POAC'25
St. John's, Newfoundland and Labrador, Canada

Proceedings of the 28th International Conference on Port and Ocean Engineering under Arctic Conditions
Jul 13-17, 2025
St. John's, Newfoundland and Labrador
Canada

Preliminary Analysis of Parameter Effects on Oil Spill Simulations in Ice-Covered Waters

Akihisa Konno[1], Mitsuki Saito[1], Motomu Oyama[2,3], Takatoshi Matsuzawa[4]
[1] Kogakuin University, Tokyo, Japan
[2] Kogakuin University Graduate School, Tokyo, Japan
[3] National Institute of Polar Research, Tokyo, Japan
[4] National Maritime Research Institute, Tokyo, Japan

ABSTRACT

Modeling oil spills in ice-covered waters is challenging due to complex interactions among oil, ice, and environmental forcing. This study evaluates the PyGNOME model's performance in Arctic conditions using ERA5 wind and TOPAZ4 ocean data based on the FEX2009 field experiment. Troll Blend crude oil was used as a proxy for Troll B.

Model sensitivity to ice concentration, windage, wind, ocean currents, and ice drift was examined. Evaporation was strongly reduced at ice concentrations above 80%. Ocean currents and ice drift had little effect on weathering but influenced transport. Comparing results with OSCAR simulations by Daae et al. (2011) revealed partial agreement. Reducing wind speed by half improved trajectory alignment, likely due to ERA5 overestimation or how wind forcing is implemented in PyGNOME. Doubling ocean current magnitude improved southwestward drift matching, though the cause remains unclear. Discrepancies likely stem from multiple factors, including data resolution, vertical representativeness, and model processing.

PyGNOME did not reproduce the complex clockwise drift seen in Daae et al. (2011), suggesting limitations in both data and model structure. These results emphasize the need to carefully evaluate environmental inputs and model configurations to improve oil drift simulation in ice-covered seas.

KEY WORDS: PyGNOME; FEX2009 experiment; Oil weathering; Ice concentration

INTRODUCTION

With the increasing utilization of the Arctic sea routes and the expansion of oil and gas exploration activities, the risk of oil spill accidents in ice-covered waters has become a growing concern. However, the behavior of spilled oil, including its transport and weathering processes, significantly differs between ice-covered and open-water environments, posing challenges for the direct application of conventional oil spill simulation models.

In ice-covered waters, oil transport is influenced not only by wind and ocean currents but also by ice movement and ice concentration. Afenyo et al. (2016) identified several unresolved factors affecting oil transport in ice-covered environments, including encapsulation within ice, sedimentation, and long-term weathering processes. Notably, their study indicated that while oil movement is severely restricted when ice concentration exceeds 80%, the interaction between oil and ice in the 30–80% range becomes complex, making diffusion difficult to predict.

Oyama et al. (2025) experimentally demonstrated that oil dispersion reaches its maximum at an ice concentration of 26.7%, challenging the conventional assumption that oil dispersion is monotonically suppressed as ice concentration increases. These findings suggest that existing numerical models may require modifications to accurately represent oil transport dynamics in ice-covered environments.

Several numerical models have been developed to simulate oil spills, with the most commonly used ones including GNOME/PyGNOME, OSCAR, SIMAP, and OpenOil.

- GNOME/PyGNOME (Beegle-Krause, 2001; NOAA, 2023a), developed by NOAA, is a two-dimensional and three-dimensional Lagrangian particle-tracking model designed for oil spill simulations. It includes an ice interaction module, making it applicable to ice-covered waters, and its weathering algorithm has been integrated into the OpenDrift framework.
- OSCAR (Reed et al., 1999; Nordam et al., 2019), developed by SINTEF, is a comprehensive model with a strong track record in the North Sea and the Baltic Sea, and it is capable of assessing the ecological impact of oil spills.
- SIMAP (French-McCay, 2004), created by RPS/ASA, has been applied in major oil spill incidents such as the Exxon Valdez and Deepwater Horizon spills, and it considers interactions between oil, sea ice, and coastal environments.
- OpenOil (Dagestad et al., 2018), an open-source model within the OpenDrift framework, incorporates elements of PyGNOME’s algorithms to enhance oil spill trajectory modeling in various marine environments.

