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Research Article

Research on Radionuclide Diffusion Mechanism in the Ocean and Emergency Response under Oceanic Radioactive Events

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On March 11, 2011, a serious radionuclide leakage accident occurred at Fukushima Daiichi nuclear power plant, and a large number of radionuclides were released, causing serious pollution to the ocean environment. On August 25, 2021, Japan announced the overall plan for the discharge of radioactive sewage from the Fukushima Daiichi nuclear power plant into the ocean, and the discharge will begin around the spring of 2023. All operational and under-construction nuclear power plants in China are distributed in coastal areas presently. In case of a nuclear leakage accident, radionuclides will diffuse through the ocean and pollute the ecological environment. The study of radionuclide diffusion mechanism in the ocean and emergency response plays an important role in accident mitigation under oceanic radioactive events. A radionuclide diffusion model in the ocean was established and the radionuclide diffusion mechanism in the ocean was analyzed. And then a prediction and monitoring system of radionuclide diffusion in the ocean was proposed. The results show that the short-term radionuclide diffusion is mainly influenced by the source term, flow field and decay of ^{131}I, and the degree of influence decreases in turn. On the whole, influences of the flow field and ^{131}I decay are weakened during the long-term diffusion. At the same time, the influence of ^{137}Cs decay begins to be obvious and the influence of suspended matter is increasing. The influence of ocean organisms is always small. Problems of scientific prediction and protection were analyzed, and the emergency response scheme was given. It is of great significance to improve the capacity of emergency response for oceanic radioactive events.

1. Introduction

The utilization of nuclear energy has brought new impetus to human development, but it is also accompanied by risks and challenges, so we must deal with various nuclear security challenges and maintain nuclear security. Japan was struck by a magnitude-8.9 earthquake off its northeastern coast, followed by a tsunami on March 11, 2011. A serious radionuclide leakage accident occurred at Fukushima Daiichi nuclear power plant [1], and a large number of radionuclides were released, causing serious pollution to the ocean environment [2]. Since 2011, more than 1.2 million tons of radioactive sewage have been stored in thousands of large water storage tanks at the Fukushima nuclear power plant, and it is estimated that the radioactive sewage will reach the limit of 1.37 million tons of water tank capacity by 2022 [3]. On August 25, 2021, Japan announced the overall plan for the discharge of radioactive sewage from the Fukushima Daiichi nuclear power plant into the ocean, and the discharge will begin around the spring of 2023. In the nuclear accident, the Japanese government and its rescue exposed many problems, such as slow response, chaotic deployment, improper disposal, and so on [4, 5]. After the nuclear leakage accident, there was no timely and scientific prediction for the pollution range. The division of emergency areas was not clear, and there was a lack of emergency plans and preparation for major accidents.

The Fukushima nuclear accident caused serious ocean pollution, then scholars and institutions at home and abroad have done a lot of research on the transport of radionuclides in the ocean. Kanai et al. [6] analyzed and concluded that radionuclides in the atmosphere diffused rapidly and

decreased greatly within 3 to 4 months. Inoue et al. [7] analyzed observation data of radionuclides along the coast of Japan before and after the accident. The results showed that radionuclide concentration along the coast increased rapidly after the accident, and began to decrease in June 2011. Nakano et al. [8] established a global radionuclide transport model with a resolution of $2.0^\circ \times 2.0^\circ$, and the long-term transport path of ^{137}Cs was predicted based on the tracer method. Qiao Fangli et al. [9,10] proposed that there were three channels for radionuclide transportation in the environment: rapid transportation in the atmosphere, slow transportation on the ocean surface, and very slow transportation in the ocean interior. The radionuclide tracer model with a resolution of $(1/8)^\circ \times (1/8)^\circ$ was established for regions of 99°~150°E and 0°~50°N in the Northwest Pacific with the POM ocean model. They concluded that radionuclide transport was slow on the ocean surface, reaching 150°E after 50 days, and the influence range was a narrow band. Yanchun et al. [11] regarded radionuclides as tracers to simulate long-distance transport of radionuclides in the ocean with the model MICOM, They concluded that emission scenarios and meteorological data had no significant effect on the radionuclide migration path. Yawei and Hongwei [12] simulated radionuclide migration, taking the Fukushima nuclear leakage accident as an example, in coastal waters by the Lagrangian method and POM model. After the Fukushima nuclear leakage accident, Yamamoto et al. [13] analyzed the deposition of radionuclides on the seabed near the Fukushima nuclear power plant. Saleh [14] studied the effects of biomass, light, and radionuclide concentration on radionuclide enrichment by oceanic plants. Fenghua et al. [15] studied the ^{137}Cs enrichment by organisms in the North Pacific after the Fukushima accident, and the results showed that the quantity of ^{137}Cs in sharks was the highest, as high as 1.16 Bq/kg. After a nuclear leakage accident, the most important thing is to make a timely and reasonable emergency response through the accident consequence evaluation system to minimize the accident consequences. In October 2015, the International Atomic Energy Agency held the first global nuclear emergency preparedness and response conference in Vienna [16], which was attended by members from 82 countries, and the meeting was expected to deal with possible nuclear leakage accidents from the aspects of emergency management, protection strategy, public health, and international cooperation. According to the standards of China's nuclear emergency response, Hong et al. [17] put forward the specific contents and processes that local governments need to implement in nuclear emergency response. According to the emergency response to the Fukushima accident, Ling et al. [18] put forward some suggestions that need to be improved in emergency activities. Qingdang et al. [19] established the overall scheme for the nuclear accident assessment system through analysis of ocean circulation and radionuclide transport path at home and abroad. Periáñez et al. [20] and Maderich et al. [21] researched the radionuclide transport with the Euler model. Periáñez et al. [22] studied the water/sediment interaction problem. The marine distribution coefficient for a given radionuclide was defined [23]. Benkdad et al. [24] formulated more complex water/sediment interaction models which involve parallel and consecutive reactions, but they had not been yet implemented in a marine radionuclide transport model. IAEA MODARIA program carried out a recent model intercomparison [25], and it was shown that dynamic biota models, which handle situations out from equilibrium, perform better than equilibrium models. The work was recently carried out in the MODARIA-II program [26]: ^{137}Cs concentrations in phytoplankton, zooplankton, non-piscivorous, and piscivorous fish were calculated over the whole north Pacific Ocean up to two years after the Fukushima accident. Tierney et al. [27] recently described a more complex model of ^{14}C transfer in the marine trophic web. However, advection was treated in a limited way and measurement data could not be reproduced in some areas. In Fukushima Daiichi nuclear leakage accident, radionuclides released into the atmosphere were transported eastwards by a jet stream [28], and they reached the coast of North America in four days. Some of these radionuclides were deposited on the Pacific Ocean surface by wet and dry processes. The first modeling studies into the dispersion of Fukushima releases in the Pacific Ocean were published soon after the accident. Kawamura et al. [29] simulated the spreading of ^{131}I and ^{137}Cs with the Lagrangian model. Behrens et al. [30] performed ten-year-long simulations of ^{137}Cs dispersion in the Pacific Ocean. They found that concentrations would be nearly homogeneous over the whole Pacific after some 10 years. The relevance of atmospheric deposition was also studied by some authors [31], finding that the high ^{137}Cs concentrations detected in surface waters north of 40°N one month after the accident should be attributed to atmospheric deposition. Periáñez et al. [32] reviewed the current status on the subject of numerical modeling of radionuclide transport in the marine environment and models applied to simulate Fukushima Daiichi nuclear power plant releases in the Pacific Ocean after the 2011 accident. They concluded that, in the case of the marine environment, radionuclide pathways depended on sources, dispersion by currents, and uptake by sediments and biota. They also concluded that a careful selection of the ocean model was needed and should be done after a detailed comparison with local measurements of currents.

