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Modeling and Analysis of Fukushima Nuclear Wastewater Dispersion Based on the ROMS

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Abstract: In the aftermath of the Fukushima nuclear catastrophe, the imperative to comprehensively grasp the mechanics behind the transport and dissemination of radioactive contaminants has been dramatically underscored, with a heightened emphasis placed on environmental safety measures. This research delineates the formulation of an intricate modeling structure that amalgamates the capabilities of the Regional Ocean Modeling System (ROMS) with state-of-the-art components encompassing diffusion processes, source term specifications, Eulerian transport methodologies, and radioactive decay dynamics. The primary ambition of this endeavor is to meticulously simulate and prognosticate the distribution patterns of the radioactive isotope tritium within the aquatic milieu. The constructed model is meticulously engineered to furnish elucidations that forecast the trajectory and eventual fate of radioactive effluents emanating from the Fukushima incident, thereby enabling the assessment of the ensuing ramifications on the marine ecosystem. It seeks to quantify the influence that such contamination could exert on the vitality of marine life, the economic well-being of fisheries, and the overarching sphere of public health. Of particular concern within this study is the elucidation of potential contamination threats posed to the Chinese maritime domain, ascertaining the extent to which these waters may be influenced by the radioactive plume. Through the deployment of this sophisticated simulation tool, the research endeavors to yield valuable insights into the long-term environmental impacts, thus providing a scientific basis for formulating strategic interventions to mitigate the adverse effects of such nuclear disasters on marine biodiversity and human societies alike.

1. Introduction

In the aftermath of the catastrophic events at Fukushima Daiichi in 2011, the subsequent release of radioactive materials into the marine environment has engendered significant international concern pertaining to the potential widespread contamination of the Pacific Ocean. Paramount to addressing these apprehensions is the development of precise and reliable models that can simulate the transport and fate of radioactive contaminants. The Regional Ocean Modeling System (ROMS) is at the forefront of such efforts, offering a robust computational framework capable of capturing the multifaceted dynamics of ocean systems under a variety of climatic scenarios [1].

ROMS is meticulously designed to account for the complex interactions between ocean currents, geological formations, and thermal stratification of the water column. This sophisticated modeling suite is particularly well-suited for the simulation of the dispersion of tritium and other radionuclides, which are byproducts of nuclear incidents such as Fukushima. By incorporating the nuanced physical processes governing the movement of these contaminants, ROMS enables researchers to predict their distribution and concentration over extended periods [2].

The present study harnesses the formidable capabilities of ROMS to synthesize extensive datasets, yielding a comprehensive depiction of the patterns of wastewater dispersion in the Pacific. As shown in Figure 1 for the Fukushima nuclear leak and contamination, the initial data preprocessing and exploratory analyses were carefully designed to ensure the completeness and accuracy of the model inputs [3]. By doing so, researchers are able to scrutinize the influence of climatic variables on the trajectory of the contaminants. This rigorous approach to data handling and model calibration is indispensable for enhancing the predictive accuracy of the simulations.

Subsequently, the enhanced modeling facilitated by ROMS provides a vital tool in the projection of radioactive dispersion, offering invaluable insights into the long-term environmental consequences. The implications of this research are far-reaching, encompassing not only the health of marine ecosystems but also the potential risks to public health [4]. Through the concerted application of ROMS and the detailed analysis it supports, stakeholders can be better equipped to make informed decisions regarding the mitigation of radiological impacts in marine environments.

Figure 1: The Fukushima nuclear leak and nuclear contamination

2. Related work

The "Regional Ocean Simulation System (ROMS)-based modelling and analysis of the dispersion of Fukushima nuclear wastewater" work will focus on the creation of an integrated model to simulate the dispersion of wastewater from the Fukushima nuclear disaster site into the surrounding marine environment.

This research will track the dispersion patterns of radioactive contaminants using the Regional Ocean Modelling System (ROMS), a free-surface, topography-tracking, primitive-equation ocean model widely used by the scientific community for complex ocean and coastal water studies [5]. The model is versatile and capable of simulating water column variables and currents at different spatial and temporal scales.

