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Research article

Modeling study on oil spill transport in the Great Lakes: The unignorable impact of ice cover

Yang Song [a,*], Ayumi Fujisaki-Manome [a,b], Christopher H. Barker [c], Amy MacFadyen [c], James Kessler [d], Dan Titze [d], Jia Wang [d]

[a] Cooperative Institute for Great Lakes Research, School for Environment and Sustainability, University of Michigan, Ann Arbor, MI, 48109, USA
[b] Climate & Space Sciences and Engineering, University of Michigan, Ann Arbor, MI, 48109, USA
[c] NOAA Office of Response and Restoration, Seattle, WA, 98115, USA
[d] NOAA Great Lakes Environmental Research Laboratory, Ann Arbor, MI, 48108, USA

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ABSTRACT

The rise in oil trade and transportation has led to a continuous increase in the risk of oil spills, posing a serious worldwide concern. However, there is a lack of numerical models for predicting oil spill transport in freshwater, especially under icy conditions. To tackle this challenge, we developed a prediction system for oil with ice modeling by coupling the General NOAA Operational Modeling Environment (GNOME) model with the Great Lakes Operational Forecast System (GLOFS) model. Taking Lake Erie as a pilot study, we used observed drifter data to evaluate the performance of the coupled model. Additionally, we developed six hypothetical oil spill cases in Lake Erie, considering both with and without ice conditions during the freezing, stable, and melting seasons spanning from 2018 to 2022, to investigate the impacts of ice cover on oil spill processes. The results showed the effective performance of the coupled model system in capturing the movements of a deployed drifter. Through ensemble simulations, it was observed that the stable season with high-concentration ice had the most significant impact on limiting oil transport compared to the freezing and melting seasons, resulting in an oil-affected open water area of 49 km^2 on day 5 with ice cover, while without ice cover it reached 183 km^2. The stable season with high-concentration ice showed a notable reduction in the probability of oil presence in the risk map, whereas this reduction effect was less prominent during the freezing and melting seasons. Moreover, negative correlations between initial ice concentration and oil-affected open water area were consistent, especially on day 1 with a linear regression R-squared value of 0.94, potentially enabling rapid prediction. Overall, the coupled model system serves as a useful tool for simulating oil spills in the world's largest freshwater system, particularly under icy conditions, thus enhancing the formulation of effective emergency response strategies.

1. Introduction

The global economic growth and intensification of oil transportation are raising growing concerns and potential risks of oil spills in water bodies worldwide, with over 7 million tons of oil having spilled into the environment over the past century (Albeldawi, 2023; Bullock et al., 2019; Cakir et al., 2021; Chang et al., 2014). Oil spills can have detrimental effects on aquatic environments and ecosystems, such as contaminating water, damaging marshes, killing seabirds and aquatic life, and even threatening human health (Bertrand and Hare, 2017; Beyer et al., 2016; Jeznach et al., 2021). The economic losses associated with oil spills can be significant and long-lasting, including costs for cleanup and restoration (Albeldawi, 2023; Zhang et al., 2019). Furthermore, as oil exploitation expands into northern regions such as the Arctic, the potential for oil spills under cold and icy conditions is gaining attention (Li et al., 2016; Nordam et al., 2017, 2019; Wang et al., 2007). Ice cover complicates the oil spill process, making it more difficult to predict, as it significantly affects the transport and weathering of the oil (Afenyo et al., 2016b; Wilkinson et al., 2017). Therefore, advancing our understanding of oil spill processes in ice-covered environments is both urgent and crucial for the future of energy transportation and socioeconomic development.

Numerical modeling is a critical tool for predicting the trajectories of oil in ice and planning emergency responses in ice-covered waters

* Corresponding author.
E-mail addresses: songyangscu@hotmail.com, soyang@umich.edu (Y. Song).

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(Spaulding, 2017; Wilkinson et al., 2017). Previous studies on oil in ice modeling have mostly focused on marine environments (Afenyo et al., 2016a; Arneborg et al., 2017; French-McCay et al., 2017). For instance, a model that considers the pumping of floating in-leads oil onto or under ice floes was developed and validated through a field experiment in the Barents Sea, as well as an accidental spill in the Gulf of Finland (Babaei and Watson, 2020). The accuracy of oil trajectory modeling for the Runner 4 oil spill accident in the Gulf of Finland on March 5, 2006 is highly sensitive to the hydrodynamic and ice models used (Arneborg et al., 2017). Furthermore, a valid model for predicting oil thickness with an ice edge has been developed and validated through flume experiments, with the aim of improving sea oil spill response (Nordam et al., 2020). Therefore, simulations of oil with ice in marine environments have been relatively well-studied compared to freshwater environments. It is important to note the significant hydrological and environmental differences, such as tides, waves, large-scale ocean currents, and various physical and chemical factors including salt content, density, and temperature, between freshwater and marine environments (Keramea et al., 2021; Lee et al., 2020; Li et al., 2022; Song et al., 2021; Zhu et al., 2022). Furthermore, besides variations in boundary settings and parameterization in oil spill simulations, there are additional distinctions concerning emergency response. For example, addressing the freshwater environment typically involves considering its water source characteristics, while handling the marine environment may require broader efforts, such as cross-country collaboration (Cederwall et al., 2020; Song et al., 2023; Zhang et al., 2021). Collectively, there is an urgent need to establish oil spill models and parameters for freshwater environments, where relevant studies are scarce, particularly under icy conditions.

The Laurentian Great Lakes (hereafter referred to as the Great Lakes) serve as vital water resources for both the United States and Canada. Due to climate change, there could be a decreasing trend in water level and an increasing trend in the number of shipping trips (Millerd, 2011), which consequently raises the risk of oil spills in the region. Previous studies have primarily focused on analyzing the potential damages and risks associated with worst-case oil spills at the Straits of Mackinac (Melstrom et al., 2019; Schwab, 2016; Strychar et al., 2018). These studies have employed ensemble simulations (a group of related simulations) to assess parameters such as oil-affected open water area and risk maps (Schwab, 2016). However, an important factor that has been overlooked in these studies is the influence of ice cover during the winter months (generally October to March) on oil spill transport. Furthermore, the lack of an oil-ice model and the absence of observational spill and validation data for the Great Lakes pose significant challenges to effective emergency responses in the event of oil spills in this region. Without such crucial tools and data, it becomes difficult to accurately assess and mitigate the impacts of oil spills under icy conditions, further exacerbating the potential threats and risks associated with oil spill incidents, as exemplified by the Exxon Valdez oil spill on March 24, 1989.