Direction and time of radionuclide diffusion in the ocean were mostly studied [33], and there was little literature to explore the influences of the source term, flow field, decay, suspended matter, and ocean organisms on radioactivity. Therefore, the radionuclide diffusion mechanism in the ocean was studied, and the radionuclide concentration distribution was given, then a prediction and monitoring system was put forward. Problems of scientific prediction and protection were analyzed. It is of great significance to improve the capacity of emergency response for oceanic radioactive events.

2. Research Object

2.1. Location of Nuclear Power Plant. All operational and under-construction nuclear power plants in China are

distributed in coastal areas presently. In case of a nuclear leakage accident, radionuclides will diffuse through the ocean and pollute the ecological environment. AP1000 is an advanced third-generation nuclear power unit. Haiyang nuclear power plant was successfully completed the full power operation test of 168 hours on October 22, 2018, and then it was officially put into commercial operation. The location of Haiyang nuclear power station is special, which is located near the Yellow Sea, and the nearby coast is mostly scenic spots and residential areas. Therefore, Haiyang nuclear power station and its adjacent ocean areas were selected to research. The specific location of the Haiyang nuclear power plant is the eastern end of the cape which is surrounded by the ocean on three sides. According to the topographic data of the General Bathymetric Chart of the Oceans, the nuclear power plant, which was marked with a red flag, and its surrounding environment were drawn, as shown in Figure 1.

As can be seen from Figure 1, the longitude and latitude of the hydrodynamic field which is near the coastal waters of the nuclear power plant are 119.5°E~122.5°E and 35.5°E~37°N, respectively. The regional scope is about 270 km from east to west and about 160 km from north to south.

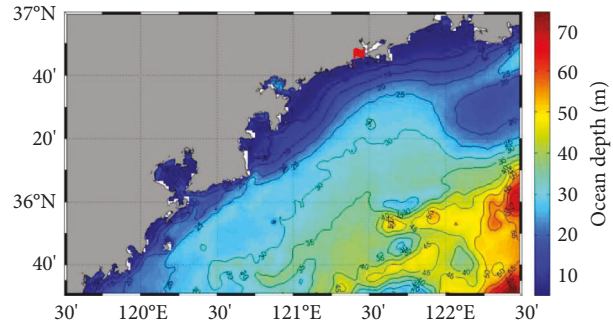

Figure 1: The location of Haiyang nuclear power plant.

