Predicting the Fate of Oil Spills Trapped in Arctic Sea Ice
A Beaufort Sea case study using ensemble sea-ice simulations

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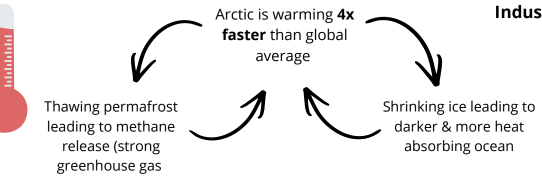
LPHYS2268
Forecast, prediction and projection
in climate science

1. Why does Arctic oil spill prediction matter ?


Arctic is warming **4x faster** than global average

Shrinking ice leading to darker & more heat absorbing ocean

Thawing permafrost leading to methane release (strong greenhouse gas

Industrial opportunities... and risks !

Melting ice opens new shipping routes (Figure 1) and accessible oil reserves

Greater industrial activity **= higher spill risk !**

Oil trapped in ice = transported over hundreds of km before release

Release location often **remote & inaccessible** for ecosystems → catastrophic

Figure 1: Main trans-Arctic shipping corridors.

2. Objective

Estimating a forecast distribution of possible oil fate, with the aim to answer :
Where could oil trapped in Beaufort Sea ice go, and what does this imply for Arctic spill-response policies?

3. Methodology

1. Initialisation: 100 oil beads released at grid cell [130, 130] (Beaufort Sea, ~75°N 160°W) on day 172 (November 20), distributed homogenously in the grid cell

2. Velocity interpolation: beads velocities estimated through Inverse Distance Interpolation (IDW) of grid cells sea ice velocities (2x2 nearest neighbours) for each daily time steps (= simplified dynamical transport model)

3. Advection: beads moved forward by one day (86,400 s), with beads velocities (m/s) converted to beads displacement (m) assuming uniform grid resolution (25 km)

4. Melt-out criterion: if sea ice concentration of the grid cell containing the bead is lower than 0.15 (=15%), bead is considered "melted-out" (= released in water)

5. Strand criterion: if sea ice concentration of the neighbour of the grid cell containing the bead is NA (=land), bead is considered "stranded" (= released on land)

6. Iteration: steps 2–5 repeated daily until all beads have melted out or stranded or the end of the simulation period has been reached (May 31, after 193 days)

6. Ensemble approach: simulation performed independently on 10 ensemble members, using NEMO-SI3 model initialized on June 1 2024 (sea ice dynamics), forced with ERA5 atmospheric circulation data (2014 for Member 1 to 2023 for member 10)

Conversion of continuous trajectories into event-based forecast

4. Results

4.1 Seasonal evolution of sea-ice concentration

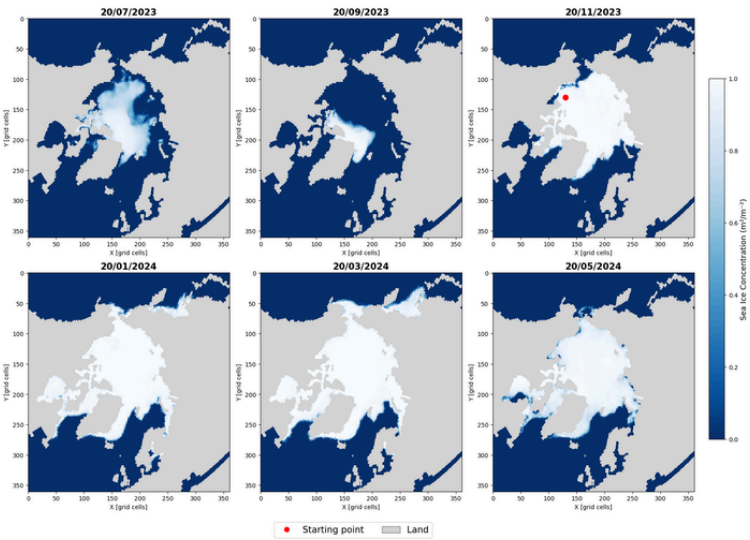


Figure 2: Sea ice concentration evolution for the simulation member 10 (2023-2024 atmospheric circulation forcing).