The first step in the analysis is to set up the ROMS with bathymetric data, initial conditions, boundary conditions, and the location of the wastewater discharge. The bathymetric data will ensure that the modelled topography accurately reflects the underwater landscape around Fukushima. The initial conditions will encompass the ocean at the time of wastewater discharge, including temperature, salinity, and current profiles.

The modelling will then focus on the discharge of wastewater, which is characterised by the presence of radioactive contaminants in the wastewater. Due to the presence of complex combinations of isotopes with different half-lives and biological impacts, the physical and chemical properties of each contaminant must be accurately presented in the model [6]. This is essential for predicting their behaviour in the marine environment, their interactions with marine organisms and ultimately their impact on human health and the economy.

The simulations will be run over defined time scales, spanning from a few days to a few years, to observe the long-term dispersion and dilution of the pollutants. By analysing the outputs, it will be possible to determine the areas affected and the concentration levels of various pollutants over time. This information is essential for assessing the risks to marine life and human communities and for developing mitigation and response strategies [7].

In summary, ROMS-based dispersion analyses of Fukushima nuclear wastewater will provide valuable insights into the environmental impacts of the disaster. It will also guide the decision-making process for remediation efforts and future policies to protect public health and the environment from such events.

3. Establishment of Radionuclide Hydrodynamic Dispersion Model

The Regional Oceanic Modeling System (ROMS) is a prevalently deployed tri-dimensional, free-interface, topography-adaptive coordinate marine model, purposed for the analysis of regional ocean circulation and its concomitant physical, biological, and chemical attributes. Distinguished by its topography-responsive coordinate framework, adaptable marine surface, modular architecture, integration techniques, data incorporation capabilities, and parallel processing prowess, this system represents a collaborative innovation by Rutgers University and the University of California, Los Angeles [8]. It is extensively utilized for the emulation of marine and estuarine ecosystems. Through the application of ROMS, we have developed a model that encompasses both hydrodynamic behavior and radionuclide diffusion, aimed at projecting the propagation patterns of radionuclides within oceanic environments.

$$\frac{\partial u}{\partial t} - fv + \vec{v} \cdot \nabla u = -\frac{\partial \varphi}{\partial x} - \left(\frac{g\rho}{\rho_0}\right)\frac{\partial z}{\partial x} - g\frac{\partial \zeta}{\partial x} + \frac{1}{H_z}\frac{\partial}{\partial \sigma}\left[\frac{K_{\mathrm{M}}}{H_z}\frac{\partial u}{\partial \sigma}\right] + F_{\mathrm{u}} + D_{\mathrm{u}} \tag{1}$$

$$\frac{\partial v}{\partial t} + fu + \vec{v} \cdot \nabla v = -\frac{\partial \varphi}{\partial y} - \left(\frac{g\rho}{\rho_0}\right)\frac{\partial z}{\partial y} - g\frac{\partial \zeta}{\partial y} + \frac{1}{H_z}\frac{\partial}{\partial \sigma}\left[\frac{K_{\mathrm{M}}}{H_z}\frac{\partial v}{\partial \sigma}\right] + F_{\mathrm{v}} + D_{\mathrm{v}} \tag{2}$$

$$\frac{\partial \varphi}{\partial \sigma} = \frac{-gH_z\rho}{\rho_0} \tag{3}$$

$$\frac{\partial H_z}{\partial t} + \frac{\partial (H_z u)}{\partial x} + \frac{\partial (H_z v)}{\partial y} + \frac{\partial (H_z \Omega)}{\partial \sigma} = 0 \tag{4}$$

$$\frac{\partial C}{\partial t} + \vec{v} \cdot \nabla C = \frac{1}{H_z}\frac{\partial}{\partial \sigma}\left[\frac{K_{\mathrm{C}}}{H_z}\frac{\partial C}{\partial \sigma}\right] + F_{\mathrm{T}} + D_{\mathrm{T}} \tag{5}$$

