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Microplastic Pathways in the Arctic: Integrating the TELEMAC-3D Hydrodynamic Model with Advanced Ray Tracing Particle Tracking

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Abstract. Microplastic pollution in the Arctic represents a critical environmental challenge, driven by the region's intricate hydrodynamics and rapidly evolving climatic conditions. This study integrates high-resolution TELEMAC-3D, TOMAWAC, and CaMPSim-3D models to analyze source-receptor pathways and identify accumulation zones for microplastics. The modeling framework incorporates wind, wave dynamics, and other processes influencing particle transport. Hydrodynamic validation was conducted via a combination of in-situ and remote sensing datasets. Results highlight potential accumulation areas and underscore the necessity of accounting for diverse transport mechanisms to accurately predict microplastic movement and deposition in Arctic waters.

Keywords: TELEMAC · CaMPSim-3D · Modelling · Microplastics · Arctic

1 Introduction

Increasing microplastic pollution marine environments presents a significant ecological concern, driven by both local sources and long-range transport mechanisms. These particles, with characteristic diameters below 5 mm and greater than 1 μm, are capable of producing toxic effects in a wide variety of organisms, and are an important emerging contaminant [1]. While this trend is occurring throughout global waterbodies, the Arctic Ocean, as an environment already under stress from climate change and falling sea-ice concentrations, is both a uniquely vulnerable and highly complex site [2]. The Arctic's unique hydrodynamic, wave, and salinity conditions influence the dispersion and fate of microplastic particles, yet the processes governing their pathways remain insufficiently understood. And recent reviews have highlighted the importance of better understanding these transport pathways [3]. Particular emphasis has been placed on determining the relative impacts on transport from tidal currents, wind-driven currents, wave action, and buoyancy processes [4, 5]. This is particularly important in the Canadian arctic archipelago, where multiple ocean currents interface with complex shorelines, compounded by a limited amount of validation data.

While arctic microplastic concentrations have been measured in a number of recent investigations [2, 6], relatively few investigations have attempted to apply numerical

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modelling to develop a more comprehensive understanding of transport pathways, which has been repeatedly cited as a vital research area [5]. A global NEMO model [7] with a focus on the Fram Strait was used to understand the impact of Arctic sea ice microplastic concentrations, and identified concentration trend aligning with some observational data [6]. The impact of wave action has also been investigated in the surf zone, finding that it can be an important factor in transport [8].

To effectively understand microplastic source-receptor pathways, it is therefore important to account for these processes. This study aims to address these knowledge gaps by applying the TELEMAC-3D (hydrodynamic), TOMAWAC (spectral wave), and CaMPSim-3D [9, 10] particle tracking model (PTM). This combination of state-of-the-art tools provides a comprehensive approach to modeling microplastic transport by including a full range of processes. The integration of TELEMAC-3D with wave action and ray tracing particle tracking marks a methodological advancement in simulating microplastic dynamics in the unique arctic environment.

1.1 Grid and Study Area

An overview of the study area and model bathymetry is shown in Fig. 1. Stretching from the Beaufort Sea, through the Northwest Passage, through to Baffin Bay and Hudson Bay, the domain spans approximately 1 million square kilometers. The domain also includes a segment of the Mackenzie River starting in Inuvik. The large area covered in this investigation is necessary to capture the full range of tidal and large-scale currents, wind-driven flows, and river discharges that drive microplastic transport. The domain has been discretized in the horizontal plane using triangular elements with edge lengths ranging from 100 m and 2 km, comprising approximately ~250,000 nodes. The mesh was generated using OceanMesh2D [11], and the model utilizes bathymetry data from the ETOPO 2022 dataset [12].

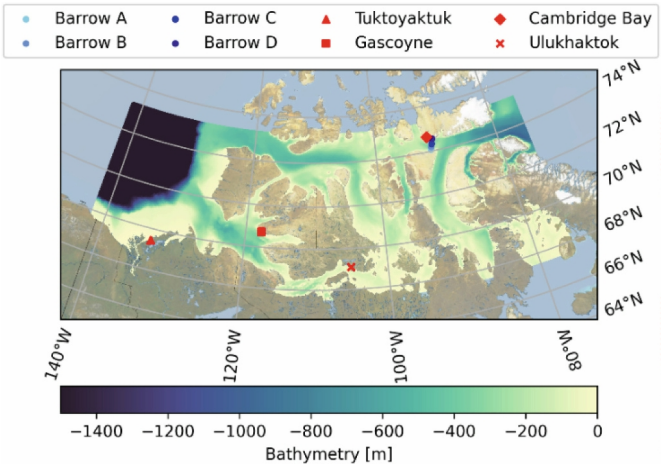

Fig. 1. Overview of model domain and bathymetry.