Sea-ice concentration strongly increases between late summer and November, indicating rapid autumn freeze-up in the Beaufort Sea. From November to May, melting remains limited, with stronger melt expected mainly after the end of the simulation period. These boundary conditions control available predictability window :

- It supports the choice of 20 November as the release date, avoiding immediate melt-out of the oil beads.
- Given the limited melt before 31 May, oil released in late November is expected to remain trapped in sea ice for most of the simulation period.

4.2 Oil beads trajectories

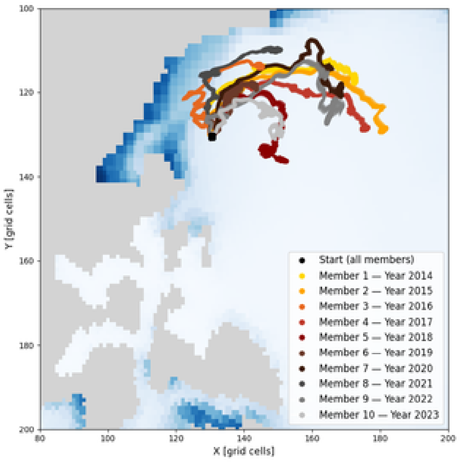


Figure 4: Oil beads trajectories for all simulation members (2014-2015 to 2023-2024 atmospheric circulation forcings). The background represents the sea ice concentration on May 31 (last day of simulation) : dark blue = 0 m^2/m^2, white = 1 m^2/m^2.

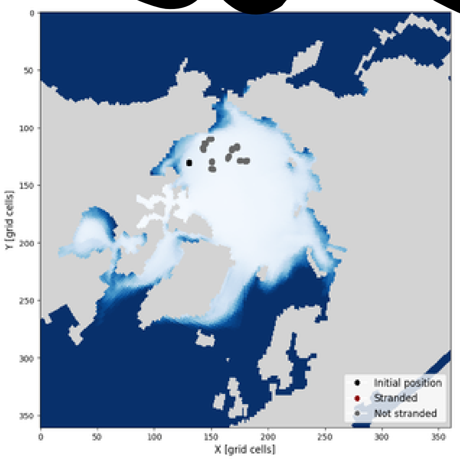


Figure 5: Oil beads final positions for all simulation members (2014-2015 to 2023-2024 atmospheric circulation forcings). The background represents the sea ice concentration on May 31 (last day of simulation) : dark blue = 0 m^2/m^2, white = 1 m^2/m^2.

Across the 10 ensemble members, none of the 100 oil beads reached the coast or melted out before the end of the simulation period (Figures 4 and 5). Instead, the trajectories followed a dominant northwestward pathway, suggesting a highly probable initial transport direction from the selected release location.

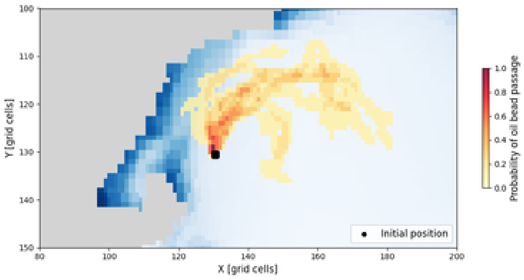


Figure 6: Oil beads probability density map for all simulation members (2014-2015 to 2023-2024 atmospheric circulation forcings) combined. The background represents the sea ice concentration on May 31 (last day of simulation) : dark blue = 0 m^2/m^2, white = 1 m^2/m^2.

However, the ensemble progressively spread and the probability density fell, leading to a broad area of potential oil presence by 31 May. This highlights the importance of ensemble simulations for representing uncertainty in oil spill forecasting.

A striking feature of the simulated trajectories is their circular pattern. Although the pathways diverge, most beads appear to rotate around a central region. This suggests that oil transport is strongly influenced by a large-scale circulation mechanism: the Beaufort Gyre.

