Prediction of the Distribution of Tritium Over the Pacific Ocean from Fukushima Wastewater Until 2090

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Abstract
The Fukushima nuclear wastewater release into the Pacific Ocean, starting August 25th, 2023, has prompted global concerns. This project, the first of its kind, investigates the distribution of tritium radioactive particles and assesses their impact on the U.S. west coast. Utilizing IAEA monitor, ECCO currents, and AOML drifter data, the model simulates tritium movement, revealing its arrivals at the U.S. coast. Potential adjustments to U.S. power plant emissions are considered, with the first wave reaching Hawaii in the 5th year and U.S. coastal regions experiencing subsequent waves post-2033. Adjustments aim to mitigate potential west coast Pacific overload.

1 Introduction

Amidst growing concerns surrounding the Fukushima nuclear wastewater release, the international community has turned its attention to the intricate challenges posed by the gradual dispersal of radioactive materials into the vast expanse of the Pacific Ocean. The commencement of this release on August 25th, 2023, marks the initiation of a complex environmental experiment with consequences projected to unfold over the course of several decades.

Despite concerted efforts to address potential hazards, the persistent presence of tritium in the treated wastewater presents a formidable challenge. As shown in Figure 1 (International Atomic Energy Agency (IAEA),) , a series of advanced techniques were applied to the wastewater before release but the tritium particles stayed. Tritium, a resilient radioactive element resistant to existing removal techniques, continues to raise questions about the long-term impact on marine ecosystems and human health. This dilemma has sparked intense debates at both domestic and international levels, prompting a collective search for innovative solutions and comprehensive strategies.

In response to these pressing concerns, a groundbreaking project has been initiated to construct a predictive model that delves into the intricate interplay between wastewater discharge and oceanic dynamics. Leveraging a combination of historical data and real-time information, this initiative seeks to illuminate the trajectory of tritium distribution in the Pacific Ocean, projecting its potential effects 50 years into the future. The project's ambitious scope encompasses a comprehensive simulation spanning 66 years, a duration calculated based on the 12.33-year half-life of tritium.

The predictive model aims to provide valuable insights into the spatial and temporal patterns of tritium dispersion, considering the emission and distribution of tritium particles across various sea areas. By integrating advanced data analytics and cutting-edge simulation techniques, the project aspires to offer a nuanced understanding of the long-term ramifications of the Fukushima nuclear wastewater release. As the scientific community collaborates to address the challenges posed by this unprecedented situation, this project stands at the forefront, striving to contribute vital knowledge essential for informed decision-making and sustainable environmental stewardship.

2 Materials and Methods

The foundation of this project rests on a comprehensive dataset amalgamated from various sources, each playing a crucial role in simulating and evaluating the movement and distribution of tritium particles in the ocean.

- **IAEA (International Atomic Energy Agency) monitor data** (International Atomic Energy Agency (IAEA),)
  Real-time monitoring data from the International Atomic Energy Agency, specifically focused on radioactive particle emissions from Fukushima. This dataset serves

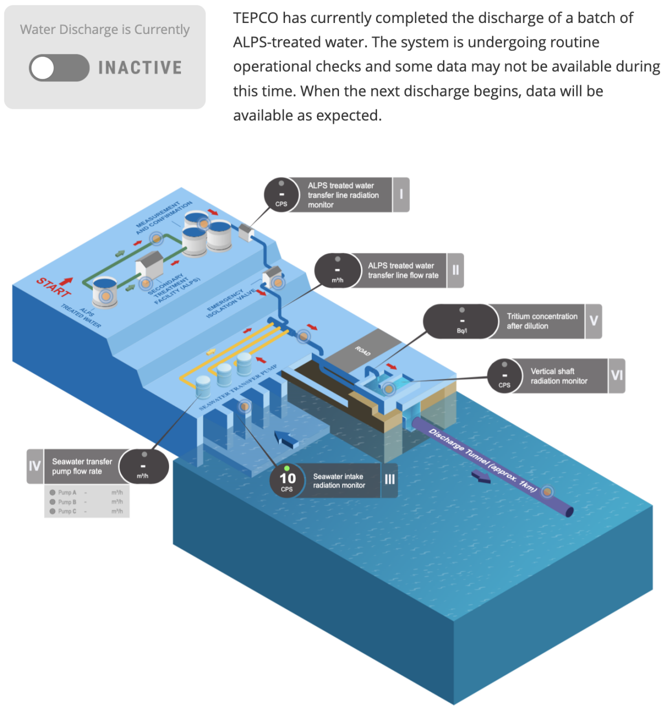

Figure 1. Illustration of how the wastewater was been treated and discharged. The wastewater will go through the ALPS treatments. While tritiums are still remain in the ALPS treated water, the concentration of tritium will get diluted before go into the discharge tunnel.

as the bedrock for initiating tritium particle positions and quantities within the simulation model.

