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Revealing Arctic Sea Ice Dynamics Under Cyclones via Simulation

Mina Bahadori, Minki Kim, Daniel M. Watkins, Monica M. Wilhelmus
Center for Fluid Mechanics, School of Engineering, Brown University, RI, USA

Overview

This study investigates the effects of Arctic cyclones on the motion of sea ice floes through simulations and reanalysis datasets. We employed an idealized vortex model for the wind velocity field. By adopting force equilibrium conditions for sea ice, wind, and ocean, we estimated the upper ocean velocity fields from the wind velocity field. Numerical simulations of sea ice projected onto the wind and ocean velocity fields were conducted using a discrete element sea ice model, Subzero, to examine sea ice trajectories under cyclones for different sea ice-wind turning angles. This study provides insights into how cyclones influence sea ice motion and ocean dynamics, and their potential contribution to sea ice melting.

Introduction & Objective

The Arctic is entering a new era characterized by thinner ice, decreased ice extent, and changing weather. Even during extreme events, such as Arctic cyclones, these dynamics exhibit significant variations. Such variations will induce notable changes in sea ice dynamics, including sea ice motion, transport, and distribution, resulting in new trends in sea ice melting. Specifically, summer cyclones can accelerate ice melt by breaking and churning the ice through strong winds and pulling warm waters upward. As a result, there is a pressing need for a more detailed investigation of Arctic cyclones to better predict their impact on sea ice.

The objective of this study is to investigate the relationship between cyclones, sea ice floes, and the upper ocean using numerical simulations and wind reanalysis datasets, and to quantify the changes in the motion of ice floes caused by cyclones.

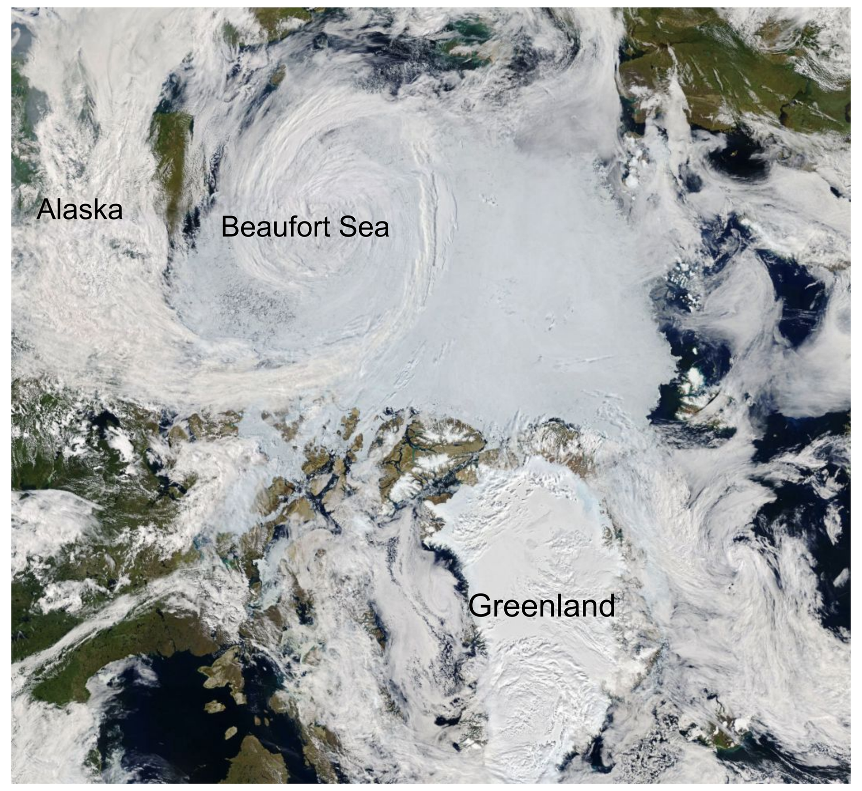

Figure 1. Arctic Cyclone
(MODIS July 28, 2020 Beaufort Gyre)

Methodology

- Sea ice Discrete Element Model (SubZero Model)

Force
$$M_{ice}\left(\underbrace{\frac{d\mathbf{u}_{ice}}{dt}}_{\text{Sea ice acceleration}} + \underbrace{f\mathbf{k}\times\mathbf{u}_{ice}}_{\text{Coriolis effect}}\right) = \iint_A \left(\underbrace{\tau_{ocn}}_{\text{Ocean stress}} + \underbrace{\tau_{wind}}_{\text{Wind stress}} - \underbrace{\rho_{ice}h_{ice}g\nabla\eta}_{\text{Sea surface height tilt}}\right) dA_{ice}$$