$$\rho = \rho(T, S, P) \tag{6}$$

The equations (1) and (2) in the model describe the changes over time t of the horizontal velocity components u (east-west direction) and v (north-south direction), respectively. The change in the velocity field directly affects the advection of radioactive wastewater, which is the process of a substance being carried along by the flow of a fluid. The terms $-fv$ and $+fu$ represent the influence of the Coriolis force on horizontal flow, which is caused by the Earth's rotation. It affects the direction of fluid flow, especially in large-scale oceanic circulation. The terms $-\frac{\partial \varphi}{\partial x}$ and $-\frac{\partial \varphi}{\partial y}$ represent the pressure gradient force, which is an important force driving fluid motion and also affects the rate and direction of diffusion [9]. The terms $-\left(\frac{g\rho}{\rho_0}\right)\frac{\partial z}{\partial x}$ and $-g\frac{\partial \zeta}{\partial x}$ consider the buoyancy effects due to density inhomogeneity (such as density differences caused by temperature and salinity) and the displacement of the free water surface, which affect both vertical and horizontal flow. The term $\frac{1}{H_z}\frac{\partial}{\partial\sigma}\left[\frac{K_M}{H_z}\frac{\partial u}{\partial\sigma}\right]$ and the similar term for v in its respective equation represent the vertical diffusion of momentum, i.e., viscous effects, which slow down the rate of diffusion. Equation (5) is the transport equation for the concentration of nuclides C. It includes the advection term $\vec{v}\cdot\nabla C$, which describes the diffusion manner and direction of the nuclides with the flow of seawater, and the diffusion term $\frac{1}{H_z}\frac{\partial}{\partial\sigma}\left[\frac{K_C}{H_z}\frac{\partial C}{\partial\sigma}\right]$, which describes the molecular diffusion of nuclides in water due to concentration gradients. Equation (4) is the continuity equation, which ensures mass conservation of the water body in the absence of sources or sinks [10]. It guarantees the equilibrium state of the entire system, allowing us to track the overall movement of nuclides in the water body. Equation (6) provides the relationship between density ρ and temperature T, salinity S, and pressure P, which is crucial for calculating the physical state and flow characteristics of seawater [11].

By solving these equations jointly, we can simulate the velocity field u and v that change over time and space, as well as the nuclide concentration C. The velocity field u and v determine the direction of diffusion, while the time change of nuclide concentration $\frac{\partial C}{\partial t}$ gives the rate of diffusion.

4. Pollution Prediction Model

The release quantity model employs a condition-based source term estimation, utilizing pre-calculated severe accident source terms from collected data as shown in Equation (7).

$$S_i = FPI_i \times CRF_i \times \prod_{j=1}^{N} RDF(i,j) \times EF_i \tag{7}$$

The Eulerian method can describe the distribution of nuclide concentrations as well as retrospectively estimate the total leak amount of nuclides based on monitoring data. It is suitable for calculating the changes in the radioactive activity of nuclides [12]. The governing equation is shown in Equation (5), and the diffusion of radioactive nuclides requires the addition of a source term F_c, which is defined as shown in Equation (8).

$$F_{\mathrm{c}} = -\left(\frac{\partial w_{\mathrm{c}}}{\partial s} + \xi_{\mathrm{b}}\right) C + \mathrm{e}^{-\lambda t} S_{\mathrm{c}} \tag{8}$$

In the equation, C denotes the radioactivity concentration, expressed in becquerels per liter (Bq/L).

The relationship between radioactivity and the decay constant is expressed as shown in Equation (9).

$$A = A_0 \mathrm{e}^{-\lambda t} \tag{9}$$

The release model, Eulerian model, and decay model described above, in conjunction with the hydrodynamic dispersion model from section 3.1, collectively constitute the pollution prediction model. The next step involves setting up the grid for the model. Where the zonal direction has 211 grids and the meridional direction has 255 grids [13]. The grid spacing is set to 3" "km, covering the majority of Japan and parts of the eastern oceanic region. The model's vertical stratification consists of 12 layers, and the study area is depicted in Figure 2.