- **ECCO (Estimating the Circulation and Climate of the Ocean) currents data** (Marshall et al., , ,)
  Incorporating both *in situ* observations and calculated data points from the Massachusetts Institute of Technology general circulation model (Marshall et al.,), this dataset includes variables such as currents, eddies, temperature, and salinity. The project primarily utilizes the 3-dimensional velocity field for predicting particle distribution and movement. In this article, we use ECCO version 4 release 4, which is a global dataset spans from 1992 to 2017.
- **NOAA (National Oceanic & Atmospheric Administration) global drifter data** (National Oceanic and Atmospheric Administration (NOAA), Atlantic Oceanographic and Meteorological Laboratory, Physical Oceanography Division,)
  Derived from buoys in the global drifter program, this dataset provides real-time movement information across the Pacific Ocean. It serves as evaluation data for the prediction model.

2.1 Methods: Model of Particle Drift and Decay

The primary aim of this project is to simulate the trajectory and distribution of tritium particles released into the ocean, with a specific focus on evaluating their impact along the U.S. coast and potential implications for ecosystem safety. The simulation model comprises three fundamental components:

1. **Particle Initiation**

To initiate particle movement, the model relies on data from the International Atomic Energy Agency (IAEA) and self-disclosed measurements from Tokyo Electric Power Company Holdings ((TEPCO),). These sources provide essential information regarding the termination points of wastewater pipes. Considering the initial release of 7,800 tons of wastewater in the first 17 days and a planned total release of 1,340,000 tons over the next 43 years with a tritium concentration of 140,000 Bq/L, the model adopts a release strategy distributing 31,200 tons annually for 43 years starts from 2023.

2. **Particle Drifting in Lagrangian Trajectory**
Utilizing data from the Estimating the Circulation and Climate of the Ocean (ECCO) project, the model approximates future ocean current fields. The Seaduck package, accessible at `github.com/MaceKuailv/seaduck`, is employed to compute Lagrangian trajectories of particles based on the velocity field at specific timestamps. This approach facilitates a dynamic representation of particle movement, accounting for oceanic currents and variations over time.
3. **Particle Decay**
The model incorporates a decay formula to calculate tritium concentration within the released wastewater over time.

$$N = N_0 e^{-\lambda t} \qquad ; \quad \lambda = 5.63 * 10^{-2} \quad /year$$

The decay equation above considers an annual update of released wastewater. Here, N represents the tritium particle amount , N_0 is the initial amount, λ is the decay constant (set at $5.63\times10^{-2}/year$), and t denotes the time elapsed since release.

These three interconnected components form a comprehensive model that allows for a dynamic and nuanced analysis of tritium particle movement, decay, and distribution in the ocean, contributing to a better understanding of the potential impacts of Fukushima wastewater along the U.S. coast.

3 Model Statistics and Results

The simulation model yields a comprehensive 79,376 * 1518 * 3 matrix, representing 79,376 data points released over 43 years, each corresponding to 15.6 tons of wastewater. Notably, particle positions were updated 512 times per year in the model, but only 23 updates were stored, resulting in a total of 1518 (23 * 66) recorded position updates spanning 66 years. The stored particle positions encompass the longitude, latitude, and depth into the ocean.

The visualization of the simulation results is presented in an animation, accessible online[1]. Figures 2-5 display representative screenshots from the animation, depicting the discharge process from initiation to completion. Each dot on the graph signifies 15.6 tons of wastewater, initially containing 0.002184±0.000122 TBq tritium particles upon release. The color variation in the dots reflects the decreasing concentration of tritium over time, transitioning from purple to yellow.

Figures 6-7 provide insights into key distribution features. Figure 6 illustrates the annual tritium arrival at different U.S. regions. Notably, particle presence remains zero until 2028 for Hawaii and 2033 for other U.S. regions, signifying the arrival of the first wave in Hawaii in 2028 and in other U.S. regions in 2033. After a sustained high particle count from 2040 to 2070, the tritium levels on the West Coast U.S. see a significant decline, influenced both by the cessation of wastewater discharge and the decay of tritium in released water.