4.3 Beaufort Sea's Gyre

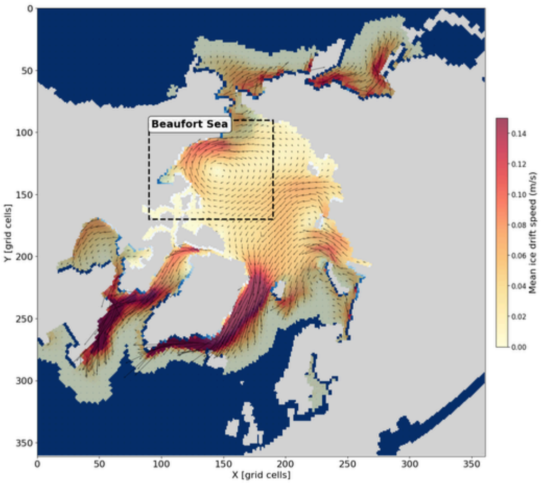


Figure 7: Mean sea ice velocity of each day from November 20 to May 31 2024 of each simulation members (2014-2015 to 2023-2024 atmospheric circulation forcings).

Mean sea-ice velocity fields calculated from 20 November to 31 May reveal strong circulation patterns in the Beaufort Sea (Figure 7). These patterns explain the circular oil bead trajectories observed in the simulations. The region is influenced by the Beaufort Gyre, a large-scale circulation system that transports both ocean water and sea ice.

Although this circulation may suggest predictable oil pathways, the Beaufort Gyre varies from year to year in strength, centre position and sometimes even rotation direction. This variability explains why some ensemble members show tighter circular trajectories, while others transport oil over a broader area.

Sea-ice velocity also varies strongly in space: the gyre centre is almost stationary, whereas the coastal side shows the fastest ice motion. Therefore, a spill occurring at a slightly different location or date could follow a very different pathway. Depending on the prevailing ice and ocean conditions, oil may remain trapped in sea ice, melt out, strand near the coast, or diverge toward another region.

The Beaufort Gyre acts thus as a source of internal variability, increasing uncertainty depending on the chosen initial conditions (start date and location).

4.4 Spill location sensitivity of the trajectories

A sensitivity test on the initial conditions (starting location) has been done by repeating the calculations for six release locations representing major Beaufort Sea shipping corridors: the original location [130,130], one shared Beaufort Sea route, two coastal-route locations, and two Beaufort Gyre route locations (Figure 8).

The results show that oil trajectories and final fate strongly depend on the initial release location (Figure 9). Spills released along the Beaufort Gyre route mostly remained trapped in sea ice until 31 May, whereas coastal-route spills showed more diverse outcomes, including stranding, melt-out, or continued trapping in sea ice.

Differences between ensemble members highlight the key role of Beaufort Gyre-induced internal variability. Changes in gyre strength, centre position and rotation can strongly modify oil transport pathways. As a result, two spills occurring only a few grid cells apart may lead to very different environmental risks.

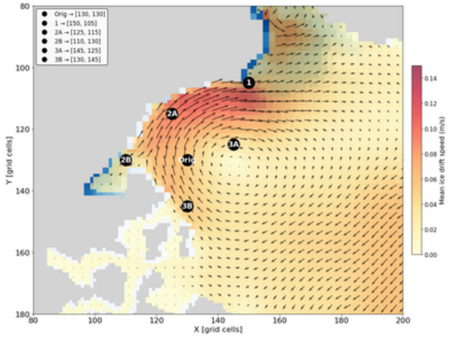


Figure 8: Mean sea ice velocity of each day from November 20 to May 31 2024 of each simulation members (2014-2015 to 2023-2024 atmospheric circulation forcings) in the Beafort Sea, with six tested oil spill starting points marked by black dots.

