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Evaluation of A Global Total Water Level Model in the Presence of Radiational S_2 Tide

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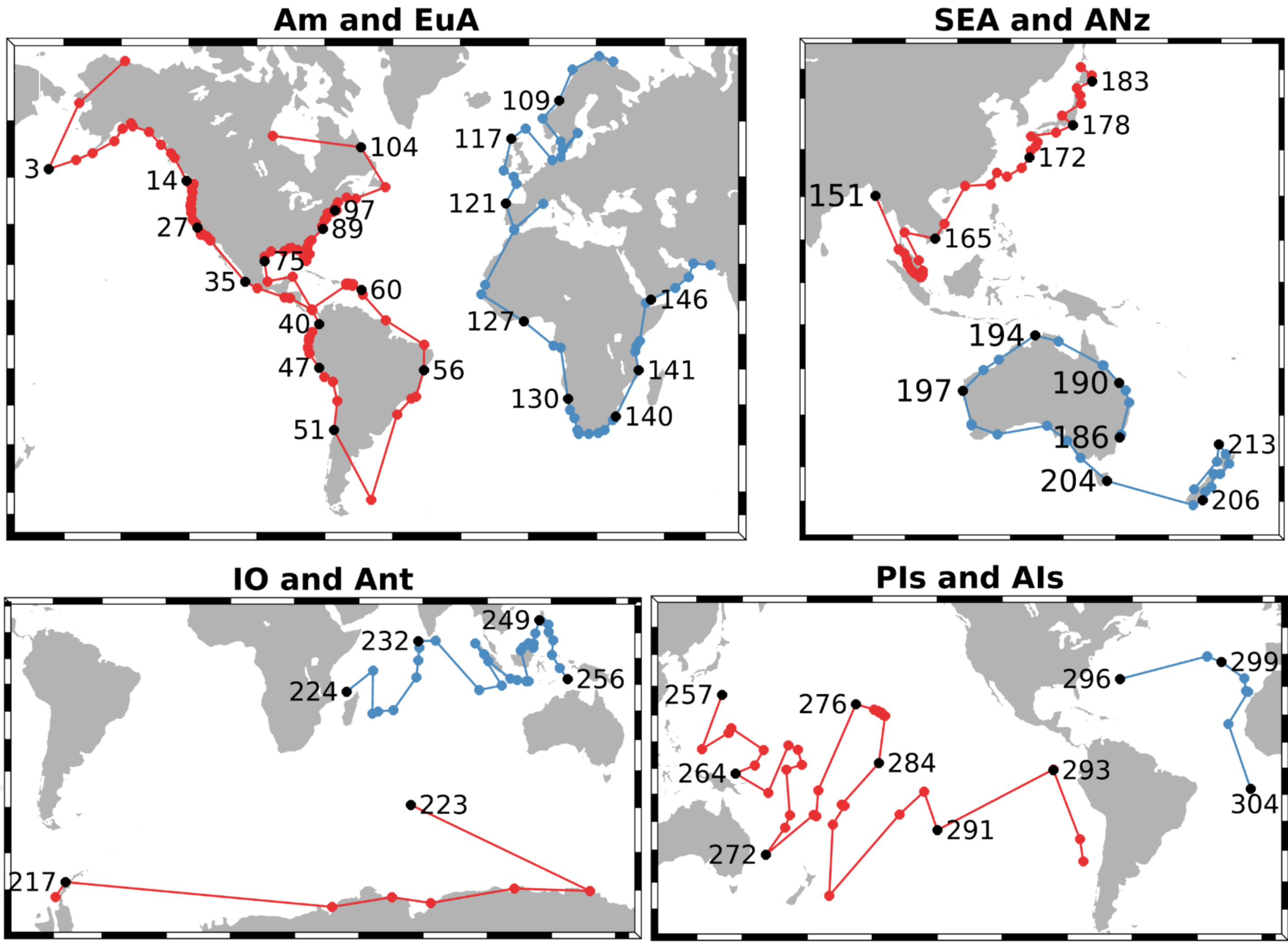
MOTIVATION

- Need for total water level (TWL) forecast for the benefits of Canadians
- Need for a global model
  - Allow enough room to resolve important coastal wave guides
  - Allow the inclusion of global processes (e.g., the oceanic response to atmospheric S_2 forcing over the tropics)
- Address the two following questions
  - How can we best predict tides using a model with limited spatial resolution? “Tidal nudging”?
  - What is the impact of neglecting nonlinear interactions on TWL prediction by a global model forced by hourly forcing?

