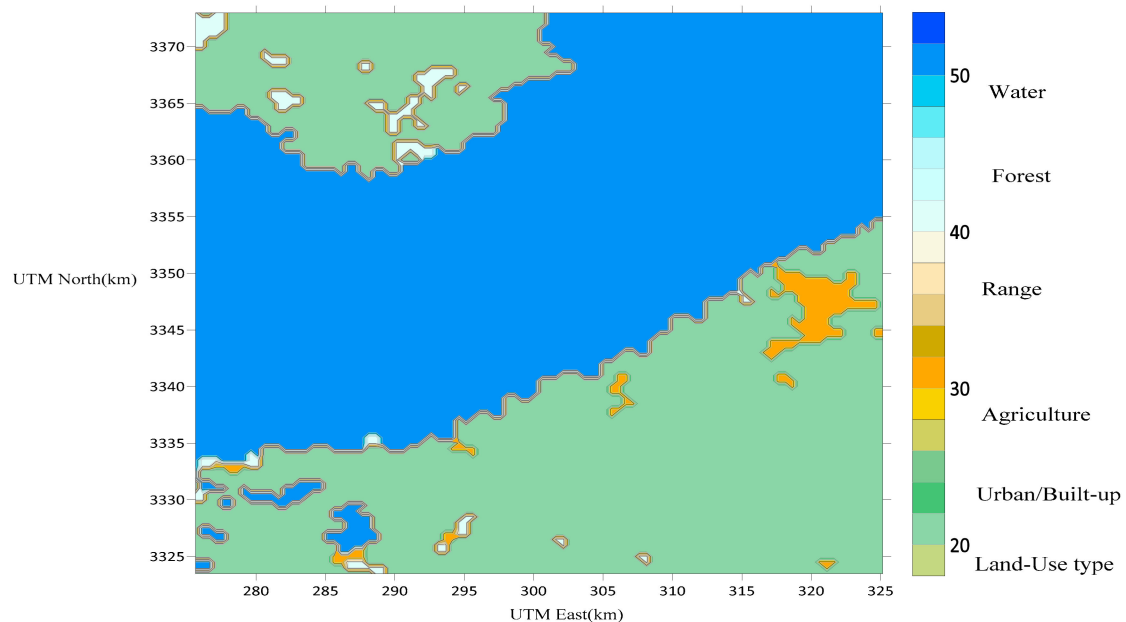


Figure 2. Map of land cover types in the study area.

2.3.3. Setting Sensitivity Parameters

Through document research, it was found that some of the main factors affecting radionuclide diffusion in accidents of floating nuclear power plants at sea are meteorological factors. In this paper, four meteorological parameters, wind speed, temperature, air pres-

sure and cloud cover, are selected for sensitivity analysis [25]. By analyzing the influence of various meteorological parameters on the simulation output results, the importance of each parameter is interpreted, and the influence degree of each meteorological parameter on the floating nuclear power plant LOCA is obtained.

3. Results and Discussion

3.1. Results of Activity Concentration Distribution under Navigation and Power Supply Conditions for Floating Nuclear Power Plants at Sea

Figures 3a,b, 4a,b, 5a,b, 6a,b, 7a,b and 8a,b show the activity concentration distribution of ^{131}I from 0:00 to 5:00 on 1 January 2019 for the power supply condition and navigation condition of the offshore floating nuclear power plant. V_1 indicates wind speed and wind direction, and V_2 indicates sailing speed and heading in Figures 3–8. Collating the grid information is performed in surfer 15, as shown in Tables 1 and 2. After LOCA in the floating nuclear power plant, affected by meteorological conditions such as wind speed, atmospheric temperature, wind direction and air pressure, the maximum concentration and average concentration of radionuclides show a downward trend. Under the same conditions, the hourly average concentration value and peak value under power supply conditions are usually greater than those under sailing conditions.