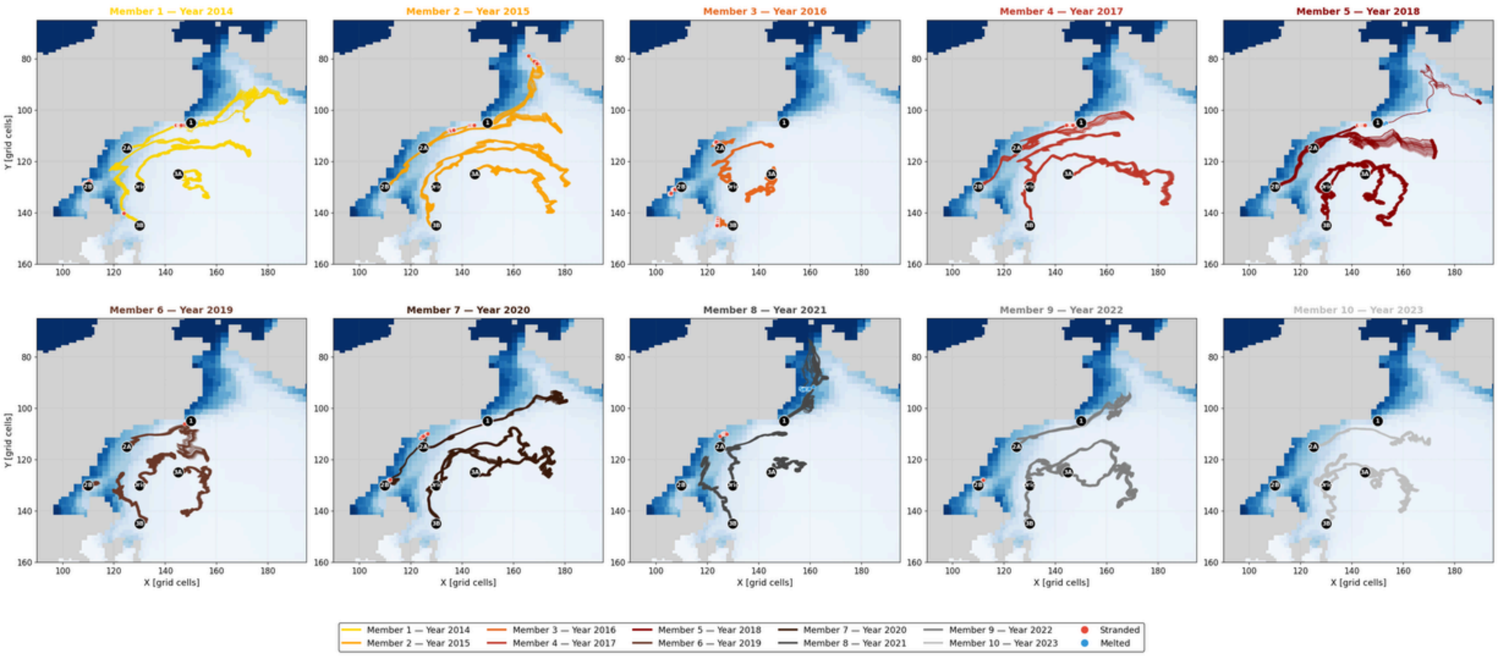


Figure 9: Oil beads trajectories for all simulation members (2014-2015 to 2023-2024 atmospheric circulation forcings) considering the initial oil spill location (Orig, [130,130]), one oil spill location on the common Beaufort route (1, [150,105]), two oil spill locations across the Beaufort coastal route (2A and 2B, [125,115] and [110,130]) and two oil spill locations across the Beaufort gyre route (3A and 3B, [145,125] and [130,145]) . The background represents the sea ice concentration on May 31 (last day of simulation) : dark blue = 0 m^2/m^2, white = 1 m^2/m^2.