Barreto et al. (2021) conducted a comparative study of oil spill models, reporting that OSCAR tends to underestimate surface oil spreading, whereas CMOP tends to overestimate dispersion. Additionally, Venkatesh et al. (1990) found that when ice concentration exceeds 30%, oil transport is dominated by ice movement, and at concentrations above 80%, oil movement nearly ceases.

To evaluate the accuracy of oil spill simulations in ice-covered waters, numerical results must be compared with experimental data. Among the most representative field experiments, FEX2009 (Faksness et al., 2010), conducted in the Barents Sea, reported that the ice field drifted nearly 80 km over six days. As the oil was observed to move with the ice and remain confined between ice floes, it is inferred that the oil slick followed a similar drift trajectory. The study also found that the effectiveness of chemical dispersants was significantly reduced, and emulsification was delayed under ice-covered conditions.

The Svalbard Experiment (Dickins et al., 2006), carried out in 2006 under ice-covered conditions, demonstrated that the horizontal spreading of oil beneath ice was significantly limited.

The NOFO Experiment (Faksness et al., 2016) in 2016 investigated in-situ burning (ISB) under drifting ice conditions and confirmed the effectiveness of fire-resistant booms for oil removal.

To evaluate the accuracy of oil spill simulations in ice-covered waters, it is essential to compare numerical results with established benchmarks. While field experiments such as FEX2009 provide valuable observational data, it is often more practical to validate models against published simulation results that have already been calibrated and compared with such experimental observations. In this study, we reference the numerical results reported by Daae et al. (2011), who used the OSCAR model to simulate oil drift and weathering under the environmental conditions of the FEX2009 field experiment. Their study includes detailed comparisons with observational data, making it a suitable benchmark for evaluating the performance of other numerical models.

The primary objective of this study is to improve the reliability of numerical simulations of oil drift phenomena in ice-covered waters. Specifically, this research employs PyGNOME to simulate oil transport and weathering based on the same environmental conditions used by Daae et al. (2011), and examines how key input parameters affect simulation outcomes. By comparing the results with those reported in Daae et al. (2011), we aim to assess the validity and limitations of PyGNOME in ice-covered scenarios and identify areas for potential model improvement.

MATERIALS AND METHODS

In this study, we utilized the oil spill simulation tool PyGNOME, developed by the National Oceanic and Atmospheric Administration (NOAA), to analyze the dynamics of oil spills in ice-covered environments. PyGNOME is an oil spill model based on the Lagrangian particle tracking method, which enables the analysis of oil movement and weathering under the influence of wind, ocean currents, and ice drift. To evaluate the applicability of this model under Arctic conditions, simulation results were compared with those reported by Daae et al. (2011), who used the OSCAR model under the same environmental conditions as the FEX2009 field experiment.

Simulation Setup and Input Data

The parameters used in the PyGNOME simulations were selected to approximate the environmental conditions described in Daae et al. (2011), which correspond to the FEX2009 experiment. While the original study utilized in-situ meteorological and oceanographic measurements collected during the experiment, such data were not fully available for this study. Instead, we employed the best-available reanalysis datasets to construct a comparable simulation environment. Table 1 summarizes the main parameters used.

For the wind field, we used eastward and northward wind vector components at 10 meters above sea level from the ERA5 reanalysis dataset (Hersbach et al., 2020). Ocean current and ice motion vector fields were derived from the Arctic Ocean Physics Reanalysis dataset (TOPAZ4; Sakov et al., 2012) at a depth of 5 meters, and included sea ice concentration, as well as eastward and northward components of ice drift. Although these datasets may not perfectly replicate the original FEX2009 conditions, they provide a reasonable approximation for comparative modeling purposes.

Although the FEX2009 field experiment employed Troll B crude oil, PyGNOME's ADIOS Oil Database (NOAA, 2023b) does not include data for this specific oil type. Therefore, we used

Troll Blend as a proxy. While both oils are produced from the Troll field, their physical properties may differ. This substitution could influence weathering behavior, particularly evaporation and emulsification rates.