1.2 Numerical Setup

The hydrodynamic modelling of the study was conducted with the TELEMAC-3D 9p0 [13] suite, which employs a finite element approach on an unstructured mesh to solve Navier-Stokes equations. This widely applied [14] model is noted for its accuracy and excellent properties in high performance computing environments. The three-dimensional, hydrostatic implementation of the model was used with a k-ε turbulence closure model in conjunction with the TOMAWAC spectral wave model [13]. The mode boundary conditions for water levels and velocities were imposed using TPXO-10 tidal constituents [15] and spectral waves from ERA-5 [16], along with Mackenzie River discharges [17] and wind forcing derived from ERA-5 [16].

Particle tracking modelling was performed using CaMPSim-3D [9, 10], a high-performance particle tracking model for simulating various particle types, with a focus on microplastics, using a parallelized ray tracing algorithm that handles ray reflection and refraction to track particle locations across three-dimensional unstructured grids. CaMPSim-3D incorporates numerical corrections for round-off errors, water surface discontinuities, and includes partially reflective boundary conditions along with the ability to simulate microplastic beaching and washout in shallow or dry areas [10].

2 Results

The hydrodynamic and wave model validation was successfully performed using a combination of in-situ and remote sensing observations during two periods in September 2006 and 2018. Results showed that model is able to effectively simulate water levels, velocities, and significant wave heights across the domain, providing confidence in its application to understand particle transport processes. Water levels (Fig. 2) showed excellent agreement compared to in-situ observations at Tuktoyaktuk [18], Gascoyne [19], Cambridge Bay [19], and Ulukhaktok [18], with minor tidal phasing discrepancies at the Gascoyne station.

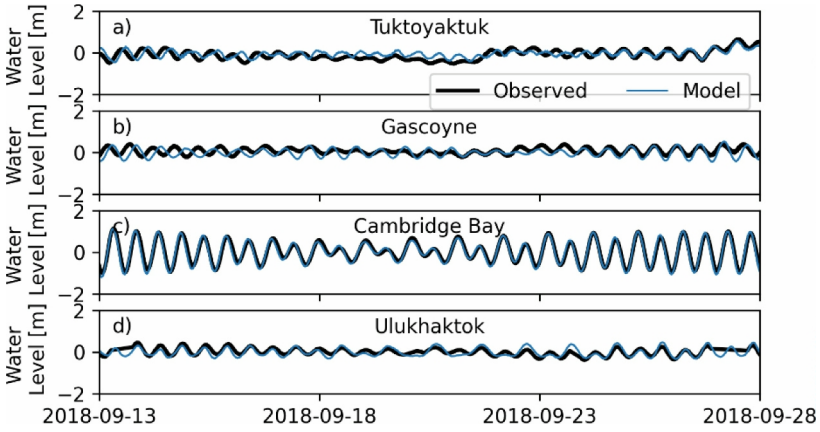

Fig. 2. Water level validation at four selected sites shown in Fig. 1.

Velocity validation (Fig. 3) was conducted by comparing modelled velocities against ADCP observations from the Barrow Strait in June to September 2006 [20]. Results show generally good agreement, with velocity magnitudes typically below 1 m/s, alignment in tidal phase timings, and a consistent vertical structure. Notably, the ADCPs at sites C and D (Fig. 3e, g) were not deployed to capture the full water column, limiting deep-water comparisons. At Site A (Fig. 3b), the vertical structure agreement was less accurate, indicating additional investigating may be required to fully quantify velocity patterns in this area.