3. Calculation Model

3.1. Hydrodynamic Model. Based on the ROMS model [34], the hydrodynamic model and radionuclide diffusion model were established. The momentum equation is shown in formulas (1)–(3), and the continuity equation is shown in formula (4). The diffusion equation is shown in formula (5), and the state equation is shown in formula (6). The dynamic pressure equation is shown in formula (7).

$$\frac{\partial u}{\partial t} + \vec{V} \cdot \nabla u - fv = -\frac{\partial \varphi}{\partial x} - \frac{\partial}{\partial z}\left(\overline{u'w'} - \nu \frac{\partial u}{\partial z}\right) + F_u + D_u, \quad (1)$$

$$\frac{\partial v}{\partial t} + \vec{V} \cdot \nabla v + fu = -\frac{\partial \varphi}{\partial y} - \frac{\partial}{\partial z}\left(\overline{v'w'} - \nu \frac{\partial v}{\partial z}\right) + F_v + D_v, \quad (2)$$

$$\frac{\partial \varphi}{\partial z} = \frac{-\rho g}{\rho_0}, \quad (3)$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0, \quad (4)$$

$$\frac{\partial C}{\partial t} + \vec{V} \cdot \nabla C = -\frac{\partial}{\partial z}\left(\overline{C'w'} - \nu_\theta \frac{\partial C}{\partial z}\right) + F_c + D_c, \quad (5)$$

$$\rho = \rho(T, S, P), \quad (6)$$

$$\varphi(x, y, z, t) = \frac{p}{\rho_0}, \quad (7)$$

where u is the velocity component in x direction, m/s; v is the velocity component in y direction, m/s; w is the velocity component in z direction, m/s; $\vec{V}$ is the average velocity vector, m/s; f is the parameter of Coriolis force, rad/s; φ is the kinetic pressure, Pa·m^3/kg; is the kinematic viscosity, m^2/s; ρ is the water density, kg/m^3; ρ_0 is the water reference density, kg/m^3; g is the gravitational acceleration, m/s^2; T is the temperature, °C; S is the salinity; P is the pressure, Pa; C is a scalar which represents temperature, salinity or pollutant concentration; F_u and F_v are forced terms; F_c is the source term; D_u, D_v and D_c are horizontal diffusion terms; $\overline{u'w'}$ and $\overline{v'w'}$ are reynolds stress terms; $\overline{C'w'}$ is the flux of turbulent particles.

The terrain data of the hydrodynamic model was selected from the General Bathymetric Chart of the Oceans. The data were interpolated into $1' \times 1'$ as the topographic field of this model. The results of temperature and salt which were calculated by the dynamic model near China coastal waters were used as the initial field and open boundary field of this model. The wind speed, air pressure, air temperature, rainfall and other data in the meteorological data set of NCEP-DOE were adopted as ocean surface boundary conditions. Harmonic constants of 10 tidal components were selected to calculate the water level of the open boundary.

3.2. Eulerian Model. The eulerian method can describe the distribution of radionuclide concentration, and it can also deduce the total leakage amount of radionuclides according to the monitoring data. It is suitable for calculating the change of radionuclide concentration. The governing equation is shown in the formula (5), and the source term F_c needs to be setting. The source term calculation is shown in formula (8).

$$F_c = -\left(\frac{\partial w_c}{\partial s} + \xi_b\right) C + e^{-\lambda t} S_c. \quad (8)$$

Where F_c is the radionuclide source term, Bq; $\partial w_c/\partial s$ is the deposition rate; ξ_b is the bioabsorption rate; C is the radioactivity, Bq/m^3; S_c is the initial leakage, Bq.

3.3. Influence Model of Decay. The relationship between radioactivity and decay constant is shown in formula (9).

$$A = A_0 e^{-\lambda t}, \quad (9)$$

where A_0 is the original radioactivity, Bq; A is the radioactivity after the time t, Bq; λ is the constant of decay, 1/s.

3.4. Influence Model of Suspended Matter. Suspended matter in the ocean comes from a wide range of sources, such as river particles, atmospheric dust, biological particles, and crustal weathering. It is not a static state, and the material exchange process is very complex. In this paper, the influence model of the suspended matter was proposed. Considering the renewal process of the suspended matter, the following assumptions were made.

(1) The radionuclide concentration in the analysis range is uniform.

(2) The amount of suspended matter entering the water and that deposited on the seafloor are equal and they are in a dynamic equilibrium state.

(3) Radionuclides enriched by suspended matter can reach a stable state in a very short time, and the enrichment time is ignored.

(4) The water depth in the analyzed area is an average value.

(5) The radionuclide concentration in a small area remains unchanged for a short time.

(6) When the system is in equilibrium, the enrichment factor of suspended matter is the ratio of the radionuclide amount enriched by per unit of suspended matter to radionuclide concentration.

Based on the above assumptions, a box model of enrichment and deposition process by suspended matter was established. It is shown in formula (10).

$$C = C_0 \cdot \left(\frac{1}{1 + (\varphi \cdot \Delta t \cdot K_d / 100 \cdot h)} \right)^{t/\Delta t}, \quad (10)$$

where C is the radionuclide concentration after enrichment and deposition with the suspended matter, Bq/L; C_0 is the radionuclide concentration before enrichment and deposition with the suspended matter, Bq/L; φ is the deposition flux of suspended matter, g/(cm^2·a); t is the time, a; Δt is a time interval, a; h is the water depth, m; K_d is the enrichment factor of suspended matter, L/kg.

3.5. Influence Model of Ocean Organism. There are many organisms in the ocean, which will enrich radionuclides through surface enrichment and internal digestion. Therefore, oceanic organism is an important factor in radionuclide concentration. In order to establish the oceanic organism enrichment model, the following assumptions were made.

(1) The radionuclide concentration in the analysis range is uniform.

(2) The organism in the ocean is evenly distributed within the analysis range.

(3) The total amount of ocean organisms is in dynamic equilibrium, and enriched radionuclides circulate in the biosphere.

Based on the above assumptions, the calculation model of radionuclide concentration after enrichment by ocean organism was established, as shown in formula (11).

$$C = C_0 \frac{1}{1 + F_d \cdot W_b}, \quad (11)$$

where C_0 is the radionuclide concentration before enrichment by ocean organism, Bq/L; C is the radionuclide concentration after enrichment by ocean organism, Bq/L; F_d is the enrichment factor of ocean organism, L/kg; W_b is the ocean organism quantity in the ocean, kg/L.