To address the aforementioned research challenges, this study focuses on coupling the General NOAA Operational Modeling Environment (GNOME) model and the Great Lakes Operational Forecast System (GLOFS) model (Anderson et al., 2018). Specifically, the GNOME model, a particle tracking model, is driven by currents and ice data output from the GLOFS model, which is a hydrodynamic and ice model. This coupled model system aims to predict oil spills, with a specific emphasis on scenarios involving icy conditions in the Great Lakes. The aim is to (1) evaluate the performance of the new coupled model system through observed drifter data, (2) explore oil transport characteristics with and without ice cover during freezing, stable, and melting ice seasons, and (3) reveal the effects of ice cover on oil spill transport processes. These results can fill the knowledge gap in oil with ice modeling in freshwater environments and provide a scientific basis for enhancing readiness for emergency spill response.

2. Materials and methods

2.1. Study area and drifter data collection

Lake Erie is one of the five Great Lakes, located on the border between the United States and Canada (Fig. 1A). It has a surface area of 25667 km^2, with a maximum depth of 64 m and an average depth of 19 m (Fig. 1B). It spans approximately 1402 km of coastline and is known for its sandy beaches, wetlands, and cliffs (Farhadzadeh et al., 2018). Lake Erie serves as a valuable natural resource, offering ecological, economic, and recreational benefits to surrounding communities and beyond (Arnillas et al., 2020). Lake Erie often freezes over in winter, achieving a historical average ice cover of over 60% in February due to its shallowness and smaller heat capacity relative to the other four Great Lakes (Fig. 1 and Fig. S1) (Wang et al., 2012). Although there have been no serious oil spill events in Lake Erie, and most incidents have involved small volumes (less than 100 gallons), the potential for large oil spills poses significant threats to the delicate ecosystem of the Great Lakes region. Furthermore, there is currently no available observational data on oil spills to aid in the validation of oil spill models. In our study, offshore drifter datasets were collected in Lake Erie to evaluate the performance of the coupled GNOME-GLOFS model system in simulating drifter trajectories.

A drifter was deployed on August 31, 2018, at the water surface near the shoreline in Cleveland (Fig. 2A). The drifter recorded its location data until October 25, 2018. Our primary focus was on conducting emergency response simulations for oil spill events, specifically short-term simulations spanning five days (Babaei and Watson, 2020; Nordam et al., 2019). Therefore, to assess the hydrodynamic performance of the model, we utilized the drifter trajectories from four distinct ice-free periods: September 5–10, 2018; September 20–25, 2018; October 5–10, 2018; and October 20–25, 2018. The drifter employed in this study consisted of a 1-m long vertical tube with four wings and remained fully submerged to minimize the influence of wind (De Dominicis et al., 2016). For the single drifter trajectory simulation, winds and diffusion are deactivated, and currents are the sole driving force utilized in the GNOME model to propel a single particle, symbolizing the drifter. The diffusion process is deactivated because a single drifter will realize only one of the many possible trajectories from the initial location, even if the diffusion parameterization is perfect (Barker et al., 2023; Csanady, 2012).

2.2. GNOME model

The GNOME model, developed by the NOAA Office of Response and Restoration, Emergency Response Division, is employed in this study to simulate oil spill transport processes in Lake Erie (https://github.com/NOAA-ORR-ERD/PyGnome) (Barker et al., 2023; Zelenke et al., 2012). The GNOME model, primarily used as a 2D model, has proven successful in predicting oil spill trajectories in various marine and coastal environments (Akinbamini Oluyemi et al., 2022; Amir-Heidari and Raie, 2019; Naz et al., 2021). The GNOME model utilizes the Euler-Lagrangian Particle Tracking Method to simulate the movement of oil particles (referred to as Lagrangian elements) driven by factors such as currents, wind, and sub-grid diffusion. The principal equation used for simulating advective transport is described as follows.

$$L_{t_0+\Delta t} = L_{t_0} + \int_{t_0}^{t_0+\Delta t} \mathrm{v}_t[x(t_0), y(t_0), t_0]dt \quad (1)$$

where $L_{t_0+\Delta t}$ is the new position of an oil particle at the moment of $t_0 + \Delta t$, L_{t_0} is the original position of the oil particle at the moment of t_0, v_t is the velocity of the oil particle at the moment of t. The particle movement in the GNOME model is based on the simple linear superposition of currents, winds, and diffusion. A random-walk algorithm is used to represent the sub-grid diffusion process. The calculation processes of

