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

Pengcheng Wang and Natacha B. Bernier (ECCC)

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K. R. Thompson (Dalhousie University)

O. Huziy, B. Pouliot, F. Dupont (ECCC)

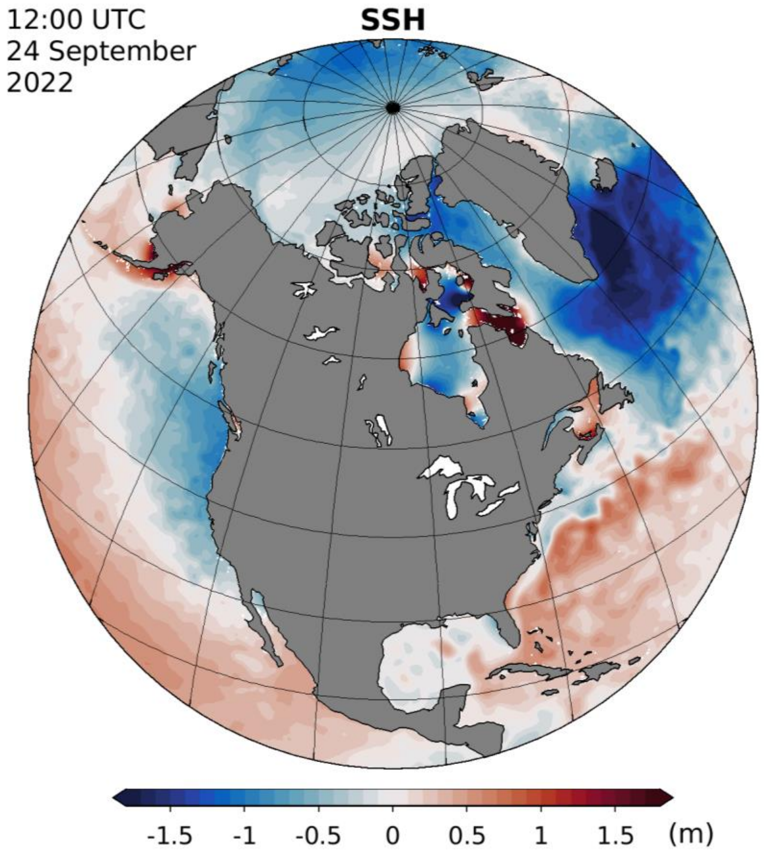
Introduction

- A global barotropic system (1/12°, NEMO) was recently developed at ECCC to provide total water level (TWL) forecast for all Canadian ocean coasts.

- Effects of **baroclinicity** and **sea ice** are typically neglected due to their computational cost and/or reliability.

- Address the two following questions:

1. **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?**
2. **What are their impacts on predicted water level?**



Baroclinicity

The Ocean Model (Global 1/12°, NEMO)

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

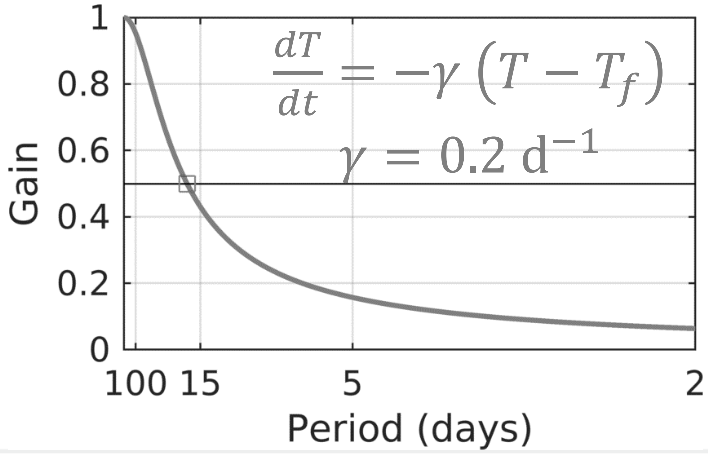
$$\left. + g \int_z^0 \frac{\rho - \rho_0}{\rho_0} dz \right] + A_h \nabla_h^2 \mathbf{u}_h + \frac{\partial}{\partial z}\left(A_z \frac{\partial \mathbf{u}_h}{\partial z}\right) + \lambda(\mathbf{x}) \langle \bar{\mathbf{u}}_{obs} - \bar{\mathbf{u}}_h \rangle$$

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

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

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

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).