[1] `https://drive.google.com/file/d/1MxjcmApWGOzPqGMkEBNndQ1h4yMw7HbG/view?usp=sharing`

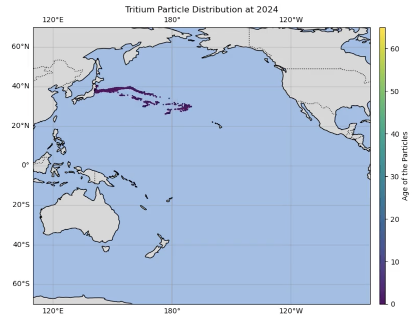

Figure 2. Predicted Distribution of Tritium Among Pacific in 2024

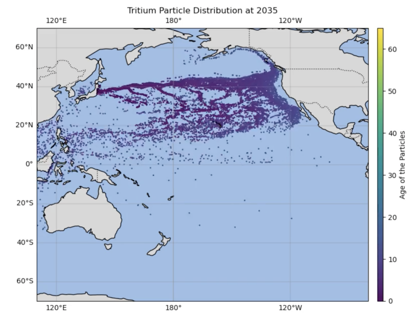

Figure 3. Predicted Distribution of Tritium Among Pacific in 2035

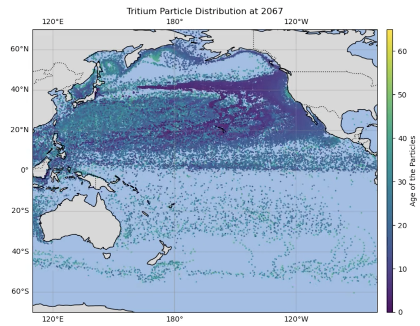

Figure 4. Predicted Distribution of Tritium Among Pacific in 2067

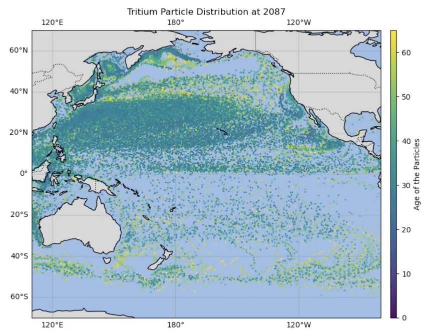

Figure 5. Predicted Distribution of Tritium Among Pacific in 2087

Table 1. Comparing Tritium Amount Arrived the US Coast Each Year From Fukushima with Tritium Release From Diablo Canyon Power Plant

Tritium Type	**Yearly Amount (TBq)**	**Upper Bound**	**Lower Bound**
Fukushima Mean	25.85	27.29	24.41
Fukushima Max	42.07	44.41	39.72
Diablo Canyon (2019-2022)	80.00	102.93	39.96

Figure 7 complements Figure 6 by displaying the age distribution of wastewater in different U.S. regions. Confirming Figure 6, it emphasizes that most wastewater reaching the West Coast U.S. has surpassed the first ten years since its release, with Hawaii being the exception. These insights contribute to a nuanced understanding of the temporal and spatial dynamics of tritium distribution resulting from the Fukushima wastewater discharge.

4 Evaluation and Conclusion

In assessing the safety implications of Fukushima wastewater on the West Coast of the United States, this project employs the annual tritium emissions from U.S. power plants as a benchmark for comparison. Table 1 utilizes data from Diablo Canyon (Gas & (PGE),), the largest nuclear power plant in the U.S. and the sole facility in Califor-