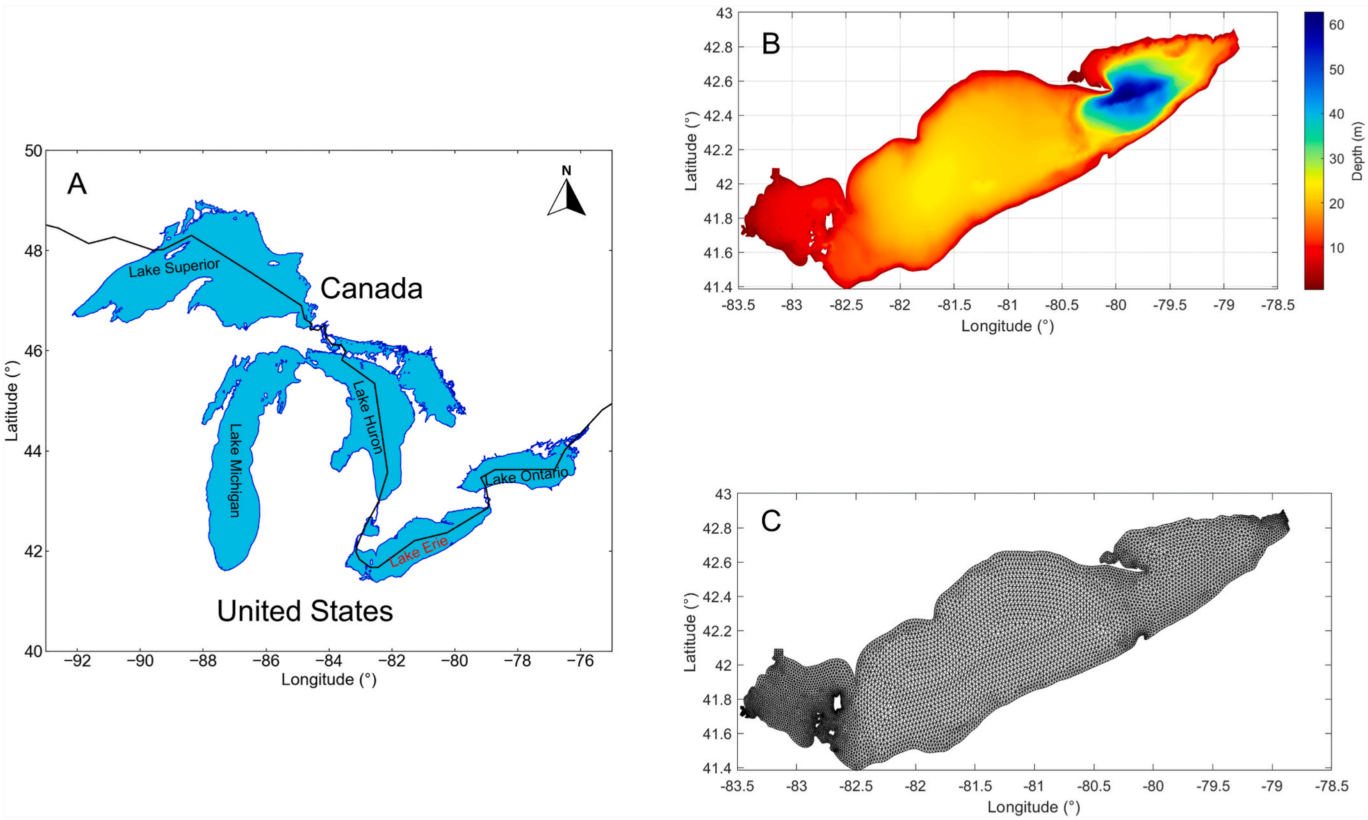

Fig. 1. (A) Locations of the five Great Lakes, including the main study area, Lake Erie, (B) Bathymetry map of Lake Erie, (C) Triangular mesh grids of Lake Erie in the GLOFS model. The black line represents the border between the United States and Canada. Positive degrees represent North latitude. Negative degrees represent West longitude.

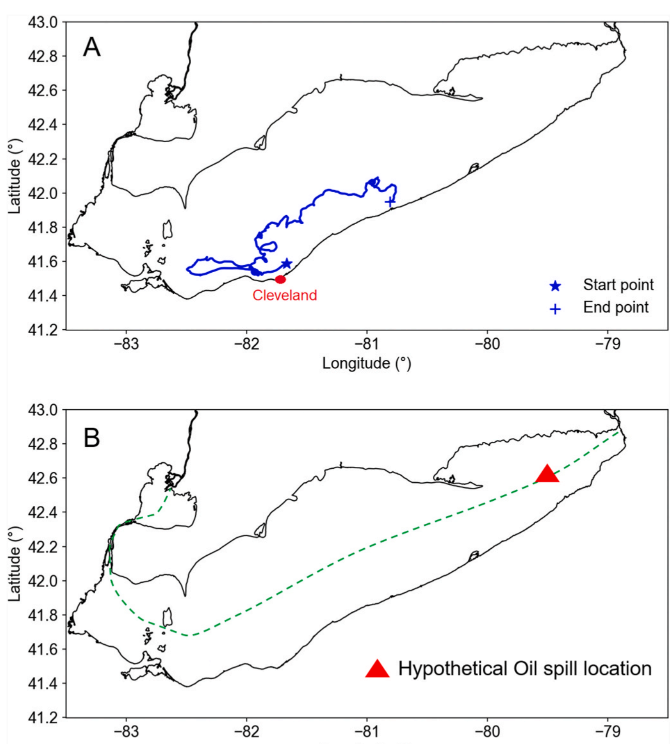

Fig. 2. (A) Drifter trajectory from August 31, 2018 to October 25, 2018, (B) Shipping route (source: https://www.marinevesseltraffic.com/LAKE-ERIE/ship-traffic-tracker) and the initial location of a hypothetical oil spill in Lake Erie.

particle movement in the GNOME model are elaborated in detail in the technical documentation (Barker et al., 2023; Zelenke et al., 2012).

For incorporating the effects of ice, the GNOME model incorporates an "80-20 rule" to simulate the movement of oil under varying ice coverage (Nordam et al., 2019; Venkatesh et al., 1990). When the ice coverage is 20% or less, the oil behaves as if there is no ice and moves with water currents. When the ice coverage reaches 80% or more, the oil behaves as if there is full ice coverage and moves with the ice. If the ice coverage falls between 20% and 80%, then the process is linearly interpolated between those values. To achieve this, the model scales down the currents based on the ice coverage and the "80-20 rule". For example, when the ice coverage is 50%, the oil moves at the average velocity of both the ice and the current.

2.3. GLOFS model

To drive the GNOME model, we extract current, wind, and ice data from the GLOFS output and develop interface code to convert the output format to match the input format of the GNOME model. The GLOFS model has been developed using the Finite Volume Community Ocean Model (FVCOM) (Chen et al., 2013), which incorporates an internally coupled unstructured grid version of the Los Alamos Sea Ice Model (UG-CICE) (Gao et al., 2011). The GLOFS model is built upon the FVCOM model, which is a three-dimensional, triangular mesh, free-surface, primitive equation, sigma-coordinate oceanographic model that solves the integral form of the governing equations (Chen et al., 2013). The internally coupled UG-CICE model is utilized to simulate ice thermodynamics and ice dynamics within the GLOFS framework (Fujisaki-Manome et al., 2020). In this study, the GLOFS model output was configured for Lake Erie to obtain the necessary hydrodynamic and ice input for the GNOME model.

The unstructured grid used for Lake Erie in this study consists of

11509 triangular elements and 6106 nodes in the horizontal domain, with a resolution ranging from approximately 300 m near the shore to 3.5 km offshore (Fig. 1C). The vertical water column in the GLOFS model consists of 21 sigma layers that are evenly distributed throughout the water column. Moreover, the GLOFS nowcast model is driven by surface meteorological data from the High-Resolution Rapid Refresh, a 3-km data-assimilated implementation of the Weather Research and Forecasting model, which has undergone thorough evaluation (Benjamin et al., 2016; Dowell et al., 2022). Detailed information on boundary conditions, including inflows and outflows to the lake, can be found in previous work (Kelley et al., 2018). The GLOFS model has undergone thorough validation for ice concentration, water level, water temperature, and heat flux in Lake Erie from 2003 to 2018, demonstrating its capability in accurately reproducing and forecasting these variables (Anderson et al., 2018; Fujisaki-Manome et al., 2020; Fujisaki et al., 2013).