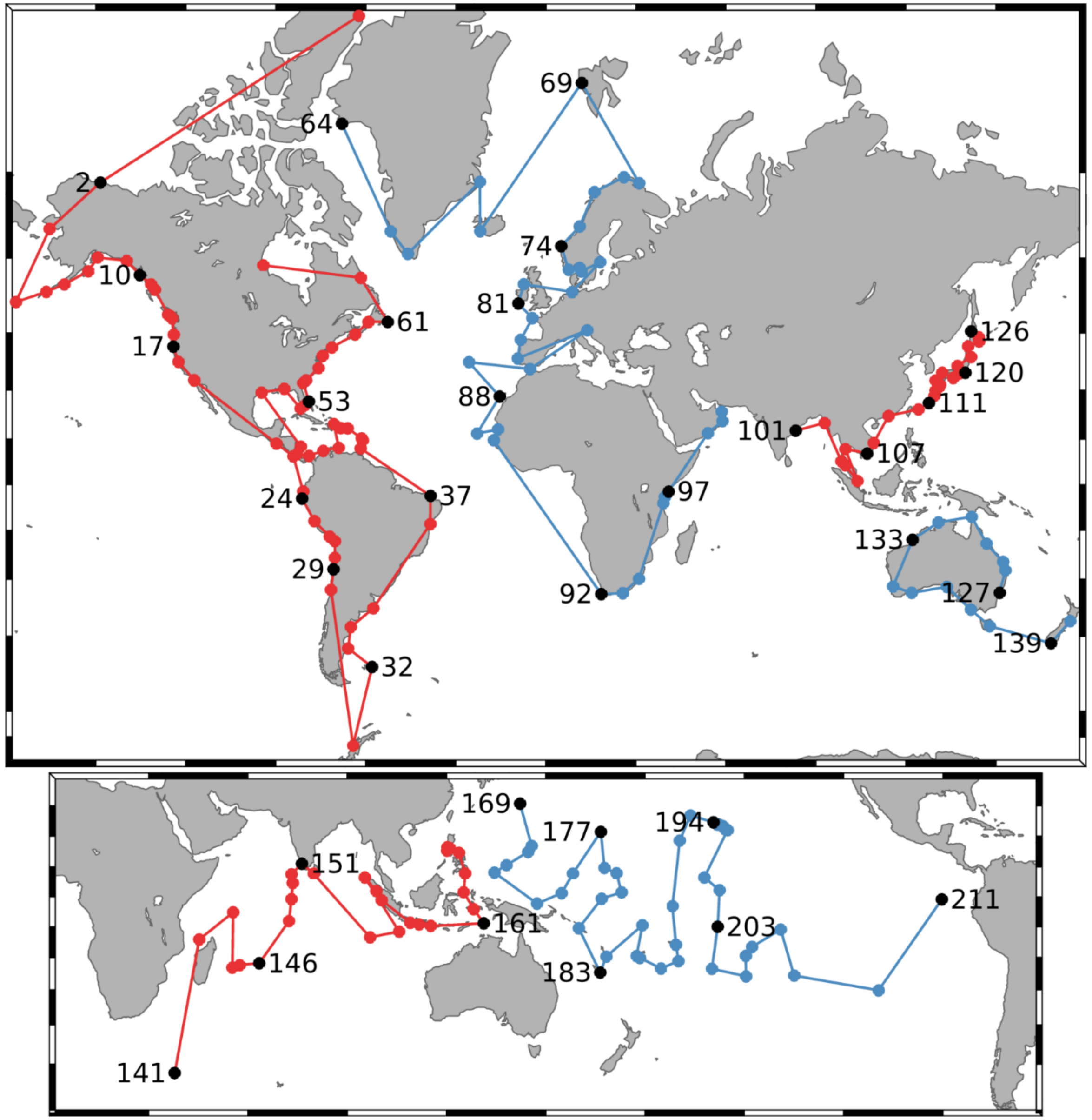


- At low frequencies (> ~15 d), T is guided by the 1/4° T_f.
- At high frequencies, T is less or not constrained by T_f.

Observations

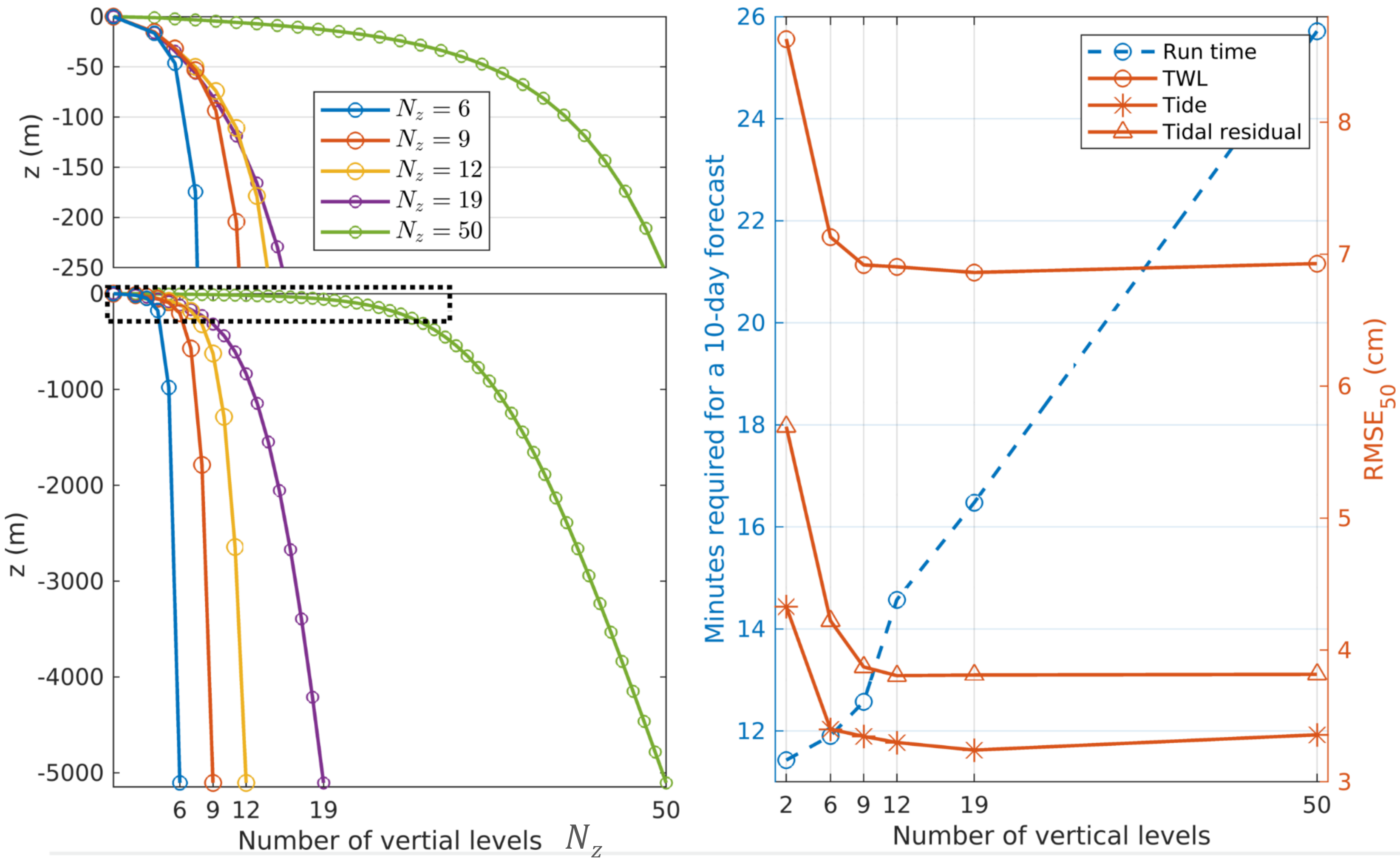
211 tide gauges from University of Hawaii Sea Level Center

