Global Storm Surge Modeling: From Dynamic Sea Surface Drag to Ice-Influenced Surge Predictions

Feyza Nur Özkan[1,2], Martin Verlaan[1,2], Sanne Muis[2,3], Firmijn Zijl[2]

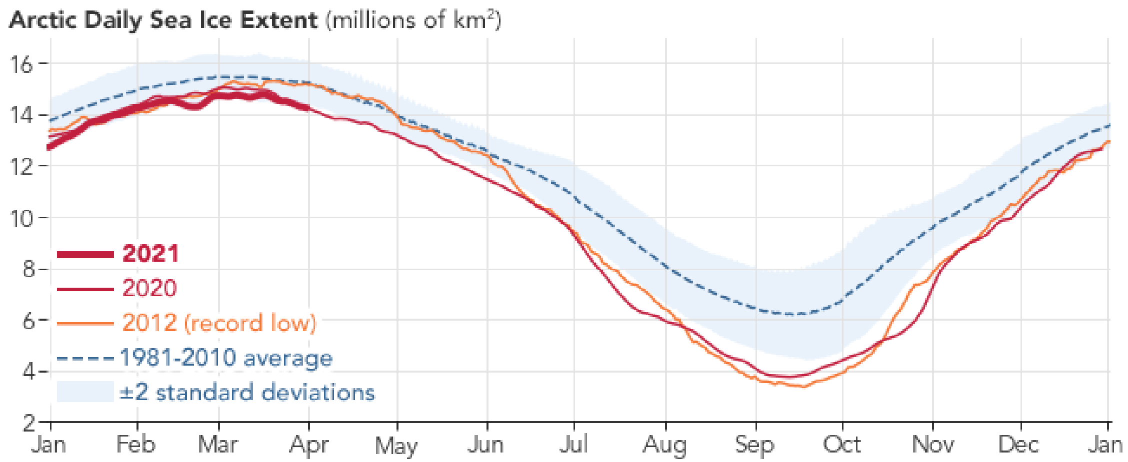
[1] Delft Institute of Applied Mathematics, Delft University of Technology, Delft, The Netherlands (F.N.Ozkan@tudelft.nl)
[2] Deltares, Delft, The Netherlands
[3] Institute for Environmental Studies (IVM), Vrije Universiteit Amsterdam, Amsterdam, The Netherlands

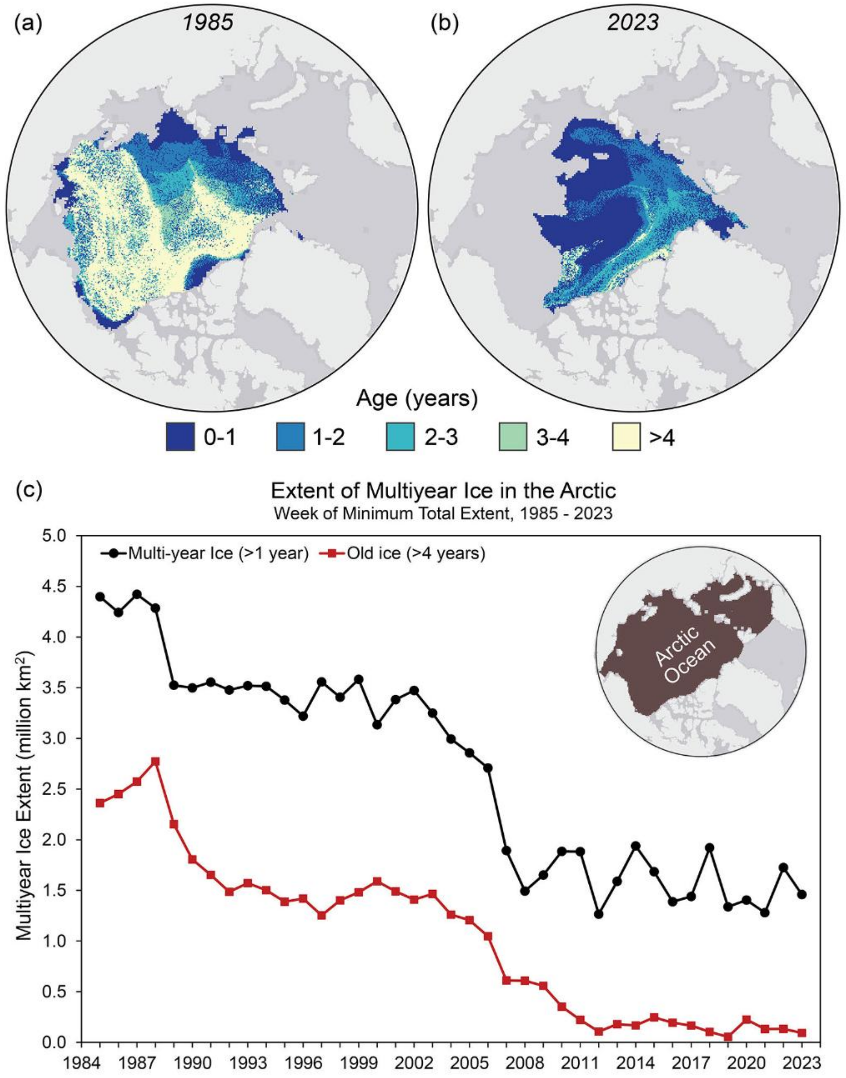
Outline

1. Motivation: Why storm surges in ice regions matter
2. Methods & Model Design: Model and forcing set-up
3. Experiments: Three configurations of wind stress and ice drag
4. Initial Results: Case studies in Bering Sea, East Canada, Tuktoyaktuk
5. Conclusions: Key findings and next steps

Why Storm Surges in Ice Regions Matter

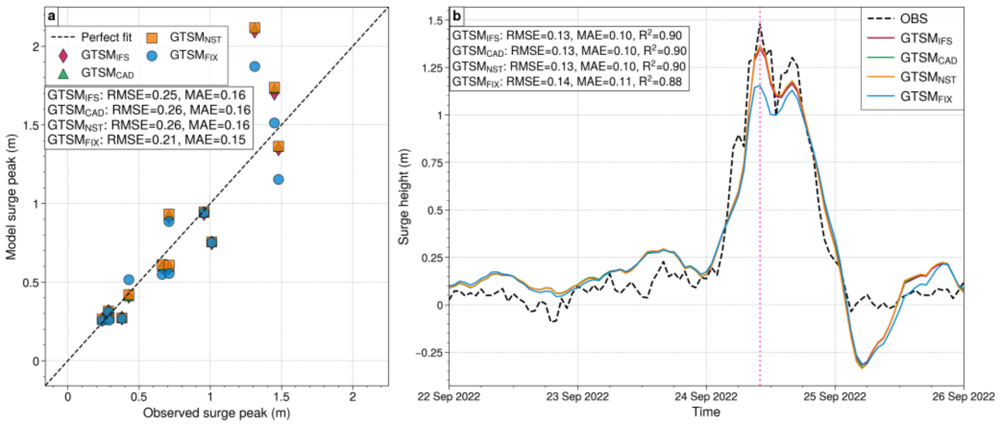
- **Rapid loss of Arctic ice:** Satellite record shows declining extent and thickness; old multi-year ice is disappearing.
- **Longer open-water seasons** + stronger winds and more cyclones = greater wave exposure.
- **Higher surge risk:** In partially ice-covered regions, declining ice cover leads to increased wave action, higher storm surges and flood hazards (Greenan et al., 2018)
- **Motivation for this study:** Test different ice-drag parameterisations to improve surge simulations.

