UCLouvain

PREDICTION OF OIL SPILL TRAJECTORIES IN THE ARCTIC

LPHYS2268 - FORECAST, PREDICTION AND PROJECTION IN CLIMATE SCIENCE

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ABSTRACT

Due to the rapid decline in Arctic sea-ice cover, the Arctic is becoming a strategic region for maritime routes. This transformation raises important environmental and socio-economic concerns, particularly regarding the risk of oil spills in this remote and fragile region. This study aims to predict the areas most likely to be affected by oil dispersion by modelling the trajectories of oil beads released from a specific spillage location. The prediction is based on sea-ice concentration and velocity from ten different years, from 2014 to 2024, providing 10 possible trajectories.

CONTEXT

The Arctic is one of the regions most affected by climate change because of the rapid decline of its sea-ice cover. From an environmental perspective, this is a major concern because polar ecosystems are fragile, slow to recover, and remote [1], [2].

Meanwhile, decreasing sea-ice cover is increasing the socio-economic and geopolitical importance of the Arctic. New opportunities are emerging for shipping, resource exploration, fishing and tourism. Arctic maritime routes are particularly attractive because they can shorten travel time between Europe and Asia [3].

However, expanding human activities also increase the risk of oil spills in these remote regions where response operations are difficult. Past accidents in polar environments, such as the Norilsk diesel spill in Arctic Russia, show how challenging oil-spill responses can be in these conditions [4]. Therefore, developing forecasting tools to estimate oil spreads in sea-ice environments is essential to prepare containment strategies and guide decision-makers.

METHODOLOGY

100 oil particles are released on November 20th from a specific position, situated at the Fram Strait, between Greenland and the Spitsberg, where the sea ice is transitioning from the North to the South [9]. The starting location is [x,y] = [180,200] on the EASE-Grid covering the Arctic.
The estimated trajectories of the particles are simulated using NEMO4.2-SI3, an ocean-sea ice model forced with the ERA5 atmospheric conditions (or forcing) from 2014 until 2023, giving ten ensemble members.

Two groups of files were provided:

- The sea ice concentration, *siconc_(..).nc*
- The sea ice velocity is divided into two components, component u and v of the velocity: *sivelv_(...).nc* and *sivelu_(...).nc* respectively.

The paths of the oil particles were displayed on a grid, the EASE-Grid, an equal area grid which is necessary to do the Lagrangian tracking of each particle through time. The grid shape is [361,361] with each grid cell measuring 25km x 25km. The grid was imported with the file named *EASEGRID_x_y_lat_lon.nc.*
Then, inverse distance weighting was used to interpolate the sea ice velocity.

A threshold value of 15% was set for the sea ice concentration. If sea ice concentration is above 15%, then the particle is considered embedded in the ice and moves with it. If the sea ice concentration is under 15%, the ice containing the particle is considered melted and the oil is released in the water. On the trajectory maps, the concentration of sea-ice represented is the sea-ice concentration from the first day of the oil spill.

The simulation for each ensemble member continues until all the 100 oil particles are considered "melted" meaning all the oil is released into the water. In some cases, the particles were not all "melted" after 31 of Mai, the simulation was then extended until all the particles were released into the water. It provides the supposed final destination of the oil. This extended part is represented in yellow on the trajectory maps.

HYPOTHESES

- When the sea ice concentration at the position of a particle goes under the 15% threshold, the particle is considered "melted" and stops moving on the graphs.
- When a particle leaves the geographical limits or the Arctic domain, it is considered "melted" and the simulation of its trajectory stops.
- Particles are only moving with the sea ice velocities, u and v.
- The velocities u and v are considered constant during an entire day, intra-day variations are not considered

LIMITATIONS

- Only 10 ensemble members were used for the analysis, which represents a limited ensemble size. Extreme climatic events could be then underrepresented.
- Since the study is based on a hypothetical oil-spill scenario, no observational data from a comparable event are available. It is therefore not possible to directly compare the forecast with observed reality. Thus, the verification of the forecast is limited to assessing the physical coherence and plausibility of the simulated trajectories.

VERIFICATION

The directions of the currents in the Arctic were verified and coincide with the results obtained for the trajectory of the oil beads.

Sea-ice is circulating from the North to the South and passes in the Fram Strait, along Greenland, going from the Arctic Ocean to the Atlantique Ocean.