4. Result Analysis

4.1. Flow Field Verification. The Institute of Seaology, Chinese Academy of Sciences monitored the water level data of the seabed base in June 2014, which was used to test the calculation results. The simulated result was compared with the monitored data, which is shown in Figure 2.

It can be seen from Figure 2 that the coastal water's tide of the Haiyang nuclear power plant is a semidiurnal tide, including two high tides and two low tides. The error between simulated and monitored magnitudes and directions of water velocity is within 10%. It shows the accuracy of the model.

4.2. Influence of Flow Field. Based on the hydrodynamic model and Euler model in Section 3, the radionuclide total leakage of ^{137}Cs was set as 1×10^{18}Bq, and radionuclides were continuously released within five days. The concentration distribution of ^{137}Cs was calculated within two weeks, from June 8, 2014 to June 21, 2014, after a nuclear leakage accident in the summer. And the concentration distribution of ^{137}Cs was calculated within two weeks, from January 8, 2014 to January 21, 2014, after a nuclear leakage accident in winter. The influence of the flow field in different seasons on radionuclide concentration distribution was analyzed. The concentration distribution of ^{137}Cs in the surface layer, near the coastal waters of the nuclear power plant, within two weeks in winter is shown in Figure 3(a) and Figure 3(b). And the concentration distribution of ^{137}Cs in the surface layer, near the coastal waters of the nuclear power plant, within two weeks in summer is shown in Figure 3(c) and 3(d).

It can be seen from Figure 3(a) and 3(b) that ocean surface radionuclides diffuse about 60 km from the nuclear power plant to the northeast along the coastline after the accident in winter, and then radionuclides quickly diffuse 60 km to the south two weeks later. In winter, radionuclides in the east and west directions of the nuclear power plant diffuse to the south rapidly, while the radionuclides near the nuclear power plant diffuse to the south slowly. The reason is that ocean surface radionuclides quickly diffuse southward with the ocean current under the action of the strong north wind. The reason of radionuclides near the nuclear power plant diffuse to the south slowly is that a warm water tongue comes from Jeju Island which is in the South and entered into the South Yellow Sea which is in the north in winter.

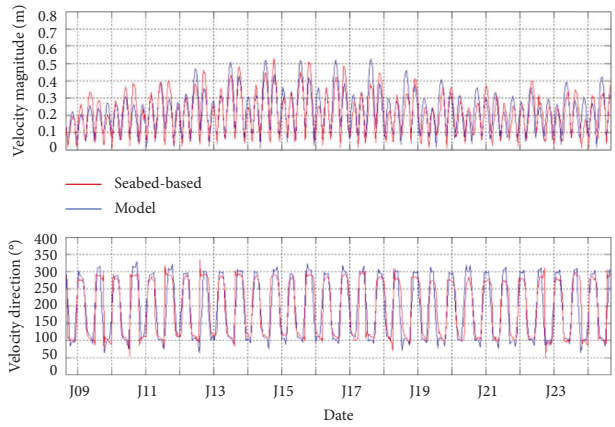

Figure 2: Water velocity of simulation and monitor.

Compared with radionuclide diffuse in winter, it can be seen from Figure 3(c) and 3(d) that the radionuclide diffusion area is not obviously banded, but radionuclides diffuse around the nuclear power plant. Compared with the radionuclide diffusion speed in winter, the diffusion speed is relatively slow in summer, and radionuclides diffuse about 35 km to the south of the nuclear power plant two weeks later. This is mainly due to the formation of a uniform low-temperature and high-salinity water mass in the whole Yellow Sea in winter, and a stable water layer with high temperature and low salt is formed on the surface of the Yellow Sea in summer. Because the wind is weak in summer, a stable cold water mass is formed at the botom of the Yellow Sea. Finally, due to the weak current in the Yellow Sea in summer, radionuclides do not migrate in a band, but migrate slowly and diffuse rapidly at the same time. In general, the radionuclide distribution area in winter is significantly different from that in summer. Under the influence of ocean currents, the speed of radionuclide migration and diffusion is very fast in winter. And radionuclides mainly diffuse in summer and migrate slowly with the ocean current.

The vertical distribution of ^{137}Cs, near the coastal waters of nuclear power plant, within two weeks in summer is shown in Figure 4(a) and 4(b).

It can be seen from Figure 4 that radionuclides with high concentrations diffuse to the bottom in the first hour in summer. Compared with Figure 3, there is also a good corresponding relationship between surface concentration and vertical concentration, and it also shows the accuracy of the calculation results.

4.3. Influence of Decay. The half-life of ^{137}Cs is 30.17 years, the half-life of ^{137}Cs is 2.06 years, and the half-life of ^{131}I is 8.04 days. According to the influence model of decay in section 3, Radioactivity was set as 1×10^{18}Bq and radioactivity changes of different radionuclides with time were calculated, as shown in Figure 5.

It can be seen from Figure 5(a) that the radioactivity of ^{137}Cs and ^{134}Cs decrease little and basically remain unchanged for 300 days. The radioactivity of ^{131}I decreases by about 12 orders of magnitude in 300 days. It can be seen from Figure 5(b) that the radioactivity of ^{131}I basically disappears, and the radioactivity of ^{134}Cs decreases by about three orders of magnitude. The radioactivity of ^{137}Cs decreases little and basically remains unchanged. In general, for radionuclide diffusion in the short-term, the decay influence of ^{131}I needs to be considered, and the decay influence of ^{137}Cs and ^{134}Cs can be ignored.