Table 1. Key Parameters Used in the Analysis

Parameter	Value
Spilled Oil	Troll Blend (from ADIOS Oil Database)
Oil Spill Volume	5915 kg
Simulation Start Time	2009-05-15 08:30 UTC
Simulation Time Step	15 minutes
Number of Particles (Elements)	1000
Water Temperature	Set based on observed data
Salinity	34.3 psu
Spill Duration	1 hour (08:30-09:30)

Table 2. Summary of Analysis Cases

Case	Conditions
Case 1	Effect of ice concentration (0–100%, 10% increments)
Case 2	Modification of Windage_range (1 to 4% (default), 5 to 8%)
Case 3	Evaluation of wind influence alone (excluding ice effects)
Case 4	Evaluation of ocean current influence alone (excluding ice effects)
Case 5	Evaluation of ice drift influence (fixing wind and ocean currents)

Weathering and Transport Analysis Conditions

To evaluate the effects of oil weathering and transport, the following analysis cases were established (Table 2).

In PyGNOME, windage_range represents the fraction of wind speed that directly influences the movement of floating oil particles, also referred to as leeway. The windage value is randomly assigned within the specified range for each particle. A higher windage_range results in stronger wind-driven transport, whereas a lower windage_range makes the oil transport more dependent on ocean currents and ice movement.

The PyGNOME simulation was conducted by inputting wind, ocean current, and ice data in NetCDF format, and the resulting oil movement trajectories were calculated. The FEX2009 experiment reported that the ice field drifted nearly 80 km over six days. As the oil was observed to follow the ice drift and remain confined between ice floes, it is inferred that the oil slick exhibited a similar displacement. In the present study, simulation results were compared with those reported by Daae et al. (2011), who reproduced this drift behavior using the OSCAR model under FEX2009 conditions, in order to assess the consistency of PyGNOME simulations.

Simulation Procedure

Each simulation was initialized by placing 1000 particles at the designated spill location, representing the released oil. The movement of particles was computed using environmental forcing including wind, ocean currents, and ice drift, based on the input datasets described previously. The simulation time step was set to 15 minutes, and the total simulation period was consistent with the conditions outlined in Daae et al. (2011). The simulations were conducted using PyGNOME's standard configuration for oil weathering, incorporating the physical properties of Troll Blend oil.

RESULTS AND DISCUSSION

Qualitative Evaluation of Parameter Variations

The impact of varying PyGNOME settings on oil weathering and transport was assessed to identify the sensitivity of the model to key environmental parameters. These analyses were conducted independently of external simulation results, and are intended to characterize internal model behavior under different forcing conditions.

Effect of Ice Concentration on Oil Weathering

The impact of ice concentration on oil weathering is illustrated in Figure 1, which presents results for ice concentrations of 0%, 50%, 70%, and 80%. The findings indicate that ice concentration primarily affects the initial phase of oil evaporation.

- Evaporation progresses more rapidly and reaches equilibrium sooner at lower ice concentrations, while higher ice concentrations suppress evaporation and slow the approach to equilibrium. Nevertheless, within the range of 0% to 70% ice concentration, the total amount of evaporated oil eventually converges over time.
- In PyGNOME, when ice concentration exceeds 80%, oil evaporation is set to be nearly negligible. This is a model assumption rather than a direct representation of natural phenomena.
- These findings highlight the importance of considering both the timescale of evaporation and model assumptions when interpreting simulation results. While this study compares PyGNOME behavior with previous simulation results (Daae et al., 2011), further validation against field observations is necessary to refine the representation of oil weathering in ice-covered environments.

Effect of Windage_range Parameter Variation

The oil weathering process in simulations with Windage_range set to 1–4% (default) and 5–8% is shown in Figure 2. As seen from the comparison, there is almost no difference between the results. This indicates that Windage_range has no significant impact on weathering.

Effect of Wind Influence

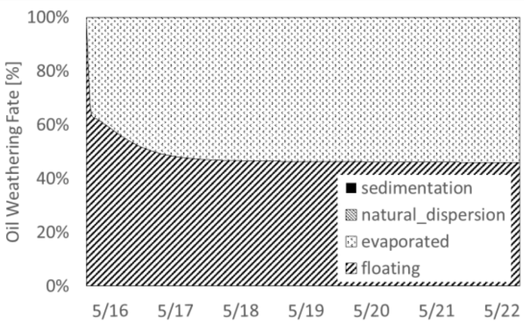
The impact of wind on oil weathering and transport in ice-covered environments is illustrated in Figure 3. A comparison between Figures 1 and 3 reveals the following key observations:

- Even in the presence of wind, the trend remains consistent with the windless case: oil evaporates more quickly at lower ice concentrations. However, when ice concentration is low, the difference in evaporation between wind and no-wind conditions is more pronounced. In contrast, at an ice concentration of 70%, the effect of wind on evaporation is minimal.
- Natural dispersion of oil occurs only in the presence of wind, suggesting that wind-driven mixing plays a crucial role in breaking up the oil into smaller droplets.