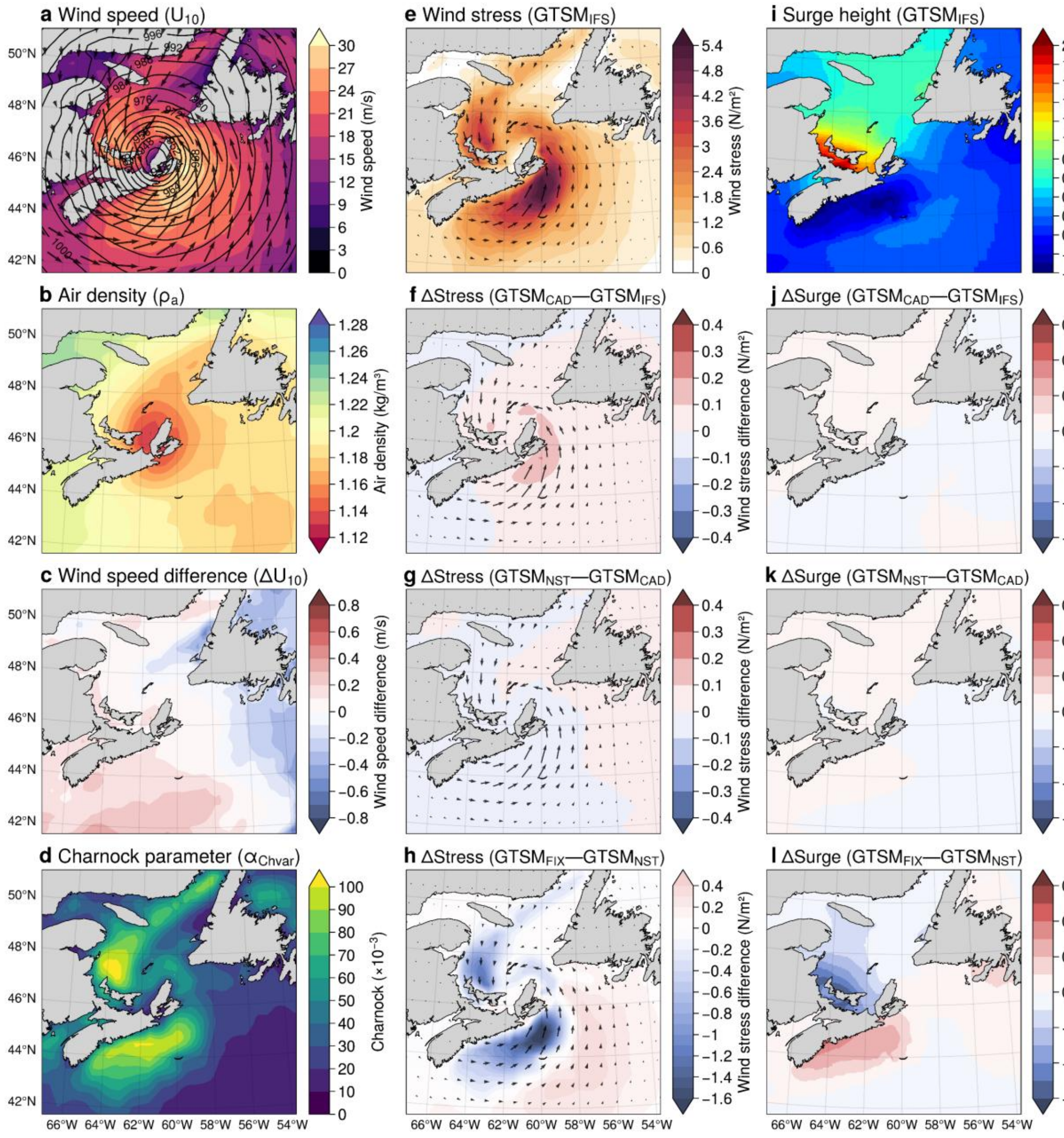




Recap of the Previous Study

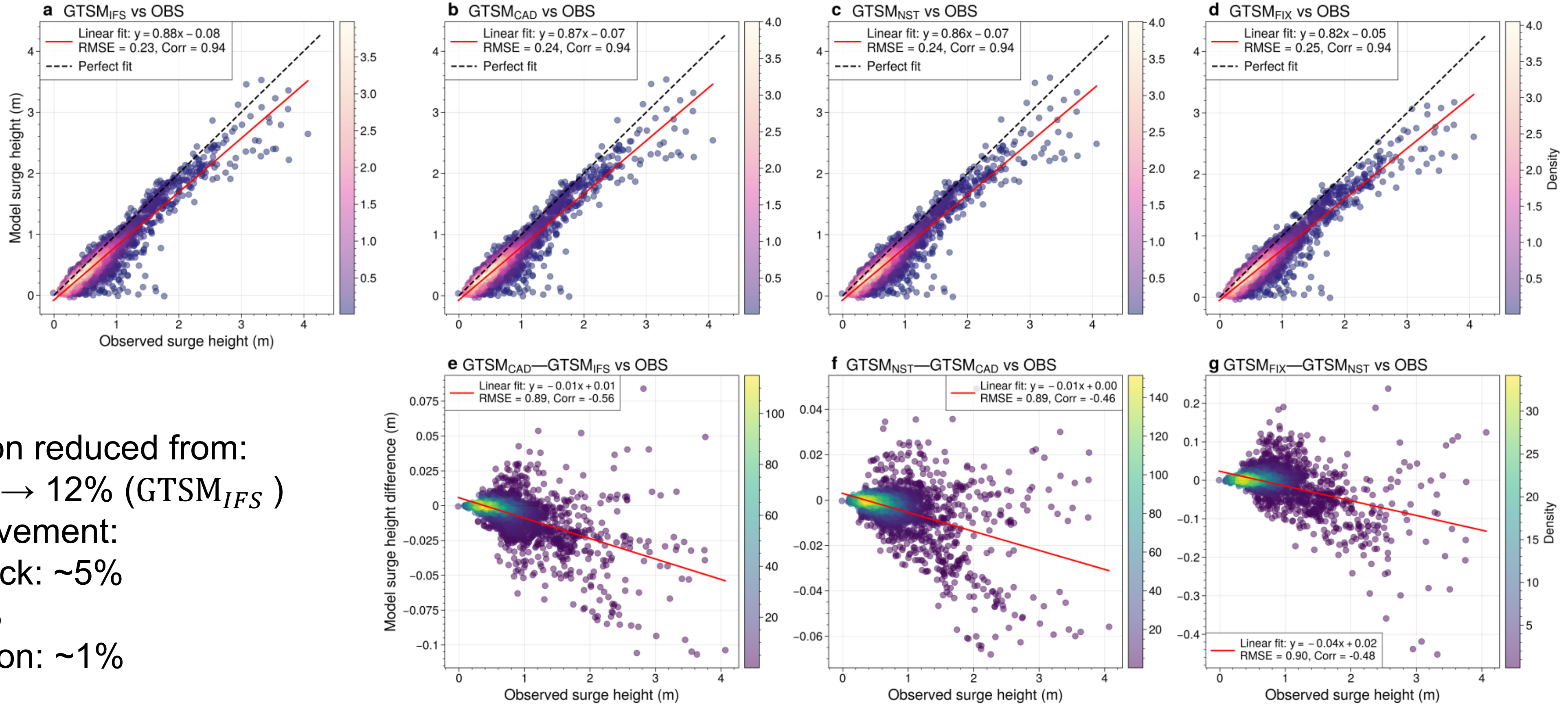
- Variable Charnock parameterization is the dominant factor in accurate storm surge modeling.
- Dynamic surface roughness reduces model bias, especially during extreme events.
- Surge underestimated in all models





Özkan, F.N., Verlaan, M., Muis, S. et al. Sensitivity of global storm surge modelling to sea surface drag. Ocean Dynamics 75, 66 (2025). https://doi.org/10.1007/s10236-025-01713-3

Recap of the Previous Study



