Adding Baroclinicity and Sea Ice Effects to a Global Total Water Level Forecast Model

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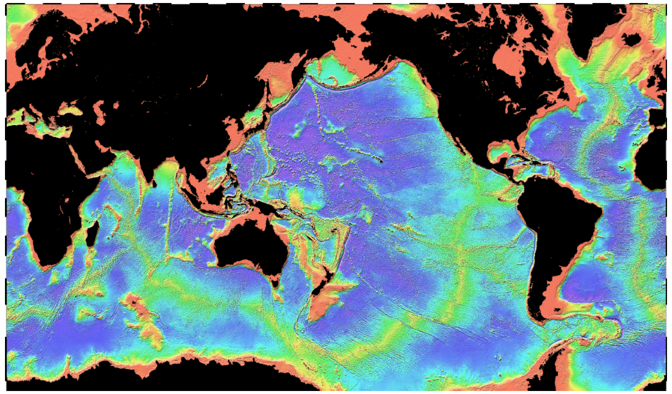
Introduction

1. **Baroclinic contributions**: several decimeters, hours to seasons (e.g., seasonal cycle, equatorial waves, Rossby waves, coastal trapped waves, tides).

Characteristics of coastal trapped waves (CTWs):

$$Bu = \frac{N^2H^2/f^2}{L^2} \begin{cases} Bu \ll 1 & \text{Barotropic shelf wave} \\ Bu \gg 1 & \text{Baroclinic Kelvin wave} \end{cases}$$

N, H, and L are typical values of buoyancy frequency, depth and shelf width, f Coriolis parameter (Huthnance, 1978)



Bathymetry of the ocean floor showing the continental shelves (red) (NOAA)

2. **Sea ice** can modulate tides and attenuate storm surges.

Questions:

- *How to include the two processes in the global system in an efficient way so that the model can also be used for ensemble forecasts and climate studies?*
- *What are their impacts on predicted water level?*

Baroclinicity

The Ocean Model (Global 1/12°, NEMO)

$$\frac{\partial \mathbf{u}_h}{\partial t} + \mathbf{u}\cdot\nabla\mathbf{u}_h + f\times\mathbf{u}_h = -\nabla_h[\frac{p_a}{\rho_0} + g(1-\alpha_s)\eta - g\eta_A$$

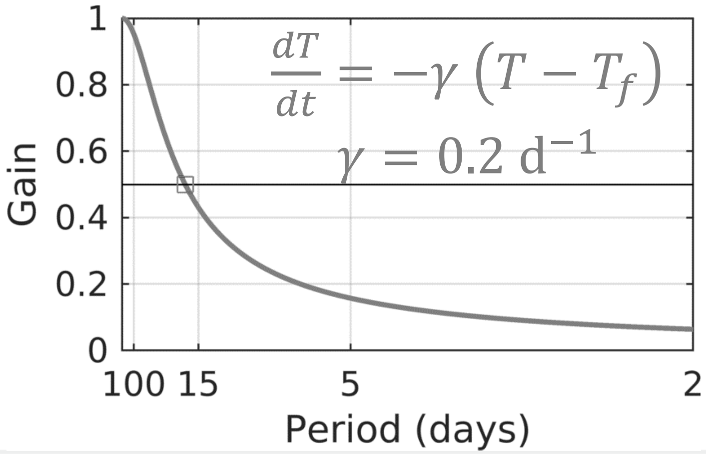
$$+g\int_z^0 \frac{\rho-\rho_0}{\rho_0}dz] + A_h\nabla_h^2\mathbf{u}_h + \frac{\partial}{\partial z}(A_z\frac{\partial \mathbf{u}_h}{\partial z}) + \lambda(\mathbf{x})\langle\bar{\mathbf{u}}_{obs} - \bar{\mathbf{u}}_h\rangle$$

$$\nabla\cdot\mathbf{u} = 0$$

$$\frac{\partial T}{\partial t} + \nabla\cdot(T\mathbf{u}) = K_h\nabla_h^2 T + \frac{\partial}{\partial z}(K_z\frac{\partial T}{\partial z}) - r(T-T_f)$$

$$\frac{\partial S}{\partial t} + \nabla\cdot(S\mathbf{u}) = K_h\nabla_h^2 S + \frac{\partial}{\partial z}(K_z\frac{\partial S}{\partial z}) - r(S-S_f)$$

Weakly nudged to daily T_f, S_f provided by a coarser resolution, data-assimilative model (i.e., ECCC's 1/4° GIOPS, Smith et al., 2018).

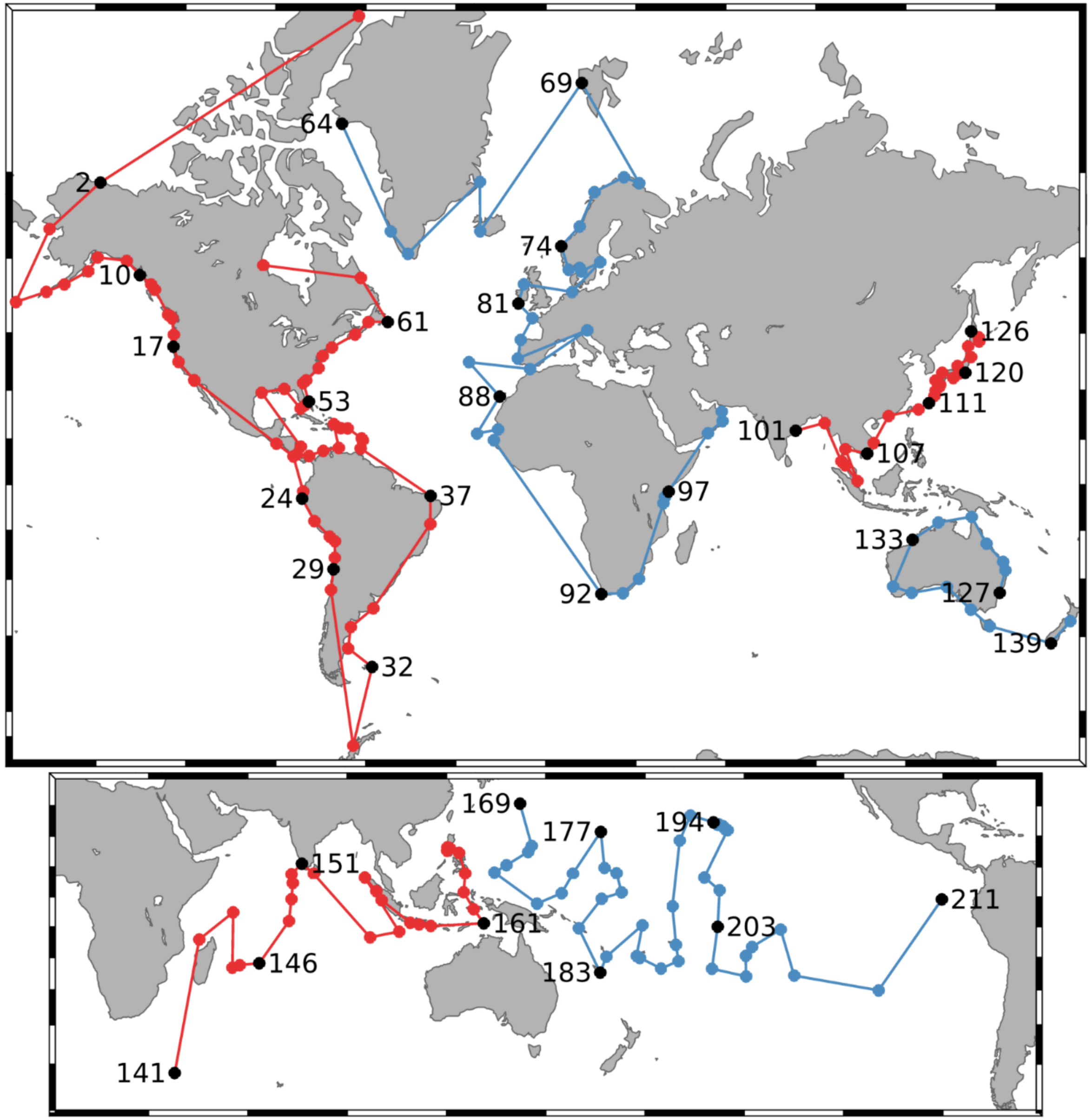


- At low frequencies (> ~15 d), T is guided by the 1/4° T_f.
- At high frequencies, T is less or not constrained by T_f.