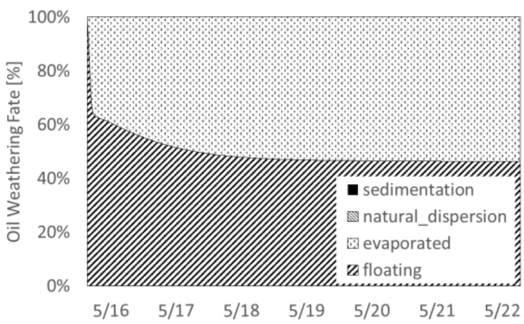
- The final amount of floating oil remains approximately constant across ice concentrations ranging from 0% to 70%, with a difference of less than 1%. This suggests that the concentration of ice influences the distribution and behavior of the oil, but does not significantly affect the total amount of floating oil within this range.

Effect of Ocean Currents and Ice Drift

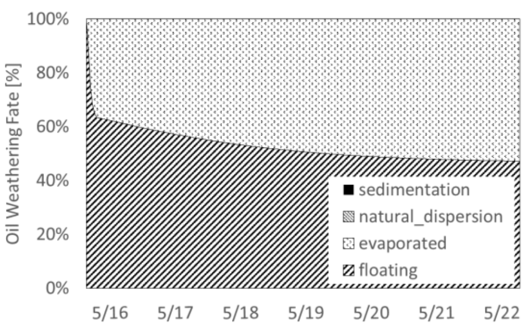
Simulations considering ocean currents and ice movement were also conducted; however, the oil weathering process closely resembled that shown in Figure 1, with minimal influence observed from either ocean currents or ice movement.