Bias Reduction:

- Model underestimation reduced from:
  - 18% ($\mathrm{GTSM_{FIX}}$) → 12% (GTSM_{IFS})
- Contribution to improvement:
  - Variable Charnock: ~5%
  - Air density: ~1%
  - Stability correction: ~1%

Operational implications:

- Air density and stability adjustments have minor effects on surge accuracy.
- Dynamic Charnock parameterization should be prioritized in real-time forecasting.

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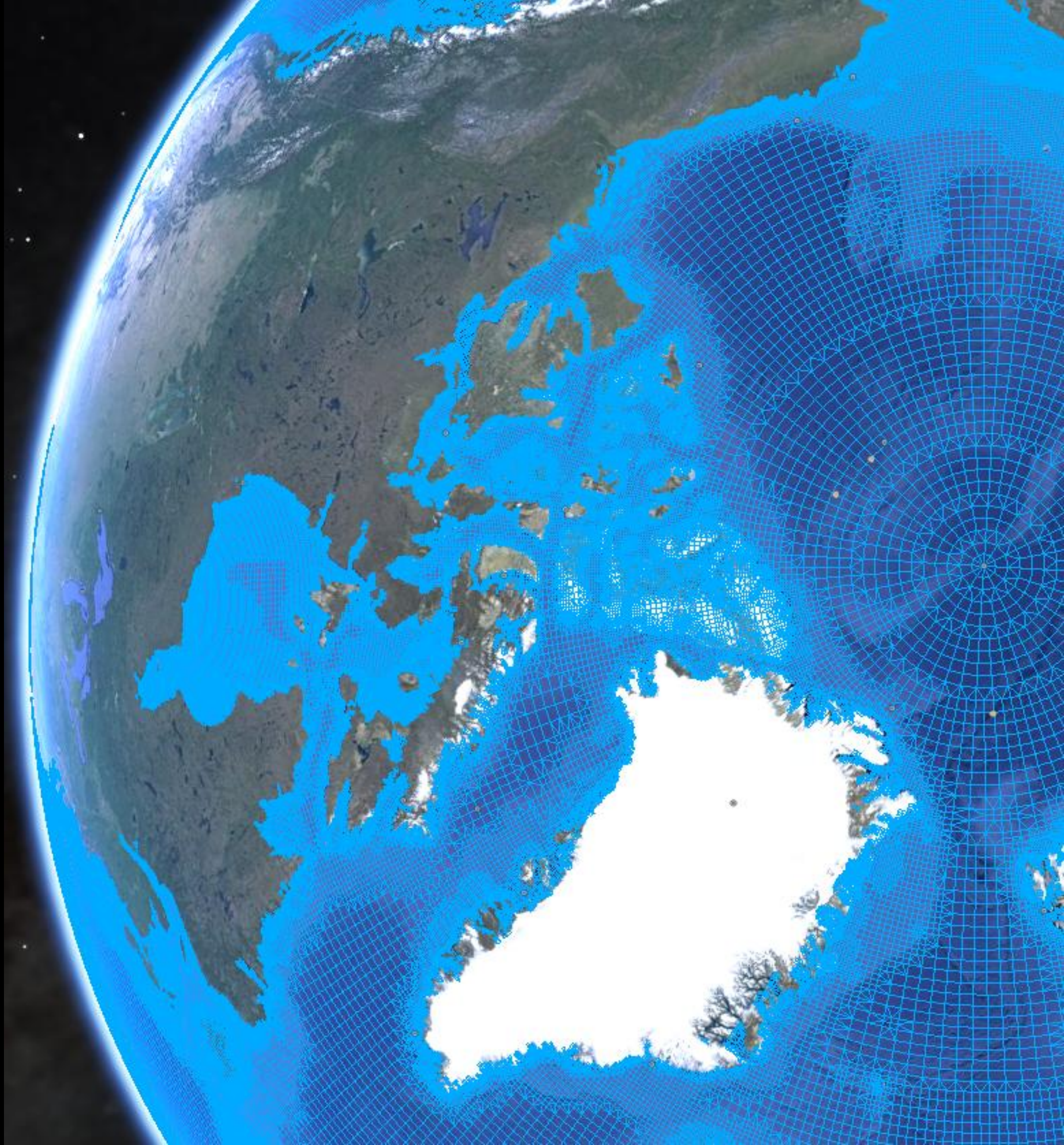
Global Tide and Surge Model