4.4. Influence of Suspended Matter. Mckinley et al. [35] summarized the enrichment factor values of more than a dozen radionuclides such as plutonium isotopes in different media, generally in the range of 0 L/kg~100000 L/kg. According to the influence model of suspended matter in Section 3, enrichment factors of suspended matter were set as 10 L/kg, 1000 L/kg, and 100000 L/kg Respectively, and the water depth was set as 44m, and the deposition flux of suspended matter was set as 0.76 g/(cm^2·a) [36]. The radionuclide residual ratio change with time in the ocean was calculated with upper limit values of parameters, as shown in Figure 6.

It can be seen from Figure 6 that, under the set conditions, radionuclides attach to suspended matter and deposit with them, and the radionuclide residual ratio will continue to decrease with time. When the enrichment factor is 1000 L/kg, the radionuclide residual rate is about 50% after four years, about 18% after ten years, and about 3% after twenty years. For plutonium isotopes, when the enrichment factor is 100000 L/kg, Plutonium isotopes will be quickly enriched and deposited on the seafloor.

The enrichment factor of the suspended matter was set as 40 L/kg, the water depth was set as 44m, and the deposition flux of suspended matter was set as 0.03 g/(cm^2·a) [37]. The radionuclide residual ratio change with time in the ocean was calculated with lower limit values of parameters, as shown in Figure 7.

It can be seen from Figure 7 that when the lower limit values of deposition flux and enrichment factor of suspended matter are taken, the radionuclide residual ratio is about 92% after 300 years. In this case, the influence of suspended matter is much smaller than the decay of ^{137}Cs.

In practice, the influence of suspended matter is much smaller than the influence with the upper limit values of parameters. On the one hand, actual values of enrichment factor and deposition flux of suspended matter are much smaller than the upper limit values. Actual values can be several orders of magnitude smaller than the upper limit values. On the other hand, the model does not consider the resuspension of suspended matter. In fact, the seabed suspended matter will have strong resuspension under the action of ocean currents. Therefore, in the short-term analysis, the influence of suspended matter can be ignored. But the influence needs to be considered when the time is decades or longer.

4.5. Influence of Ocean Organism. According to the influence model of ocean organism in Section 3, the radionuclide residual ratio change with organism enrichment factor was calculated

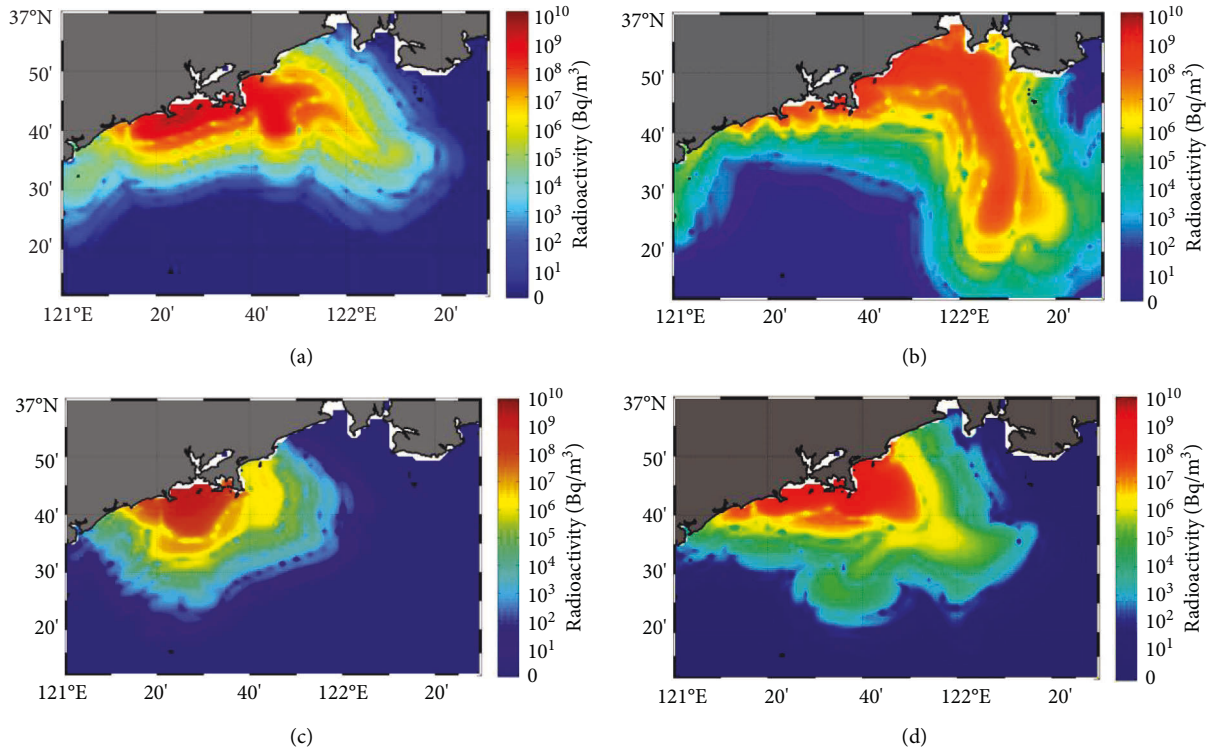

FIGURE 3: Surface diffusion of ^{137}Cs in two weeks of summer and winter. (a) The 7th day in winter. (b) The 14th day in winter. (c) The 7th day in summer. (d) The 14th day in summer.