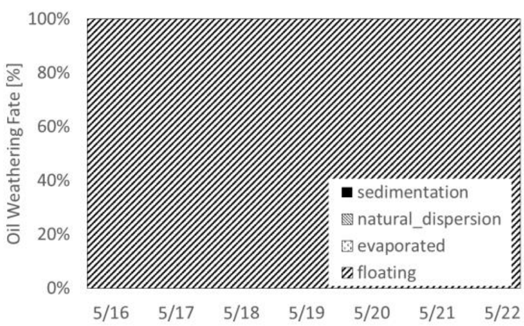
Ice concentration: 0%



Ice concentration: 50 %

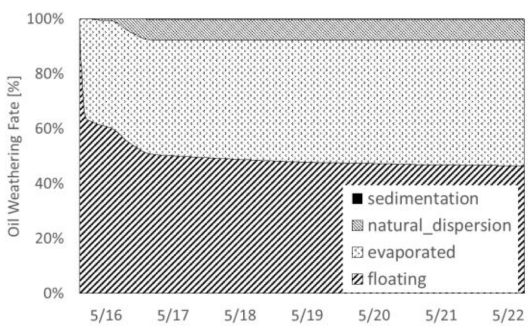


Ice concentration: 70 %

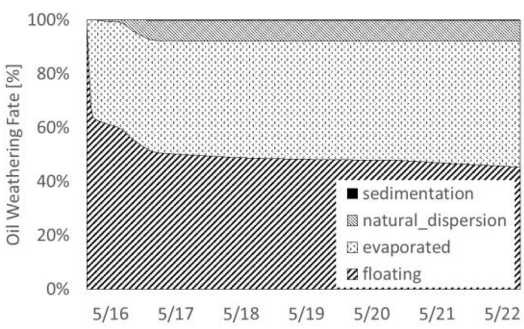


Ice concentration: 80 %

Figure 1. Oil weathering simulated by PyGNOME under varying ice concentrations

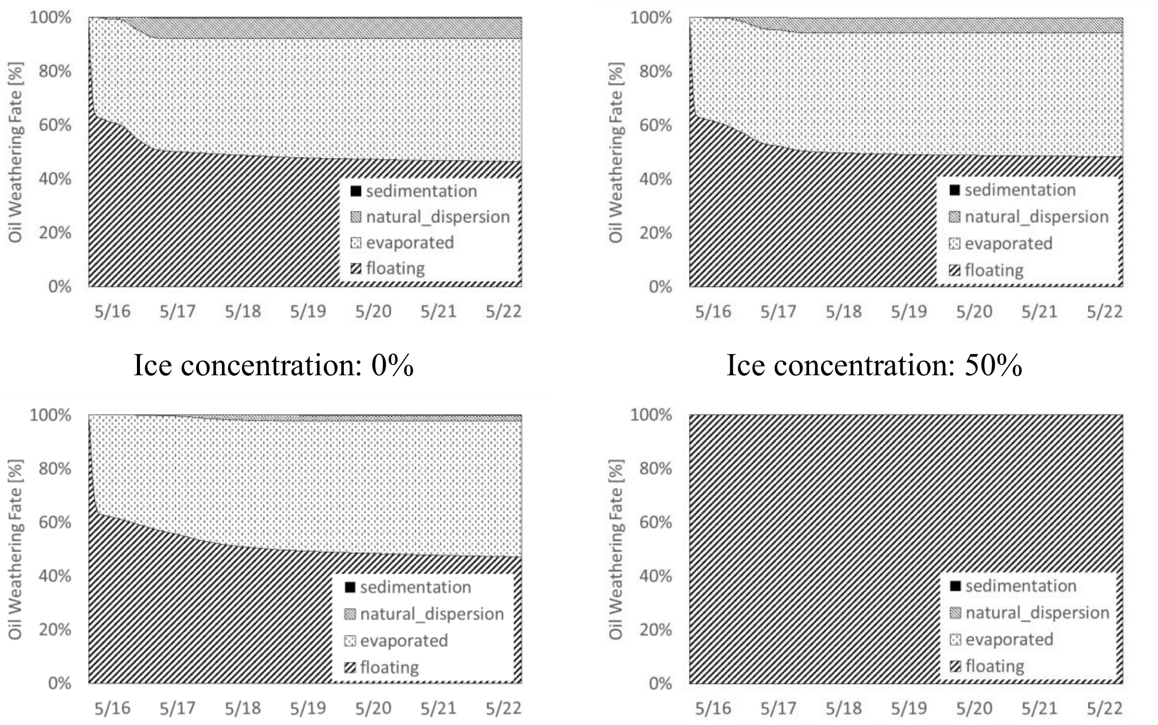


1 to 4%



5 to 8%

Figure 2. Effect of Windage_range variations on oil weathering fate simulated by PyGNOME



Ice concentration: 0% Ice concentration: 50%

Ice concentration: 70% Ice concentration: 80%

Figure 3. Oil weathering fate considering wind effects under different ice concentrations simulated by PyGNOME

Model Behavior Evaluation Based on OSCAR Simulations of the FEX2009 Experiment

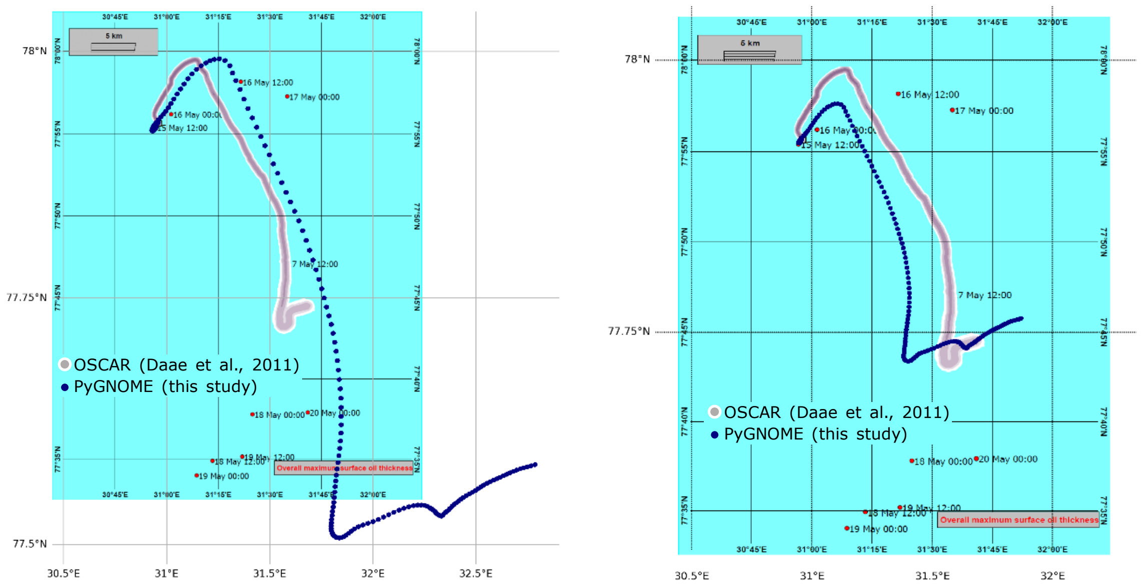
To assess the consistency of PyGNOME with previously published modeling results, we compared our simulation outputs with those reported by Daae et al. (2011), who used the OSCAR model under environmental conditions derived from the FEX2009 experiment. Their simulations, calibrated with observational data, serve as a benchmark for evaluating the effectiveness of PyGNOME in replicating oil drift behavior in ice-covered waters.