Observations

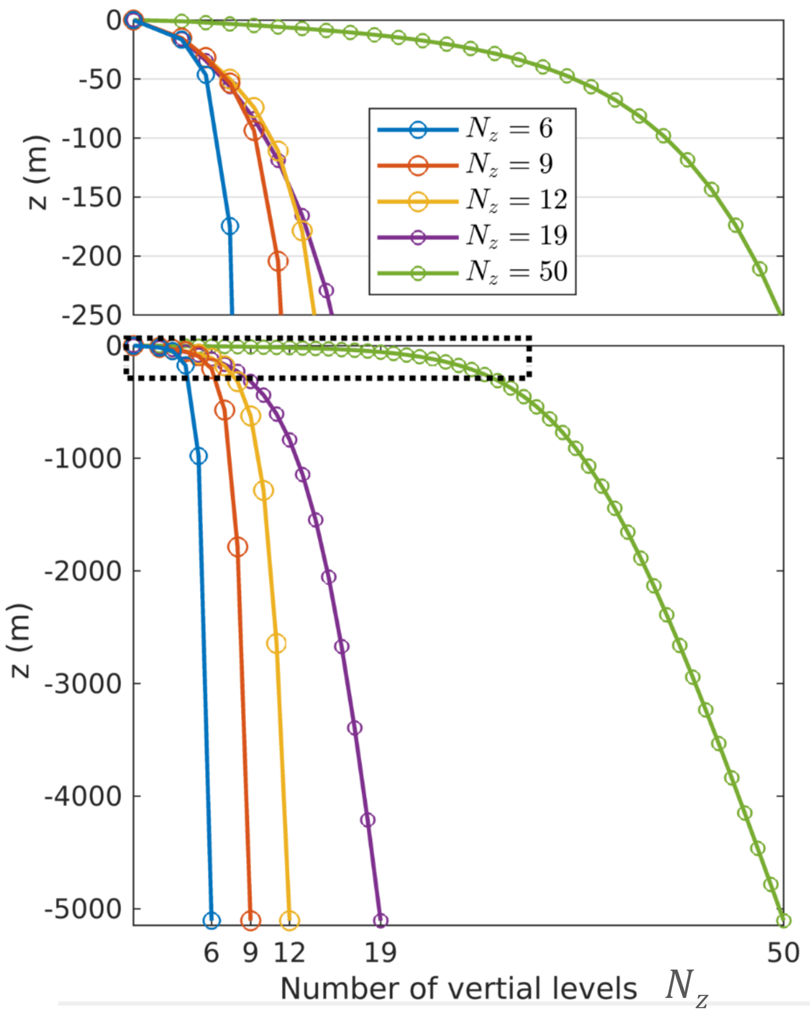
211 tide gauges from University of Hawaii Sea Level Center