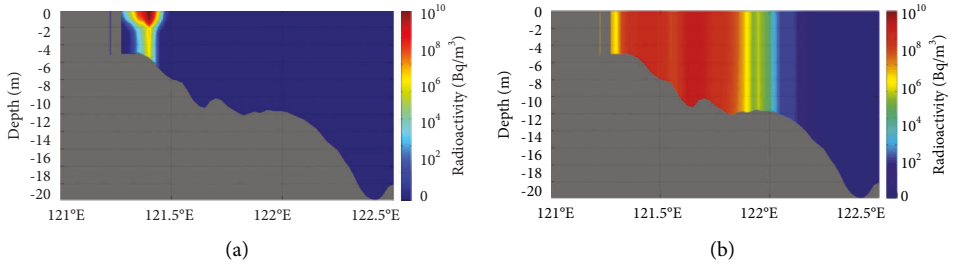

FIGURE 4: Vertical diffusion of ^{137}Cs in two weeks of summer. (a) The 11th day in summer. (b) The 14th day in summer

when the ocean organism quantities were set as 10^{-5} kg/L, 10^{-6} kg/L and 10^{-7} kg/L respectively, as shown in Figure 8.

It can be seen from Figure 8 that when the ocean organism quantity is constant, the radionuclide residual ratio decreases with the increase of the enrichment factor of ocean organisms, and the influence of ocean organisms becomes more obvious with the increase of enrichment factor of ocean organisms. But the enrichment factor of ocean organisms is basically less than 10^4 L/kg. When the ocean organism quantity is 10^{-6} kg/L or 10^{-7} kg/L, the influence of ocean organisms is very small, and its influence can be ignored. When the ocean organism quantity is 10^{-5} kg/L, the influence of ocean organisms begins to be obvious. With the increase of enrichment factor, the radionuclide residual ratio gradually decreases. When the enrichment factor reaches 10^4 L/kg, radionuclides decrease by about 10% under the action of ocean organism. The calculation results above are based on the given conditions. In fact, the ocean organism quantity is far lower than 10^{-5} kg/L, and the average enrichment factor is also much less than 10^4 L/kg. At the same time, most radionuclides that are enriched by ocean organisms do not deposit to the seabed, but transfer between ocean organism and still exist in the ocean. For the reasons above, it can be concluded that the influence of ocean organism has little influence on the radioactivity of the ocean.

5. Radionuclide Diffusion Mechanism in the Ocean

5.1. Short-Term Diffusion. The influence degree of each factor was analyzed, and the mechanism of short-term radionuclide diffusion in the ocean was studied, as shown in Figure 9.

It can be seen from Figure 9 that the short-term radionuclide diffusion in the ocean is mainly influenced by the source term, flow field, and decay. And the degree of influence decreases in turn.

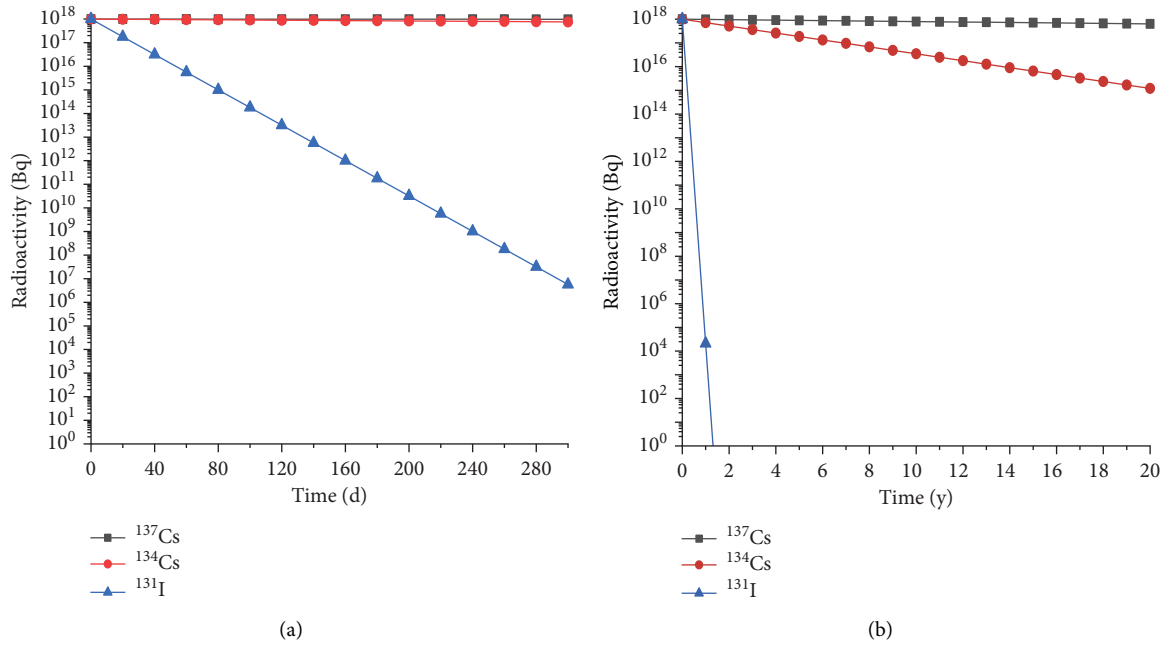

Figure 5: Radioactivity changes of different radionuclides with time. (a) Radioactivity changes within 300 days. (b) Radioactivity changes within 20 years.