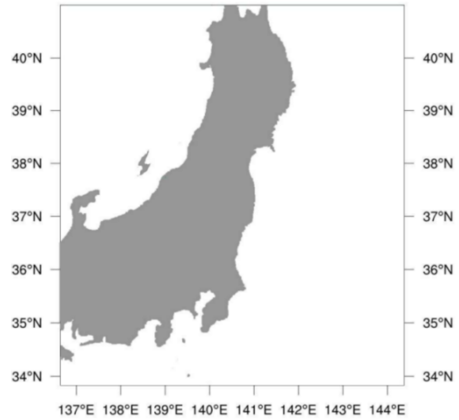
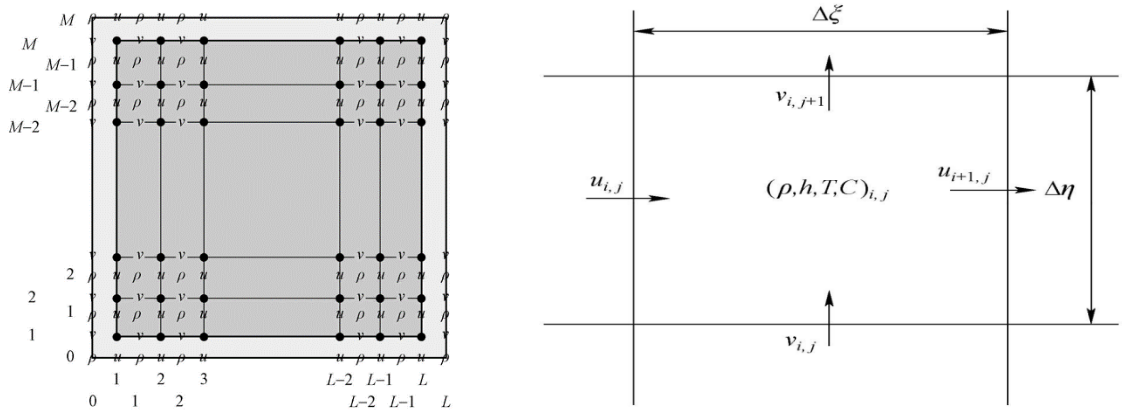


Figure 2: Study Area



(a) The horizontal direction grid cell (b) Variable distribution and value range

Figure 3: Model Grid

As shown in Figure 3(a), within a grid cell, the meridional and zonal flow velocities are distributed along the cell boundaries, with the meridional flow moving from west to east and the zonal flow from south to north. At the center of the grid cell, parameters such as density, height, temperature, salinity, and nuclide concentration are located [14]. Due to the distinct distribution of different variables within the grid cell, there are varying ranges and distributions for each variable in the horizontal direction. The distribution of these variables is illustrated in Figure 3(b). From Figure 3(b), it can be observed that the nodal ranges for different variable types are distinct. The variable values outside and on the frame boundaries are provided by the boundary conditions, while the values within the frame are obtained through computation. The hydrodynamic model is vertically configured with 12 layers, and the vertical stratification is shown in Table 1.

Table 1: Vertical layering

Layer	Parameter	Layer	Parameter
1	-1.0000	2	-0.6065
3	-0.3678	4	-0.2231
5	-0.1352	6	-0.08201
7	-0.04966	8	-0.02999
9	-0.01798	10	-0.01055
11	-0.0058	12	-0.0025
1	-1.0000	2	-0.6065

5. Prediction results

Based on the hydrodynamic conditions of the Fukushima marine environment and the Eulerian model, and considering the actual Fukushima accident scenario, the diffusion of tritium within 30 days after the discharge of Fukushima nuclear wastewater was calculated (from August 27, 2023, to September 27, 2023). Taking into account only the transport of nuclides by the flow field and the diffusion of nuclides, a continuous input of tritium leakage was added to the stable hydrodynamic field of the Fukushima marine area to simulate the diffusion area of the nuclide [15]. The diffusion of tritium in the surface layer of the Fukushima marine area 30 days after the nuclear leak accident is shown in Figure 4.