The oil particles' trajectories are following the same path, confirming the physical coherence of the simulations.

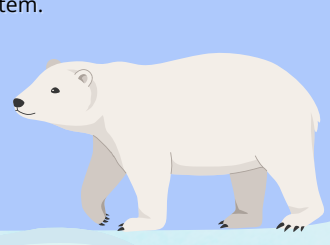
CONCLUSION

The decline of Arctic sea-ice cover is expected to increase the accessibility of Arctic maritime routes, making the region attractive for shipping. By mid-century, European routes to Asia would become around 10 days faster via the Arctic than through conventional alternatives [3]. This growing accessibility may increase the risk of accidental pollutant releases, particularly in ice-covered waters where navigation remains dangerous. Statistics show that, in the 2020s, 43 tanker spills have been recorded, releasing 42 000 tonnes of oil, with most spills historically caused by collisions, allisions and groundings [8].

These simulations draw an area of high sensitivity for potential oil releases near the simulations' starting point. The model indicates that the areas most likely to be affected are the east coast of Greenland and the pathway towards the Denmark Strait. This result is coherent due to the southward sea-ice drift along Greenland. Also, it underscores the need for monitoring and preparedness for future accidents.

Oil-spill response in polar environments is challenging due to remoteness, sea-ice and low temperatures. Coastal ecosystems, Arctic fauna and local communities, including Indigenous populations relying on marine resources and subsistence fishing, could be strongly affected. Past incidents such as the Norilsk diesel spill show that clean-up in Arctic conditions can be very costly and may take several years [1].

Therefore, methods to tackle oil spills in the Arctic must include stricter navigation rules, emergency planning, local response capacity and probabilistic forecasting tools. However, prevention remains the major priority: limiting global warming is essential to reduce the rapid changes of the Arctic and its negative impacts on ecosystems, communities and the global climate regulation system.



RESULTS

OIL TRAJECTORY MAPS

These graphs represent the trajectory for each ensemble member of the oil beads released on November 20th and tracked until 31 May, or slightly longer when some particles had not yet left the ice-covered area (represented by yellow). The ensemble members are ordered from the most recent to the oldest forcing years: E1 = 2023–2024 and E10 = 2014–2015. November being early winter, the ice has the capacity to trap the oil particles. This allows the model to represent an entire season cycle of ice dynamics, going from freezing to melting in spring [6].

Arctic Ocean Currents Map [5]

Observations:

- For each trajectory map, there is dominant southward transport along the eastern coast of Greenland, towards the Denmark Strait. It is coherent with the regional sea-ice circulation caused by the East Greenland Current, which transports Arctic sea ice through the Fram Strait [7].
- Path irregularities are detected between different ensemble members, especially near Denmark Strait. It can be due to mesoscale variability (e.g. eddies, meandering currents) [7].
- Even though the oil beads are spilt with a small initial position variation, they stay clustered and move in the same general direction.

PROBABILISTIC OIL TRAJECTORY FORECAST

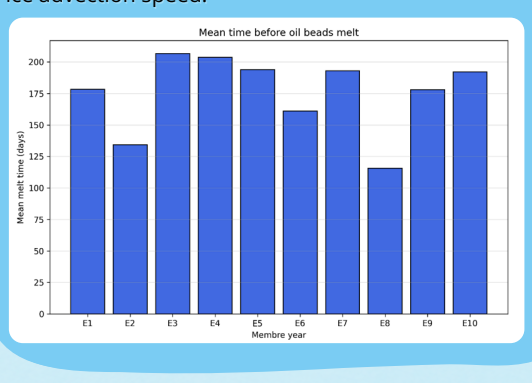
The probabilistic forecast highlights the areas where oil beads are most likely to be found by adding up all the ensemble members' trajectories. The highest probabilities occur along the eastern Greenland coast and towards the Denmark Strait. This information is useful for identifying priority zones for monitoring, preparedness, and containment strategies.