2.4. Oil spill scenario design

To investigate the impact of ice cover on emergency response to spills from shipping incidents, we simulated a hypothetical oil spill scenario in Northeastern Lake Erie (−79.5°W, 42.6°N), an area near the shipping route and susceptible to ice cover (Fig. 2B and Table 1). The simulations were conducted with and without considering the presence of ice cover (Table 1), and the movement of the oil was tracked over a period of 5 days. Given the complex interaction between oil and ice, and considering that the relevant weathering processes within the GNOME model are still under development, this study primarily focuses on the oil transport process. For each simulation, we released 1000 unique tracer particles at the water surface in the GNOME model to simulate the oil spill event. It is worth noting that, unlike drifter simulations, the wind effect is activated, and we used a suggested and default diffusion coefficient of 10 $m^2 s^{-1}$ to account for particle diffusion (Schwab, 2016). These tracer particles were conservative and did not decay, allowing us to track their movement and study the transport behavior of the oil spill (Barker et al., 2023; Zelenke et al., 2012). The objective was to identify general patterns of how ice cover impacts oil transport characteristics, irrespective of oil type, volume, or weathering effects. This simplified approach aligns with other modeling efforts conducted in previous studies (Blanken et al., 2017; Bourgault et al., 2014; Nordam et al., 2019).

To illustrate the impact of ice cover on oil spill transport, we selected the recent years 2018–2022 as the study period. Based on the observed ice concentration and dynamic evolution in Lake Erie (source: https://www.glerl.noaa.gov/data/ice/glicd.php?year=2022, 2021, 2020, 2019, 2018), we classified January as the freezing season, February as the stable season, and March as the melting season (Table 1). In each simulation, the characteristics of the released oil particles including release location and particle number remained the same, and the differences in particle movement were solely attributed to the varying current, wind, and ice conditions obtained from the GLOFS model at different simulation durations.

Table 1
Illustration of model cases during three ice seasons.

Scenario	Ice cover	Study period (2018–2022)	Number of simulations
Case 1	Without	Freezing season (January)	620
Case 2	With	Freezing season (January)	620
Case 3	Without	Stable season (February)	564
Case 4	With	Stable season (February)	564
Case 5	Without	Melting season (March)	620
Case 6	With	Melting season (March)	620

2.5. Statistical analysis

In this study, we introduced ensemble simulations to investigate the possible results of hypothetical oil spills and the effects of ice cover on oil spill transport processes (Nordam et al., 2017; Schwab, 2016). We conducted a total of 620 simulations (at a 6-h interval, with 4 simulations per day for 31 days in January of each year from 2018 to 2022) for the freezing season, with each simulation lasting for 5 days (Table 1). Similarly, there were 564 simulations for the stable season and 620 simulations for the melting season. For each 5-day simulation, we used the corresponding hydrodynamic and ice outputs from the GLOFS model to drive the GNOME model. In addition, we developed Matlab (R2024a) scripts to calculate the average oil-affected open water area for each case.

$$\overline{S} = \frac{1}{N}\sum_{i=1}^{N}\sum_{j=1}^{M} A_{ij} \quad (2)$$

where $\overline{S}$ is the average oil-affected open water area for each case (km^2), N is the total number of simulations during that case, A_{ij} is the area of the mesh cell that contains at least one oil particle (km^2), M is the total number of mesh cells that contain at least one oil particle in each simulation.

To gain in-depth insights into the influence of ice cover on oil spill transport and provide guidance for emergency response, we generated risk maps for each case. The risk map is generated by calculating the probability of oil presence at each mesh cell. This probability is determined by calculating the percentage of simulations in which at least one oil particle was present in each mesh cell.

$$P_{cell} = \frac{1}{N}\sum_{i=1}^{N} E_i \quad (3)$$

where P_{cell} is the probability of oil presence at a mesh cell, E_i represents whether there is at least one oil particle in the mesh cell. If there is at least one oil particle, E_i is equal to 1; otherwise, E_i is equal to 0.

3. Results

3.1. Model performance evaluation using observed drifter data

In general, the movement of the released particles in the GNOME model, including their direction and trajectory shape (such as an L-shape observed during September 5–10, 2018, as shown in Fig. 3A), was consistent with the observed drifter during the four ice-free validation periods (Fig. 3). However, there were differences between the simulated and observed trajectories. For example, the simulated trajectory was nearly twice as long as the observed one during October 5–10, 2018 (Fig. 3C–c). Additionally, the simulated trajectories in September 2018 were longer than the observed ones (Fig. 3A-b). There were also cases where the simulated trajectory was shorter than the observed one, as seen during October 20–25, 2018 (Fig. 3D–d).

3.2. Comparison of oil transport processes with and without ice cover

For a clear comparison, we presented the 2022 results as an example due to the highest annual ice cover, approximately 95%, since 2020 (Fig. 4 and Fig. S2). The mid-month simulations, starting from the 10th to the 15th of each month, were selected as representative samples and plotted to exhibit the impacts of ice cover on oil spill transport (Fig. 4). In general, the presence of ice cover had an impact on the transport processes of oil spills by restricting the movement of oil, particularly during the stable season when ice cover was more prevalent and the ice concentration was higher (Fig. 4). Based on ensemble simulations and considering the entire month, the average oil-affected open water area in case 4 consistently remained below 50 km^2 throughout the 5-day

