福島第一核電廠 ALPS 處理水排放之海洋傳輸研究：黑潮大蜿蜒（KLM）對擴散路徑與濃度分佈之效應

Assessment of the Kuroshio Large Meander's Impact on the Dispersion Pathways of Fukushima Tritium-treated Water

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摘　要

中央氣象署福島第一核電廠將 ALPS 處理水排放至北太平洋，其傳輸與擴散過程主要受黑潮延伸流（Kuroshio Extension, KE）系統所控制。然而，自 2017 年 8 月起，上游黑潮經歷了長達 7 年 9 個月的持續性「黑潮大蜿蜒（Kuroshio Large Meander, KLM）」事件。由於黑潮延伸流的動力特性與日本南方黑潮路徑緊密耦合，本研究旨在探討黑潮大蜿蜒如何影響下游流場，進而改變處理水在不同黑潮模態下的傳輸路徑、擴散範圍及對臺灣周遭海域的潛在環境威脅，以期提升我國作業化海洋氣象預報系統的早期預警能力。

本研究利用半隱式跨尺度水文科學整合模式（SCHISM）中的拉格朗日顆粒軌跡模式進行連續排放模擬。採用相同的 HYCOM 模式配置，針對兩個截然不同的流態時期進行 5 年期對比分析：非大蜿蜒時期（NLM，以 2011–2016 年為代表）與大蜿蜒時期（KLM，以 2017–2022 年為代表）。示蹤劑的擴散與濃度計算係基於東京電力公司（TEPCO）實際排放數據。

結果顯示，在 KLM 時期，東向流速在黑潮延伸流主軸區域顯著增強，顯示其擁有一條更強大且穩定的 KE 噴流；同時，北向流速在日本東部沿岸（約北緯 35° 至 40° 之間）明顯增加。在此模態下，受沿岸強烈向北海流驅動，部分顆粒產生顯著的「近岸北向平流與滯留效應」，被輸送至北緯 38° 以北（甚至達 40°N 附近）並在該區累積；其他顆粒則被強勁的東向噴流迅速向東帶離，並高度侷限於 KE 主軸通道上，導致高濃度（如 10^{-5} Bq/L 尺度）沿著窄帶狀的主流軸累積。相較之下，NLM 時期的黑潮延伸流動能較弱且較不穩定，使顆粒極易受到中尺度渦流（Mesoscale Eddies）的捕獲與捲裹。這導致顆粒出現顯著的向南分流與擴散，並向西南方長程傳輸，進而增加了影響台灣周遭海域的潛在機率。然而，由於 NLM 模態下的擴散範圍更為寬廣且稀釋均勻，海域中較不易形成極端的高濃度累積區。

本研究成功量化了黑潮大蜿蜒對 ALPS 處理水傳輸路徑的雙重效應。KLM 時期會將放射性物質侷限於北緯 38° 以北及東向 KE 主軸，形成局部高濃度累積；而 NLM 模態則使放射性物質易向南擴散至台灣周圍海域，但整體濃度場顯著稀釋。

關鍵字：ALPS處理水、黑潮大蜿蜒

Abstract

The discharge of ALPS treated water from the Fukushima Daiichi Nuclear Power Station into the North Pacific Ocean has necessitated a detailed assessment of long-term dispersion pathways. The transport of this ALPS treated water is primarily governed by the Kuroshio Extension (KE) system. However, the upstream Kuroshio has been

experiencing a persistent “Kuroshio Large Meander (KLM)” event since August 2017. Since the variability of the KE is dynamically linked to the path of the Kuroshio south of Japan, understanding how the KLM modulates the downstream flow field is critical for evaluating environmental impacts.

In this study, we investigate the influence of the KLM on the dispersion of tritium-treated water by Lagrangian particle tracking model with a continuous release scheme. The model was forced by ocean current data from the Hybrid Coordinate Ocean Model (HYCOM) to capture the spatiotemporal variability of the Kuroshio Current. We specifically examined the differences in transport patterns during the KLM period (2017–2022) versus non-meander period (2011–2016).

Preliminary results indicate that the presence of the upstream Large Meander induces specific downstream responses in the Kuroshio Extension that distinctively deviate from the reference non-meander period. We focus on how the KLM modulates the stability and position of the KE jet, thereby altering the initial advection pathways of the ALPS treated water. The analysis aims to clarify whether these KLM-induced changes in the KE system act to retard zonal transport or enhance regional retention, creating significant discrepancies in tracer arrival times and concentration fields between the two periods.

This study quantifies these deviations and discusses the implications of the “Kuroshio-Kuroshio Extension coupling” mechanism in determining the dispersion patterns and concentration distributions of passive tracers. The findings highlight the necessity of incorporating low-frequency climate variability into environmental risk assessments for oceanic discharges.. .

Key words : ALPS treated water、Kuroshio Large Meander