Figures 4 and 5 present the sensitivity of the simulated oil trajectories to environmental forcing. In Figure 4, wind vector fields were scaled by factors of 1.0 (default) and 0.5 to evaluate the influence of wind strength. In Figure 5, ocean current fields were scaled by 1.0 and 2.0 to assess their contribution to the trajectory.

When only wind forcing was considered, both Daae et al. (2011) and our simulation results showed oil drift that could be divided into three distinct phases: an initial northeastward movement, a dominant south-southeastward displacement, and a subsequent return toward the northeast along a curved path. Among these, the second phase exhibited the greatest displacement. According to Daae et al. (2011), this segment extended approximately 32 km. Under default wind forcing, PyGNOME overestimated this movement to around 56 km, whereas halving the wind magnitude reduced the displacement to about 27 km, closely matching the benchmark. While this result may suggest that ERA5 wind data overestimate surface wind forcing under ice-covered conditions—potentially due to the attenuation of wind stress by sea ice—it is also possible that the discrepancy arises from other factors, such as the way wind input is handled in PyGNOME, including temporal resolution, interpolation methods, and the parameterization of ice–wind interactions. Therefore, the observed overestimation likely reflects a combination of data limitations and model sensitivities, and warrants further investigation.

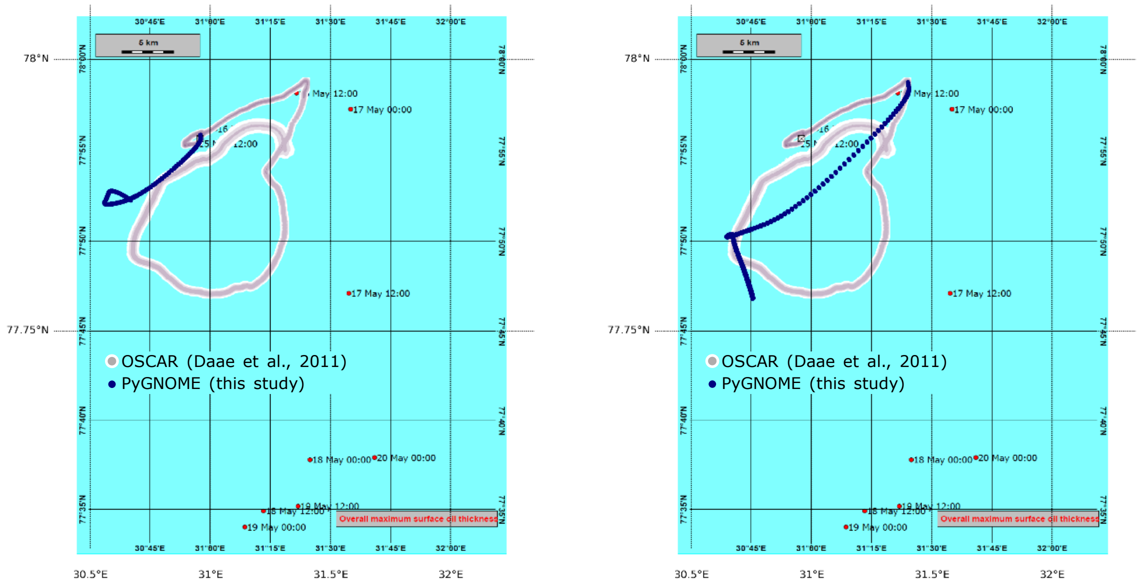
When ocean current forcing was considered in isolation, additional differences emerged. The current vector field derived from the TOPAZ4 dataset was predominantly directed northeastward throughout the simulation domain. In contrast, Daae et al. (2011) reported a clockwise-curving trajectory driven by ocean currents, in which the oil initially moved northeast before reversing toward the southwest. To reflect this behavior, we adjusted the initial release point in our simulation to the location where southwestward movement begins. This behavior was reproduced only when the ocean current field was scaled by a factor of 2.0.