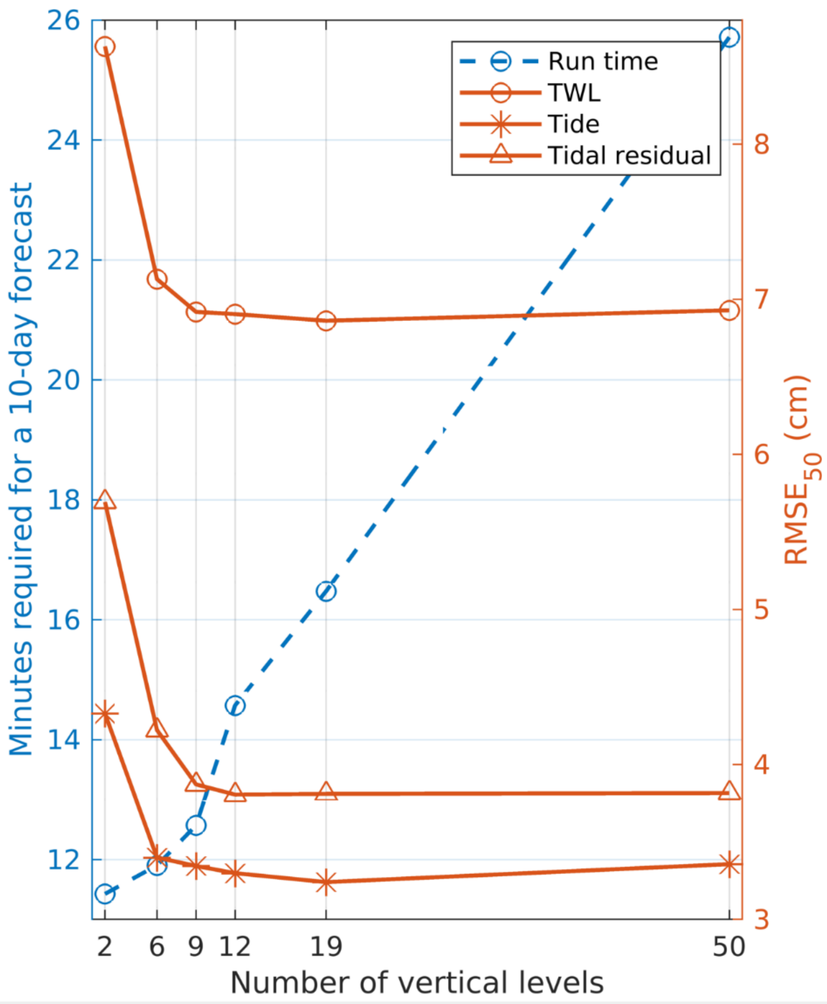
Oct. 2019 - Feb. 2021



Capturing baroclinicity with an optimized vertical grid

Balancing model performance and computational cost

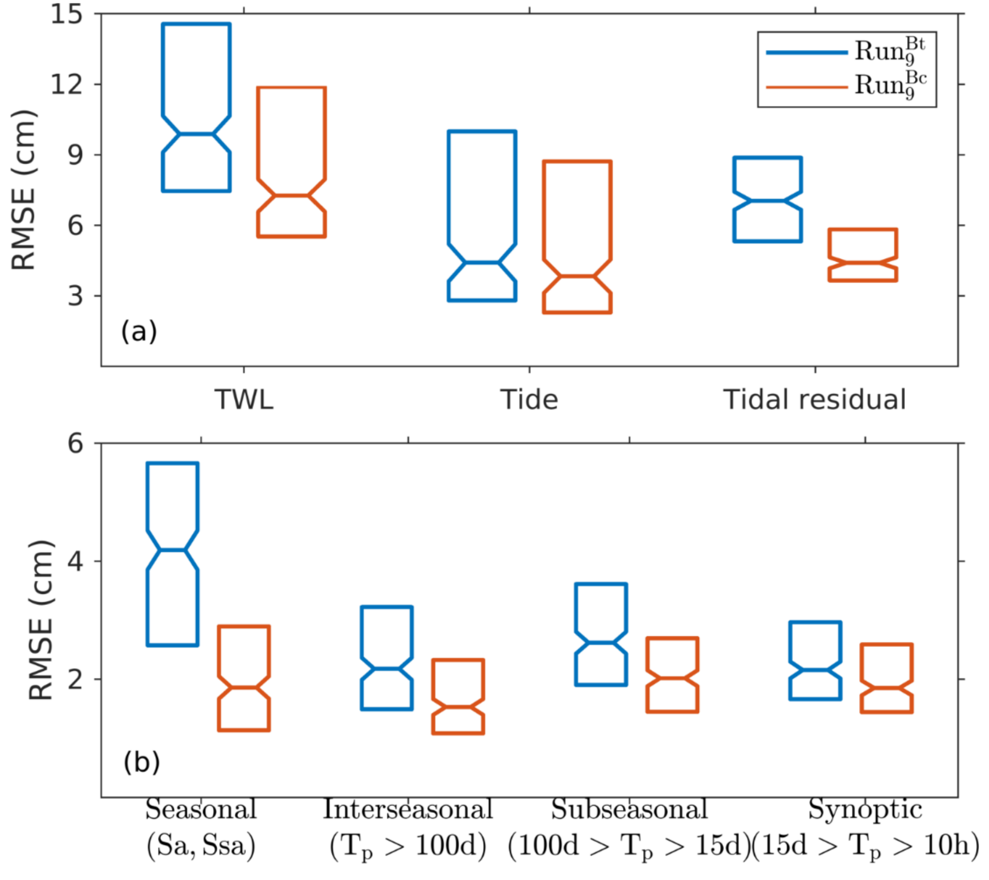




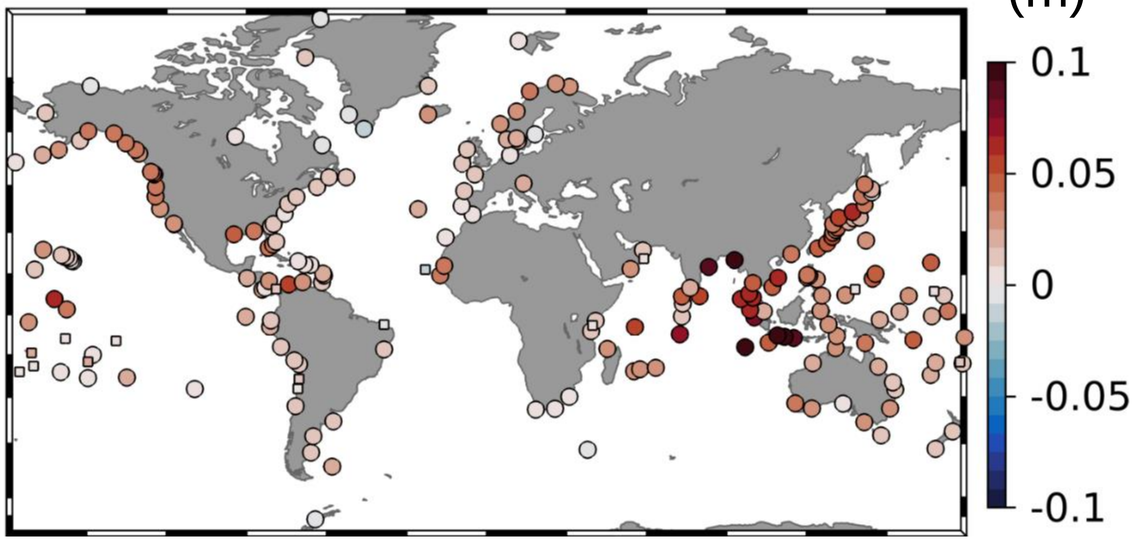
A 9-level configuration can sufficiently capture baroclinic effects, at only 10% additional cost compared to the barotropic model.

Impact of adding baroclinicity on predicted water level

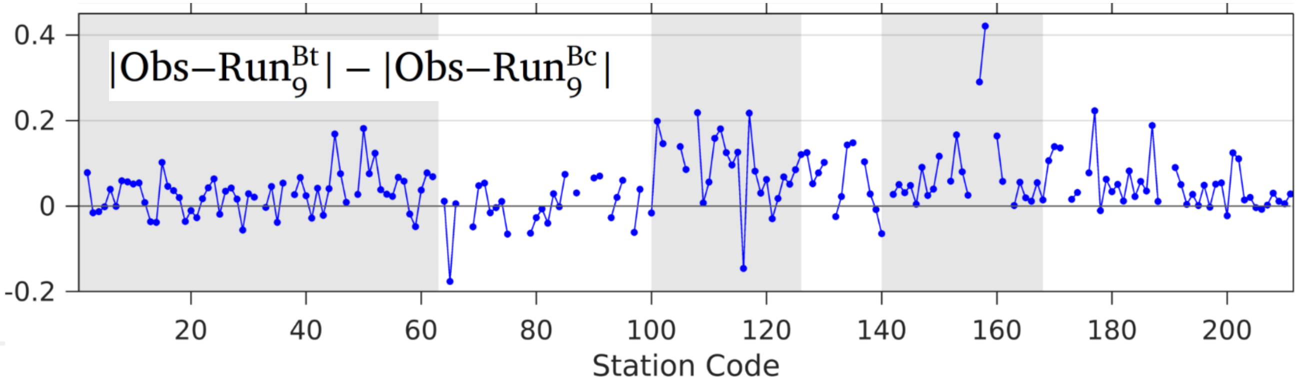
Run_9^{Bt}: barotropic run with 9 levels
Run_9^{Bc}: baroclinic run with 9 levels



Improvements in residuals
$\Delta RMSE\ (Run_{z9}^{Bt} - Run_{z9}^{Bc})$

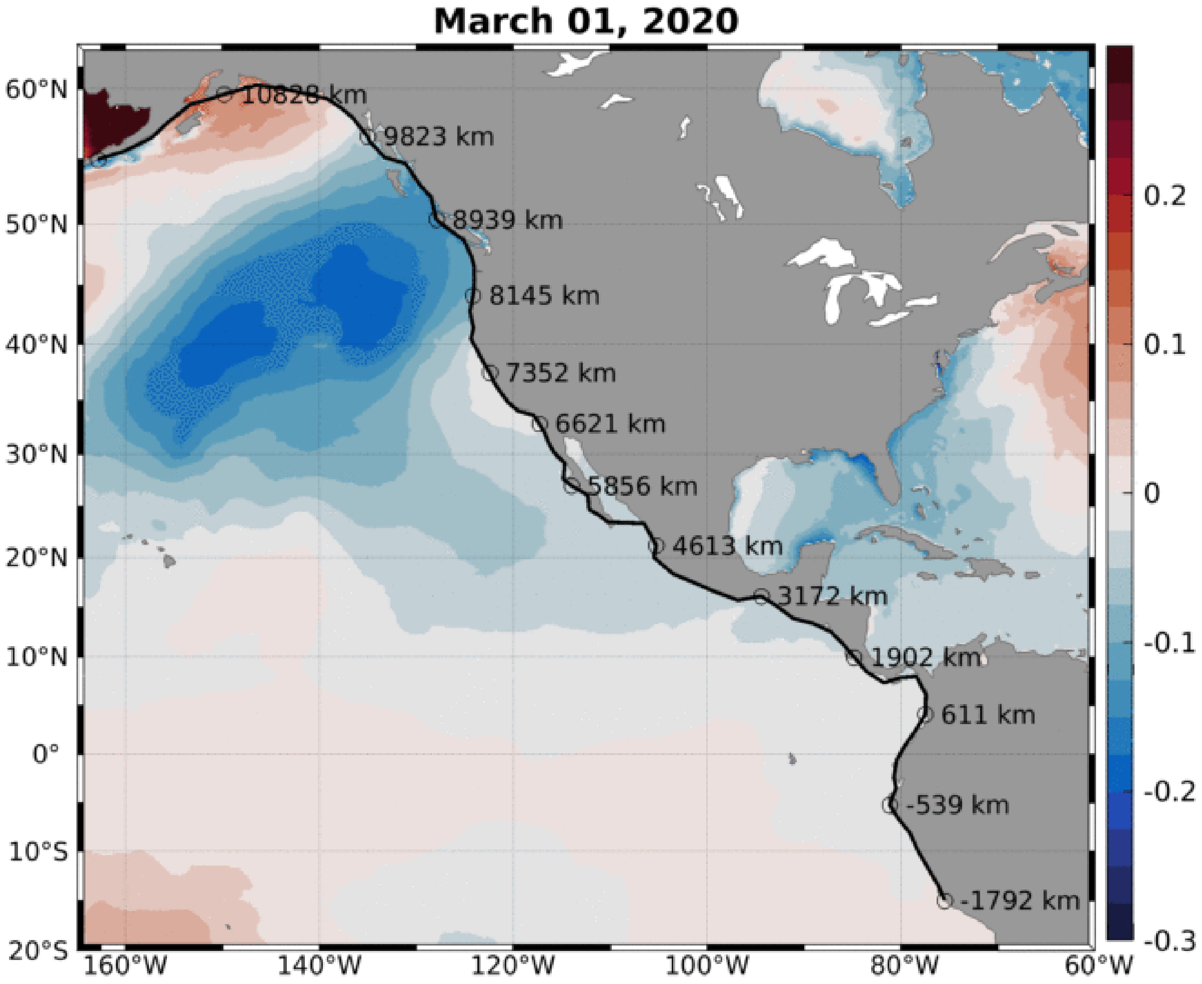


Improvements in extremes (up to 0.42 m in Indonesia due to a large subseasonal CTW)