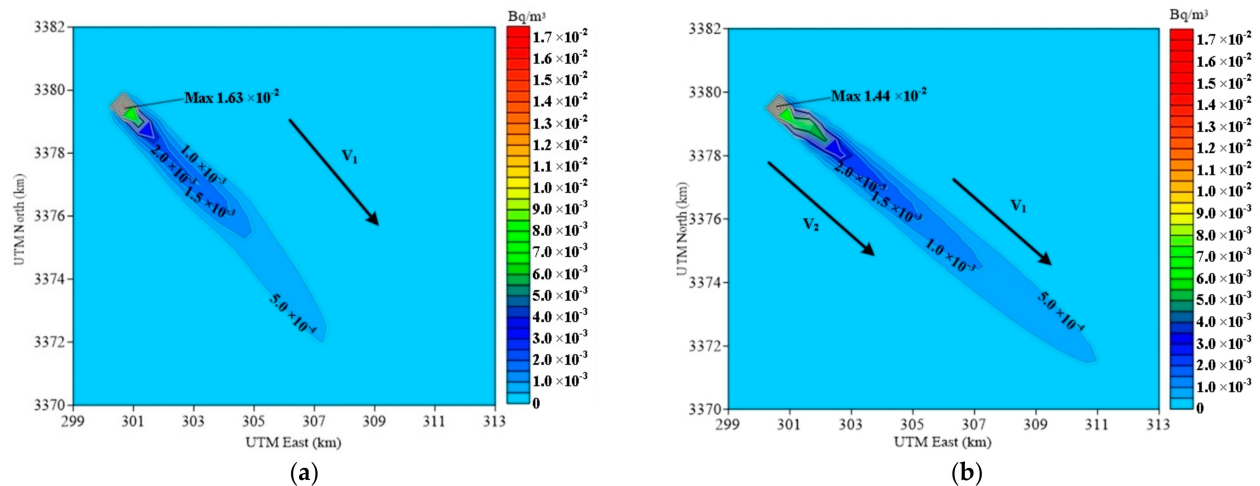


Figure 3. Activity concentration distribution of ^{131}I at 0:00 (a) power supply conditions, (b) sailing conditions.

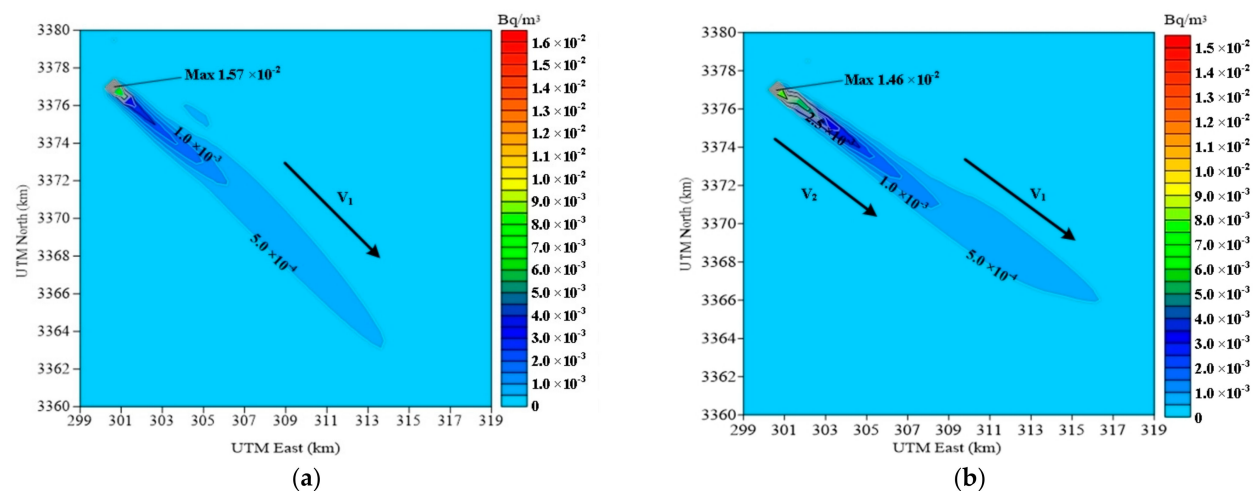


Figure 4. Activity concentration distribution of ^{131}I at 1:00 (a) power supply conditions, (b) sailing conditions.

