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Adding sea ice effects to a global operational model (NEMO v3.6) for forecasting total water level: approach and impact

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Summary of seasonal modulations for M_2, S_2, K_1 and O_1

Figure S1 (right two columns) summarizes the observed and predicted seasonal modulations in March relative to September ($\Delta\tilde{A}_{\text{Mar}}$, $\Delta\phi_{\text{Mar}}$) as a function of station code for four major tidal constituents (M_2, S_2, K_1 and O_1). For reference, the amplitudes in September are also given in the left column. The impact of adding ice effects on S_2 is very similar to that on M_2 (top two rows; see main text for details). We note that the seasonal modulation of S_2 also has a non-negligible astronomical contribution from its neighbouring constituent T_2, which has one cycle per year (cpy) below S_2. The amplitude of the astronomical T_2 is about 5.8% of S_2 (Cartwright and Tayler, 1971). The superposition of S_2 and T_2 explains the bulk of the observed $\Delta\tilde{A}_{\text{Mar}}$ (middle colum, second row) of about 7% for S_2 at stations 47-52 and 54-58 in the Gulf of St. Lawrence (We note that at station 53, the signal is also present but the SNR is below 2 and thus neglected). This modulation is missed by our model as it does not include T_2.

The impacts of adding ice effects for K_1 and O_1 (bottom two rows) are also similar. Large improvements (20–40% in amplitude, 15–40° in phase) are found at station 18 in the Russian Arctic, and stations 6–8 in the CAA except for an overestimated $\Delta\tilde{A}_{\text{Mar}}$ for O_1 at station 8. Adding ice effects also improves the phase modulation (15–30°) at Nome, Alaska (station 15), but the predicted amplitude modulations are underestimated by about 35% for both K_1 and O_1. Egbert and Ray (2017) showed that the non-tidal variability at Nome is large compared to tides, implying potential effects of the nonlinear tide-surge interaction (TSI). We speculate that the observed large modulations of K_1 and O_1 are affected by both sea ice and the TSI. Both are not well captured locally (the model underestimates the amplitudes of K_1 and O_1, by up to half in ice-free months). It is also interesting to note that in contrast, the semidiurnal tides do not display large modulations. This may be attributed in part to the more complex semidiurnal amphidrome systems over this region (see the left panel of Fig. 9 in the main text), characterized with smaller wavelength than diurnal tides.

For other stations, the impact of adding ice effects is generally negligible, and there are no significant modulations for O_1 in both observations and predictions. K_1, however, is more complicated: observations show moderate amplitude modulations (7-20%) along the Norwegian coast (stations 23–26), in the HB (stations 37–40) and the Gulf of St. Lawrence (stations 48–58), which are missed or underestimated by both model runs. A year-long analysis of observed TWL reveals anomalously high energy (up to 12% of K_1) at neighbouring constituents S_1 and ψ_1, each 1 cpy from K_1. As the astronomical S_1 and ψ_1 are known to be small (Ray et al., 2021), the cause is likely due to other processes (e.g., shallow water processes and climate processes, Ray, 2022) that are not fully captured in our model.

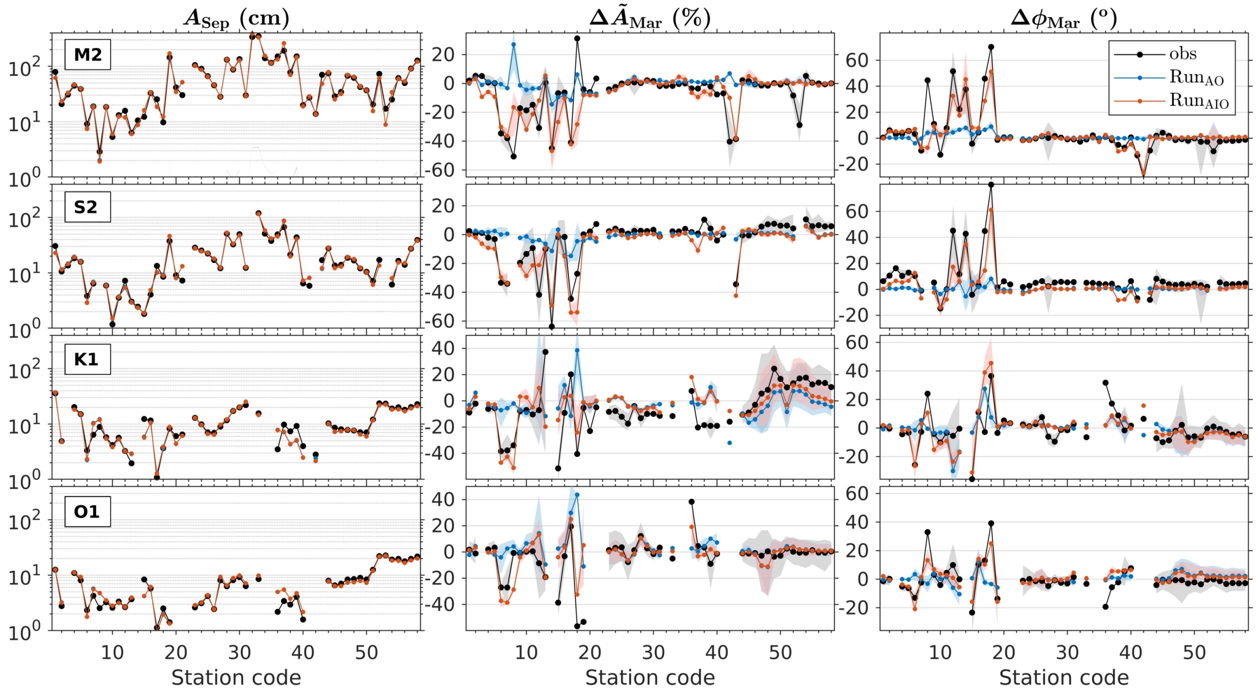

Figure S1. Tidal amplitude in September (A_{Sep}, left panels), the modulation in amplitude ($\Delta\tilde{A}_{\mathrm{Mar}}$, middle panels) and phase ($\Delta\phi_{\mathrm{Mar}}$, right panels) in March relative to September for four major tidal constituents (M_2, S_2, K_1, and O_1) observed and predicted by $\mathrm{Run_{AO}}$ and $\mathrm{Run_{AIO}}$ (see Fig. 1 for station code). Shaded area indicates the 10-90 percentile range. Only stations with SNR greater than 2 are plotted.

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