Oct. 2019 - Feb. 2021



Capturing baroclinicity with an optimized vertical grid

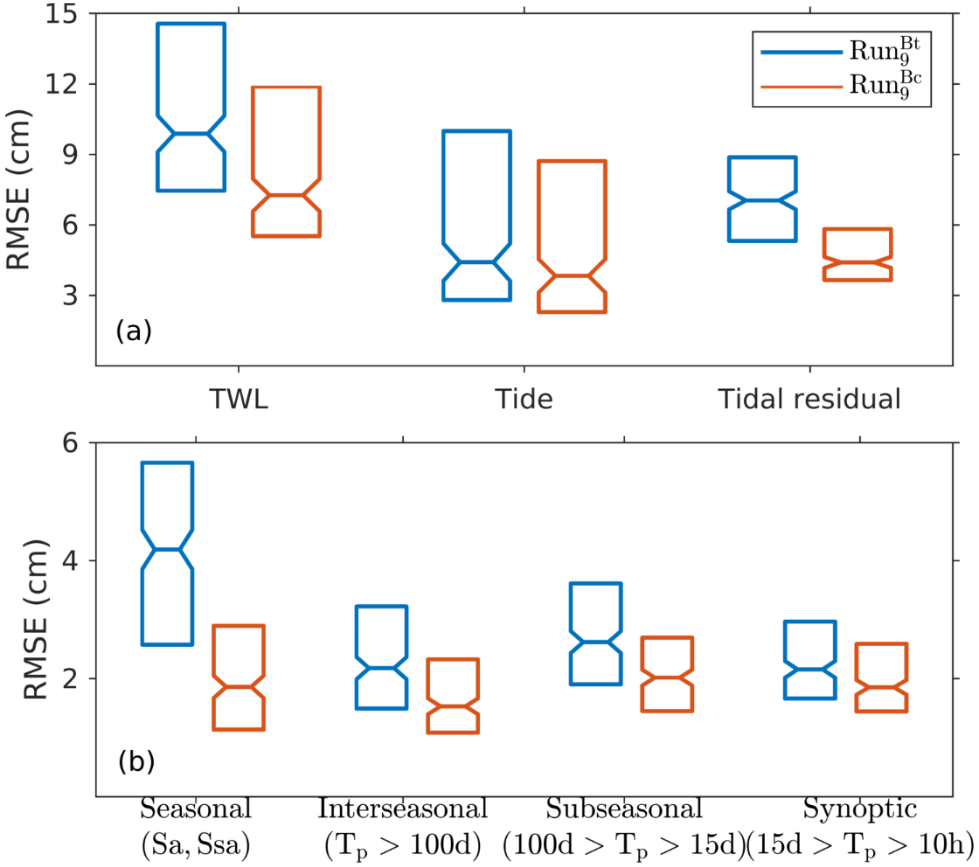
Balancing model performance and computational cost



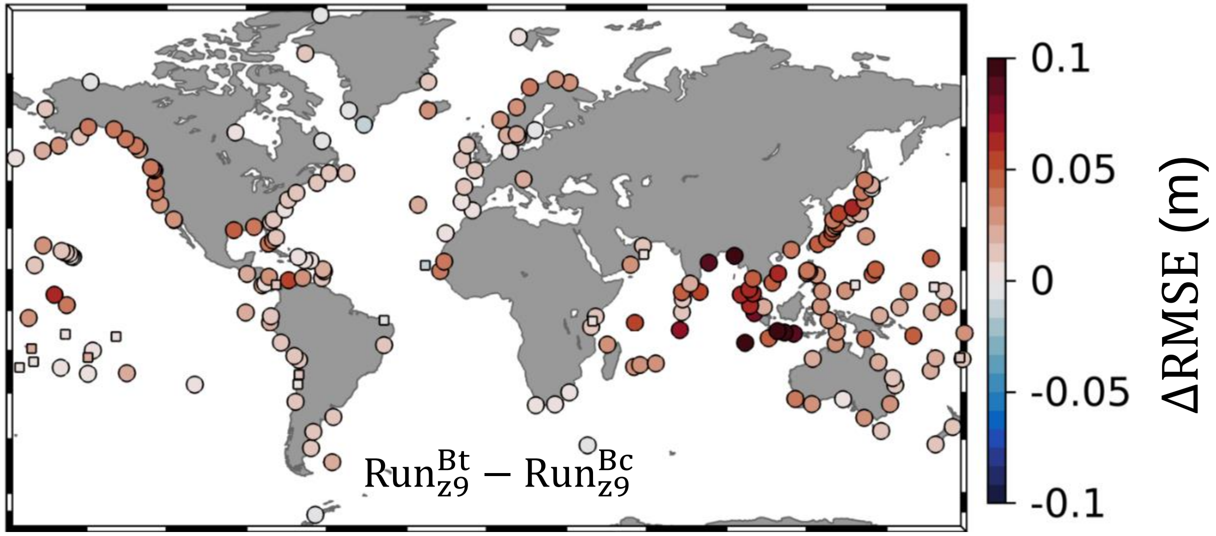
A 9-level configuration can sufficiently capture baroclinic effects at only 10% additional cost compared to the barotropic model.

Impact of adding baroclinicity on predicted water level

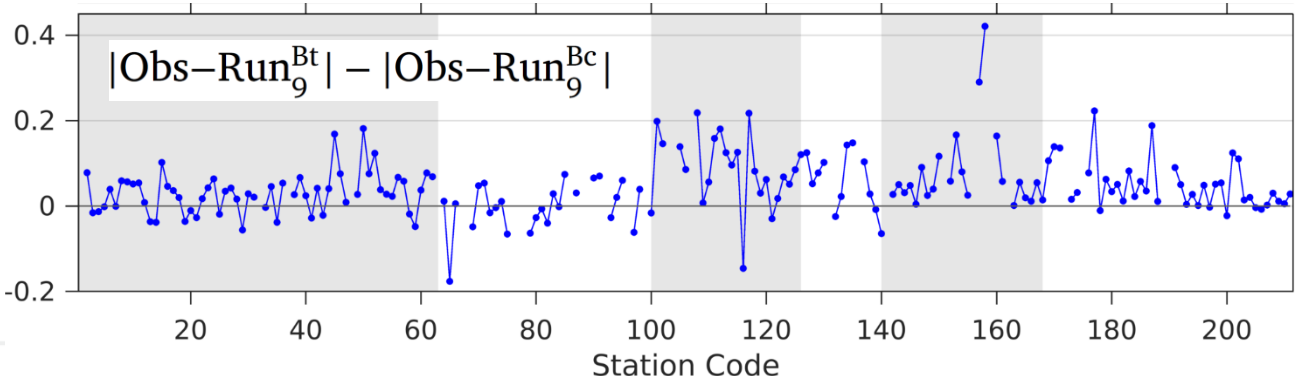
$\mathrm{Run}_9^{\mathrm{Bt}}$: barotropic run with 9 levels
$\mathrm{Run}_9^{\mathrm{Bc}}$: baroclinic run with 9 levels