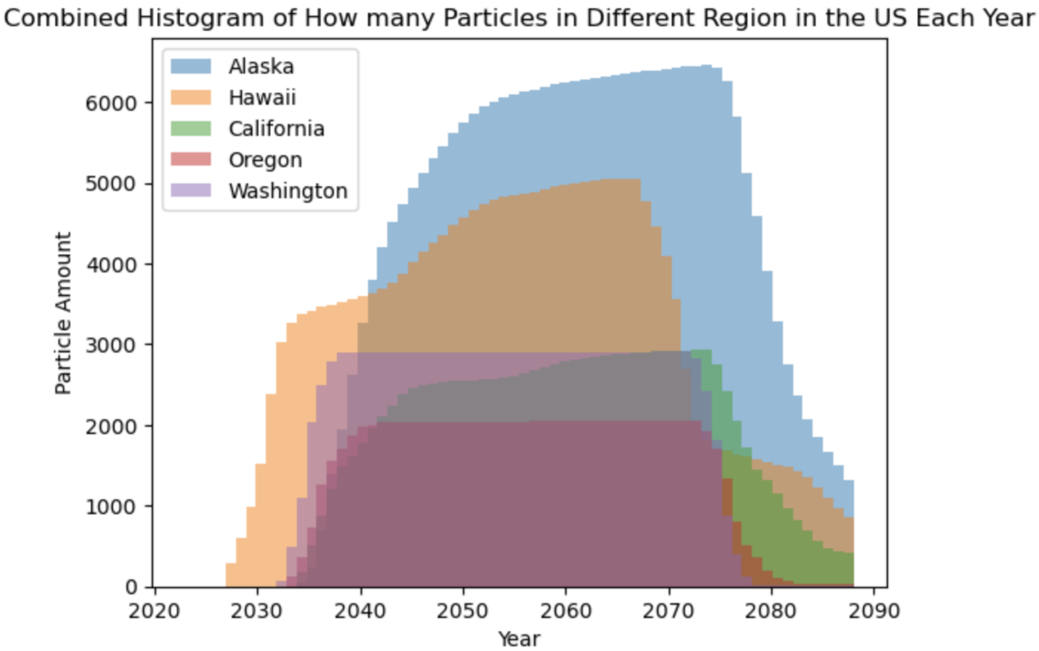

Figure 6. Here Particle Amount means number of particle representatives while taking decay into consideration; 1 particle amount = 0.002184 ± 0.000122 TBq tritium

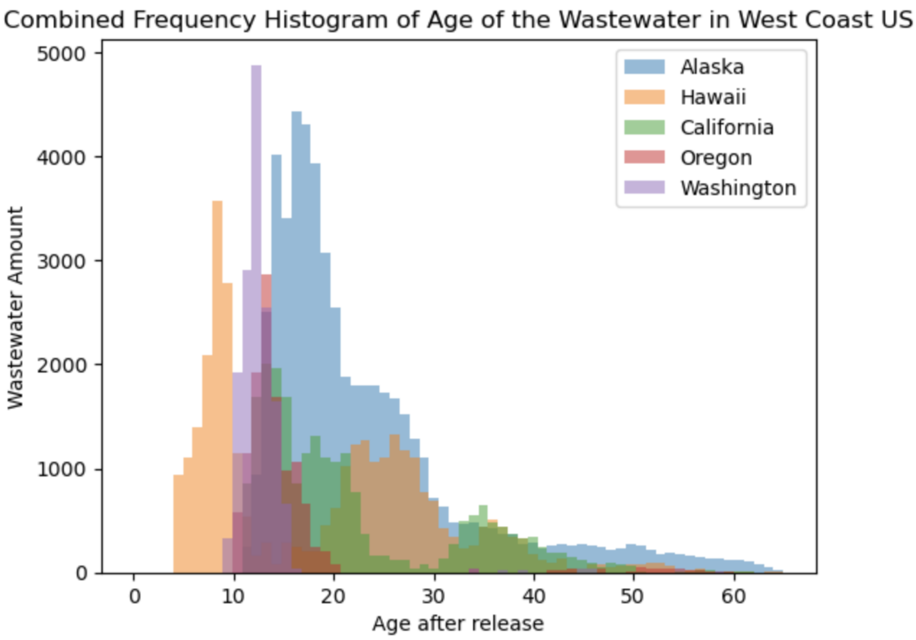

Figure 7. Here Wastewater Amount means the quantity of wastewater, notice that 1 unit of wastewater could contain different amounts of tritium when at different ages; 1 wastewater amount = 15.6 tons of wastewater

nia, to quantify the impact of Fukushima wastewater on tritium levels along the U.S. West Coast.

As illustrated in Figures 6 and 7, the initial wave of Fukushima wastewater is anticipated to reach Hawaii five years post-release, with most U.S. coastal regions experiencing this influx after 2033. Subsequent waves are projected at intervals of 20 to 40 years, and throughout their 10 to 30-year lifespan, tritium particles will consistently drift around Alaska.

The findings presented in Table 1 underscore the significant tritium contribution brought by Fukushima wastewater to the U.S. West Coast. Particularly noteworthy is the projection for 2070, where tritium levels from Fukushima are anticipated to surpass half the amount released by Diablo Canyon during its peak years. This revelation underscores the necessity of considering potential adjustments to U.S. power plant emissions during peak periods, in order to proactively manage the potential overload of tritium along the West Coast Pacific.

In conclusion, this evaluation highlights the importance of ongoing monitoring and regulatory measures to safeguard the West Coast against the potential impact of Fukushima wastewater. As we project into the future, proactive adjustments in power plant emissions may prove essential to maintaining a balance in tritium levels and ensuring the environmental well-being of U.S. coastal regions.

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