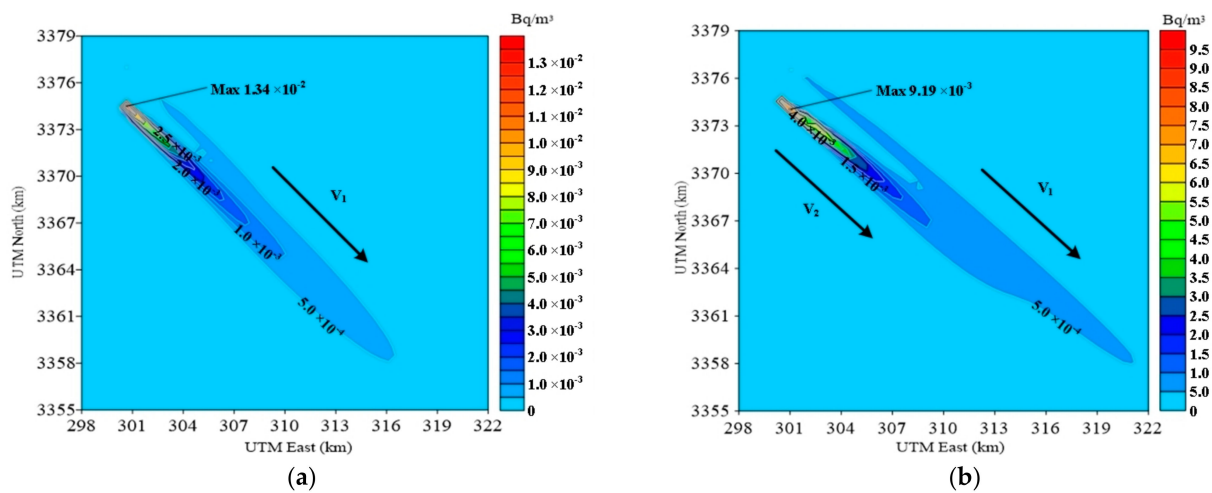


Figure 5. Activity concentration distribution of ^{131}I at 2:00 (a) power supply conditions, (b) sailing conditions.

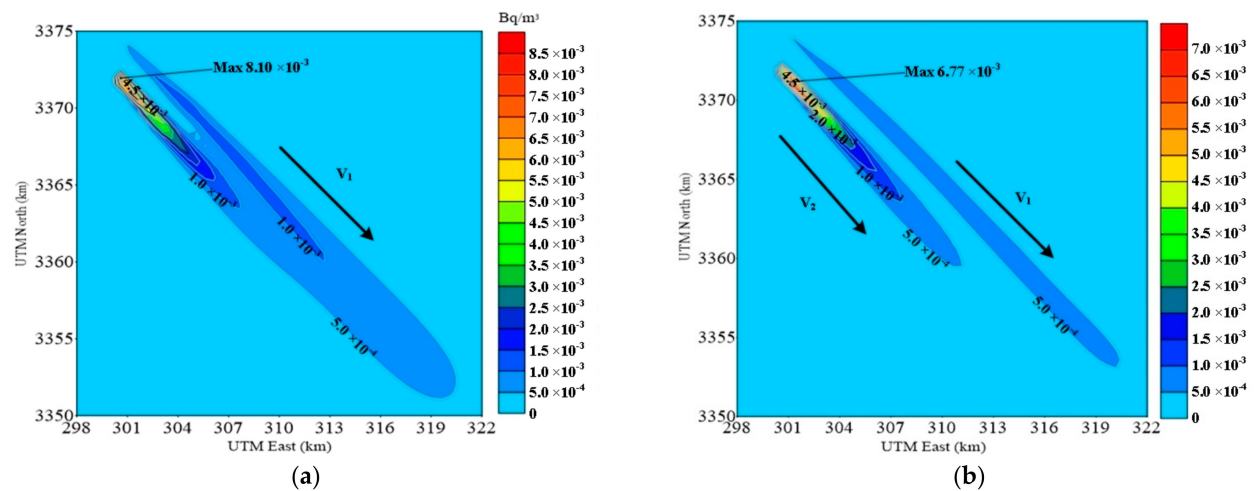


Figure 6. Activity concentration distribution of ^{131}I at 3:00 (a) power supply conditions, (b) sailing conditions.