Improvements in residuals (ΔRMSE)

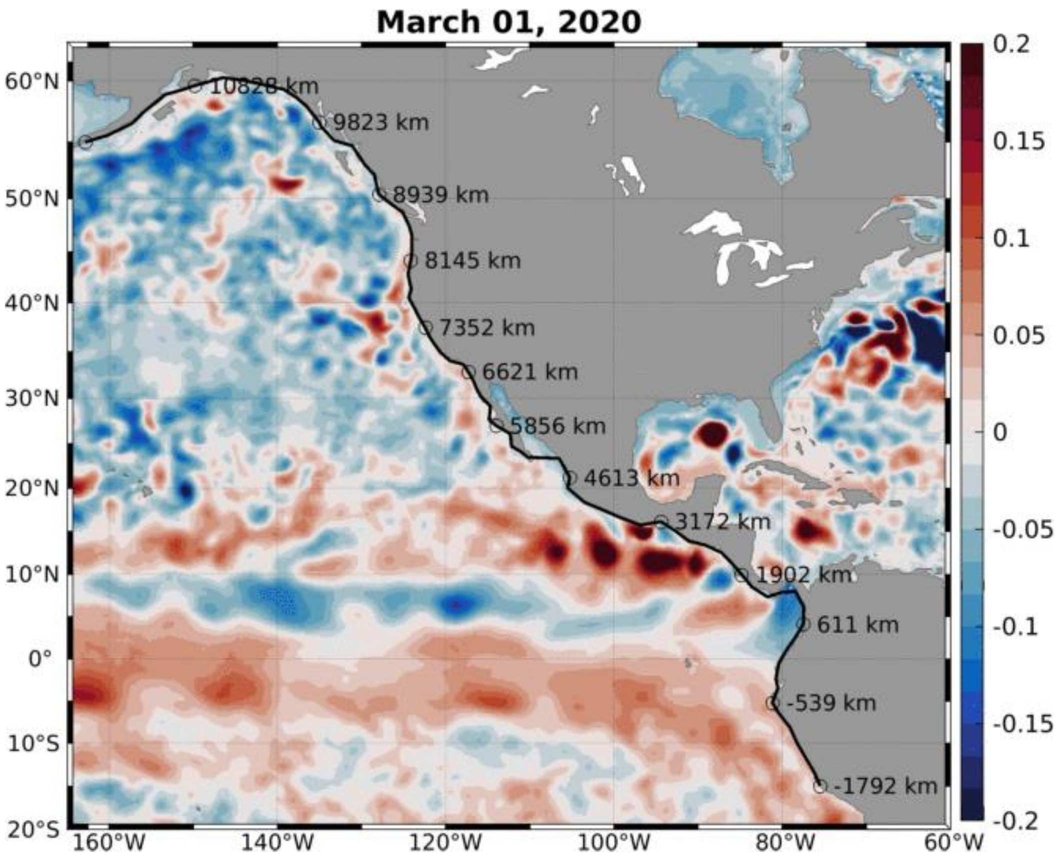


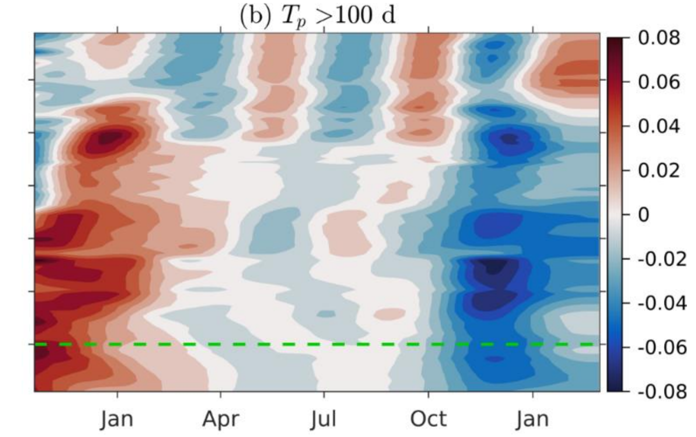
Improvements in extremes



The role of coastal trapped waves

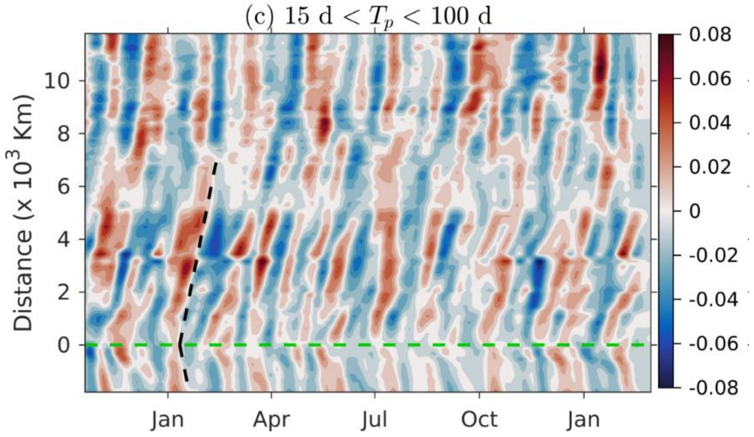
Difference in tidal residuals predicted by $\mathrm{Run}_9^{\mathrm{Bc}}$ and $\mathrm{Run}_9^{\mathrm{Bt}}$ (henceforth $\Delta\boldsymbol{\eta}_{\boldsymbol{bc-bt}}$)


March 01, 2020


(b) T_p >100 d

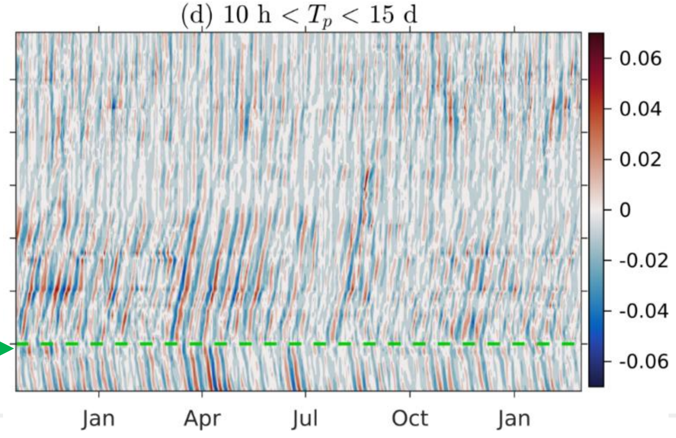
Biennial variability of ENSO

(Rasmussonet al., 1990)


(c) 15 d < T_p < 100 d

MJO

(Oliver and Thompson, 2010)


(d) 10 h < T_p < 15 d

Equator

Rossby-gravity waves

(Enfield et al., 1987)

Sea ice effects

Parameterized ice-ocean stress

landfast $a^T = 0$,

free drift $a^T = 1$.