Torque
$$I_{ice}\frac{d\Omega_{ice}}{dt} = \iint_A (\mathbf{r}-\mathbf{r}_{ice})(\tau_{ocn} + \tau_{wind} - \rho_{ice}h_{ice}g\nabla\eta)\, dA_{ice}$$

- τ_{ocn} = shear stress between ocean & ice
- τ_{ocn} = shear stress between wind & ice
- ρ_{ice} = ice density
- h_{ice} = ice thickness
- η = sea surface height

- Using the analytical approach developed by Park and Stewart (2016), we estimated surface ocean fields from an idealized Rankine vortex wind field for various wind-sea ice turning angles.

$$k_o^2\left|\mathbf{u}_{io}^*\right|^4 + 2k_o\left|\mathbf{u}_{io}^*\right|^3 + \left(1+(\alpha+1)^2\right)\left|\mathbf{u}_{io}^*\right|^2 = k_a^2\left|\mathbf{u}_{ai}^*\right|^4$$

$$\alpha = \sqrt{2K_0^*/C_{io}},\ k_a = \rho_a\sqrt{2K_0^*}/\rho_i h_i f,\ k_o = \rho_o\sqrt{2K_0^*}/\rho_i h_i f$$

- $u_{io}*$ = ice–ocean stress velocity
- $u_{ai}*$ = ice–ocean stress velocity
- K_o = the vertical eddy diffusivity

Results and Discussions

- For different sea ice-wind turning angles, we estimated the surface ocean field from the wind and sea ice fields.
- The wind and sea ice are not well aligned due to sea ice inertia and the influence of the ocean beneath the sea ice.