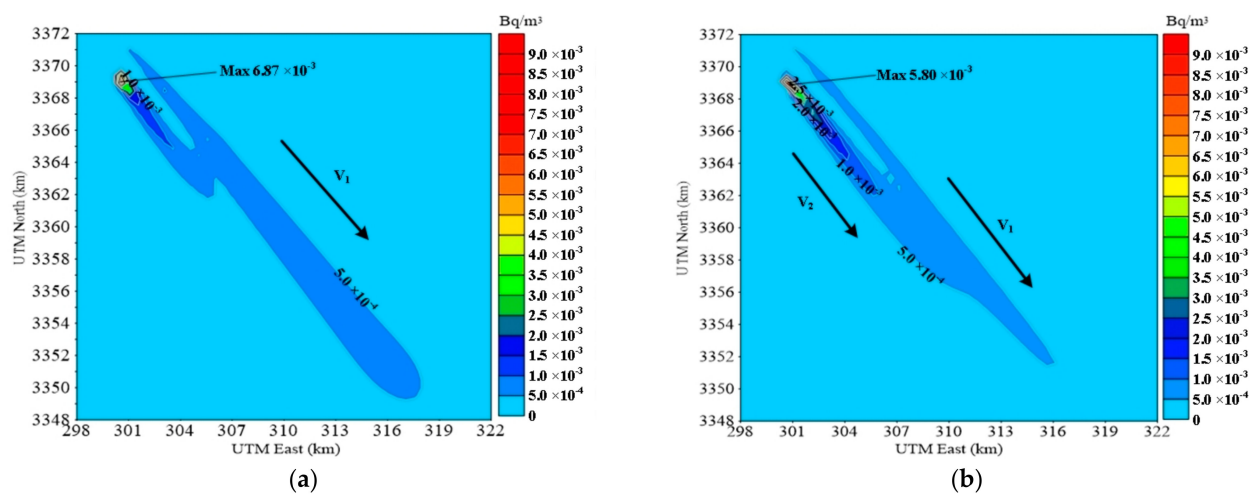


Figure 7. Activity concentration distribution of ^{131}I at 4:00 (a) power supply conditions, (b) sailing conditions.

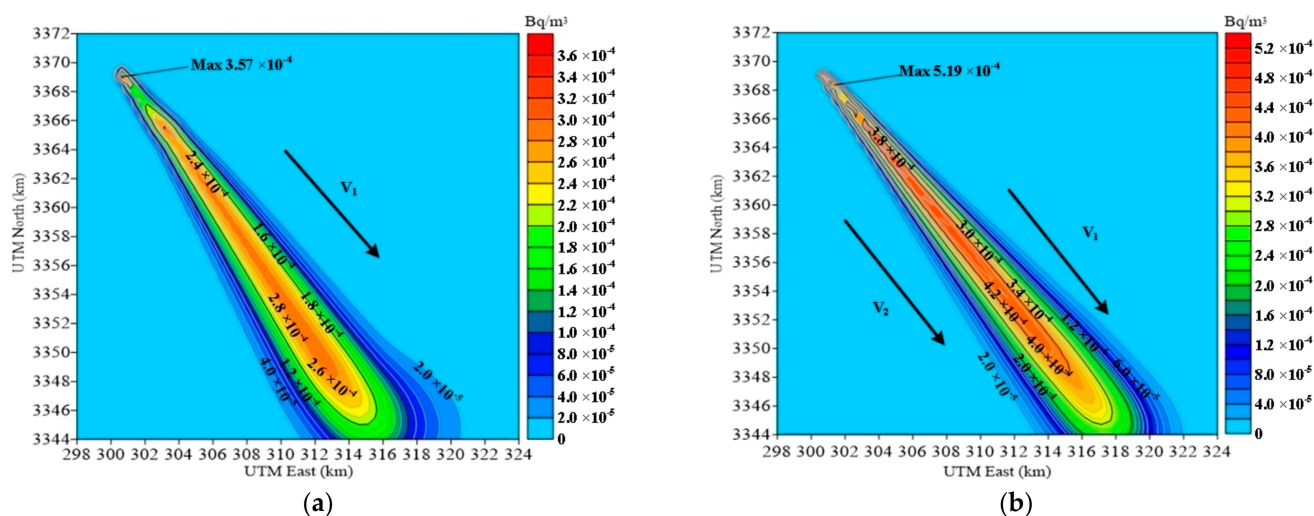


Figure 8. Activity concentration distribution of ^{131}I at 5:00 (a) power supply conditions, (b) sailing conditions.

Table 1. Comparison of hourly average concentration of ^{131}I in power supply and sailing conditions.

Hypothetical Scenario		Average Hourly Concentration (Bq/s)				
Time/h	0	1	2	3	4	5
Power supply condition	1.22×10^{-5}	3.04×10^{-5}	4.18×10^{-5}	5.14×10^{-5}	4.41×10^{-5}	9.35×10^{-6}
Sailing conditions	1.53×10^{-5}	3.27×10^{-5}	3.40×10^{-5}	4.16×10^{-5}	3.33×10^{-5}	1.29×10^{-5}

Table 2. Comparison of the peak hourly concentrations of ^{131}I in the power supply and sailing conditions.