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

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

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

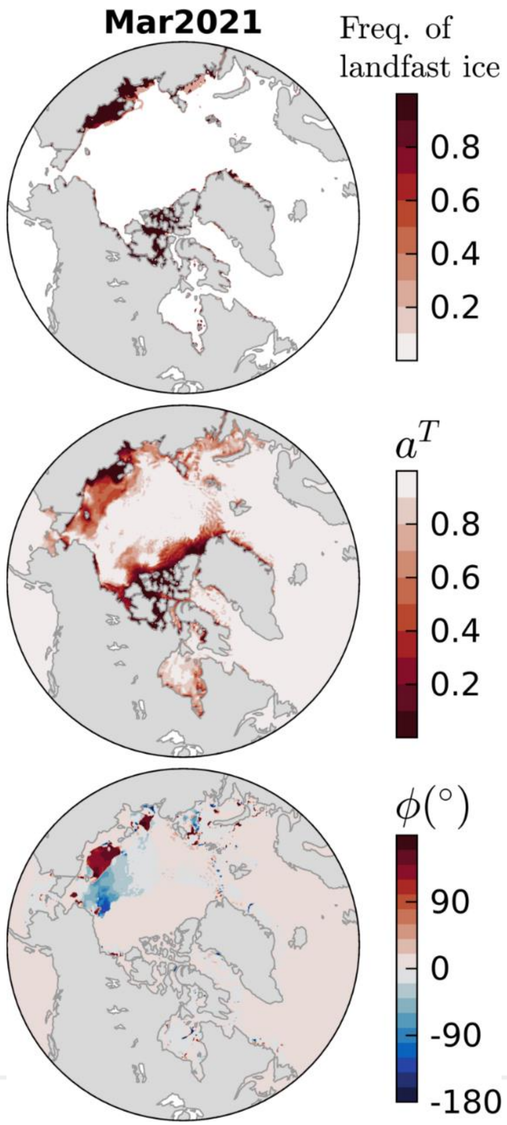
$$= [a^{\mathrm{T}}(\boldsymbol{x})\mathbf{R}(\varphi(\boldsymbol{x})) - \mathbf{I}]\boldsymbol{u}^{\mathrm{T}}_{\mathrm{surf}} + a^{\mathrm{S}}(\boldsymbol{u}^{\mathrm{S}*}_{\mathrm{ice}} - \boldsymbol{u}^{\mathrm{S}*}_{\mathrm{surf}})$$

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

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

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

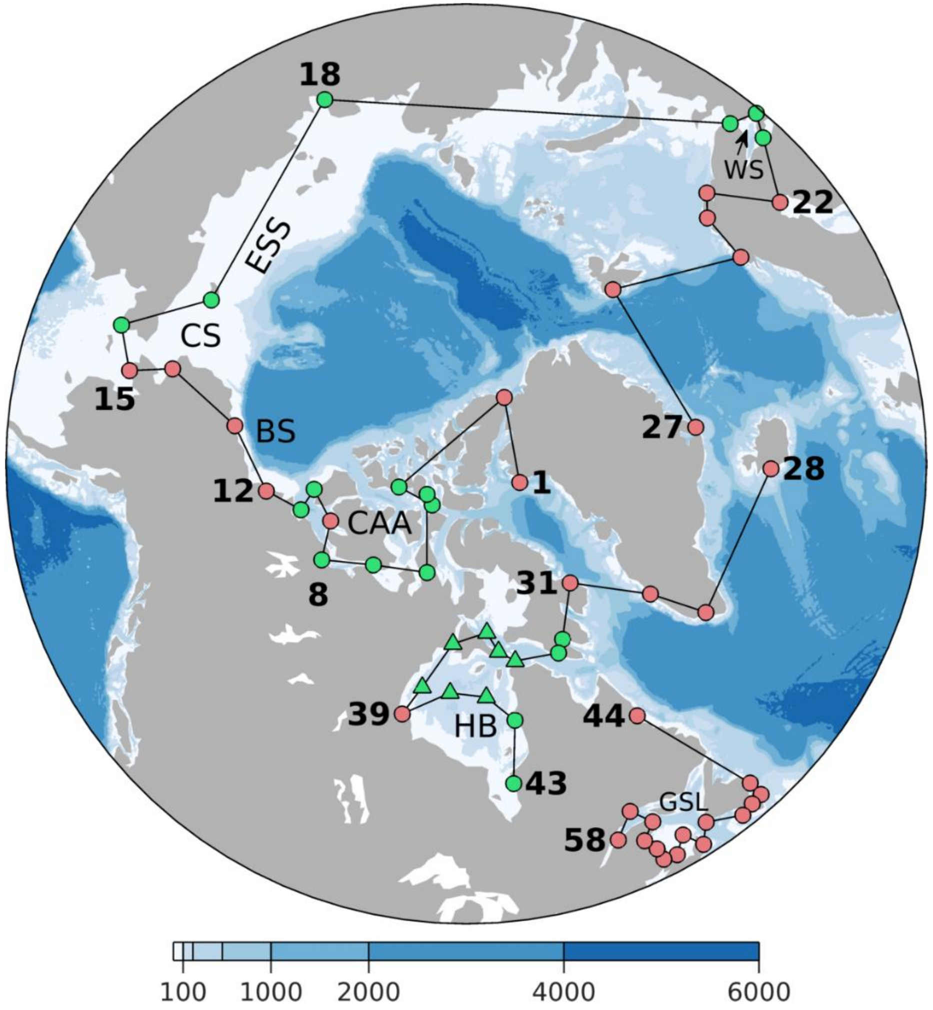
The asterisk * denotes a quantity that comes from an external ice-ocean model.