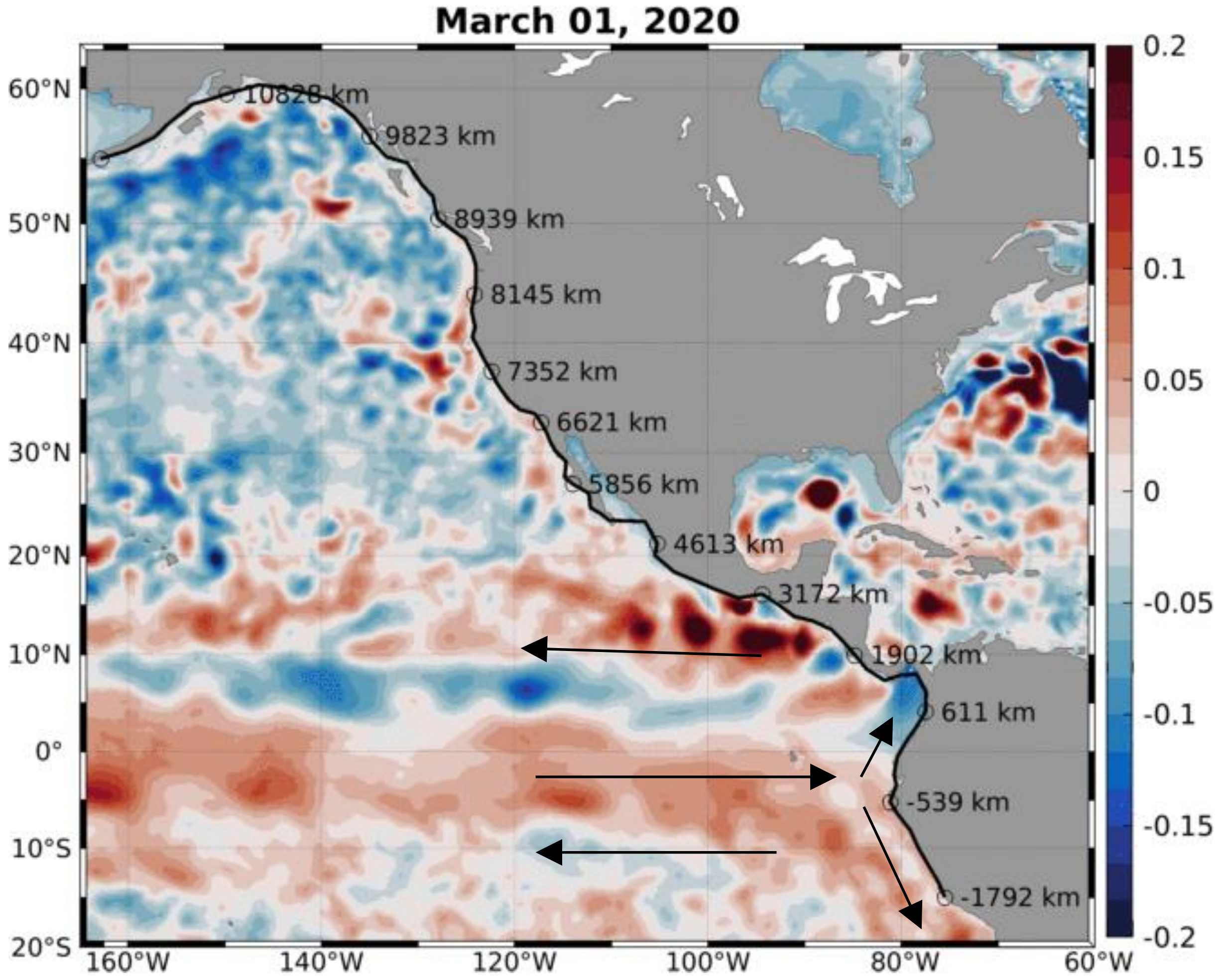


The role of coastal trapped waves

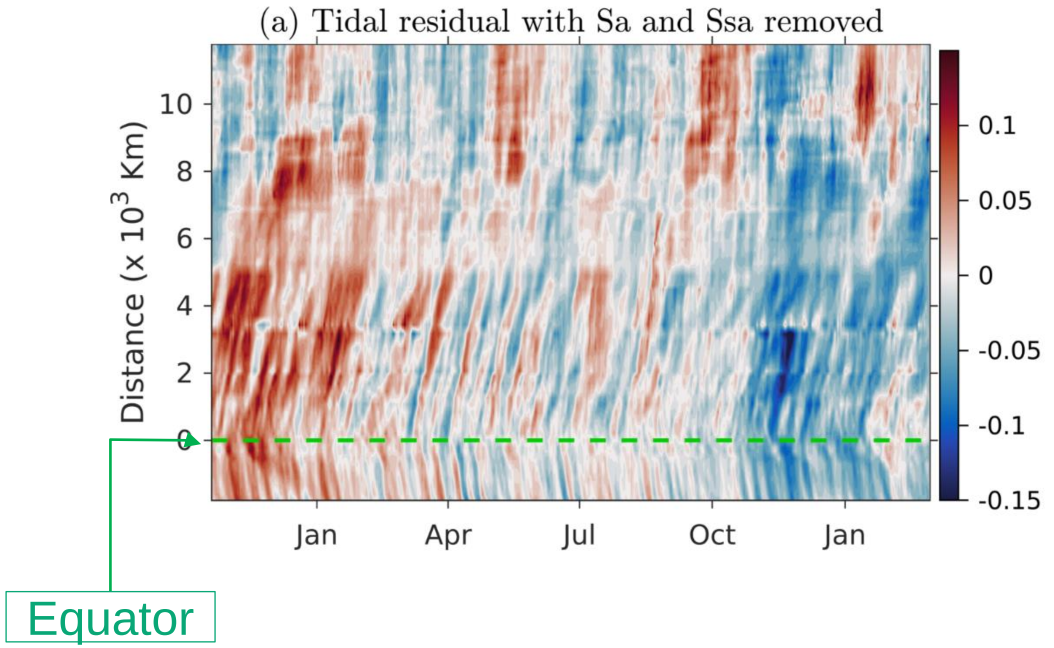
Tidal residual anomaly predicted by $\mathrm{Run}_9^{\mathrm{Bt}}$