Hypothetical Scenario	Hourly Peak Concentration (Bq/s)					
Time/h	0	1	2	3	4	5
Power supply condition	1.63×10^{-2}	1.57×10^{-2}	1.34×10^{-2}	8.10×10^{-3}	6.87×10^{-3}	3.57×10^{-4}
Sailing conditions	1.44×10^{-2}	1.46×10^{-2}	9.19×10^{-3}	6.77×10^{-3}	5.80×10^{-3}	5.19×10^{-4}

As can be seen from Figures 3a,b, 4a,b, 5a,b, 6a,b, 7a,b and 8a,b the concentration of radionuclide ^{131}I in an offshore floating nuclear power plant after a water loss accident is highest in the area of the navigation passage and gradually decreases in the surrounding area, and the transfer rate decreases more slowly in the navigation direction and more rapidly in its vertical direction. After 5 h of ^{131}I release from an offshore floating nuclear power plant, the hourly peak and average ^{131}I concentrations tend to decrease due to the effects of wind speed, atmospheric temperature, wind direction and air pressure, and the dispersion trajectory of ^{131}I is more complicated under navigation conditions than under power supply conditions. In the same time period, compared with the power supply condition, the radionuclide ^{131}I under the navigation condition spreads farther and affects a wider area. This is mainly due to the fact that the release source in the navigational condition is influenced by the meteorological conditions and has an operating speed of 2.5 m/s, which accelerates the diffusion of airborne radionuclides. The wind direction determines the diffusion direction of airborne radionuclides, which was more influenced by the southeasterly wind at that time, and the operation trajectory of ^{131}I spread in the southeasterly direction.

3.2. Sensitivity Analysis of Meteorological Parameters

3.2.1. Sensitivity Analysis of Wind Speed Parameters

The 10 h meteorological data of the simulated surface weather station on 20 January 2019 are selected, the air pressure is set to 1000 hpa, and the cloud cover is 1–4 and 7–10. Because the research area is at sea, the friction force on the sea surface is smaller than that on the land surface, the resistance is less, and the wind speed is higher than that on land. In order to explore the influence of wind speed on radionuclide diffusion in the CALPUFF model, the selected wind speed range is 2.5–20 m/s and other parameters remain unchanged. As shown in Table 3, the maximum concentration in the concentration distribution of 10 h on 20 January is output.

Table 3. Sensitivity analysis scheme of cloud cover and wind speed.

The Serial Number	Wind Speed (m/s)							
	2.5	5	7.5	10	12.5	15	17.5	20
cloud cover	1	2	3	4	5	6	7	8
	2	10	11	12	13	14	15	16
	3	17	18	19	20	21	22	23
	4	25	26	27	28	29	30	31
	7	33	34	35	36	37	38	39
	8	41	42	43	44	45	46	47
	9	49	50	51	52	53	54	55
	10	57	58	59	60	61	62	63

The experiment numbers 1–64 in Table 3 correspond to different combinations of cloud cover and wind speed, for example, experiment number 1 indicates that when the wind speed is 2.5 m/s, the cloud cover is 1. According to the values set by the above combination, the cloud amount value and wind speed value are modified in the corresponding module, which are imported into the CALMET module to drive the CALPUFF model to obtain the radionuclide concentration distribution. Compare the radionuclide maximum concentration value under the combination of different cloud cover and wind speed, and calculate the difference of the radionuclide maximum concentration value. Figure 9 shows the results of sensitivity analysis of wind speed parameters.

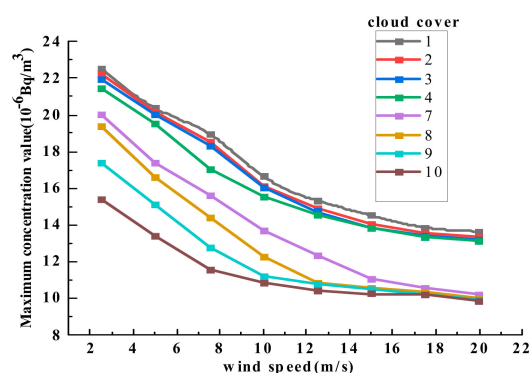


Figure 9. Sensitivity analysis of wind speed parameters.

The analysis of Figure 9 shows that the maximum concentration of radionuclides in the atmosphere is greatly affected when the cloud cover increases from 1 to 10 and the wind speed increases from 2.5 m/s to 20 m/s. The specific results are as follows:

- (1) When the cloud cover is in the range of 1–3, the greater the wind speed is, the smaller the concentration is. When the wind speed increases from 2.5 m/s to 15 m/s, the radionuclide concentration decreases, and the decreasing rate is larger. When the

wind speed increases from 15 m/s to 20 m/s, the decreasing trend of radionuclides is very slow.