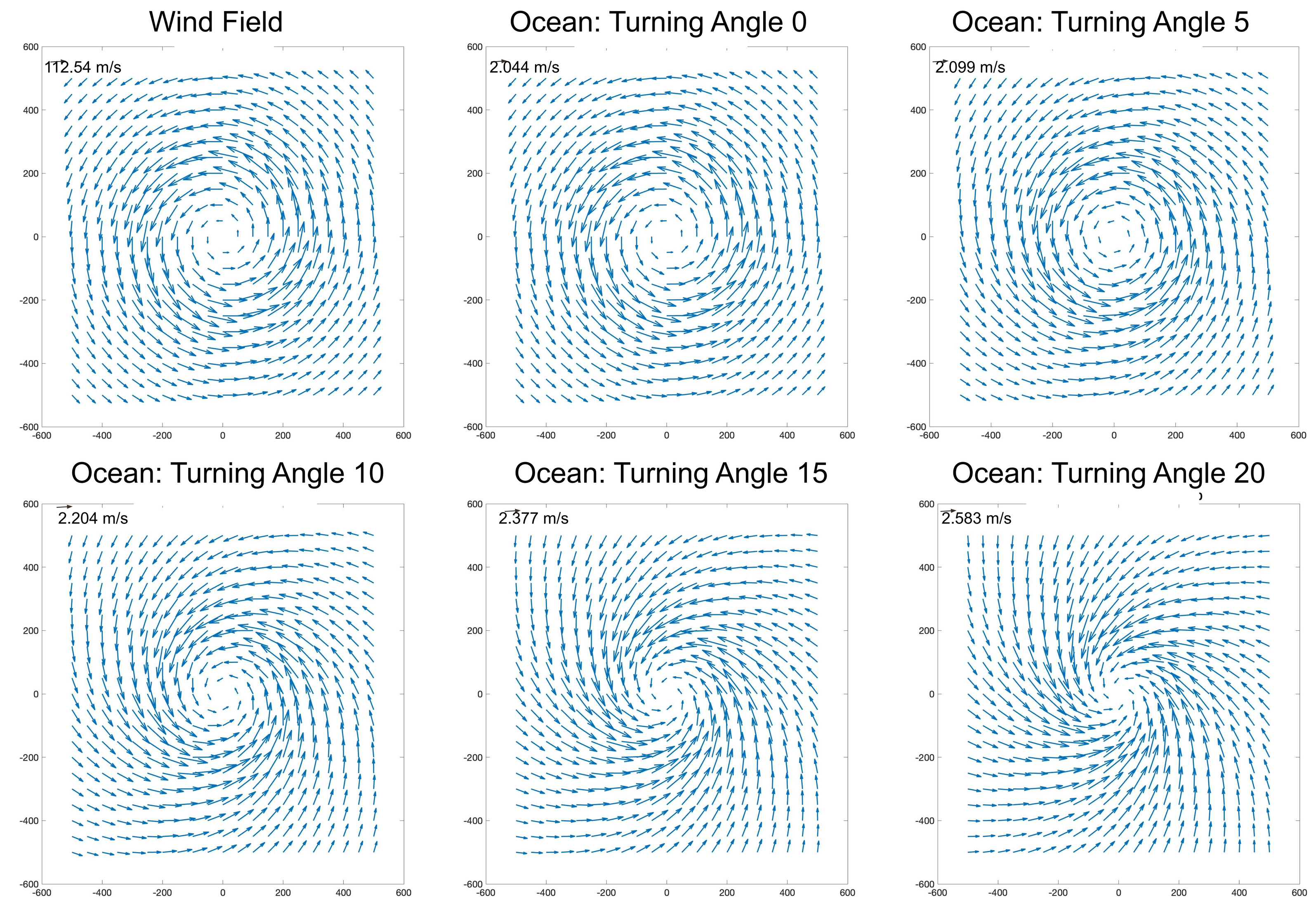

Figure 2. Wind field and ocean fields with sea ice-wind turning angles of 0-20 degrees.

- Ice floes released from the same location exhibited different trajectories for various sea ice-wind turning angles under the same wind field.

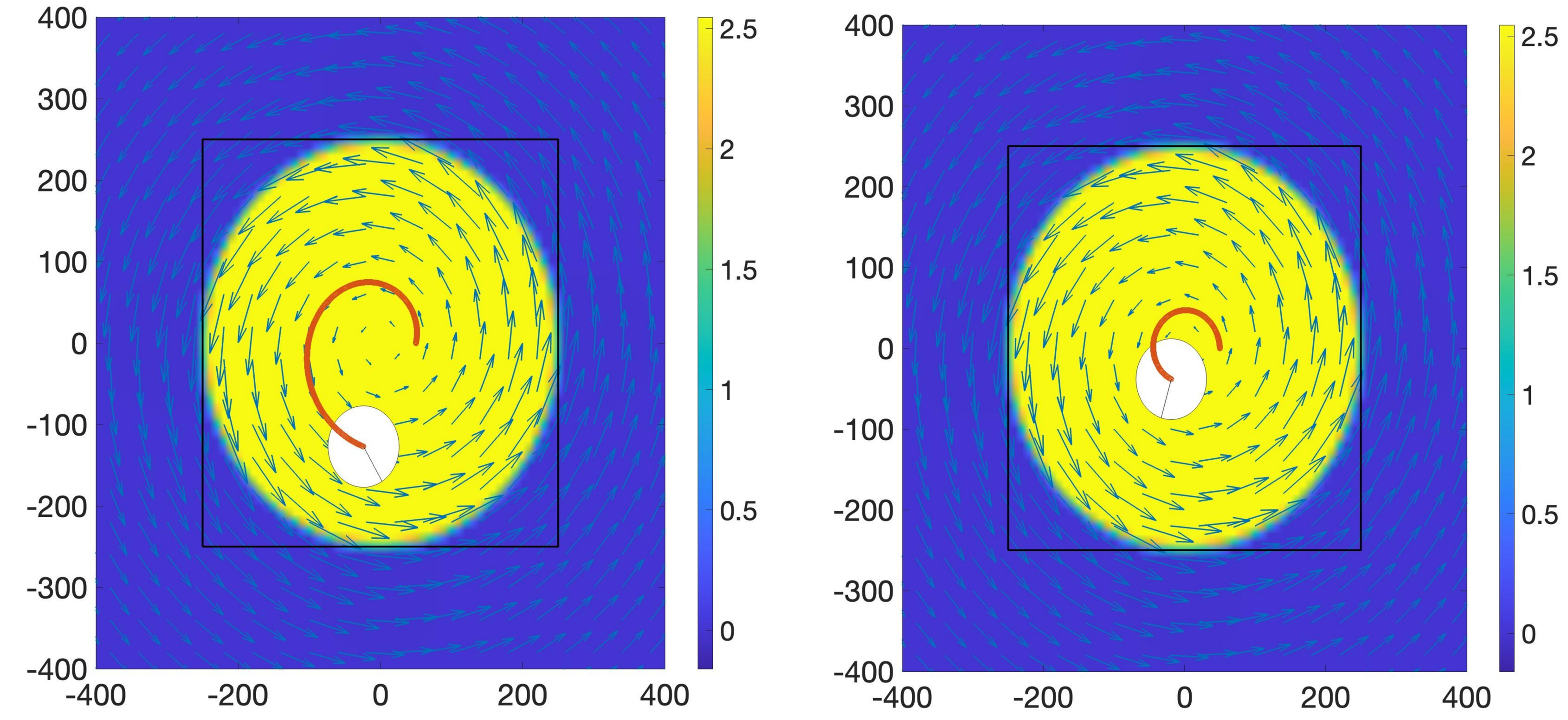

Figure 3. Ice floe trajectory for 50 km floe with a sea ice-wind turning angle of 0 (left) and 10 (right)