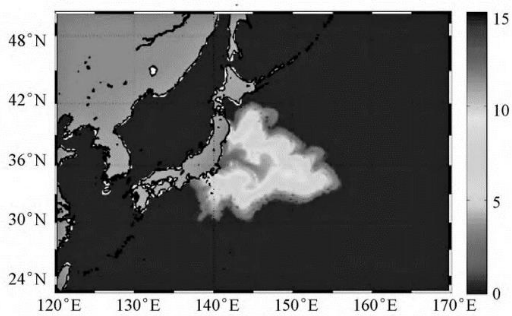


Figure 4: Fukushima nuclide diffusion calculation

6. Pollution Prediction Model Plus

The enhancement of the pollution prediction model has been robust, with the integration of various environmental factors including ocean circulation patterns, hydrodynamic mechanisms, the topography of the sea floor, variations in bathymetry, and tidal forces. To augment the current model, it is proposed that a module for predicting climate seasonal fluctuations be incorporated. This would serve to refine the model comprehensively.

In pursuit of this objective, the improved Community Climate System Model version 3 (CCSM3) has been utilized to forecast the atmospheric transport and diffusion of radionuclides emanating from a nuclear spill over a five-year trajectory. The results derived from CCSM3 offer a depiction of the atmospheric conditions post-incident, providing a crucial insight into the spread of pollutants.

The depiction is specifically illustrated in Figure 5, which delineates the mean atmospheric circulation field at 992 hPa. The period captured in this figure spans from August 27, 2023, to September 26, 2023. This representation is significant as it encapsulates the atmospheric dynamics over a one-month period, offering a granular view of the dispersion process, which is essential for both short-term and long-term environmental planning and mitigation strategies post-nuclear leakage.

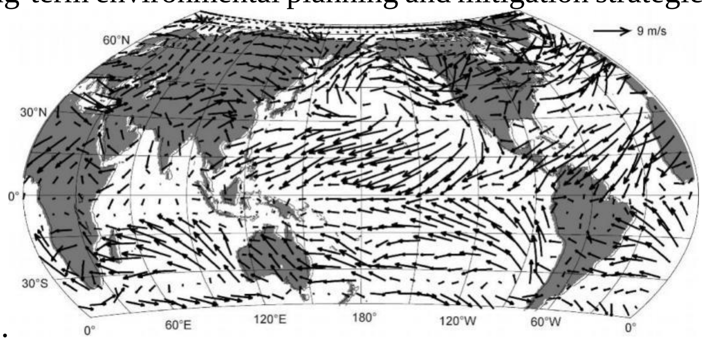
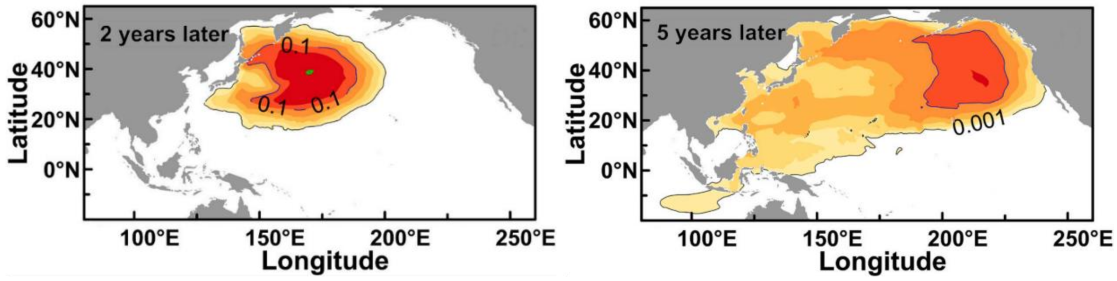


Figure 5: Monthly average atmospheric circulation field at 992 hPa from August 27, 2023, to September 26, 2023.

Upon employing the enhanced pollution prediction algorithm, a comprehensive simulation and analysis of the provided datasets, alongside the assimilated information, were conducted. This analytical approach facilitated the construction of prospective marine pollution scenarios, delineated in Figure 6, predicated upon the efflux of wastewater. It was observed that the earliest manifestation of nuclear contamination conforming to the entirety of the Chinese coastline emerged at a temporal junction of three and a half years subsequent to the initial discharge event. This projection underscores the potential latency in the detectable spread of nuclear pollutants and serves as a critical indicator for environmental monitoring timelines and the formulation of mitigation strategies.