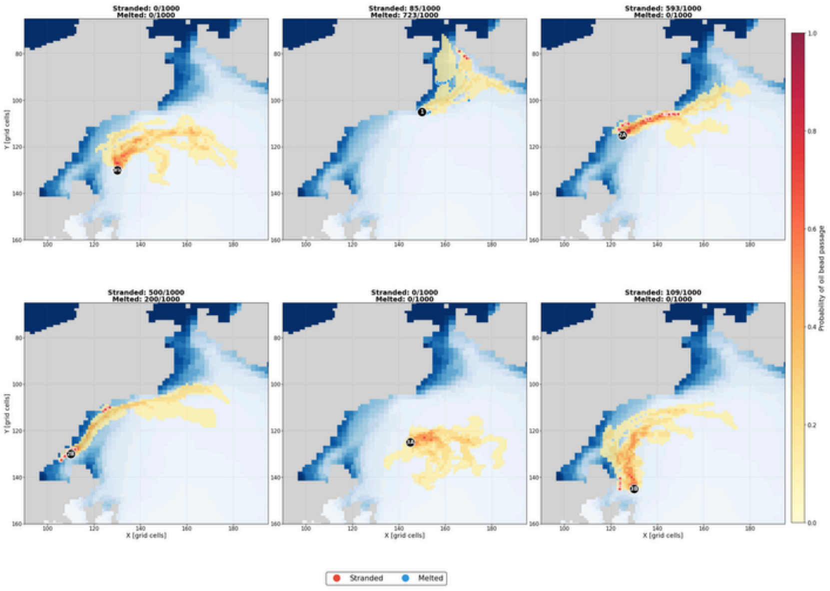


Figure 10: Oil beads probability density map for all simulation members (2014-2015 to 2023-2024 atmospheric circulation forcings) combined considering the initial oil spill location (Orig, [130,130]), one oil spill location on the common Beaufort route (1, [150,105]), two oil spill locations across the Beaufort coastal route (2A and 2B, [125,115] and [110,130]) and two oil spill locations across the Beaufort gyre route (3A and 3B, [145,125] and [130,145]) . The background represents the sea ice concentration on May 31 (last day of simulation) : dark blue = 0 m^2/m^2, white = 1 m^2/m^2.

6. Model assumptions and limitations

These results should be interpreted with caution. They are based on only 10 ensemble members and six selected release locations so, the probabilities should be interpreted as conditional on the modelling assumptions. Although the simulated patterns are relatively consistent across scenarios, more release dates and spill locations or boundary conditions (additional members) would be needed to better quantify the model uncertainty and improve the robustness of the probability estimates.

The model resolution is relatively coarse, with grid cells of 25 km × 25 km. Therefore, local coastal processes, small-scale currents and nearshore sea-ice dynamics are not fully resolved. In this study, oil is considered stranded when it reaches a grid cell adjacent to land. As a result, stranding should be interpreted as potential coastal risk rather than confirmed shoreline impact.

Finally, oil is represented as passive beads transported by sea ice. The model does not account for oil weathering, evaporation, biodegradation, dispersion or cleanup operations. The results therefore represent potential transport pathways, not a complete oil-spill impact assessment.

Probability density maps reveal contrasting levels of predictability depending on the release location (Figure 10). At the original location [130,130], oil follows a highly probable northwestward pathway, with passage probabilities close to 1 near the release point. A westward shift remains possible, but with low probability.

Spills released along the Beaufort Gyre route show similar behaviour, with dominant northward or westward transport depending on the release point. These trajectories remain relatively well defined, although occasional shifts toward land may occur with low probability.

Coastal-route spills show the highest stranding risk (Table 1). At location 2A, oil follows a predictable pathway and strands in 60% of the simulations, while melt-out is not observed. At location 2B, oil strands in 50% of the cases, either directly or after being entrained by the gyre farther away; about 20% of the oil also melts out.

In contrast, spills along the shared Beaufort Sea route are less predictable, with probability density rapidly decreasing along the pathway. However, melt-out is much more likely in this case than stranding.

Table 1: Percentage of oil beads still trapped in ice, stranded and melted out at the end of the simulation (May 31). Temporality of stranding and melting have been explored in the Appendix.

	Orig	**1**	**2A**	**2B**	**3A**	**3B**
Ice	100%	19%	41%	30%	100%	89%
Stranded	0%	9%	59%	50%	0%	11%
Melted	0%	72%	0%	20%	0%	0%

5. Support for policymakers

The simulated oil spill scenarios show that the oil's fate strongly depends on the initial release location along Beaufort Sea shipping corridors. This spatial variability has important implications on risk-based decisions : spill prevention, monitoring and emergency response planning.

Considering the ecological, economic and human risks, near-coastal routes appear to be the most sensitive areas. Oil released along coastal routes is more likely to strand, potentially threatening fragile Arctic ecosystems and Indigenous coastal communities (Beyer et al. 2016, Surprenand et al. 2020). In contrast, spills occurring farther offshore, especially along the Beaufort Gyre route, tend to remain trapped in sea ice until 31 May in our simulations, suggesting a lower short-term coastal risk. Also, nearshore and coastal interventions have been found to cost four to five times more than off-shore interventions (Cao Thi Thu Trang, 2006)

However, offshore spills should not be considered safe. Trajectory predictability decreases rapidly with time, meaning that oil may become difficult to locate and recover if response actions are delayed. Therefore, rapid early tracking, continuous monitoring and pre-positioned response capacity are essential after any spill.