- Depth-averaged hydrodynamic model
- Global coverage with an unstructured grid that spatially varying resolution increasing towards the coast:
  - 25 km in the ocean
  - 2.5 km along the coast - 1.25 km in Europe

- Delft3D Flexible Mesh software by Deltares
- Simulates water levels caused by tides and storm surges
- Applications;
  - Operational forecasting
  - Reanalysis of historical extremes
  - Future climate projections



Wind Stress Formulation in GTSM (Open-water)

The wind field is transformed into wind stress to capture the necessary air-sea momentum exchange for storm surge, utilizing a drag coefficient that accounts for air density and wind speed at a given location.

$$\tau_a = \rho_a C_D U_{10}^2$$

Logarithmic velocity profile law: $\frac{u_{10}}{u_*} = \frac{1}{k}\left(ln\frac{z}{z_0}\right)$

The drag coefficient C_D: $C_D = \frac{k^2}{\left[\log\left(\frac{10}{z_0}\right)\right]^2}$

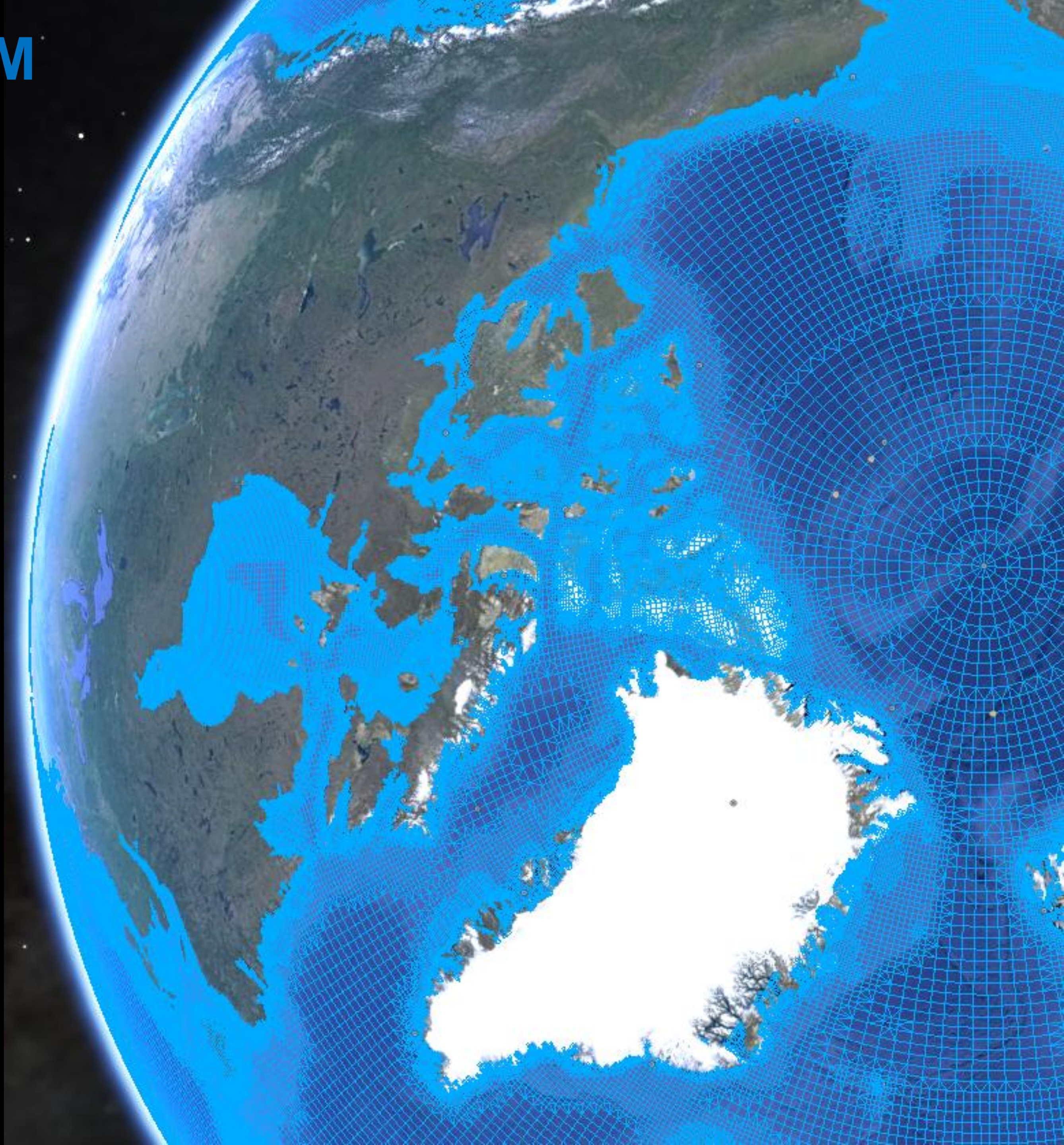
Roughness length

Charnock (1955) z_0's dependence on u_*: $z_0 = \alpha_{Ch}\frac{u_*^2}{g}$

Charnock parameter

$\alpha_{Chvar} = \frac{\hat{\alpha}}{\sqrt{1-\frac{\tau_w}{\tau}}}$ with $\hat{\alpha} = 0.006$

Wave induced stress



Surge Modeling in GTSM (Sea Ice)