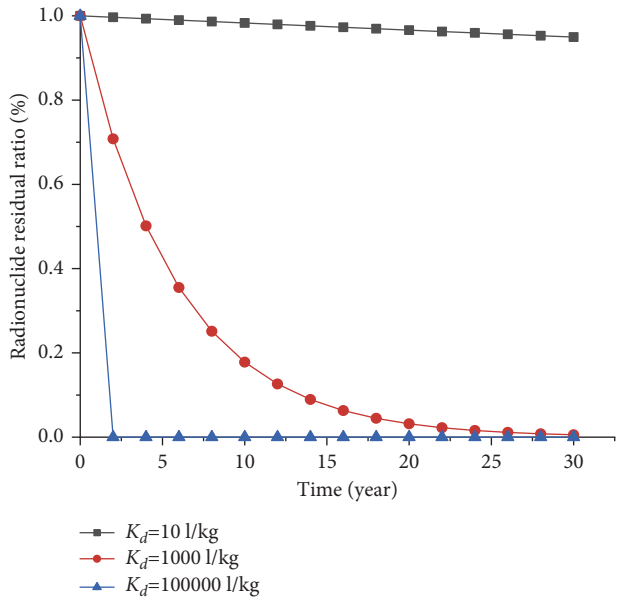

Figure 6: Radionuclide residual ratio change with time with upper limit values of parameters.

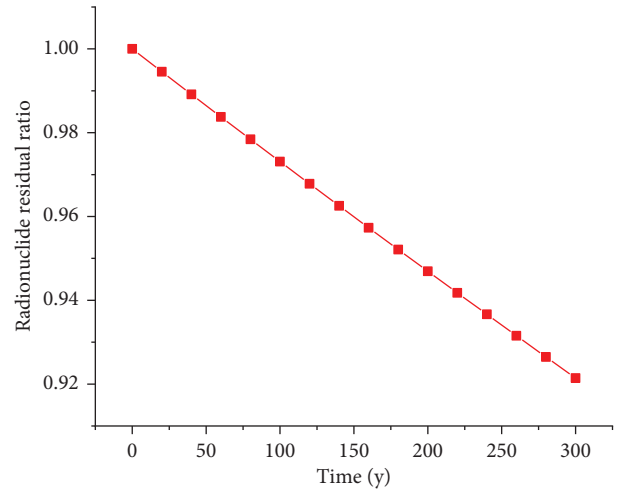

Figure 7: Radionuclide residual ratio change with time with lower limit values of parameters.

5.2. Long-Term Diffusion. The influence degree of each factor was analyzed, and the mechanism of long-term radionuclide diffusion in the ocean was studied, as shown in Figure 10.

It can be seen from Figure 10 that, whether long-term diffusion or short-term diffusion, the source term has a great influence for the reason that the order of magnitude of the source term varies greatly. In the long-term radionuclide diffusion, the radionuclide concentration in the ocean tends to be uniform, so the influence of flow field will be getting weaker and weaker. With the increase of time, most radionuclides in the atmosphere have deposited on the ocean surface, and the influence of atmospheric radionuclides will be getting weaker and weaker. On the whole, influences of flow field and ^{131}I decay are weakened during the long-term diffusion. At the same time, the influence of ^{137}Cs decay begins to be obvious and the influence of suspended matter is increasing. The influence of ocean organism is always small.

6. Prediction and Monitoring System

The environment of the atmosphere and ocean is complex and changeable, so it is difficult to calculate the radionuclide concentration distribution accurately. In order to realize

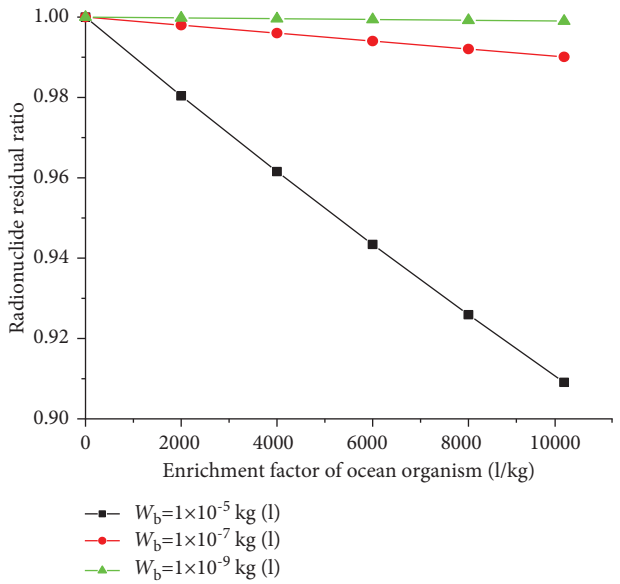

Figure 8: The radionuclide residual ratio change with the enrichment factor of ocean organism.

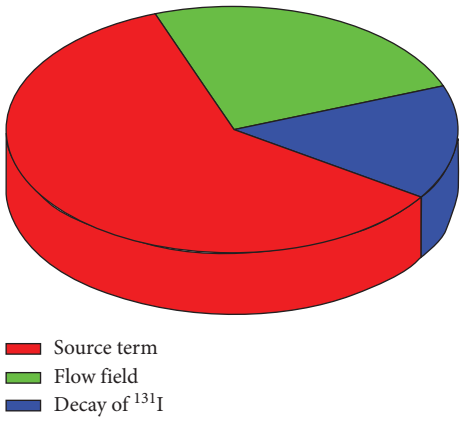

Figure 9: The mechanism of short-term radionuclide diffusion in the ocean.