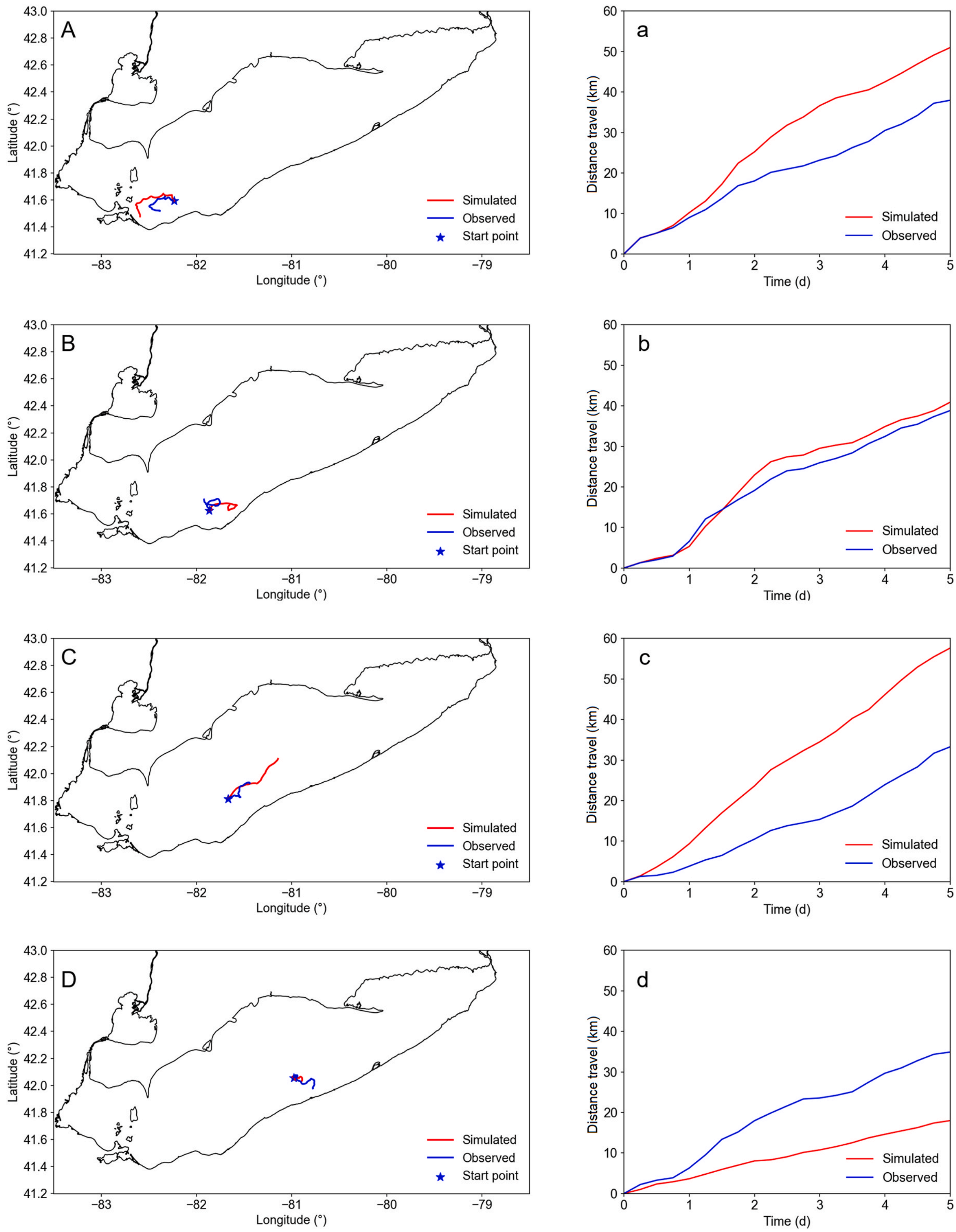

Fig. 3. Comparison of simulated and observed trajectories and distances in different periods. (A, a) September 5–10, 2018, (B, b) September 20–25, 2018, (C, c) October 5–10, 2018, (D, d) October 20–25, 2018.

simulations (Fig. 5). This was significantly smaller compared to case 3 (Fig. 5). However, during the freezing and melting seasons when there was limited ice presence, the inhibitory effect of ice cover on oil movement was diminished (Figs. 4 and 5).

3.3. Comparison of oil risk maps between conditions with and without ice cover

Through ensemble simulations, we conducted an assessment of the impacts of ice cover on the probability of oil presence on the fifth day after the release (Fig. 6). In general, regions located near the initial oil spill site exhibited a higher probability of oil presence. During the

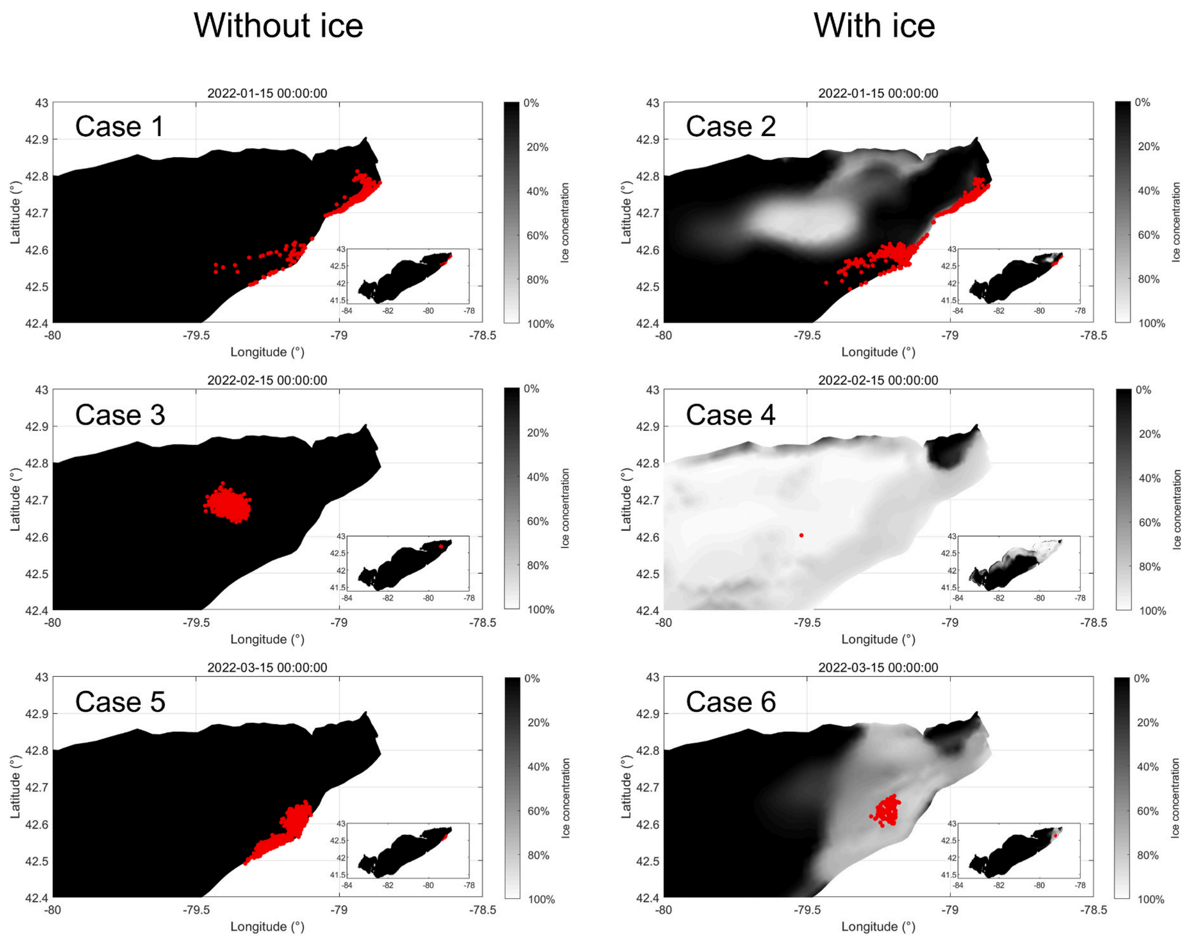

Fig. 4. Representative simulation results of oil transport on day 5 in different cases. The black area represents open water, the white area represents ice, and the red dots indicate oil particles. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