$$C_{D,w} = \frac{k^2}{\left[\log\left(\frac{10}{z_0}\right)\right]^2}$$

A_w: Water area fraction
A_i: Sea ice area fraction

1. No ice: $C_{D,eff} = C_{D,w}$

2. Linear: $C_{D,eff} = C_{D,w}\, A_w$

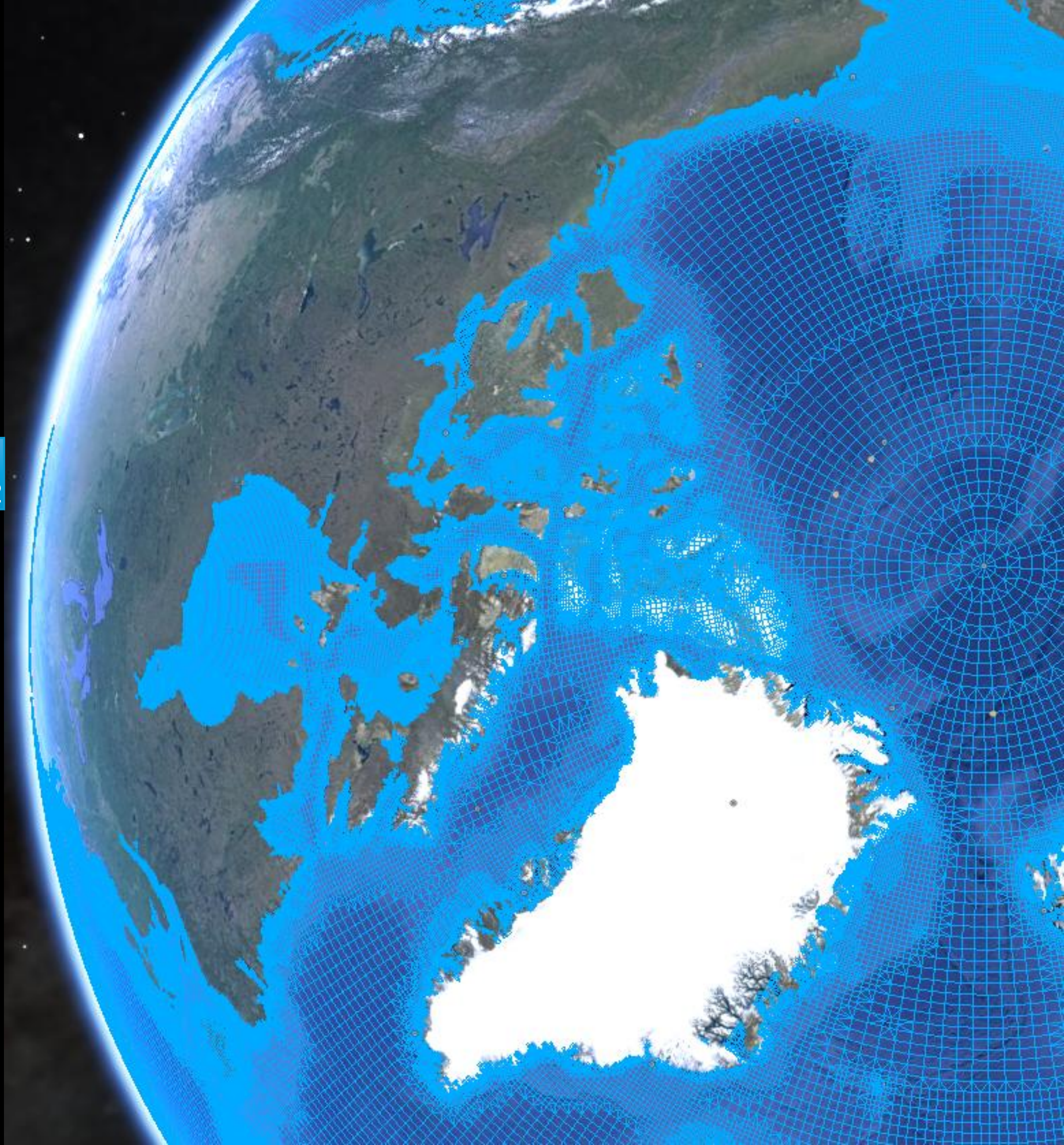
3. Cubic: $C_{D,eff} = \max(C_{D,w}\,, c_0 + c_1 A_i + c_2 A_i^2 + c_3 A_i^3)$
with c_0 = 0.00075, c_1 = 0.0075, c_2 = −0.009, and c_3 = 0.002

4. Lupkes & Birnbaum (2005): $C_{D,eff} = C_{D,w}\, A_w + C_{D,i}\, A_i + C_{D,f}$
where $C_{D,i} = 0.0015$

$$C_{D,f} = 0.34 A_i^2 \frac{A_w \left(A_w^{0.8} + \frac{1}{2}\left(1 - \frac{1}{2} A_i\right)^2\right)}{31 + 90 A_i A_w}$$

5. Andreas (2010): $C_{D,eff} = c_0 + c_1 A_i\, A_w$
with c_0 = 0.0015, c_1 = 0.002233

6. Raysice (2019): $C_{D,eff} = \max(C_{D,w}\,, c_0 + c_1 A_i\, A_w)$
with c_0 = 0.00125, c_1 = 0.005



Wind Stress Forcing Configurations

All experiments use GTSM with different wind stress formulations.

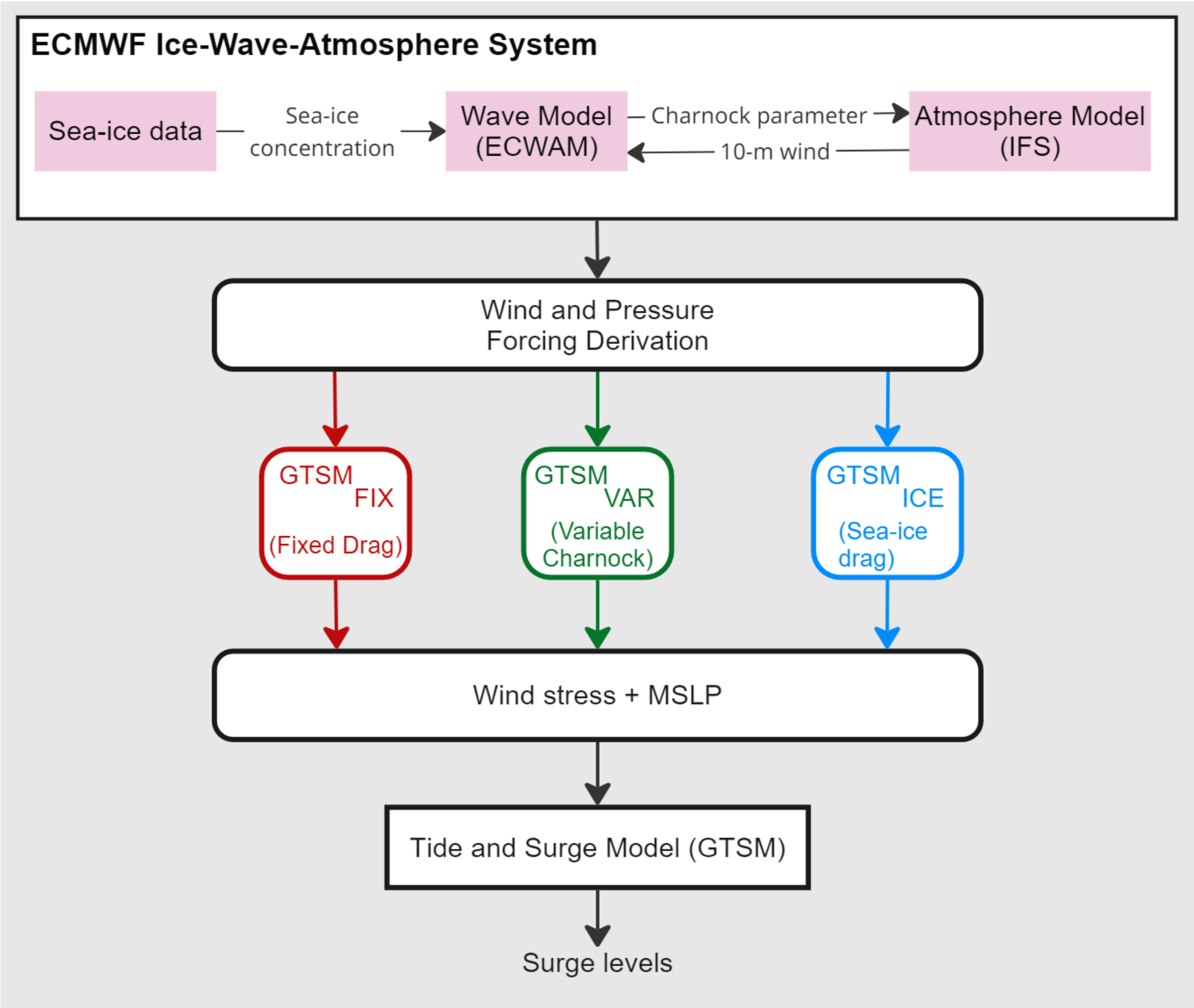
Summary of configurations:

1. $GTSM_{FIX}$ → No ice drag; fixed α_{Ch} =0.041.
2. $GTSM_{VAR}$– Variable α_{Chvar} from ERA5/ECWAM; no explicit ice drag.
3. $GTSM_{ICE}$– Fixed α_{Ch} =0.041 over water; Lüpkes–Birnbaum ice drag over ice fraction.

Configuration	Charnock	Sea-ice drag
$GTSM_{FIX}$	Fixed α_{Ch} =0.041	None
$GTSM_{VAR}$	Variable α_{Chvar}	None
$GTSM_{ICE}$	Fixed α_{Ch} =0.041	Lüpkes–Birnbaum/ Raysice parameterization over ice fraction

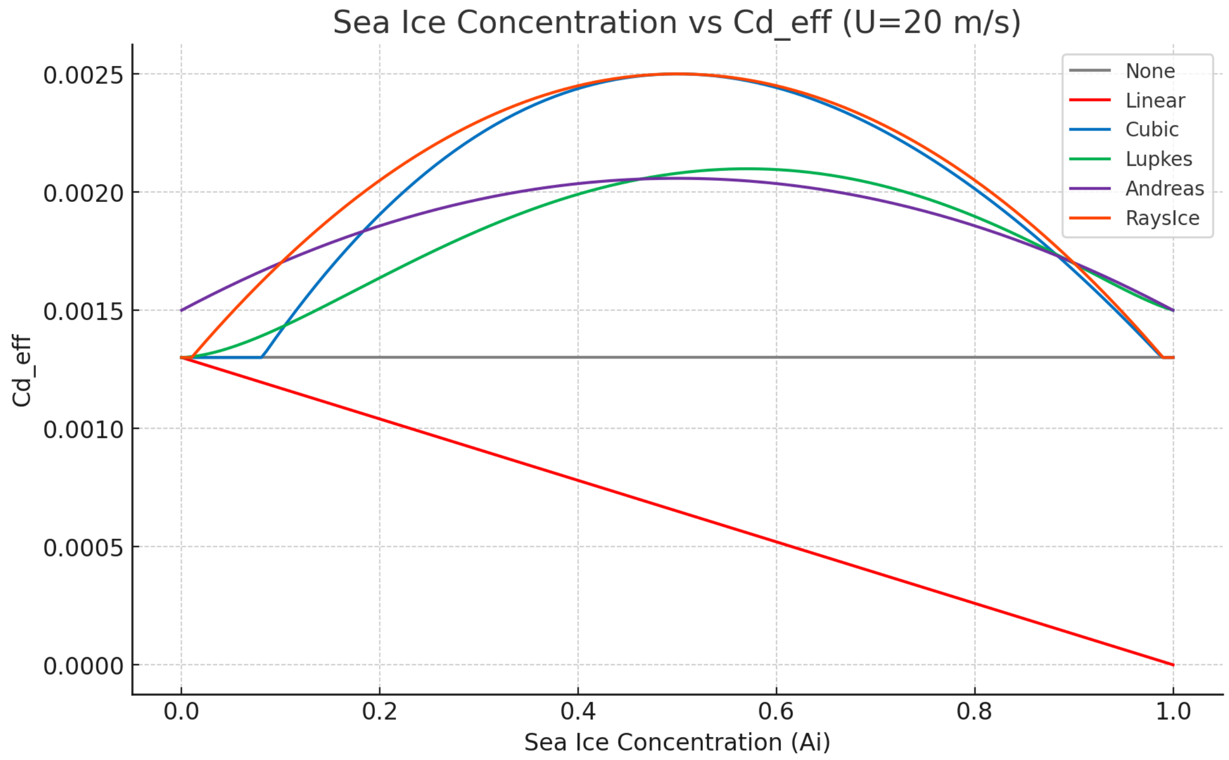
Experiments:

- Sea levels produced from meteorological forcing as <u>surge only</u>
- Time series at 10-minute resolution



Influence of Ice Cover

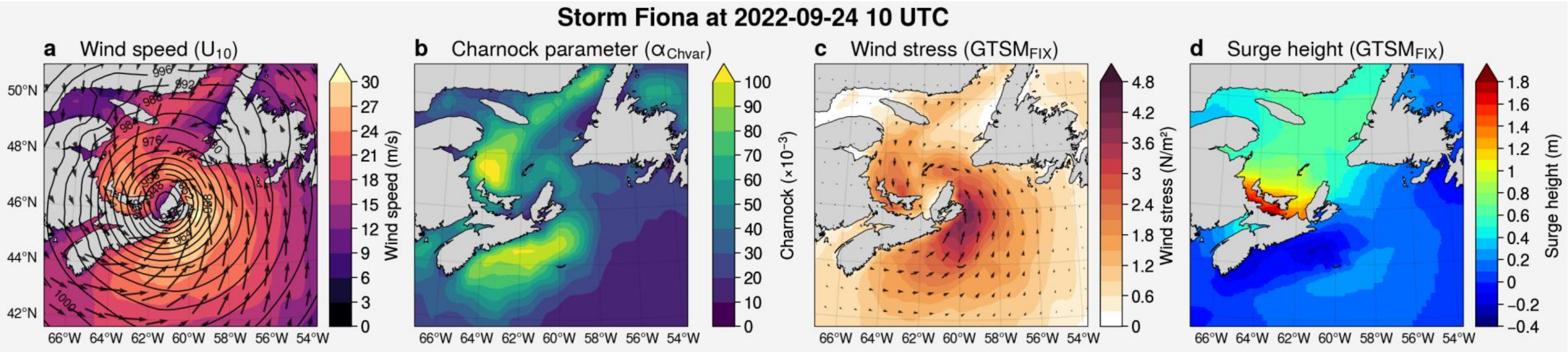
- **Linear** → Drag decreases linearly with ice; no added ice drag. Underestimates drag in ice-covered regions. Drops to zero at full ice cover, very conservative lower bound.
- **Cubic** → Nonlinear response; peaks at partial ice. Enhances drag in marginal ice zones.
- **Lupkes–Birnbaum** → Physically based. Produces strong mid-concentration peaks; non-zero drag at full ice cover.
- **Andreas** → Peaks at 50% ice
- **RaysIce** → Pronounced mid-concentration maximum