OBSERVATIONS

- TPXO8 (M2, S2, N2, K2, K1, O1, P1, and Q1)
- Tide gauge data from UHSLC in the year 2008



MODEL: GOVERNING EQUATIONS

Nudging U

Self-attraction and loading

$$\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u} \cdot \nabla \boldsymbol{u} + \boldsymbol{f} \times \boldsymbol{u} = -g\nabla((1-\alpha_s)\eta - \eta_A) + A\nabla^2 \boldsymbol{u}$$

$$+ \frac{\boldsymbol{\tau}_s - \boldsymbol{\tau}_b}{\rho H} - \frac{1}{\rho}\nabla p_a - c_{iw}\boldsymbol{u} + \lambda(\boldsymbol{x})\langle \boldsymbol{u}_{obs} - \boldsymbol{u} \rangle$$

Internal wave drag

(This study)

$$\frac{\partial \eta}{\partial t} + \nabla \cdot (H\boldsymbol{u}) = 0$$

$$\boldsymbol{u}_{obs} = \frac{\text{Transport(TPXO8)}}{\text{Depth(NEMO)}}$$

Nudging η

$$\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u} \cdot \nabla \boldsymbol{u} + \boldsymbol{f} \times \boldsymbol{u} = -g\nabla((1-\alpha_s)\eta - \eta_A) + A\nabla^2 \boldsymbol{u}$$

$$+ \frac{\boldsymbol{\tau}_s - \boldsymbol{\tau}_b}{\rho H} - \frac{1}{\rho}\nabla p_a - c_{iw}\boldsymbol{u}$$

$$\frac{\partial \eta}{\partial t} + \nabla \cdot (H\boldsymbol{u}) = \lambda(\boldsymbol{x})\langle \eta_{obs} - \eta \rangle$$

(Kodaira et al., 2019)

Model setup based on NEMO

1/4°
Too coarse to predict tides and surges

1/12°
Acceptable tide and surge predictions on a global scale

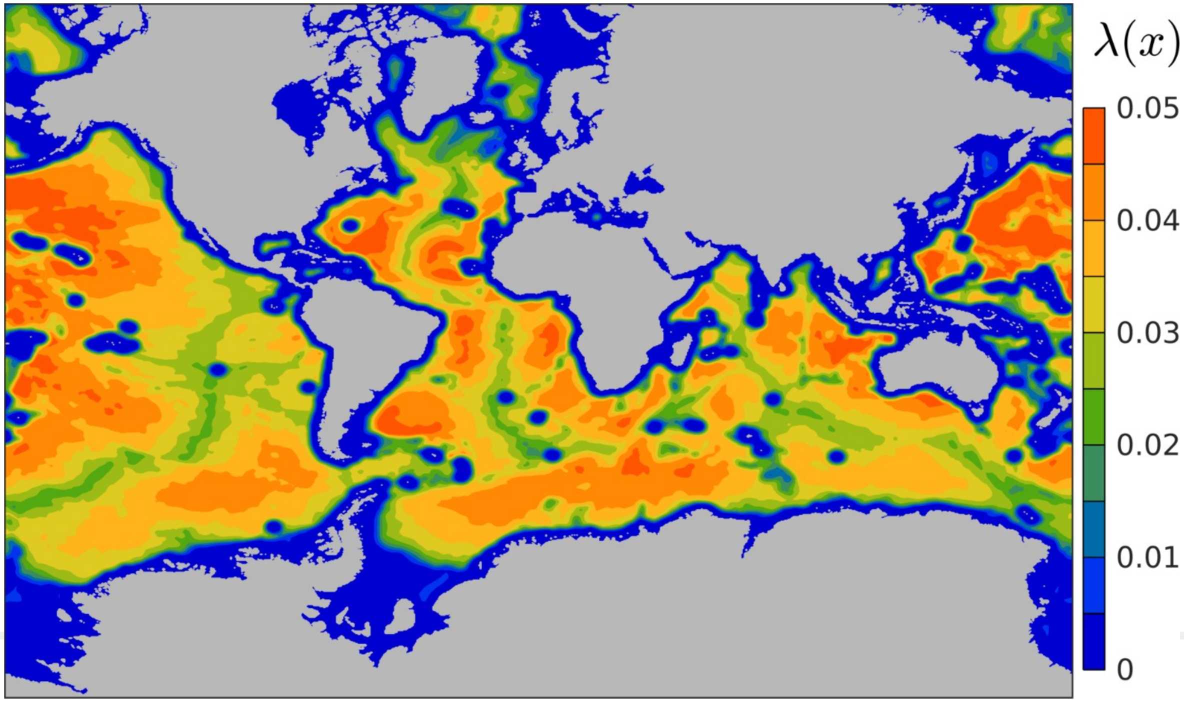
1/36°
Only localized improvements at a considerable increase in cost