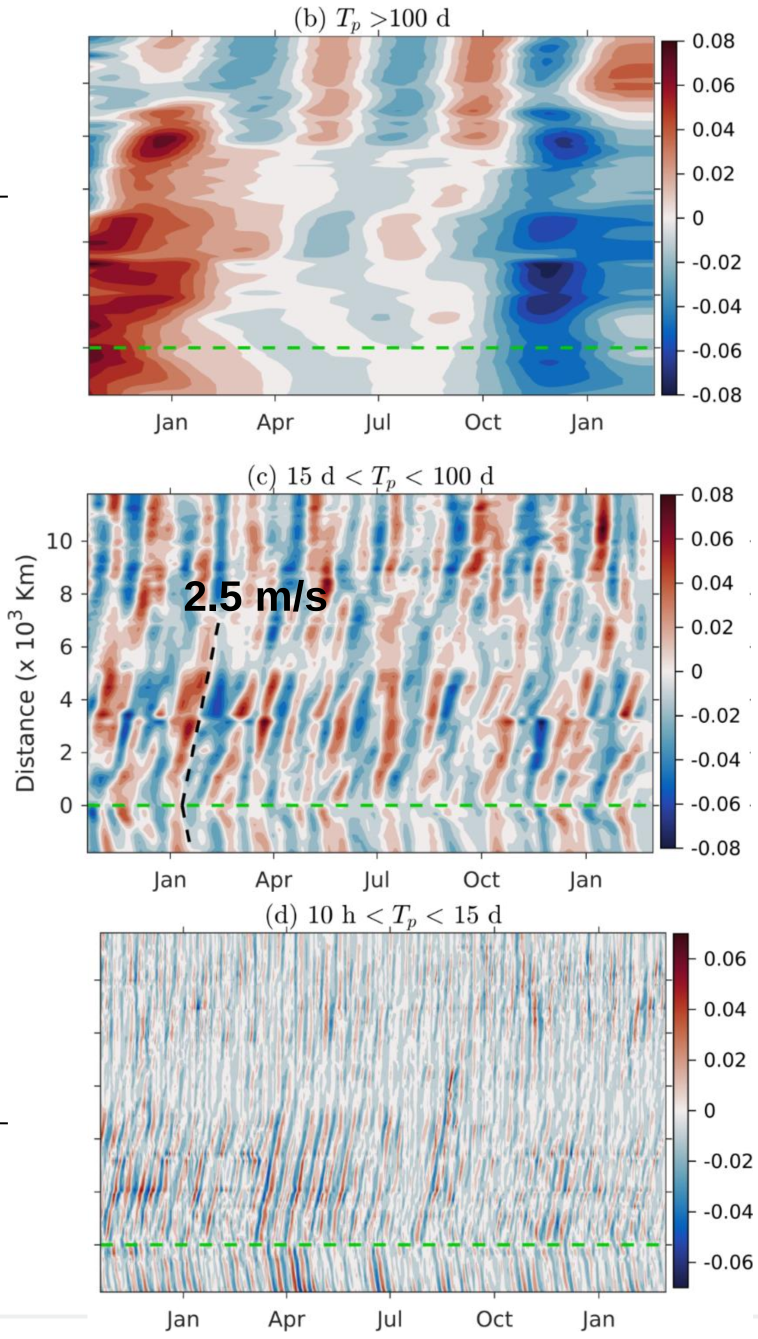


Difference in tidal residuals predicted by $\mathrm{Run}_9^{\mathrm{Bc}}$ and $\mathrm{Run}_9^{\mathrm{Bt}}$ (henceforth $\Delta\boldsymbol{\eta}_{bc-bt}$)



Hovmoller diagram of $\Delta\eta_{bc-bt}$ (m) (left panel) and its variability in interseasonal, subseasonal and synoptic bands (right panels)





Biennial variability of ENSO

(Rasmussonet al., 1990)

MJO

(Oliver and Thompson, 2010)

Rossby-gravity waves

(Enfield et al., 1987)

Sea ice effects

Parameterized ice-ocean stress

Surface stress $\boldsymbol{\tau}_s = (1-\alpha)\boldsymbol{\tau}_{\text{ao}} + \alpha\boldsymbol{\tau}_{\text{io}}$

Ice-ocean stress $\boldsymbol{\tau}_{\text{io}} = \rho_0 C_{\text{io}} |\boldsymbol{u}_{\text{ice}} - \boldsymbol{u}_{\text{surf}}| (\boldsymbol{u}_{\text{ice}} - \boldsymbol{u}_{\text{surf}})$

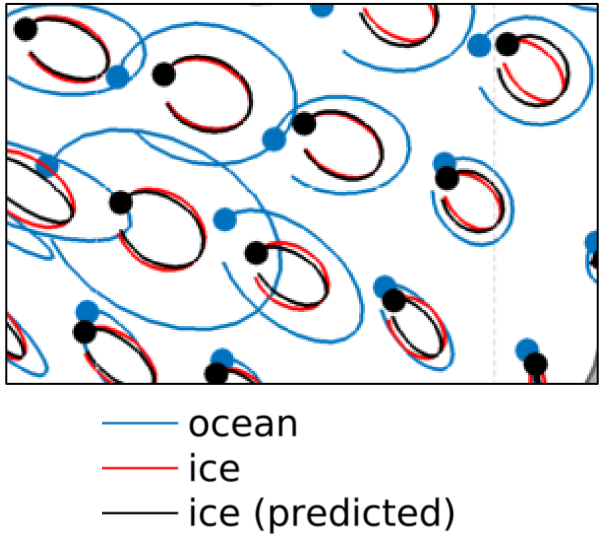
Relative velocity $\boldsymbol{u}_{\text{ice}} - \boldsymbol{u}_{\text{surf}} = (\boldsymbol{u}^{\text{T}}_{\text{ice}} - \boldsymbol{u}^{\text{T}}_{\text{surf}}) + (\boldsymbol{u}^{\text{S}}_{\text{ice}} - \boldsymbol{u}^{\text{S}}_{\text{surf}})$

$$= [a^{\text{T}}(\boldsymbol{x})\mathbf{R}(\varphi(\boldsymbol{x})) - \mathbf{I}]\boldsymbol{u}^{\text{T}}_{\text{surf}} + a^{\text{S}}(\boldsymbol{u}^{\text{S}*}_{\text{ice}} - \boldsymbol{u}^{\text{S}*}_{\text{surf}})$$

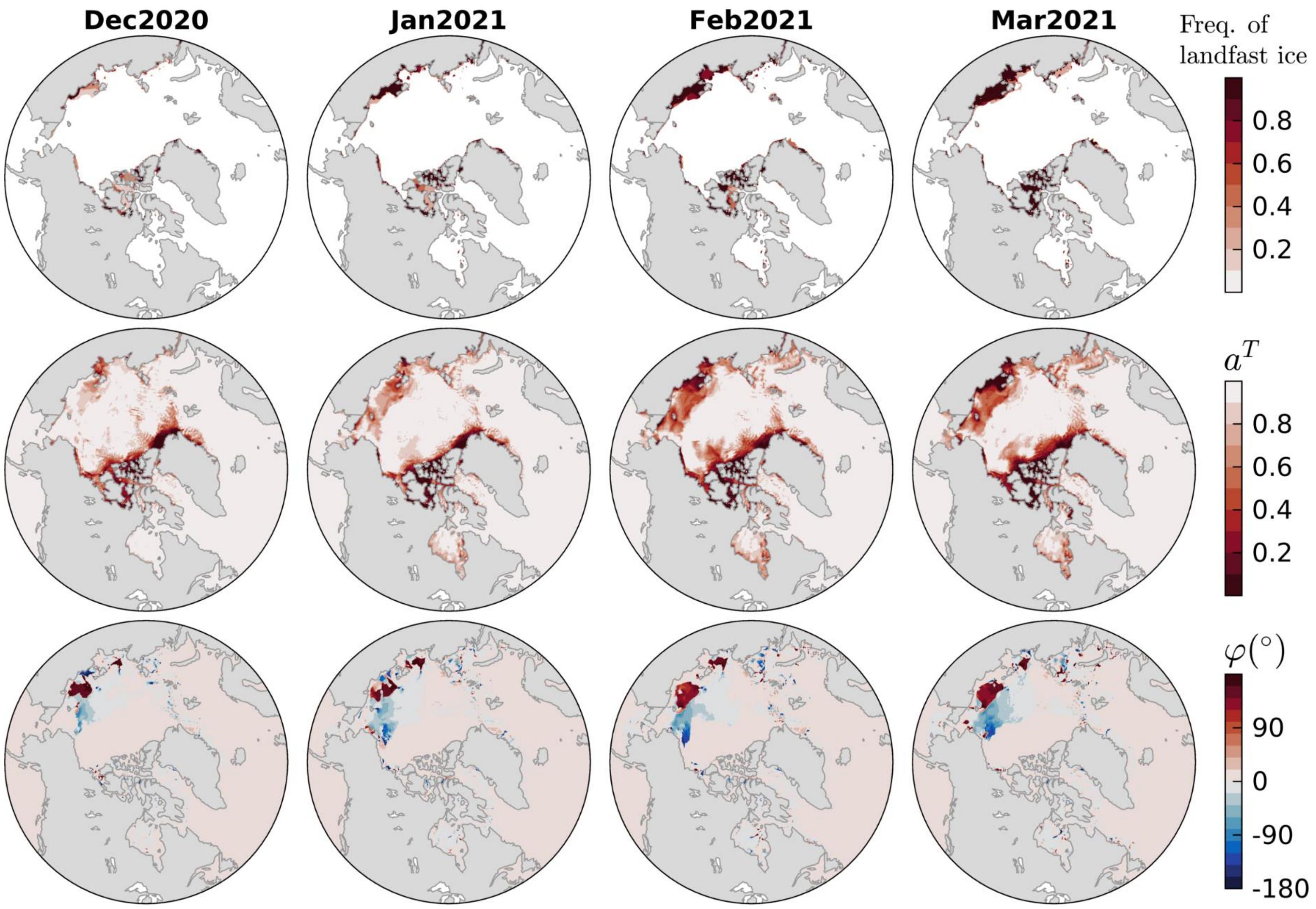
Derive a **transfer function** describing the response of $u^{\text{T}}_{\text{ice}}$ to $u^{\text{T}}_{\text{surf}}$,