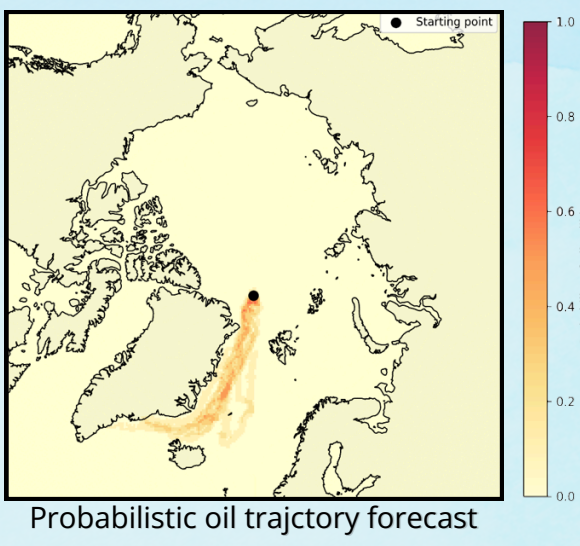
MEAN TRAVEL DISTANCE OF THE 100 OIL BEADS PER ENSEMBLE MEMBER

The mean travelled distance varies from 1 900 km in E7–E8 to more than 3 200 km in E10. However, distance and melt-out time are not proportional: E7 and E8 have similar travel distances but very different melt-out times. This implies there is a high interannual variability in sea-ice drift speed.

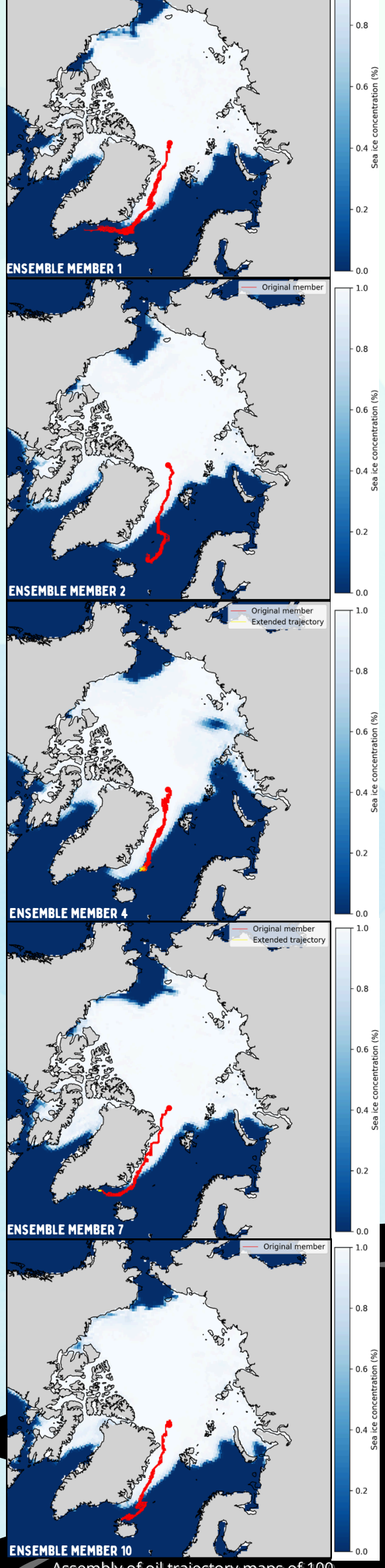
MEAN TRAVEL TIME OF THE 100 OIL BEADS PER ENSEMBLE MEMBER

The mean melt-out time ranges from 115 to more than 200 days, which shows a strong variability between ensemble members. This variability is not controlled by the total Arctic sea-ice extent because it doesn't describe spatial distribution or concentration of the ice. Therefore, different years with low Arctic sea-ice extent may have different melt-out times depending on local ice conditions, the East Greenland current, and sea-ice advection speed.





Probabilistic oil trajctory forecast



Assembly of oil trajectory maps of 100 oil beads starting from the same location for the ensemble members 1, 2, 4, 7, 10.

CHECK OUT !

TAKE A CLOSER LOOK

YOUTUBE VIDEO :
https://youtube.com/shorts/2fMJnV8S4vc?si=u88rAppfyskiKo5v
LINK TO CODE:
https://github.com/leachevalier/Oil_spill_code/blob/main/Notebook%204-2.ipynb
ACCESS TO DATA USED:
https://drive.google.com/drive/folders/1rwyM3zARN6kov7R601T7F0X4nWDbfe3j
REFERENCES:
https://drive.google.com/file/d/101aSurIJP4yn9HUx0hYp1ADzK1JxdFIn/view?usp=sharing