- (2) When the cloud cover is 4, the decrease in radionuclide concentration is slightly larger than that at 1–3 cloud cover, and the concentration trend is similar.
- (3) When the cloud cover is in the range of 7–10 and the wind speed is from 2.5 m/s to 10 m/s, the radionuclide concentration decreases, and the decreasing trend is larger. When the cloud cover is 8 and the wind speed is from 10 m/s to 12 m/s, the radionuclide concentration decreases, and when the wind speed is from 12–20 m/s, the radionuclide concentration tends to be flat. When the cloud cover is 9–10 and the wind speed is 10–20 m/s, the concentration of radionuclides tends to be flat.

To sum up, under different cloud-cover conditions, in a certain range of wind speed, the higher the wind speed, the lower the maximum concentration of radionuclides; however, when the wind speed exceeds a certain value, the maximum concentration of radionuclides will tend to be stable. When the cloud cover is 10 and the wind speed is increased from 2.5 m/s to 20 m/s, the minimum difference of radionuclide maximum concentration is 57.0%. When the cloud cover is 7 and the wind speed is increased from 2.5 m/s to 20 m/s, the maximum difference of radionuclide concentration is 90.0%. Therefore, when the cloud cover is determined, the maximum difference of radionuclides caused by wind speed is between 57.0% and 90.0%.

3.2.2. Sensitivity Analysis of Meteorological Parameters of Cloud Cover

Solar radiation is the main energy source of the earth's atmospheric motion, which has a great influence on the diffusion of pollutants. The main reason is that after the solar radiation passes through the atmosphere, the radiation intensity and energy spectrum will change, and the cloud cover in the atmosphere is the key factor for the surface to absorb solar radiation. When there are more clouds, the weakening effect on solar radiation will be stronger and the energy absorbed by the ground will be less. In order to explore the influence of cloud cover on CALPUFF model, the CALPUFF model is used to output different cloud cover, and the wind speed is in the range of 2.5–20 m/s. The experimental scheme is shown in Table 1, and the results are shown in Figure 10.

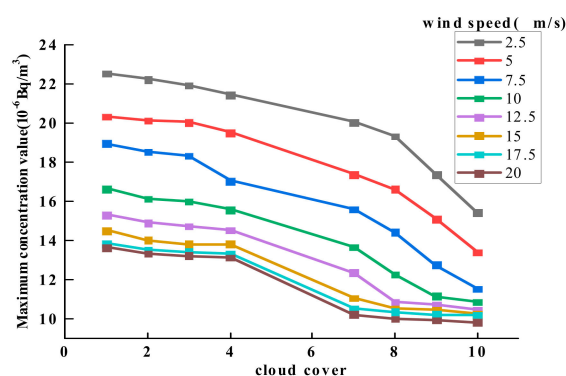


Figure 10. Sensitivity analysis of cloud cover parameters.

It can be seen from Figure 10 that the increase in cloud cover from 1 to 10 has a significant effect on the concentration of radionuclides in the range of wind speed from 2.5 m/s to 20 m/s. In general, under different wind speeds, the greater the cloud cover, the lower the concentration of radionuclides.

- (1) When the cloud cover is 1–4 and the wind speed is 2.5–17.5 m/s, the concentration of radionuclides decreases, but the decrease is not significant.
- (2) When the cloud cover is 4–7 and the wind speed is 2.5–12.5 m/s, the decrease in radionuclide concentration increases slightly compared with that when the cloud cover is 1–4. When the wind speed is 15–20 m/s, the decrease rate of radionuclide concentration is significantly higher than that when the cloud cover is 1–4.

- (3) When the cloud cover is 7–10 and the wind speed is 2.5–7.5 m/s, the decrease in radionuclide concentration is significantly higher than that when the cloud cover is 1–7. When the wind speed is 10 m/s, the decrease rate of radionuclide concentration is slightly larger than that when the cloud cover is 1–7; however, when the wind speed is 12.5–20 m/s, the decrease rate of radionuclide concentration decreases gradually and tends to be flat.
- (4) When the wind speed is 2.5 m/s, the maximum concentration difference caused by cloud cover is 46.1%, and when the wind speed is 20 m/s, the maximum concentration difference caused by cloud cover is 38.9%.
- (5) When the wind speed is determined and the cloud cover increases from 1 to 10, the range of the maximum concentration difference is approximately between 35.7% and 53.5%.
- (6) Therefore, the influence of wind speed parameters on the maximum concentration of radionuclides in offshore floating nuclear power plants is greater than that of cloud cover parameters.