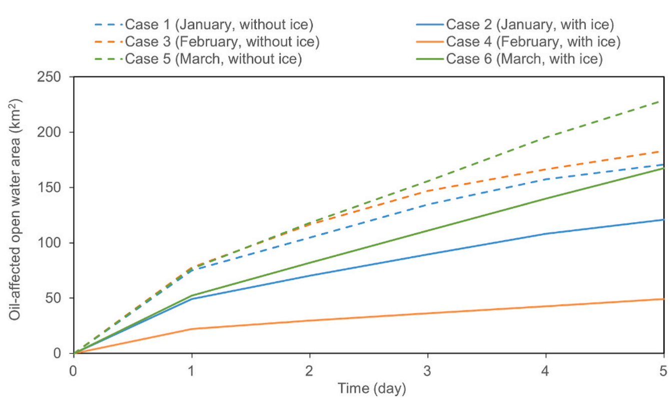

Fig. 5. Average oil-affected open water area for different cases based on ensemble simulations.

freezing and melting seasons, the risk maps showed minimal differences between cases with and without ice cover, especially when comparing case 5 and case 6 during the melting season (Fig. 6). However, for the stable season, case 4 exhibited a significant reduction in the risk of oil presence (maximum risk: 10%) compared to case 3 (maximum risk: 17%), indicating an enhanced inhibitory effect of ice cover on oil transport (Fig. 6).

3.4. Relationships between the oil-affected open water area and the initial ice concentration

The effects of the initial ice concentration (the most readily accessible information when an oil spill event occurs) at the hypothetical oil spill location on the oil-affected open water area were examined on each day from day 1 to day 5, based on ensemble simulations that considered ice cover (including cases 2, 4, and 6) (Fig. 7). The analysis revealed consistent negative correlations between the initial ice concentration and the affected open water area throughout the simulation period (Fig. 7 and Fig. S3). Linear regression was performed on day 1, day 2, day 3, day 4, and day 5, yielding R-squared values of 0.94, 0.82, 0.70, 0.62, and 0.58, respectively (Fig. 7).

4. Discussion

4.1. Uncertainty in modeling drifter trajectories

While the GLOFS model has previously undergone rigorous validation for water level, water temperature, and ice concentration, its detailed hydrodynamic characteristics such as flow field and flow velocity have not yet been validated (Anderson et al., 2018; Fujisaki-Manome et al., 2020). In this study, the observed drifter trajectories were utilized to further reflect the performance of the GLOFS model in predicting the hydrodynamic current in Lake Erie. Compared to previous research, the coupled GLOFS and GNOME model system demonstrates an effective capability to simulate drifter trajectories, including movement trends and traveling distance (Babaei and Watson, 2020; De

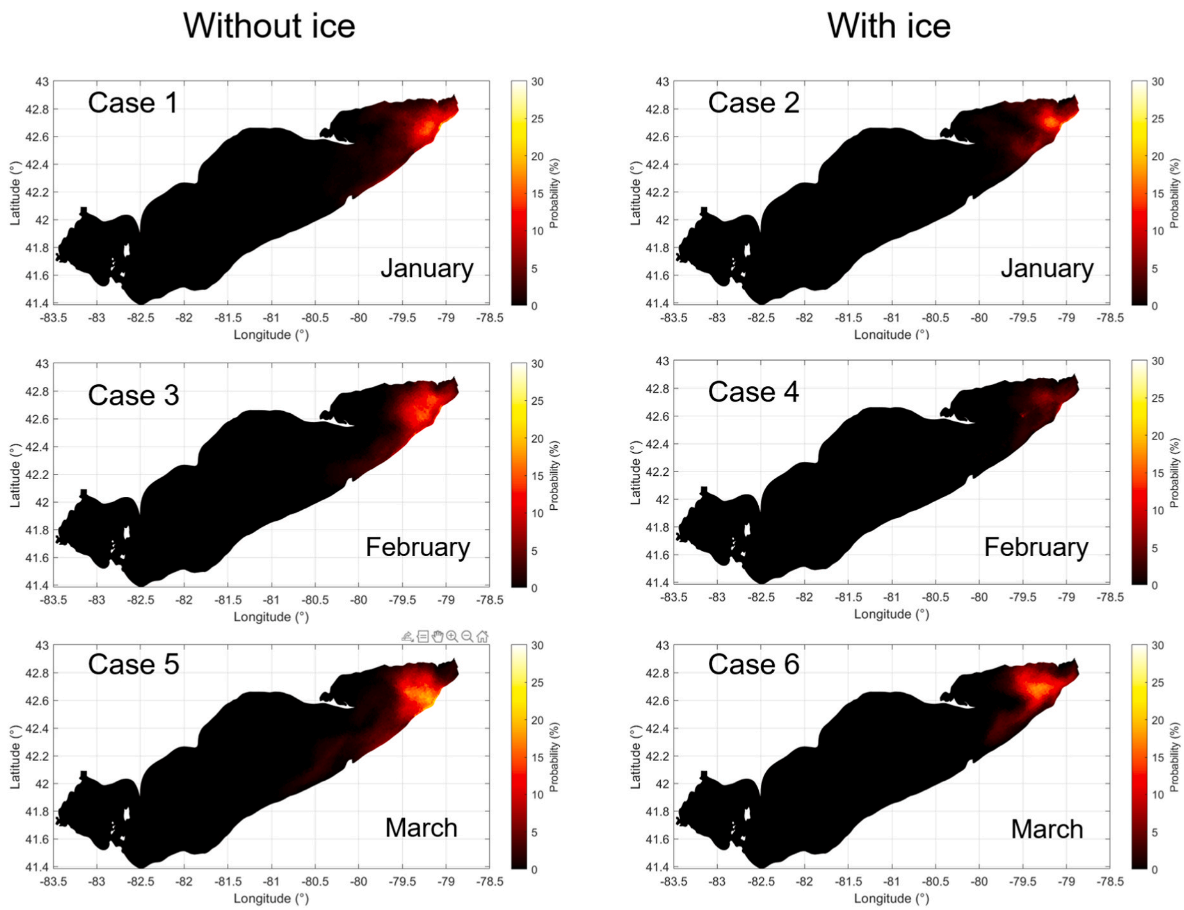

Fig. 6. Risk maps (probability of oil presence) on day 5 after the release for different cases based on ensemble simulations.