$$\boldsymbol{u}^{\text{T}}_{\text{ice}} \approx a^{\text{T}}(\boldsymbol{x})\mathbf{R}(\varphi(\boldsymbol{x}))\boldsymbol{u}^{\text{T}}_{\text{surf}}$$

where a^T, φ are inferred from $u^{\text{T}*}_{\text{ice}}, u^{\text{T}*}_{\text{surf}}$ by scaling and rotating the ice and ocean tidal ellipses so that their semi-major axes are equal.



The asterisk * denotes a quantity that comes from an external ice-ocean model.



Observed frequency of landfast ice occurrence

Derived monthly a^T

landfast $a^T = 0$,

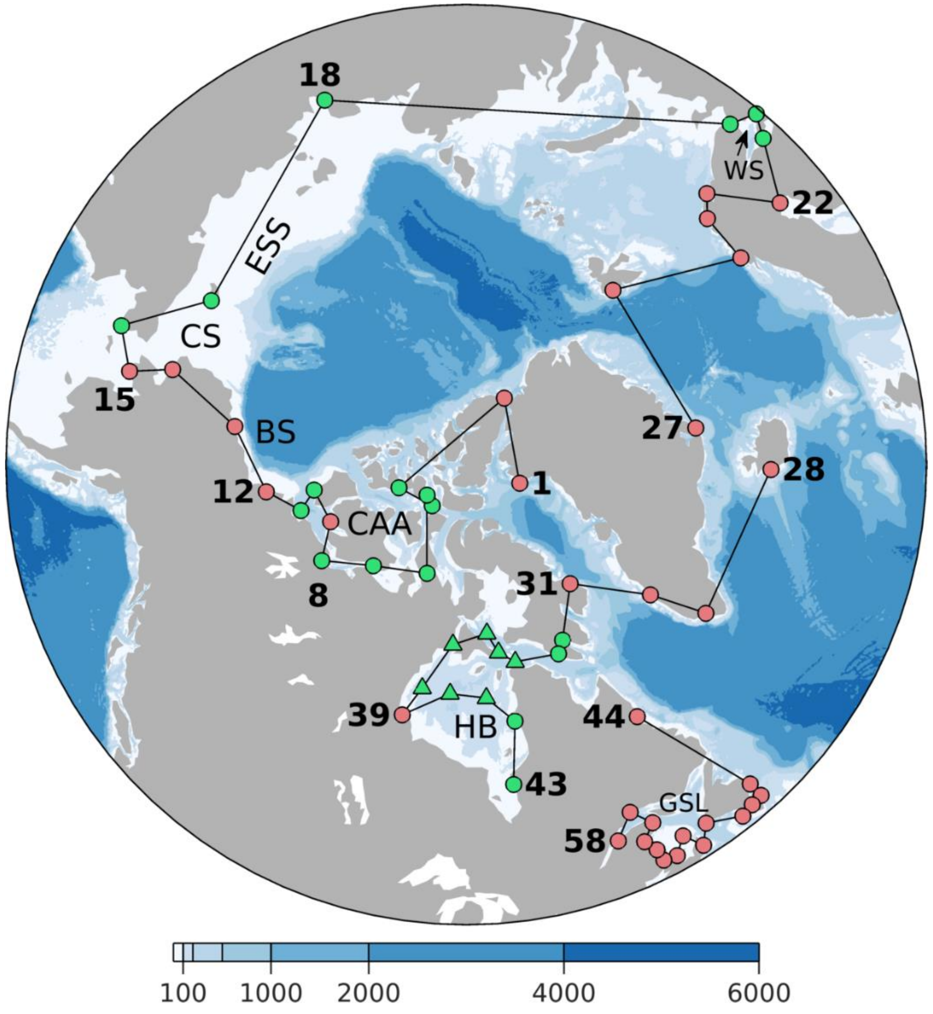
free drift $a^T = 1$.

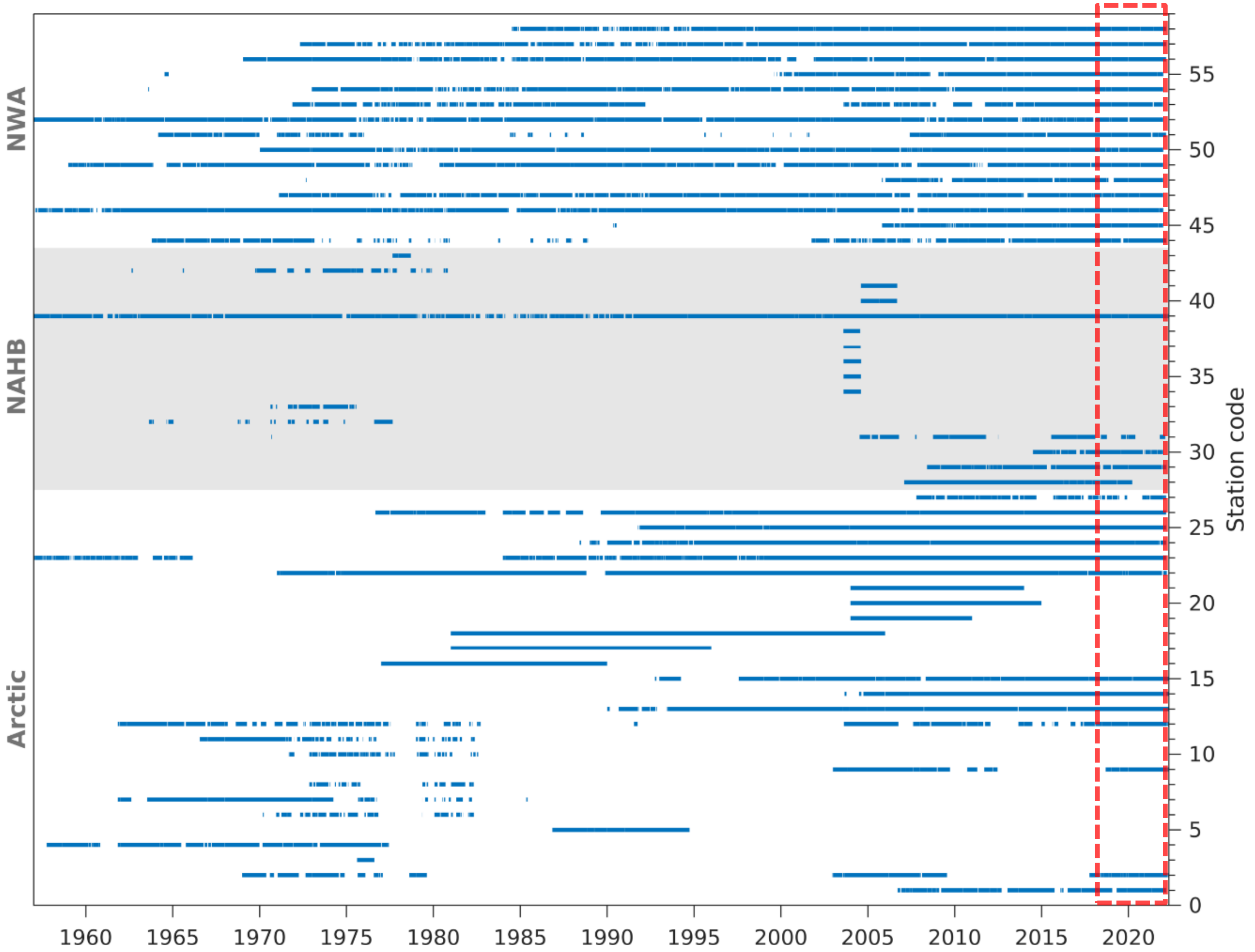
Derived monthly φ

Observations

Red: Data available in the model simulation period (Nov 2018-Apr 2022)