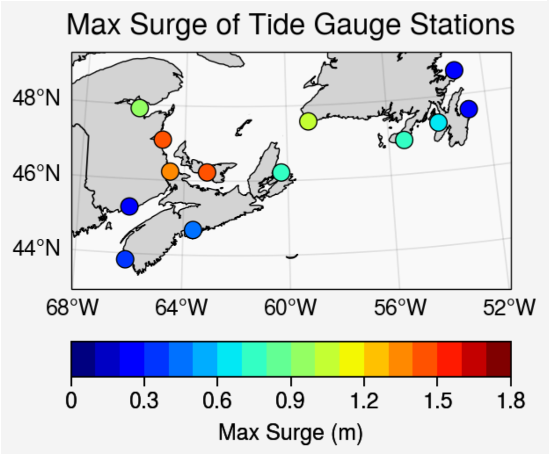
Summer Storm Validation (Ice free) – September 2022

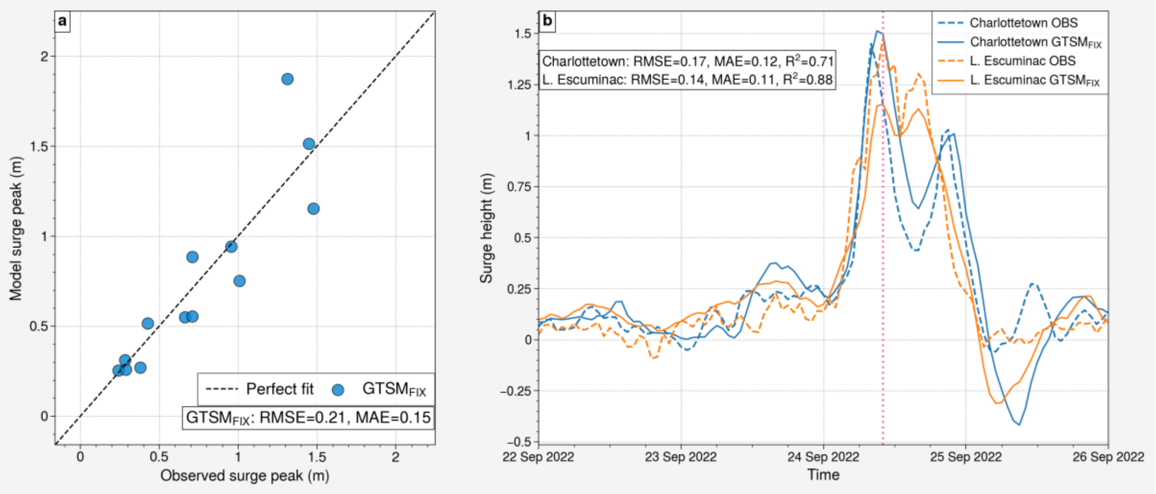
- **Wind speed (U_{10}):** Hurricane-force winds (>30 m/s) around the low-pressure center (≈975 hPa). Strongest winds to the east of the center; broad wind field impacting coastal areas
- **Charnock parameter:** Spatial variation of surface roughness; highest in storm's core region. Enhanced momentum transfer and sea state under extreme winds.

- **Wind stress:** Peak wind stress >4 N/m^2 near the eyewall, mirrors wind speed
- **Surge height:** Modelled surge up to 1.8 m in Gulf of St. Lawrence.



- **Scatter plot:** Good model skill in capturing peak surge amplitudes.
- **Time series at Charlottetown & L. Escuminac:** Slight under/over-prediction at peak but overall strong agreement.