3.2.3. Sensitivity Analysis of Temperature and Meteorological Parameters

In order to explore the influence of ambient temperature on the atmospheric diffusion of radionuclides in CALPUFF model, the wind speed is 5 m/s, the cloud cover is 5, and the pressure is 900 hpa, 1000 hPa and 1100 hpa, respectively. Since the ambient temperature in most areas of China is between $-20\text{ }^{\circ}\text{C}$ and $40\text{ }^{\circ}\text{C}$, the range of ambient temperature is between $-20\text{ }^{\circ}\text{C}$ and $40\text{ }^{\circ}\text{C}$, and the values of other parameters remain unchanged. The sensitivity analysis diagram is shown in Figure 11.

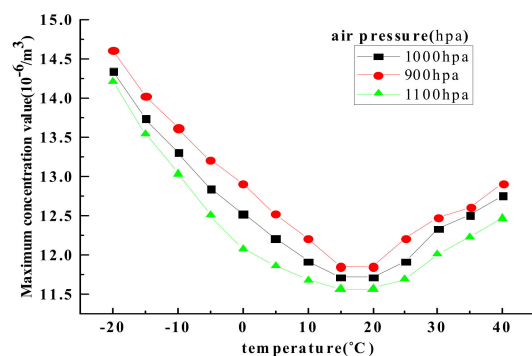


Figure 11. Sensitivity analysis of temperature and meteorological parameters.

As can be seen from Figure 11, the overall influence trend of environmental temperature on radionuclide concentration is from $-20\text{ }^{\circ}\text{C}$ to $20\text{ }^{\circ}\text{C}$. The higher the ambient temperature is, the lower the radionuclide concentration is. From $20\text{ }^{\circ}\text{C}$ to $40\text{ }^{\circ}\text{C}$, the higher the ambient temperature is, the higher the radionuclide concentration is. The specific manifestations are as follows:

- (1) When the pressure is 1000 hpa, the ambient temperature is from $-20\text{ }^{\circ}\text{C}$ to $20\text{ }^{\circ}\text{C}$, and the ambient temperature is $20\text{ }^{\circ}\text{C}$, the radionuclide concentration reaches the maximum value of $1.43 \times 10^{-5}\text{ Bq/m}^3$, and the lowest radionuclide concentration is $1.17 \times 10^{-5}\text{ Bq/m}^3$ when the ambient temperature is $20\text{ }^{\circ}\text{C}$. The difference between the two is 22.4%. According to the investigation of meteorological data, the annual average ambient temperature change is generally less than $1\text{ }^{\circ}\text{C}$, and the annual average ambient temperature change in a few extreme areas is also less than $5\text{ }^{\circ}\text{C}$. Therefore, in the above ambient temperature range, when the ambient temperature changes by $5\text{ }^{\circ}\text{C}$, the effect on the change of radionuclide concentration is 2.8%, and when the temperature change is $1\text{ }^{\circ}\text{C}$, the effect on the change of radionuclide concentration is 0.56%. When the air pressure is 1100 hpa and 900 hpa, the maximum difference of radioactivity concentration in the abovementioned ambient temperature range is 23.4% and 22.8%, respectively.

- (2) In the range of ambient temperature from 20 °C to 40 °C, the maximum radionuclide concentration is 1.27×10^{-5} Bq/m³ when the ambient temperature is 40 °C, and the lowest when the ambient temperature is 20 °C. The difference between the two is 8.9%. Therefore, when the ambient temperature changes by 5 °C, the effect on the change of radionuclide concentration is 2.22%, and when the temperature change is 1 °C, the effect on the change of radionuclide concentration is 0.45%. When the air pressure is 1100 hpa and 900 hpa, the maximum difference of radioactivity concentration in the above ambient temperature range is 8.9% and 7.8%, respectively.
- (3) The difference of the maximum concentration of radionuclides caused by ambient temperature under the pressure of 900 hpa, 1000 hpa and 1100 hpa ranges from 7.8% to 23.4%.