Green: Unavailable for Nov 2018-Apr 2022



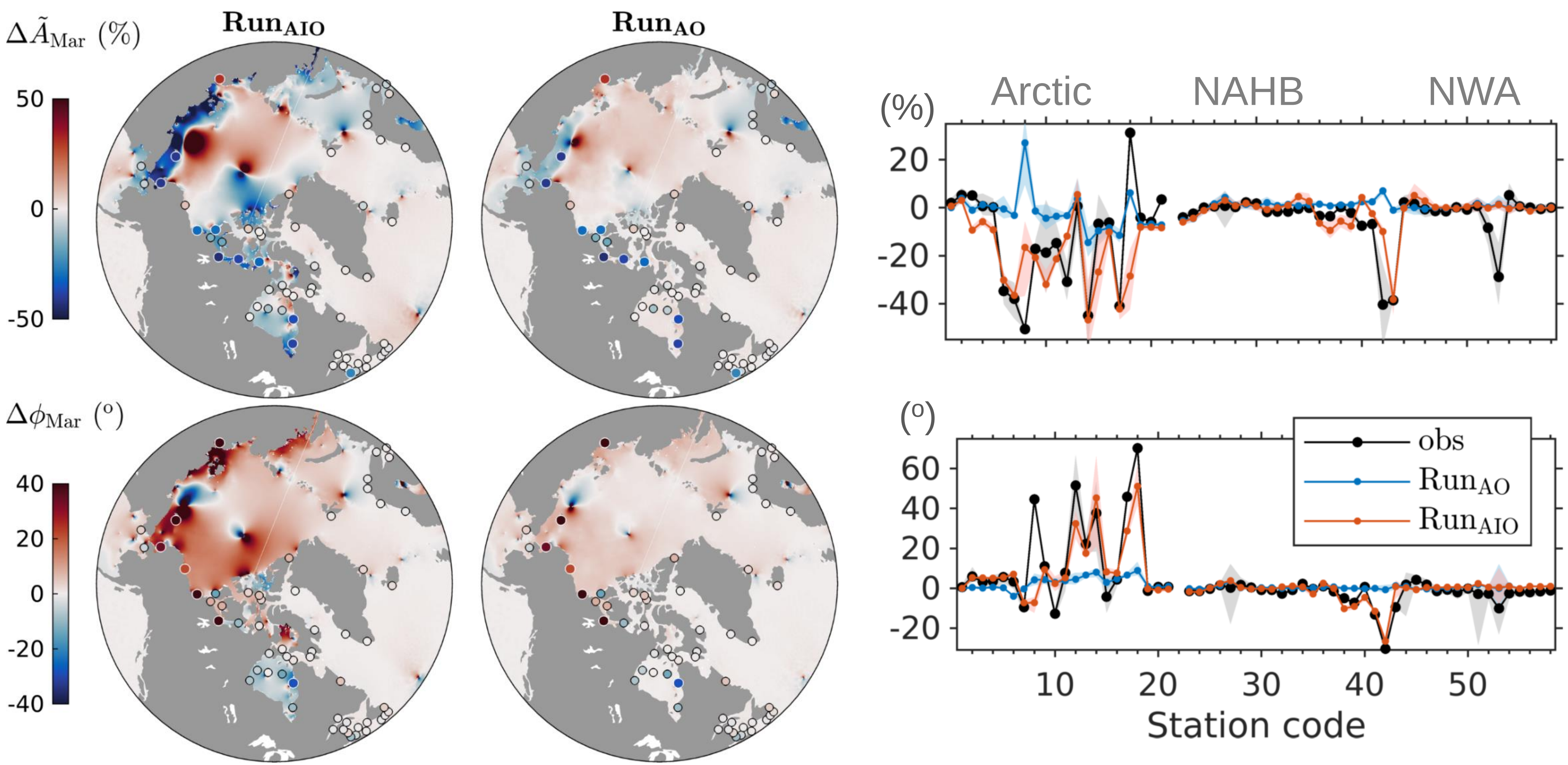


Ice effects on the max seasonal modulations in M_2 Amp (top) and Pha (bottom)

Air-Ice-Ocean Air-Ocean

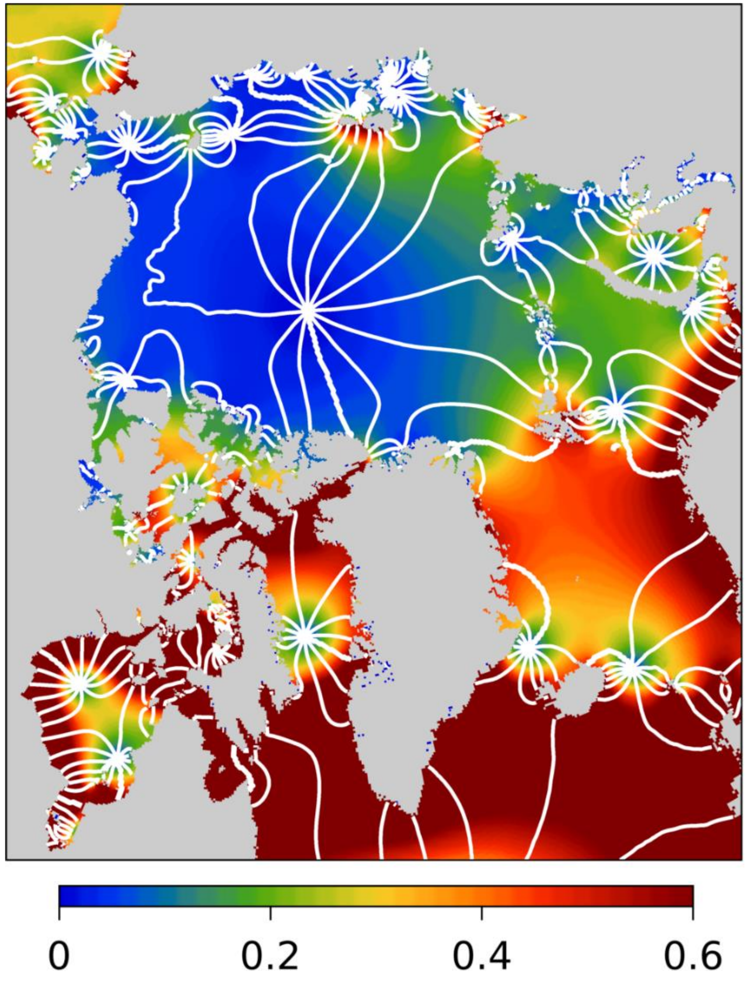
$$\frac{A_{\mathrm{Mar}} - A_{\mathrm{Sept}}}{A_{\mathrm{Sept}}}$$