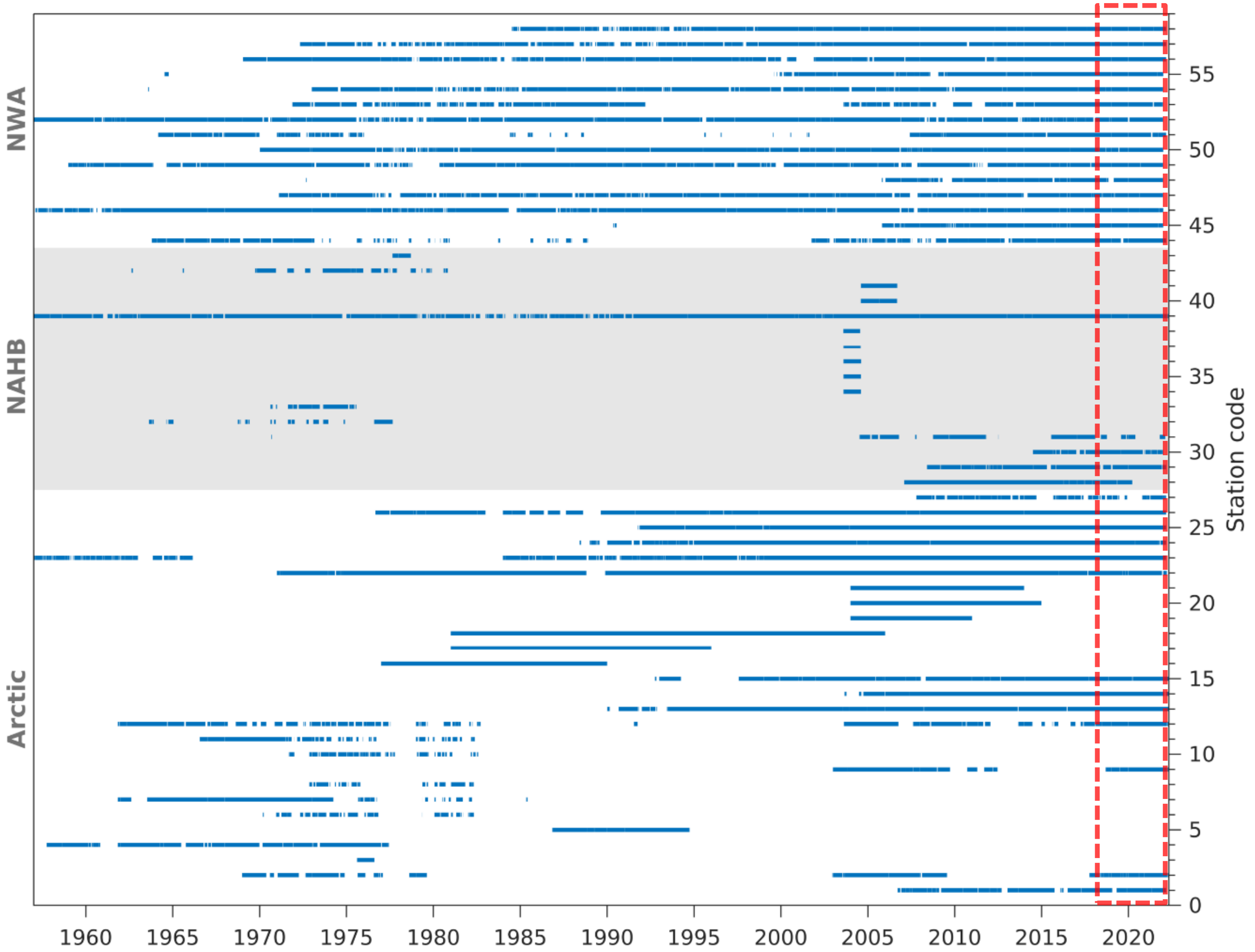


Observations

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

Green: Unavailable for Nov 2018-Apr 2022



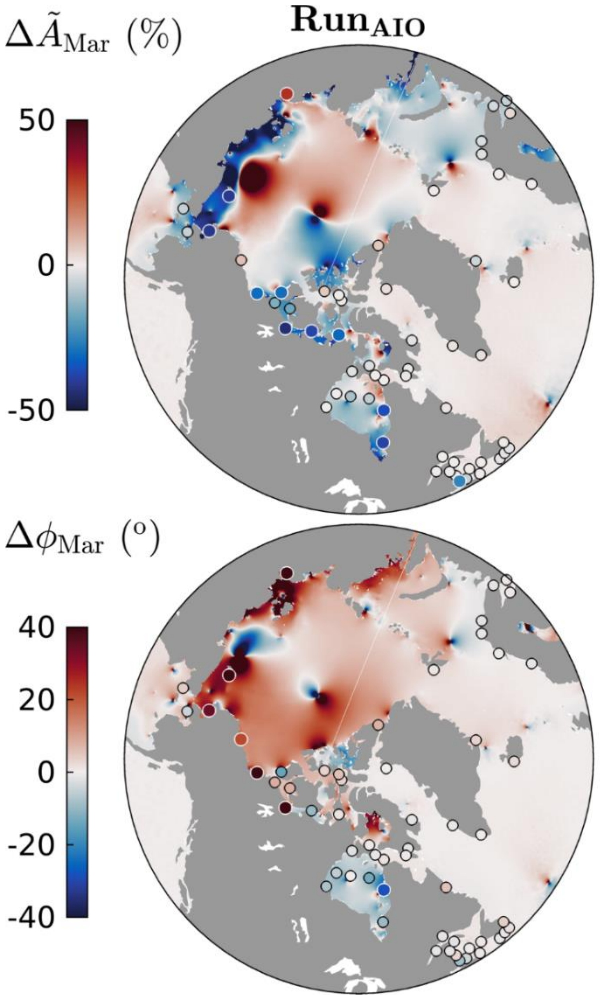


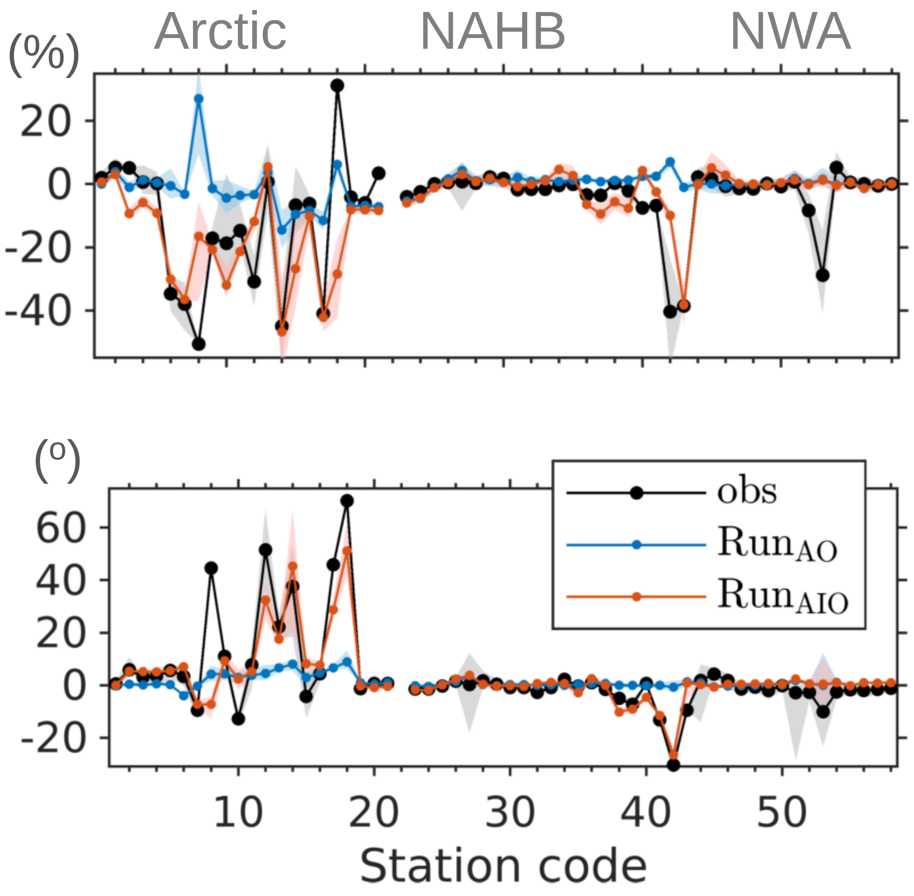
Ice effects on the max seasonal modulations in M_2 Amp (top) and Pha (bottom)