3.2.4. Sensitivity Analysis of Barometric Meteorological Parameters

In order to explore the influence of barometric parameters on the atmospheric diffusion of radionuclides, when the cloud cover is 5, the wind speed is 5 m/s, the temperature is −20 °C, 0 °C and 20 °C, and the pressure varies from 700 hpa to 1100 hpa. The values of other parameters remain unchanged. The sensitivity analysis diagram is shown in 18.

As can be seen from Figure 12, generally speaking, when the ambient temperature is between −20 °C and 20 °C and the air pressure increases from 700 hpa to 1100 hpa, the concentration of radionuclides varies within a small range. In addition, the influence of ambient temperature on the concentration of radionuclide is much higher than that of air pressure. In the temperature range from −20 °C to 20 °C, the lower the ambient temperature, the higher the concentration of radionuclide.

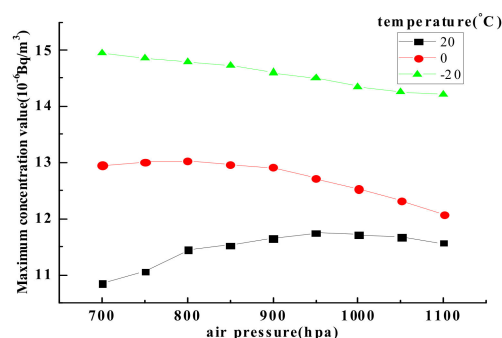


Figure 12. Sensitivity analysis of barometric meteorological parameters.

When the ambient temperature was 20 °C and the air pressure increased from 700 hpa to 1100 hpa, the overall trend of the radionuclide concentration increased slowly first. When the air pressure reached about 950 hpa, the radionuclide concentration gradually decreased, and the maximum difference of the radionuclide concentration was 6.6%. When the ambient temperature was 0 °C, the atmospheric pressure increased from 700 hpa to 1100 hpa, and the overall trend of the radionuclide concentration increased slowly. When the atmospheric pressure reached about 800 hpa, at ambient temperature of −20 °C, 20 °C and 0 °C, the maximum concentration difference caused by air pressure ranges from 5.2% to 7.9%. Therefore, when the pressure value changes by 100 hpa, the range of influence on the concentration of radionuclide is 1.3–2.0%.

Since China's offshore floating nuclear power plant is in the research and design stage and lacks relevant test conditions, this research work is based on simulation, and experimental studies can be added in future research to further enhance the theoretical value and practical guidance of the research work by comparing the simulation and the test.

4. Conclusions

In this study, the atmospheric diffusion regularity of airborne radionuclide ¹³¹I under LOCA of an offshore floating nuclear power plant was analyzed based on the CALPUFF

model under two different operating conditions and four different meteorological parameters. The following main conclusions are drawn.

The wind direction affects the diffusion direction of ^{131}I , and the maximum and average radionuclide concentrations decrease according to meteorological conditions such as wind speed, atmospheric temperature and wind direction, and the trajectory of radionuclide diffusion in hourly sailing conditions is more complicated than that in power supply conditions. In the sailing condition, the radionuclide concentration is highest in the sailing area, and decreases gradually in the surrounding area, and the rate decreases slowly in the sailing direction, and decreases faster in its vertical direction. In the same time period, the radionuclides in the navigation condition spread farther and affect a wider area compared with the power supply condition.

Under different cloud-cover conditions, in a certain range of wind speed, the higher the wind speed is, the lower the maximum concentration of radionuclides is; however, when the wind speed exceeds a certain value, the maximum concentration of radionuclides will tend to be stable. When the cloud cover is determined, the maximum difference of radionuclides caused by wind speed is 57.0% and 90.0%. When the cloud cover increases from 1 to 10, the range of the maximum concentration difference is approximately between 35.7% and 53.5%. The difference of the maximum concentration of radionuclides caused by ambient temperature under the pressure of 900 hpa, 1000 hpa and 1100 hpa ranges from 7.8% to 23.4%. When the pressure value changes by 100 hpa, the range of influence on the concentration of radionuclide is 1.3–2.0%.

When predicting radionuclide dispersion, we should pay attention to the selection and processing of wind speed data. Air pressure has less influence on the accident; therefore, when the air pressure data is not complete, the average air pressure can be used instead.

In the next step, we will consider more complex operating conditions, such as different heading, air humidity in the ocean, and the effect of ocean currents on the migration of airborne radionuclides. In addition to using the CALPUFF model to study the above issues, researchers can also use the air quality model provided by the EPA, which is also suitable for studying the dispersion of air pollutants in the atmosphere [26].

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