$$\phi_{\mathrm{Mar}} - \phi_{\mathrm{Sept}}$$

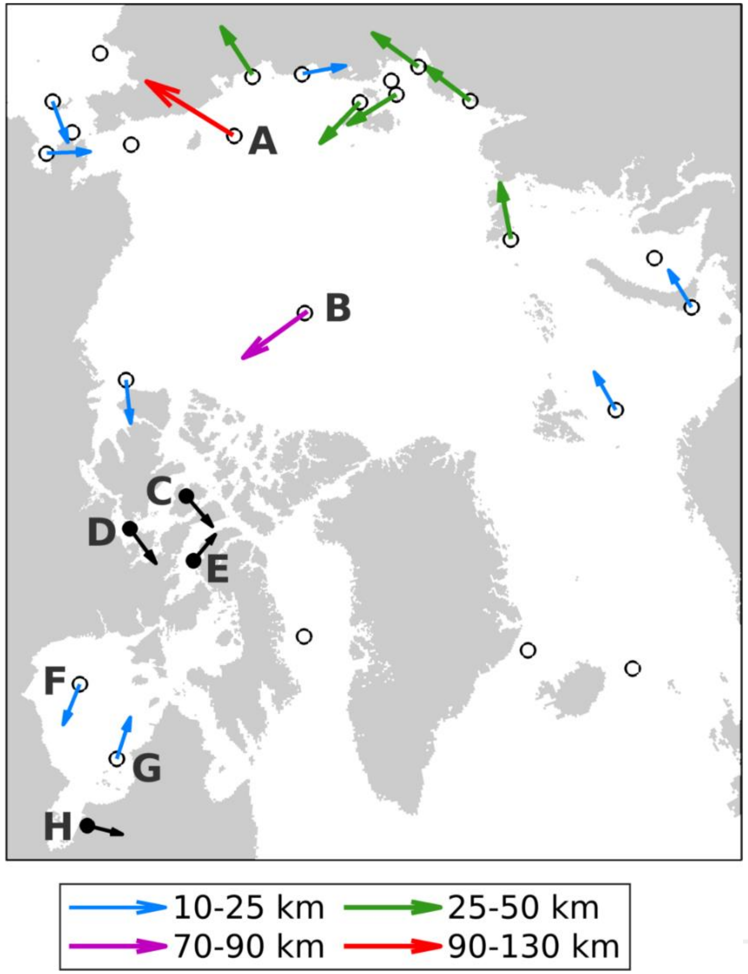


Ice-induced shifts of M_2 amphidromes

Color: amplitude
White lines: co-phase lines

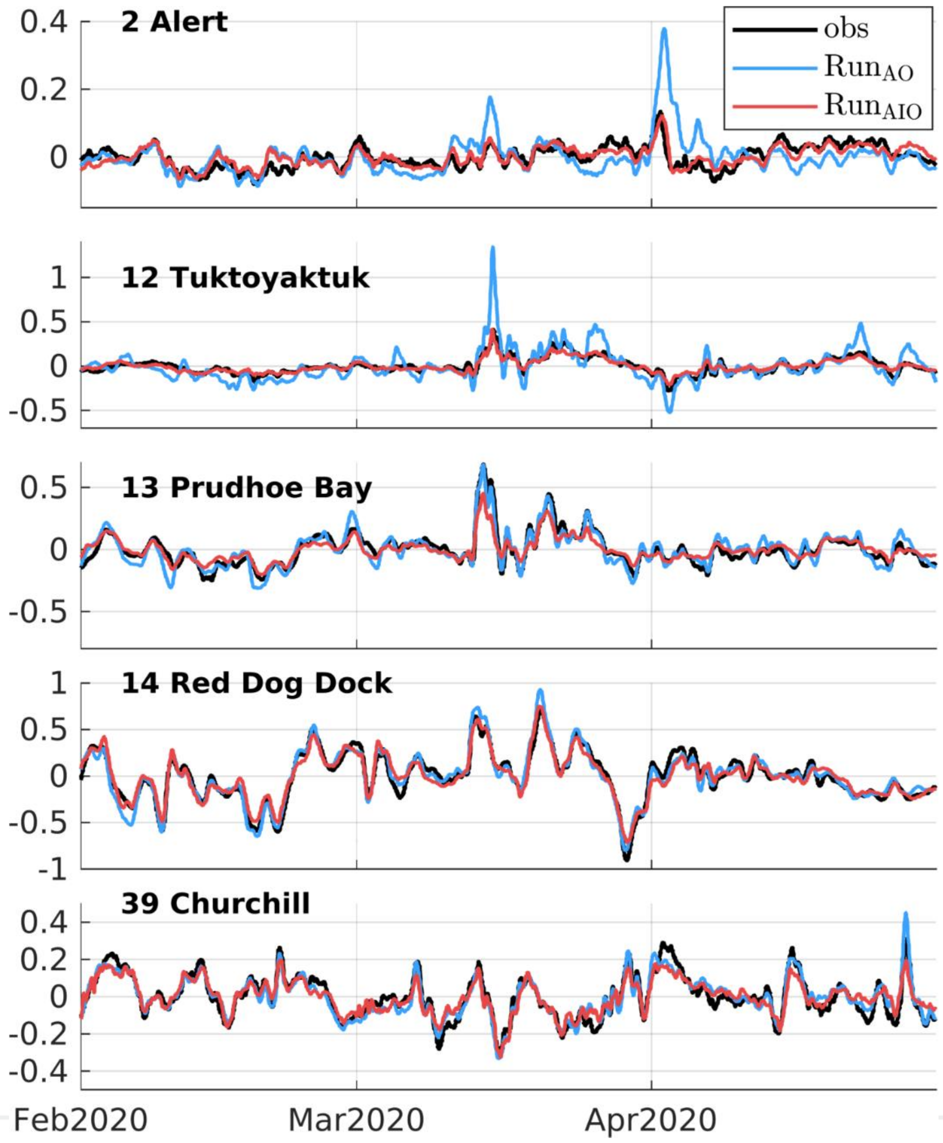


○ Amphidromes over ocean
● Amphidromes over land

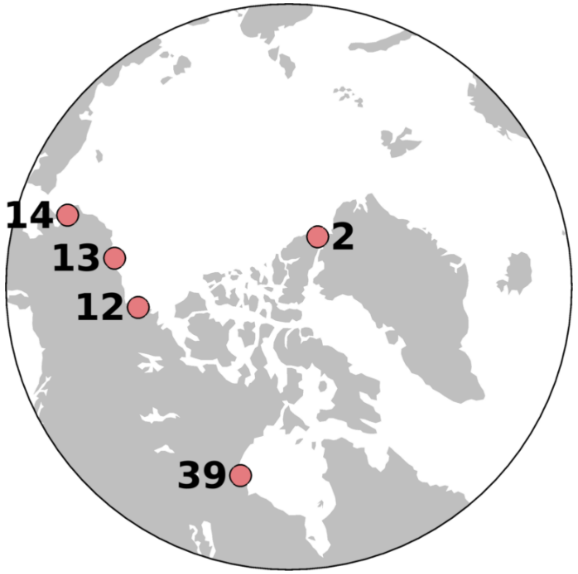


Amphidromes shift towards the coast where they experience stronger tidal dissipation, resulting in both positive and negative changes in amplitude and phase.

Sea ice effects on predicting storm surges



- Inverse barometer contribution removed from both OBS and MOD to better visualize ice effects.
- Ice-induced attenuation up to **0.25 m** at Alert, **1.0 m** at Tuktoyaktuk.



Summary

- **Efficient ways of adding baroclinicity and sea ice effects to TWL systems** are developed by taking advantage of external fields (3D T&S, ice fraction, ice velocity and surface currents) provided by advanced data-assimilative ice-ocean systems.
- **Adding baroclinicity** effectively captures variability on timescales of hours to seasons. Important contributions of baroclinically-modified CTWs (up to 42 cm) were shown to be resolved.
- **Adding ice effects** leads to significantly improved tides (seasonal changes) and surges (up to 1 m). Dominant driving mechanism for the seasonality of tide: under-ice friction, and its accompanied amphidrome shifts (up to 125 km).

References:

Wang, P., N.B. Bernier, and K.R. Thompson (2022). Adding baroclinicity to a global operational model for forecasting total water level: Approach and impact. *Ocean Modelling*, 102031. https://doi.org/10.1016/j.ocemod.2022.102031

Wang, P. and Bernier, N. B.: Adding Sea Ice Effects to A Global Operational Model (NEMO v3.6) for Forecasting Total Water Level: Approach and Impact, *Geosci. Model Dev.*, 2023. https://doi.org/10.5194/gmd-16-3335-2023