(a) 2 year late

(b) 5 year late

Figure 6: Simulation results

7. Discussion

The discussion of modelling and analysis of the dispersion of Fukushima nuclear wastewater based on the Regional Ocean Modelling System (ROMS) is inherently complex and involves a multitude of environmental, technological and societal parameters that must be carefully considered. Such analyses are essential for predicting the potential impacts of radioactive materials on the marine environment and public health.

ROMS, a hydrostatic, free-surface, topographically tracked coordinate ocean model, is particularly well suited to this task due to its high-resolution capabilities and ability to simulate physical and biogeochemical processes. Using the system to simulate the dispersion of wastewater from the Fukushima nuclear leak, researchers can consider a variety of oceanographic conditions, such as currents, water column stratification, and temperature gradients, which can affect the transport and dilution of contaminants.

The model's flexibility to incorporate observational data to improve the accuracy of simulations also enhances its usefulness in the Fukushima event. For example, the incorporation of satellite imagery, buoy survey data and other oceanographic observations into the model can refine the model's predictions of radionuclide dispersion. These predictions are critical for coastal management and can inform decisions about fisheries closures, public health advisories, and the ongoing restoration of the Fukushima nuclear power plant.

In addition to the physical dispersion of contaminants, the model must consider the complex interactions between radionuclides and marine communities, sediments, and the potential for bioaccumulation in the food web. This level of analysis requires a multidisciplinary approach combining oceanography, ecology, radiology and chemistry to assess the long-term impacts of a nuclear release.

In addition, the Fukushima event presented unique challenges for model validation. The unprecedented nature of the disaster means that there are very limited historical datasets available for comparison. Therefore, the scientific community must rely on a combination of real-time data collection and the development of new methods to assess the accuracy of model predictions.

Finally, it is important to recognise the wider significance of this research. The spread of

Fukushima nuclear wastewater has international implications because ocean currents carry contaminants to the Pacific basin. The results of the modelling study must be transparently and effectively disseminated to global stakeholders, including affected communities, international regulatory agencies and the general public. This dissemination strategy should be based on the understanding that information dissemination has a responsibility to account for the uncertainties and assumptions inherent in any model, including ROMS, in order to avoid misinterpretation of the results.

In conclusion, the application of ROMS to analyse the dispersion of nuclear wastewater from Fukushima is an important exercise with far-reaching implications. Through careful modelling, data assimilation and interdisciplinary collaboration, researchers can provide invaluable insights into the environmental and health impacts of this disaster, thereby supporting informed decision-making and contributing to the safety and sustainability of marine ecosystems.

8. Conclusion

The research presented herein has successfully developed an integrative model that enhances the capabilities of the Regional Ocean Modeling System (ROMS) through the incorporation of additional diffusion, release, Eulerian, and decay dynamics. The model's enhanced predictive capacity has been instrumental in quantifying the impact of radioactive effluents emanating from the Fukushima incident on the surrounding marine environment. The results of the modeling indicate that these discharges have had a significant effect on marine ecosystems in the vicinity, with long-term implications for both the fisheries sector and public health.

This includes the potential for contamination to reach within the maritime boundaries of China, raising concerns over the safety of seafood and the wellbeing of coastal populations. By simulating the complex patterns of marine dispersion, this study underscores the critical function of ROMS in forecasting the extended environmental consequences of radioactive pollution.

Comprehensive data processing and exploratory analysis are foundational to this research, as they enable the accurate prediction of pollution pathways and the assessment of their interaction with climatic variables. Such analyses are essential for a more informed projection of the fate of radioactive contaminants in marine environments, and they provide a crucial platform for the anticipation of future ecological challenges stemming from such pollutants. By addressing these concerns with a scientifically robust approach, the study contributes significantly to the body of knowledge required to mitigate the environmental and health risks associated with nuclear accidents and their aftermath on oceanic systems.

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