Dominicis et al., 2016; French-McCay et al., 2017). For example, in a rare oil-released experiment conducted in the Arctic, the distances between the observed and simulated trajectories on day 5 using the Oil Spill Contingency And Response model ranged from 15 km to 30 km when different driving current sources were utilized (Nordam et al., 2019). This range is comparable to the distances of 13 km (Fig. 3a), 2 km (Fig. 3b), 25 km (Fig. 3c), and 18 km (Fig. 3d) calculated in corresponding test cases for GNOME-GLOFS in Lake Erie. However, it is important to note that there were also some discrepancies, particularly regarding the length of the simulated and observed drifter trajectories (Fig. 3).

As the wind and diffusion effects were intentionally deactivated in the GNOME model to better represent the driving force acting on the actual fully submerged drifter (see Section 2.1), it can be inferred that the discrepancies between the simulated and observed trajectories primarily arose from the currents simulated by the GLOFS model (Fig. 3) (Barker et al., 2020; Dearden et al., 2022). Improving the accuracy of input boundary data and refining the grid resolution in the GLOFS model may better capture small-scale details and gradients, thereby enhancing the accuracy of simulating currents (Arneborg et al., 2017; De Dominicis et al., 2016). Moreover, this study evaluated the performance of the GLOFS model in simulating lake surface currents for the first time, highlighting the necessity for further enhancements to improve its accuracy. The challenge of accurately simulating current vectors using the current hydrodynamic model is revealed, despite the successful simulation of scalar variables such as temperature and ice concentration (Anderson et al., 2018). This finding emphasizes the need for future improvements and development in modeling techniques to better capture the dynamics of hydrodynamic currents.

4.2. Impacts of ice cover on oil spill transport

To address the lack of oil-in-ice modeling in the Great Lakes, we integrated the GNOME oil spill model with the GLOFS hydrodynamic-ice model to simulate the potential movement of an oil spill and investigate the influence of ice on oil transport in Lake Erie. The results clearly demonstrate that ice cover significantly impacts oil transport processes in freshwater environments, restricting oil transport and altering the trajectories of oil particles compared to conditions without ice cover (Fig. 4), and this aligns with previous findings in marine environments (Blanken et al., 2017; Nordam et al., 2017; Wang et al., 2008). During the stable season, high-concentration ice significantly limited oil movement, resulting in an affected open area of 49 km^2 in case 4, compared to 183 km^2 on day 5 without ice cover in case 3 (Fig. 5). However, during the freezing and melting seasons, this limiting effect weakened due to a less ice-covered region and lower ice concentration (Fig. 4 and Fig. S3), as evidenced by the shrinking differences in the oil-affected open water area between cases with and without ice cover (Fig. 5). These findings highlight the distinct impacts of different ice seasons on oil transport, providing insights for emergency response to oil spill events.

Analyzing the five-year ice season risk map, it was revealed that the closer the proximity to the initial spill location, the higher the probability of oil presence, consistent with previous studies conducted in the Straits of Mackinaw (Dynamic Risk Assessment Systems, 2017; Schwab, 2016). However, previous studies mainly focused on assessing oil spill risk in open water, without fully considering the impact of ice cover (Balogun et al., 2021; Dynamic Risk Assessment Systems, 2017; Schwab, 2016; Sepp Neves et al., 2016). In particular, during the stable season with limited oil movement with ice cover (Fig. 4), the probability of oil