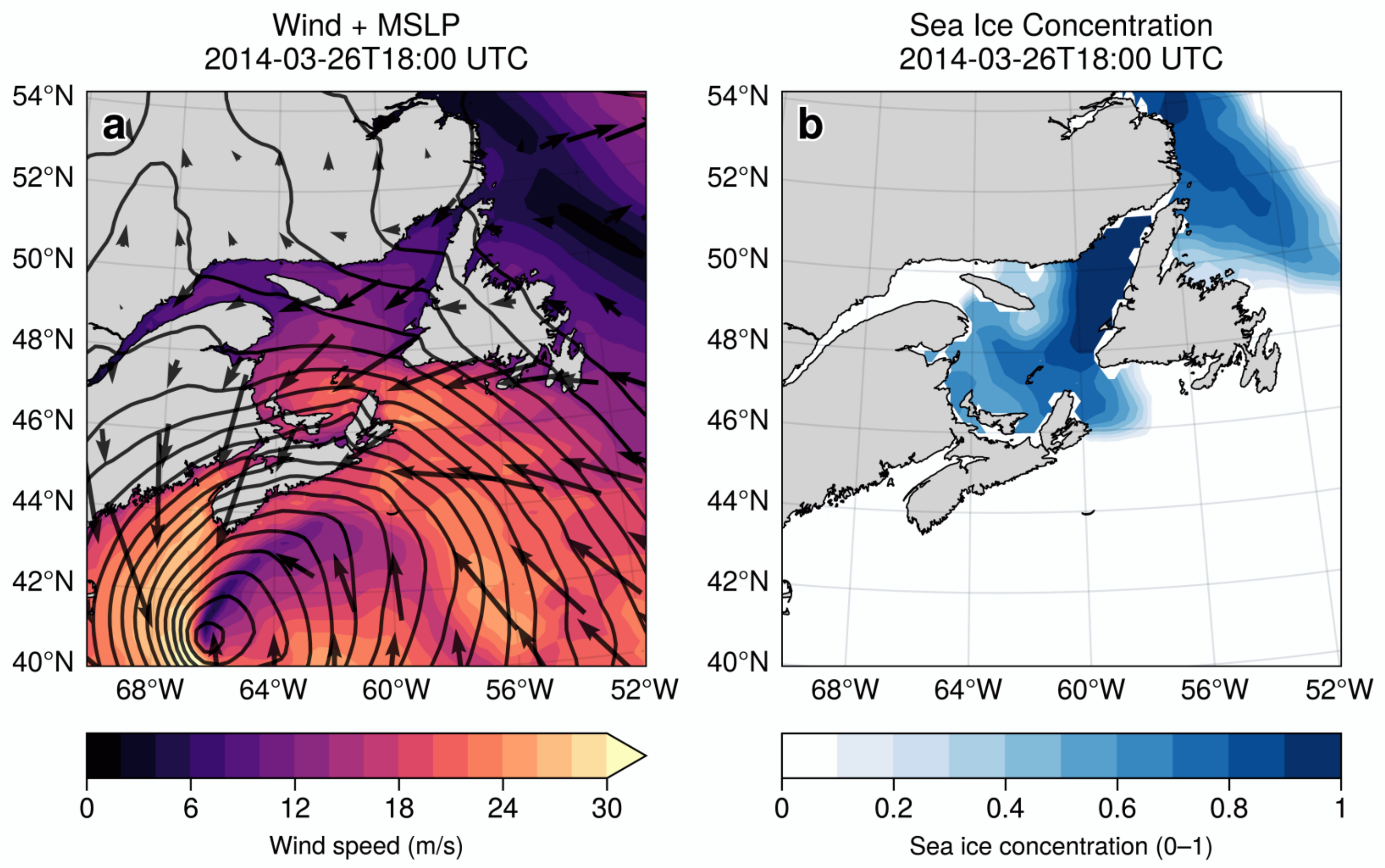


Storm during ice presence – March 2014

Storm + extensive sea ice = case to test drag parameterizations.

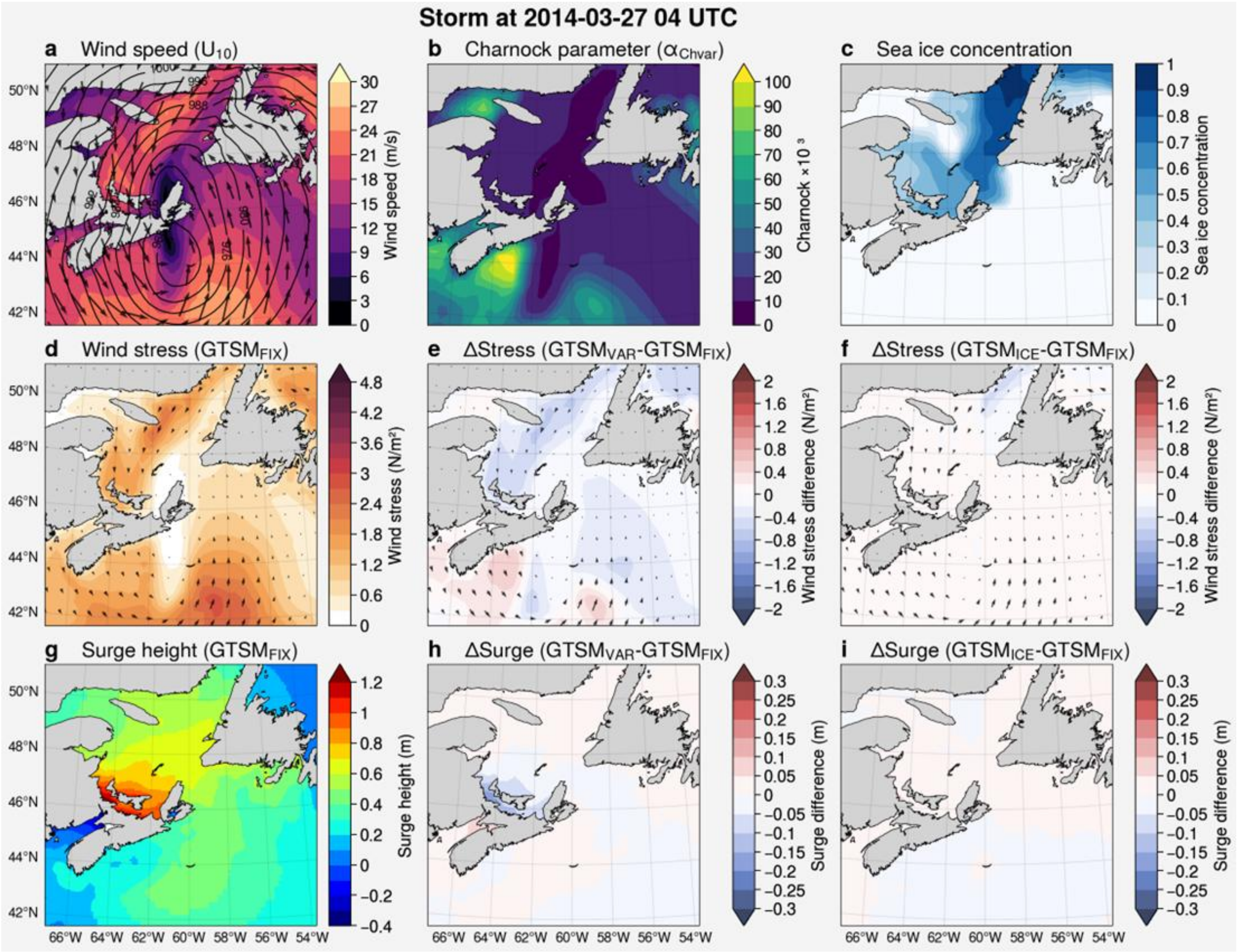
- Deep low-pressure system south of Nova Scotia.
- Strong winds >25 m/s.
- Onshore flow into Gulf of St. Lawrence.

- High sea ice concentration (>=0.8) in northern Gulf.
- Moderate ice (0.3–0.6) extending south.
- Storm directly overlapping ice cover.



Storm during ice presence – March 2014

- **Variable Charnock (VAR vs FIX):** Wind stress increases in high-wind open water but decreases over calmer/ice areas. Surge heights decreases ~10-20 cm.
- **Sea-Ice Drag (ICE vs FIX):** Wind stress pattern over ice fields and surge differences changes are minimal.



Summary

- Ice-drag methods dominate in ice areas. They override the effect of Charnock choice.
- Charnock matters mainly over open water, fixed (e.g., 0.041) vs. variable makes small differences there.
- Operationally robust setup and climatological setup, use fixed Charnock together with an explicit ice-drag method.
- Variable Charnock ≠ ice drag. If you don’t have an ice-drag implementation, forcing precomputed ice-drag stresses (RayIce/Lüpkes–Birnbaum) to the surge model.

Future Directions

- Extend validation using more tide-gauge stations and a wider range of storm cases with more variable sea-ice event (open-water, partial sea-ice and full sea ice).
- Run long-term hindcasts (10–30 years) to evaluate ice-drag impact on extreme events.

Thank you

Feyza Nur Özkan

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