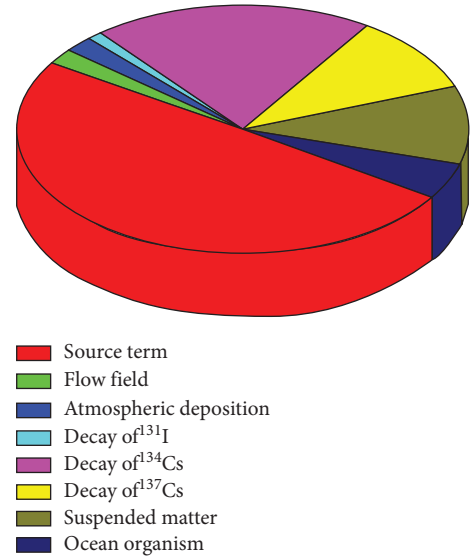

Figure 10: The mechanism of long-term radionuclide diffusion in the ocean.

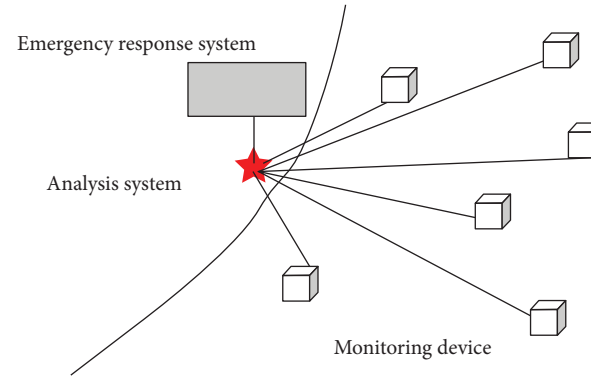

Figure 11: Prediction and monitoring system of radionuclide concentration.

multiple insurance, both model calculation and real-time monitoring are needed. In order to realize the emergency response after nuclear leakage accidents, a radionuclide calculation and monitoring system was proposed to accurately analyze the diffusion area and concentration distribution of radionuclides. It provides theoretical support for emergency response. The prediction and monitoring system of radionuclide concentration is shown in Figure 11.

As can be seen from Figure 11, the prediction and monitoring system of radionuclide concentration includes a radionuclide monitoring device, data transmission system, data analysis system, and emergency response system. Our real-time monitoring system has applied for patents, including buoys equipped with radionuclide detectors, solar panels, data processing servers, and display systems. The buoy is equipped with a data transmission system to transmit data through communication satellites. After the monitoring data is transmitted to the data processing server, the boundary conditions of the radionuclide diffusion model are updated. Then the radionuclide concentration distribution will be calculated in real-time.

After a nuclear leakage accident, the radionuclide concentration in the ocean will be calculated with the radionuclide diffusion model in the data analysis system. Then the radionuclide concentration will be predicted, and the emergency response system will make an emergency response plan according to the results of data analysis. Due to the influence of environmental conditions, there may be a deviation in the results of data analysis, so monitoring devices should be arranged in reasonable positions to form a monitoring network to monitor the radionuclide concentration. Through the data transmission system, the data is transmitted to the data analysis system as the source term of the radionuclide diffusion model. The radionuclide concentration will be further calculated and predicted. The system can monitor the radionuclide concentration in real-time and adjust the model deviation caused by the environment.

7. Conclusions

A radionuclide diffusion model in the ocean was established based on the Euler method and hydrodynamic model. Influence models of suspended matter and ocean organisms were established. And the radionuclide diffusion mechanism in the ocean was analyzed. Then a prediction and monitoring system of radionuclide diffusion in the ocean was proposed and emergency response measures after a nuclear leakage accident were given.

(1) The ocean surface radionuclides diffuse about 60 km from the nuclear power plant to the northeast along the coastline after the accident in winter, and then radionuclides quickly diffuse 60 km to the south two weeks later. Compared with the radionuclide diffusion speed in winter, the diffusion speed is relatively slow in summer, and radionuclides diffuse about 35 km to the south of the nuclear power plant two weeks later.

(2) The radioactivity of ^{137}Cs and ^{134}Cs decreases little and basically remain unchanged in 300 days. The radioactivity of ^{131}I decreases by about 12 orders of magnitude in 300 days.

(3) When the upper limit values of deposition flux and enrichment factor of suspended matter are taken, the radionuclide residual rate is about 50% after four years. When the lower limit values of deposition flux and enrichment factor of suspended matter are taken, the radionuclide residual ratio is about 92% after 300 years.

(4) When the ocean organism quantities are 10^{-6} kg/L and 10^{-7} kg/L, the influence of ocean organisms is very small, and its influence can be ignored. When the ocean organism quantity is 10^{-5} kg/L, the influence of ocean organism begins to be obvious.

(5) The short-term radionuclide diffusion is mainly influenced by the source term, flow field and decay of ^{131}I, and the degree of influence decreases in turn. Influences of flow field and ^{131}I decay are weakened during the long-term diffusion. At the same time, the influence of ^{137}Cs decay begins to be obvious and the influence of suspended matter is increasing. Influence of ocean organism is always small.

(6) Problems of scientific prediction and protection were analyzed, and emergency response measures were given. It is of great significance to improve the capacity of emergency response for oceanic radioactive events.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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