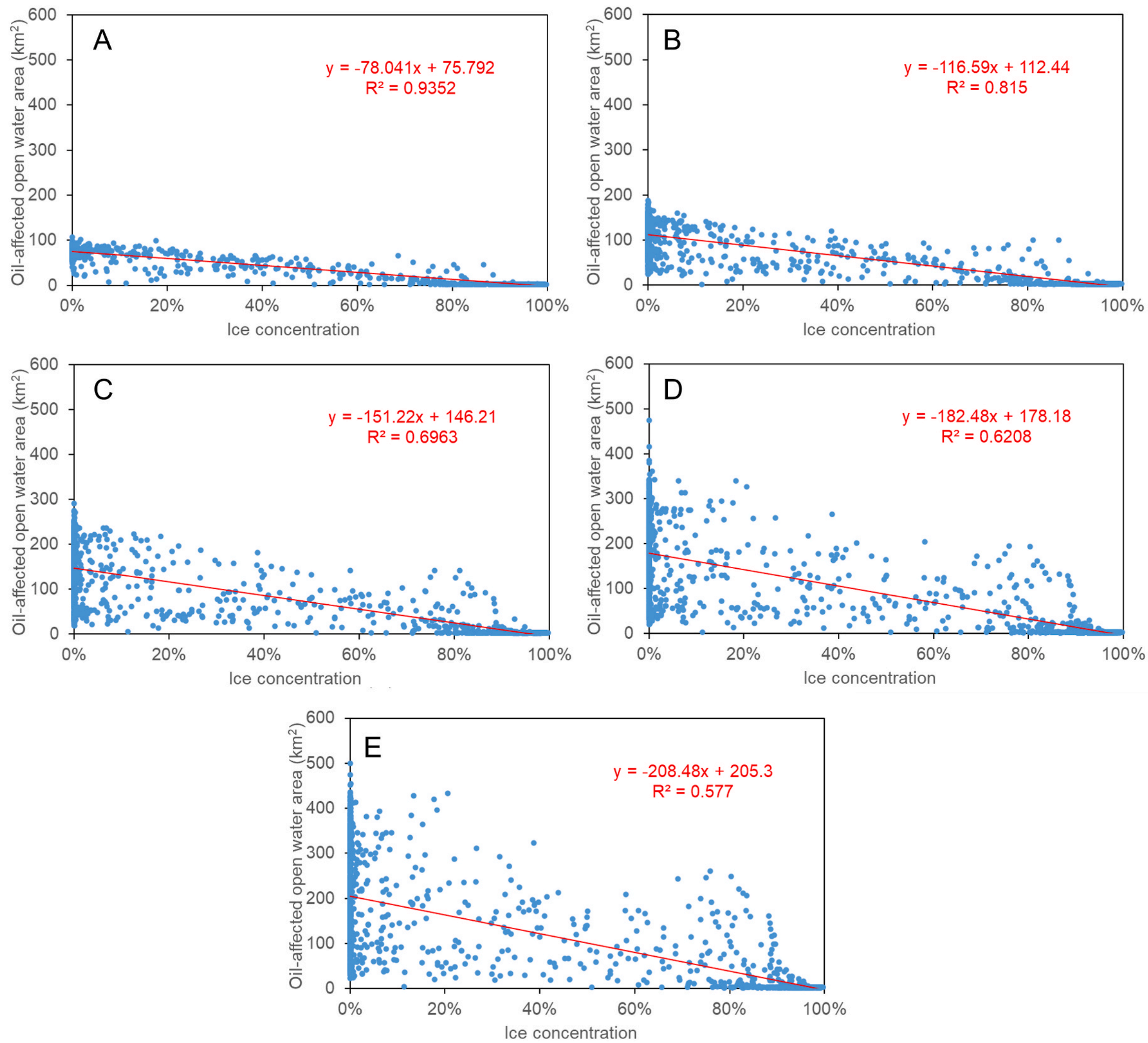

Fig. 7. Correlations between the oil-affected open water area and the initial ice concentration on (A) day 1, (B) day 2, (C) day 3, (D) day 4, (E) day 5. The red lines indicate linear regression of the scatter points. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

presence was the lowest compared to the freezing and melting seasons (Fig. 6). Thus, the risk maps of ice seasons obtained in this study can serve as a scientific basis for implementing effective emergency response strategies during winter oil spill events in Lake Erie. These findings underscore the significance of considering ice cover as a critical factor in the formulation of risk maps in the Great Lakes and other cold regions.

Through ensemble simulations, we analyzed the response of the oil-affected open water area to the initial ice concentration at the hypothetical oil spill location. A robust linear correlation was observed on day 1 (oil-affected open water area $= -78.041 \times$ initial ice concentration $+ 75.792$, $R^2 = 0.94$, Fig. 7A). The R-squared value decreases as the day increases, indicating that the reliability of the regression equation is limited to a short time frame following the occurrence of the oil spill (Fig. 7 and Fig. S4). The reason behind this is that the motion of individual particles in the model is indeed non-linear (Barker et al., 2023; Zelenke et al., 2012). These new findings demonstrate the potential utility of the empirical regression equation for efficiently predicting the oil-affected water area, particularly in the context of short-term emergency response.

4.3. Limitations

Due to the lack of oil spill observational data in the Great Lakes, this study utilized drifter data to assess the performance of the coupled GNOME-GLOFS model system. While the preliminary evaluation results indicate the effectiveness of our model system, further research, particularly in measuring lake currents and investigating an actual oil spill in this region, is still necessary to verify and improve the model performance. Compared to oil spill models in previous studies, the process-based coupled model system can simulate and consider ice impacts on oil spill transport but does not account for detailed oil-ice interactions such as over-ice oil or under-ice oil (Babaei and Watson, 2020; Hu et al., 2020; Yamaguchi and De Silva, 2022). Moreover, it should be noted that this study did not incorporate oil type and weathering processes, as our focus was on oil spill trajectory, and the relevant features in our coupled model system are still in development. To enhance the prediction accuracy of the oil transport process and risk maps, it is important to consider additional factors such as weathering effects including evaporation and emulsification in future studies. In addition, while ice cover is shown to inhibit the transport of oil, spill response in ice-covered waters presents significant challenges that may affect the response time, efficiency, and effectiveness of response efforts.

5. Conclusions

To simulate oil spills occurring under ice cover conditions and facilitate emergency response planning, we integrated the GNOME oil spill model with the GLOFS hydrodynamic-ice model for the Great Lakes. We assessed the performance of the coupled model using observed drifter data and utilized the model to examine the impacts of ice cover on oil spill transport processes. The main findings are as follows:

(1) The coupled model exhibited a relatively reliable capability in simulating particle trajectories when compared to previous studies. The simulated particle travel direction showed good consistency with the observed trajectories, although there were differences in the simulated particle travel length compared to the observed values. Meanwhile, the results from these case studies also offer insight into the performance of the GLOFS model in simulating lake surface currents.
(2) The ensemble simulations revealed the significant impact of ice cover on oil spill transport, which varied across the freezing, stable, and melting seasons. Among these seasons, the stable season with high-concentration ice exhibited the strongest limitation on oil transport, leading to an affected open water area of 49 km^2 with ice cover on day 5, compared to 183 km^2 without ice cover.
(3) In line with the oil transport process, the analysis of risk maps showed that the stable season with high-concentration ice exhibited a notable reduction in the area with a probability of oil presence. Conversely, this reduction effect induced by ice was not as evident during the freezing and melting seasons.
(4) Negative correlations between the initial ice concentration and the affected open water area were consistently observed throughout the simulation period, with particularly notable results on day 1, where the linear regression R-squared value reached 0.94. The linear regression equations derived from these findings could serve as a reference for rapid predictions in emergency response.

Collectively, the developed coupled model system serves as a valuable tool for predicting and responding to oil spill events under icy conditions in the world's largest freshwater system, addressing a significant research gap. These findings underscore the importance of accounting for the impacts of ice cover on oil spill transport when developing emergency response strategies. However, to enhance the accuracy of the coupled model, it is imperative to improve the precision of hydrodynamic current simulation and incorporate the oil weathering process into the model.

Disclaimer

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CRediT authorship contribution statement

Yang Song: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Ayumi Fujisaki-Manome:** Writing – review & editing, Validation, Software, Funding acquisition, Data curation. **Christopher H. Barker:** Writing – review & editing, Validation, Supervision, Software. **Amy MacFadyen:** Writing – review & editing, Validation, Software, Formal analysis. **James Kessler:** Writing – review & editing, Validation, Software. **Dan Titze:** Writing – review & editing, Validation, Formal analysis. **Jia Wang:** Writing – review & editing, Validation, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2024.120810.

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