Air-Ice-Ocean

Air-Ocean

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



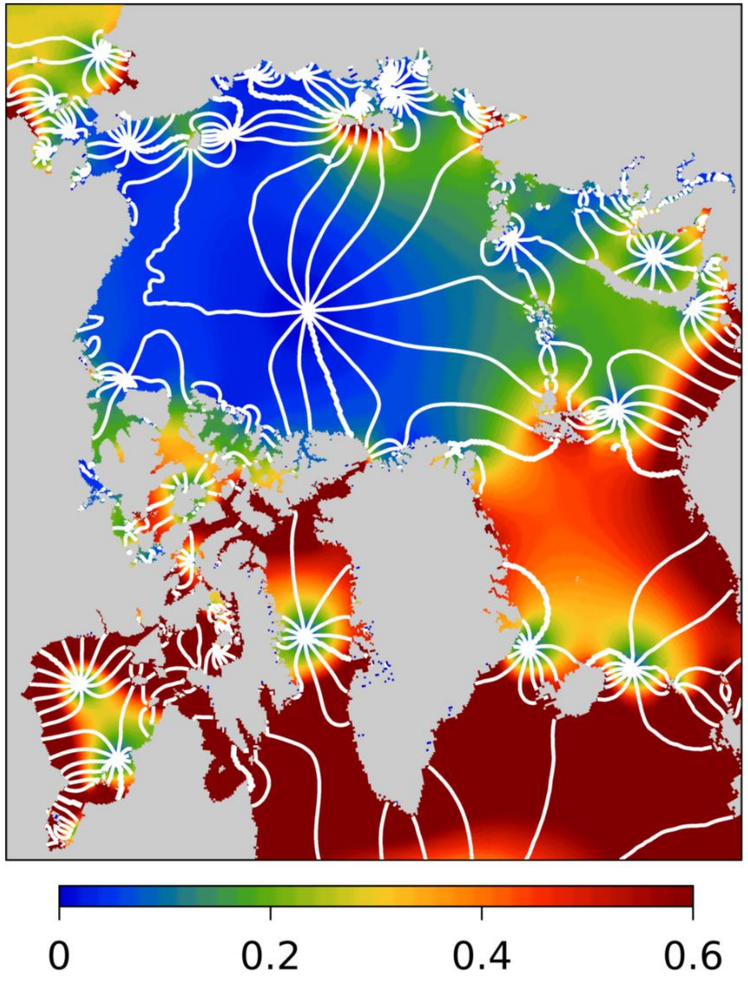


$$\phi_{\mathrm{Mar}} - \phi_{\mathrm{Sept}}$$

Ice-induced shifts of M_2 amphidromes

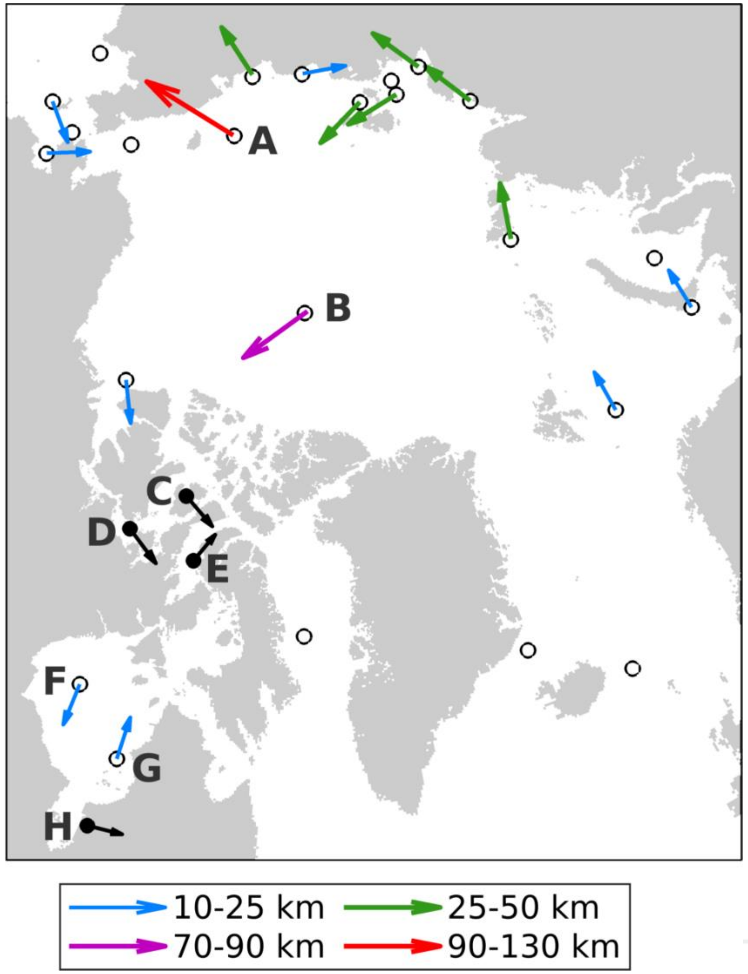
Color: amplitude

White lines: co-phase lines



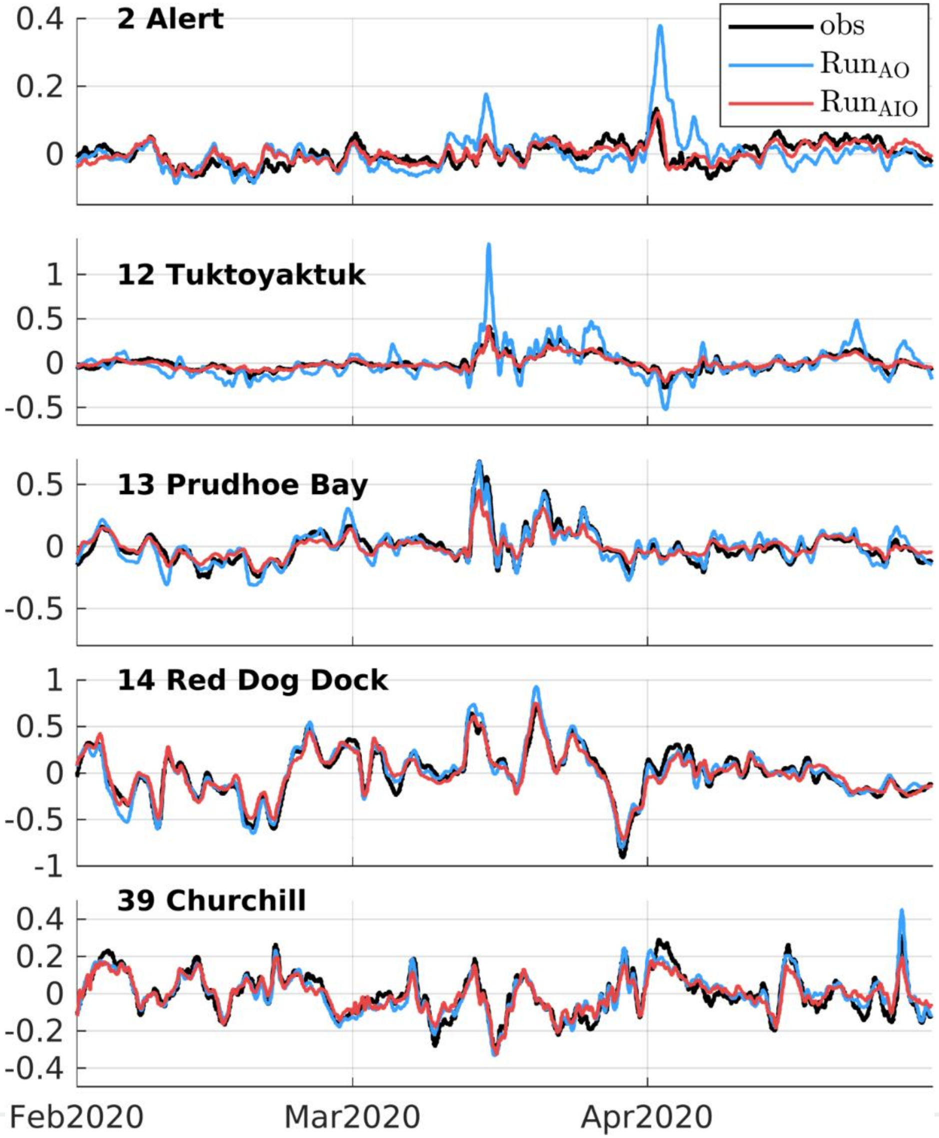
○ Amphidromes over ocean

● Amphidromes over land

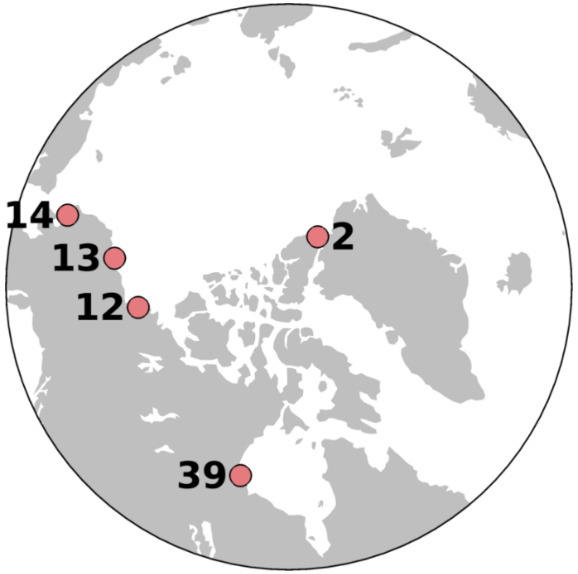


- Indirect effects of friction via amphidrome shifts cause both positive and negative changes in amplitude and phase.
- In a semi-enclosed bay, the system generally shifts towards the coast where reflected waves travel.

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 models.
- **Adding baroclinicity** effectively captures variability on timescales of hours to seasons. Important contributions of baroclinically-modified coastal trapped waves 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. Discuss.* [preprint], in review, 2023. https://doi.org/10.5194/gmd-2023-18