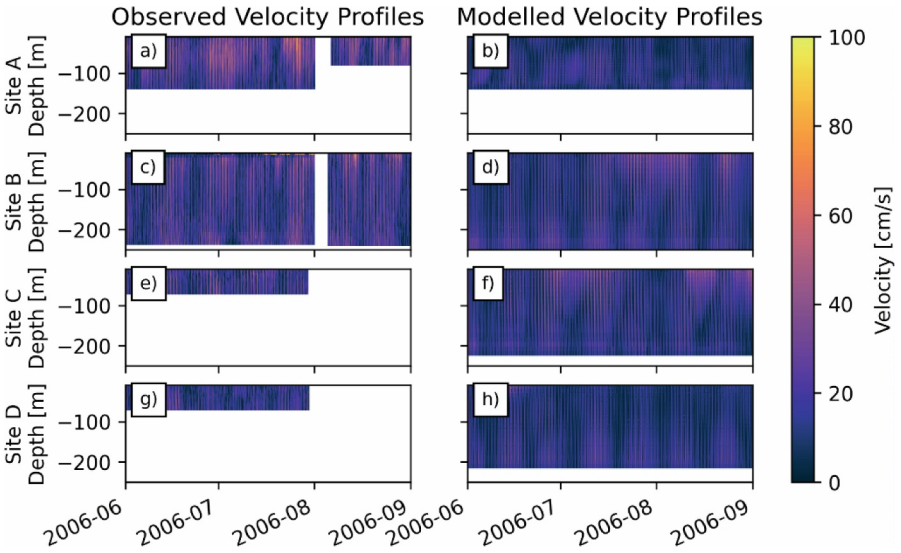

Fig. 3. Observed (a,c,e,g) and modelled (b,d,f,h) velocity at four Barrow Strait sites (Fig. 1).

Due to the lack of in-situ wave observation buoys in the modelling domain, significant wave height from satellite altimetry data of the Sentinel-3 mission [21] were used for wave model validation. This comparison (Fig. 4) was conducted during an ice-free period in the Amundsen Gulf, and showed broadly good agreement. Wave heights were comparable (~2 m), and the modelled trend of lower nearshore values was observed.

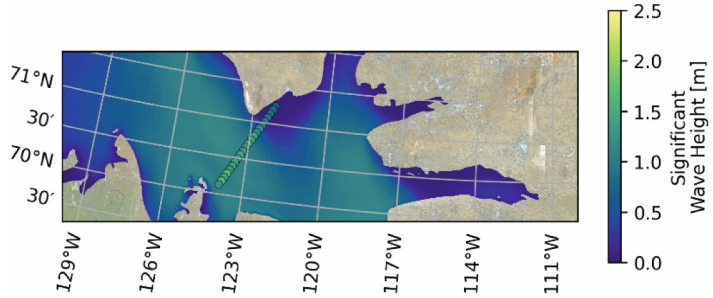

Fig. 4. Model and satellite (icons) significant wave heights on 2019-09-18, 19:49 UTC.

3 Particle Accumulation Patterns

To better understand microplastic source-receptor pathways in the Arctic, a series of three-week simulations were completed using the TELEMAC-3D model and CaMPSim-3D. All simulations started with a 1500 m uniform initial surface neutrally buoyant particle distribution (500,000-particles). Figure 5a shows the normalized concentration of particles [10] at the end of the simulation. Notably, accumulations were observed in several nearshore areas, including Admiralty Inlet and the Coronation Gulf. Differences were observed (Fig. 5b) between simulations with and without wave driven currents, slightly increasing shoreline accumulations and changing locations.

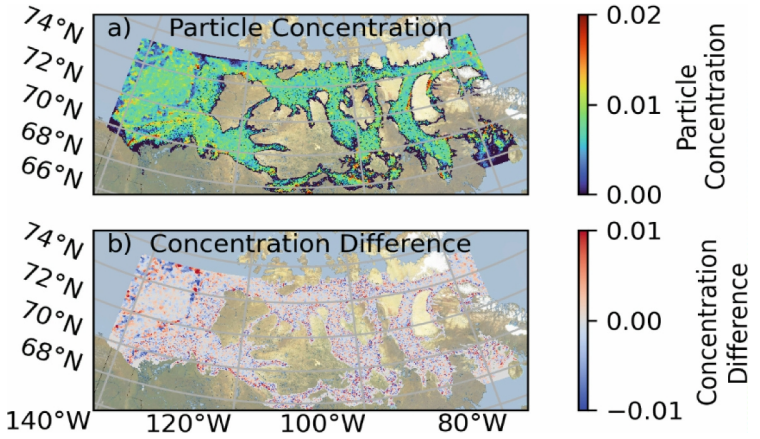

Fig. 5. a) Normalized particle concentration at the conclusion of a three-week simulation during September 2018. b) Difference in final normalized concentration with and without wave action.

4 Conclusions

The Arctic is a complex environment where the understanding the microplastic transport remains a critical challenge for effective response and monitoring programs. To address this, a high-resolution TELEMAC-3D (hydrodynamic), TOMAWAC (wave),

and CaMPSim-3D (PTM), models were applied in the Canadian Arctic. After validation, results showed that this approach provides a useful tool to identify potential particle accumulation zones, and also highlighted the importance of accounting for all relevant processes, including wind-driven currents, wave action, and salinity gradients.

Future work should focus on including the impacts of ice cover, as well as the processes of particle settling and resuspension, which are essential for capturing vertical transport dynamics. Long-term simulations will be also provide valuable information for assessing seasonal and interannual variability, while expanding observational datasets, particularly near Arctic communities, will improve model calibration and support informed decision-making for plastic pollution mitigation.

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