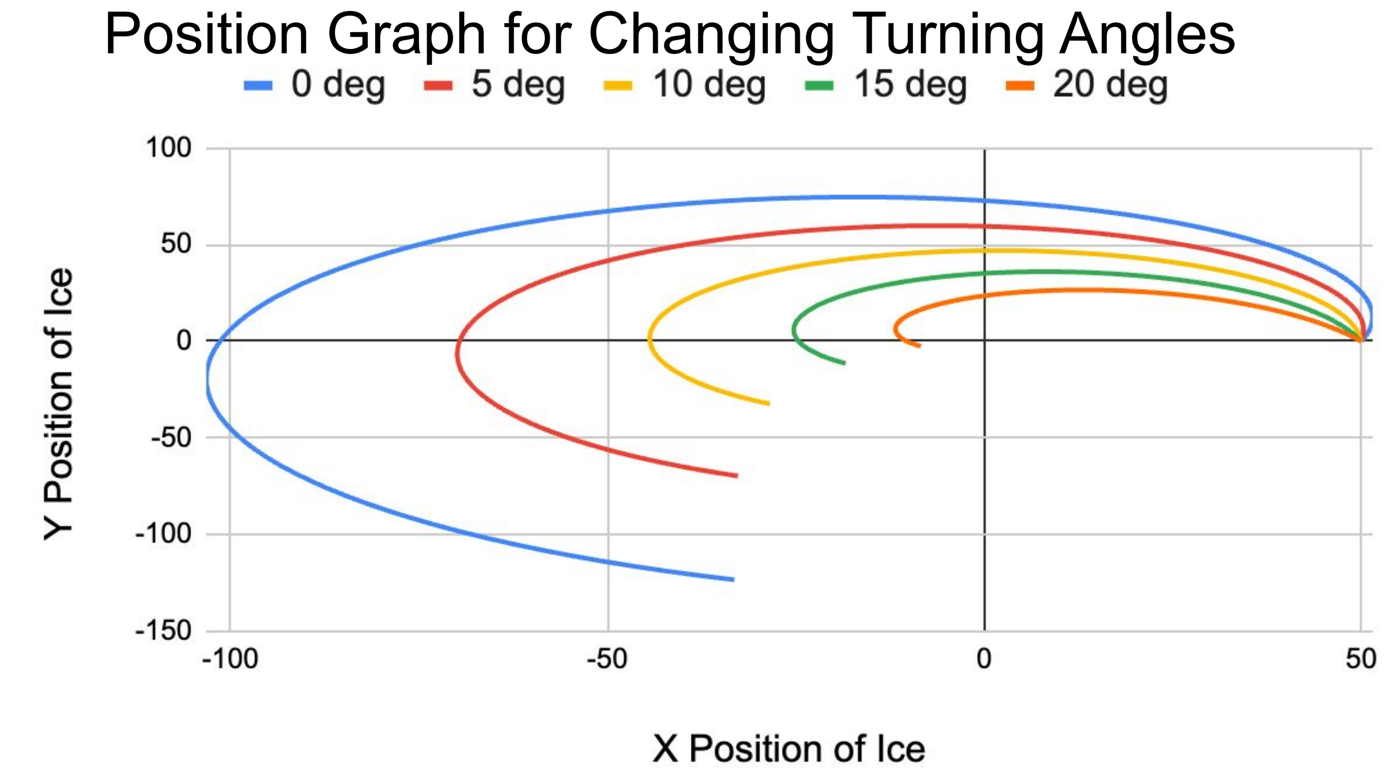

Figure 4. Trajectories of 50 km radius ice floes for different sea ice-wind turning angles

Conclusions and Outlooks

We investigated the effects of sea ice-wind turning angles on ice floe trajectories under a wind Rankine vortex field. As a next step, ERA 5 wind reanalysis data will be used to construct a more realistic wind field. For the sea ice velocity field, the NSIDC sea ice motion vectors will be used to derive the ocean field, which will be applied to the simulations to examine the motion of individual ice floes.

References

[1] Manucharyan and Montemuro J. Adv. Model. Earth Syst., 14, e2022MS003247 (2022)
[2] Park and Stewart The Cryosphere, 10, 227–244 (2016)