Overall, our results suggest that Arctic spill-response policies should prioritize stricter prevention and monitoring along near-coastal shipping corridors, while maintaining rapid-response capacity for offshore spills transported by sea ice.

Bibliography

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- Suprenand, P. M., Hoover, C., Ainsworth, C. H., Dornberger, L. N., & Johnson, C. J. (2020). Preparing for the inevitable: Ecological and indigenous community impacts of oil spill-related mortality in the United States' Arctic marine ecosystem. In Arctic Marine Sustainability (pp. 27). Springer. https://doi.org/10.1007/978-3-030-12963-7_27

7. Take-home message

Oil spill fate in the Beaufort Sea strongly depends on the release location. Coastal spills show the highest stranding risk, while offshore spills influenced by the Beaufort Gyre tend to remain trapped in sea ice for longer. However, trajectory predictability decreases with time, making rapid early tracking essential for spill-response planning.

8. Annexes

8.1 Python codes

The codes for this forecasting work are available with this link :
https://deepnote.com/workspace/LPHYS2268-Project-4969d03a-ca17-4c17-9287-c76f1d0115e2/project/Oil-spill-trajectory-forecasting-117e48d8-3565-4e7e-a128-f6e8d596f419/notebook/Main-6e2e5e9d6e474c719fd332ca6a9389e2?utm_source=share-modal&utm_medium=product-shared-content&utm_campaign=notebook&utm_content=117e48d8-3565-4e7e-a128-f6e8d596f419

8.2 Stranding & melting temporalities

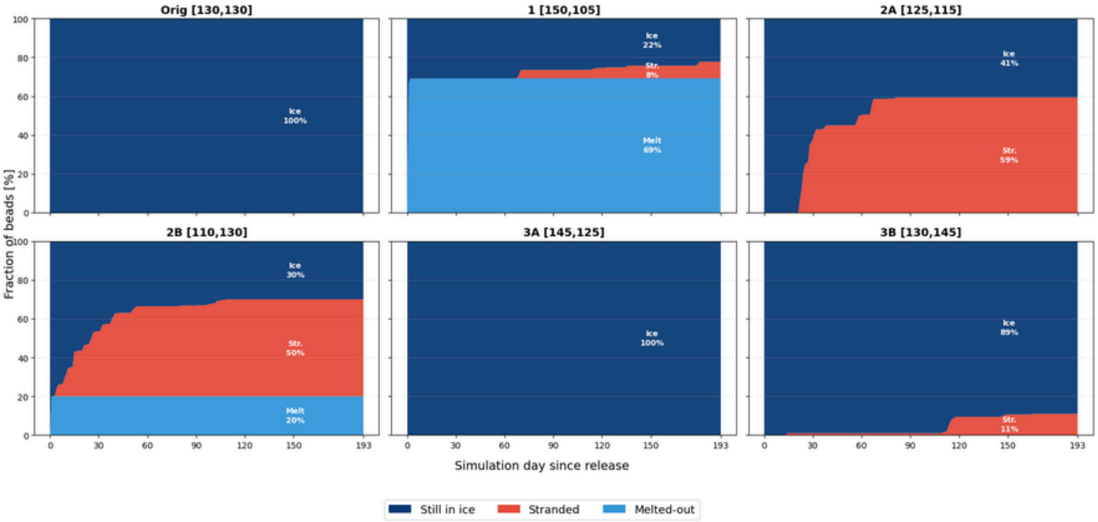

Figure 11: Temporal evolution of simulated oil fate for the six release locations. Colored areas represent the percentage of beads still trapped in sea ice, stranded on land, or melted out, aggregated over the 10 ensemble members.

The time evolution of simulated oil fate highlights rapid stranding of oil released along the Beaufort coastal route, contrasting with low melt-out occurrence.

For release point 2A, the first oil beads strand after about one month, while stranding occurs almost immediately for release point 2B. After two months, more than 50% of the simulated beads have stranded for both coastal release points. So, the probability for oil to strand increases rapidly when the spill occurs on the coastal route.

Across the Beaufort Gyre route, shoreline impact remains limited, with most beads staying trapped in sea ice until the end of the simulation (probability of oil stranding of 0.1 maximum).

Melt-out appears to either occur shortly after release or not occur at all during the simulation period. The probability for it to happen ranges from 0 to 0.7 depending on the spill location.