The PyGNOME simulations under current-only forcing showed a two-phase drift pattern: an initial southwestward displacement followed by a shift toward the south-southeast. To enable quantitative comparison with Daae et al., we focused on the southwestward segment, which represented the primary transport direction in the mid-phase of the trajectory. In the OSCAR simulations, this displacement spanned approximately 27 km. In contrast, PyGNOME produced only about 11 km under default current forcing. Doubling the current magnitude increased the displacement to 23 km, significantly narrowing the discrepancy. Nevertheless, the need to scale the ocean current by a factor of 2.0 lacks a straightforward physical justification. The TOPAZ4 dataset used in this study provides ocean current vectors at 5 m depth with a horizontal resolution of approximately 12.5 km, which is comparable to the spatial scale of the observed drift. This may lead to smoothing of submesoscale features relevant to surface oil transport. Additionally, the way ocean current forcing is treated in PyGNOME—including spatial and temporal interpolation, and its coupling with sea ice—may also contribute to trajectory differences. As with wind, the inability to reproduce the complex, clockwise-curving pattern seen in Daae et al. (2011) suggests that the divergence stems not from a single factor, but from multiple limitations in both the reanalysis data and the modeling framework.



Original wind data　　　　Wind vector field scaled to 0.5

Figure 4. Comparison of PyGNOME-simulated oil trajectories with OSCAR model results by adjusting the wind field scale (based on FEX2009 conditions) . The background figure showing the OSCAR simulation is reproduced from Daae et al. (2011).



Original current

Ocean current field scaled to 2.0 and starting point is adjusted

Figure 5. Comparison of PyGNOME-simulated oil trajectories with OSCAR model results by adjusting the current field scale and the initial release point of the PyGNOME simulation (based on FEX2009 conditions). The background figure showing the OSCAR simulation is reproduced from Daae et al. (2011).

These findings underscore the importance of carefully evaluating both input datasets and model configurations when simulating oil drift in ice-covered environments. Further studies should explore higher-resolution datasets, alternative forcing schemes, and improved representations of ocean–ice–oil interactions.

CONCLUSIONS

This study examined the performance of the PyGNOME oil spill simulation model in ice-covered waters by comparing its results with those of the OSCAR model reported by Daae et al. (2011), which were based on the environmental conditions of the FEX2009 field experiment. The simulations employed reanalysis datasets for wind and oceanographic conditions, specifically ERA5 and TOPAZ4, and used Troll Blend oil as a substitute for Troll B crude due to limitations in the PyGNOME database.

The results confirmed that ice concentration significantly affects the rate of oil evaporation. Lower ice concentrations permitted faster evaporation during the initial phase, whereas higher concentrations suppressed this process. While the windage_range parameter had minimal effect on evaporation, it influenced the oil drift pathways. Wind was also found to be a key factor in promoting natural dispersion, particularly at low ice concentrations, while ocean currents and ice drift showed limited influence on weathering behavior.

The comparison of oil trajectories revealed that applying scaling adjustments to the wind and current fields improved agreement with OSCAR model results. In the case of wind, reducing the magnitude by 50% led to better alignment with reference drift distances, which may reflect not only the attenuation of wind stress by sea ice but also sensitivities in how wind forcing is

processed within PyGNOME. For ocean currents, doubling the magnitude resulted in improved trajectory agreement, especially in terms of southwestward displacement. However, this adjustment lacks a straightforward physical explanation. The discrepancy likely arises from multiple sources, including the horizontal resolution and depth of the TOPAZ4 dataset, as well as how ocean current inputs are interpolated and coupled with ice within PyGNOME.
Notably, PyGNOME was unable to reproduce the complex, clockwise-curving drift pattern reported by Daae et al. (2011), regardless of the forcing scale. This limitation suggests that discrepancies stem from both the input data and the structural limitations of the model itself. Future improvements should therefore consider integrating higher-resolution surface current data, validating drift outputs against surface observations, and refining the treatment of near-surface and ice-interacting dynamics.

ACKNOWLEDGEMENTS

This work was a part of the Arctic Challenge for Sustainability II (ArCS II), Program Grant Number JPMXD1420318865.

REFERENCES

Afenyo, M., Veitch, B., & Khan, F., 2016. A state-of-the-art review of fate and transport of oil spills in open and ice-covered water. *Ocean Engineering*, 119, pp. 233–253.

Barreto, F. T. C., Dammann, D. O., Tessarolo, L. F., Skancke, J., Keghouche, I., Innocentini, V., Winther-Kaland, N., & Marton, L., 2021. Comparison of the Coupled Model for Oil Spill Prediction (CMOP) and the Oil Spill Contingency and Response model (OSCAR) during the DeepSpill field experiment. *Ocean and Coastal Management*, 204, 105552.

Beegle-Krause, C. J., 2001. General NOAA Oil Modeling Environment (GNOME): A new spill trajectory model. *International Oil Spill Conference Proceedings*, 2001(1), pp. 865–871.

Daae, R. L., Faksness, L. G., Durgut, I., Brandvik, P. J., & Leirvik, F., 2011. *Modelling of oil in ice with OSCAR*, SINTEF Report No. 35.

Dagestad, K. F., Röhrs, J., Breivik, Ø., & Ådlandsvik, B., 2018. OpenDrift v1.0: A generic framework for trajectory modeling. *Geoscientific Model Development*, 11(4), pp. 1405–1420.

Dickins, D., Buist, I., & Potter, S., 2006. *Svalbard experimental oil spill under ice: Final report*. Report to the Norwegian Pollution Control Authority.

Faksness, L. G., Brandvik, P. J., & Daling, P. S., 2016. The effect of ice coverage on oil weathering and dispersibility. *Cold Regions Science and Technology*, 131, pp. 89–102.

Faksness, L. G., Daae, R. L., Brandvik, P. J., Leirvik, F., & Børseth, J. F., 2010. *Oil distribution and bioavailability: Field experiment FEX2009*, SINTEF Report No. 33.

French-McCay, D. P., 2004. Oil spill impact modeling: Development and validation. *Environmental Toxicology and Chemistry*, 23(10), pp. 2441–2456.

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., De Chiara, G., Dahlgren, P., Dee, D., Diamantakis, M., Dragani, R., Flemming, J., Forbes, R., Fuentes, M., Geer, A., Haimberger, L., Healy, S., Hogan, R. J., Hólm, E., Janisková, M., Keeley, S., Laloyaux, P., Lopez, P., Lupu, C., Radnoti, G., de Rosnay, P., Rozum, I., Vamborg, F., Villaume, S., Thépaut, J.-N., 2020. The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, 146(730), pp. 1999-2049.

Nordam, T., Beegle-Krause, C. J., Skancke, J., Nepstad, R., & Reed, M., 2019. Improving oil spill trajectory modeling in the Arctic. *Marine Pollution Bulletin*, 140, pp. 86–102.

National Oceanic and Atmospheric Administration (NOAA), 2023a. *GNOME User Manual. National*. Oceanic and Atmospheric Administration (NOAA) Technical Report.

National Oceanic and Atmospheric Administration (NOAA), 2023b. *ADIOS Oil Database: A Comprehensive Oil Property Database for Environmental Response*. NOAA Office of Response and Restoration. Available at: https://response.restoration.noaa.gov/adios

Oyama, M., Konno, A., Matsuzawa, T., 2025. An investigation into oil spill dynamics affected by floe-like obstacles with various distributions. *Polar Science*, 43, 101168.

Reed, M., Johansen, Ø., Brandvik, P. J., Daling, P., Lewis, A., Fiocco, R., Mackay, D., & Prentki, R., 1999. Oil spill modeling and response technologies. *Marine Pollution Bulletin*, 38(2), pp. 191–208.

Sakov, P., Counillon, F., Bertino, L., Lisæter, K. A., Oke, P. R., and Korablev, A., 2012. TOPAZ4: an ocean-sea ice data assimilation system for the North Atlantic and Arctic, Ocean Sci., 8, pp. 633–656.

Venkatesh, S., El-Tahan, H., Comfort, G., & Abdelnour, R., 1990. Modelling the behavior of oil spills in ice-infested waters. *Atmosphere-Ocean*, 28(3), pp. 303–329.