- Self-attraction and loading, internal wave drag (Kodaira et al., 2016)
- Surface wind stress formula (Bernier and Thompson, 2007)
- ORCA12 → eORCA12 grid: allow tidal propagation under ice shelves in the Ross Sea and Weddell Sea
- Tidal nudging

Spatial distribution of the nudging coefficient

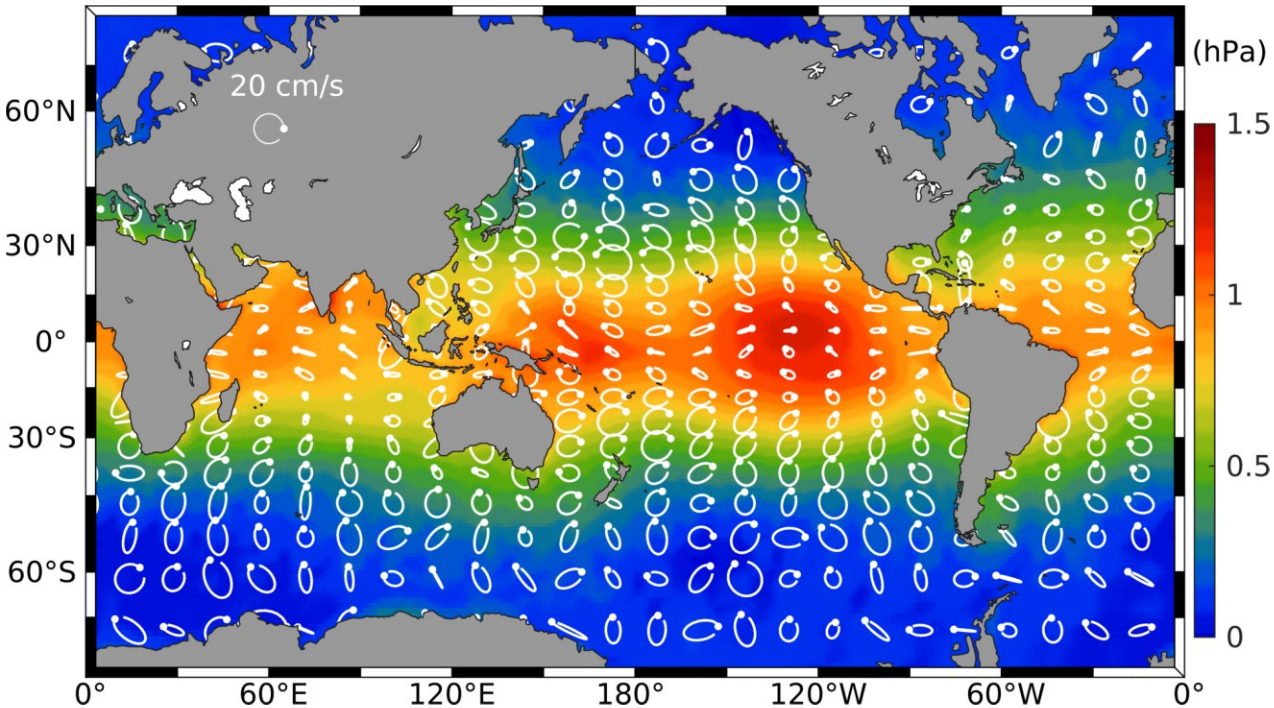
Nudge deep water only, allow surge and nonlinear processes to freely evolve on shelves

- On the shelf : $\lambda = 0$ for water depth shallower than ~400 m
- In deeper water: λ increases with water depth, spatially smoothed



ATMOSPHERIC FORCING (GDRS IN 2008, ~39 KM, HOURLY)

S_2 component of winds and air pressure



$$\tau_s = \tilde{\tau}_s + \tau_s'$$

$$p_a = \tilde{p}_a + p_a'$$

S_2 Residual

The hourly forcing has a significant S_2 tide which can trigger a global ocean response known as radiational S_2 tide (rS_2).

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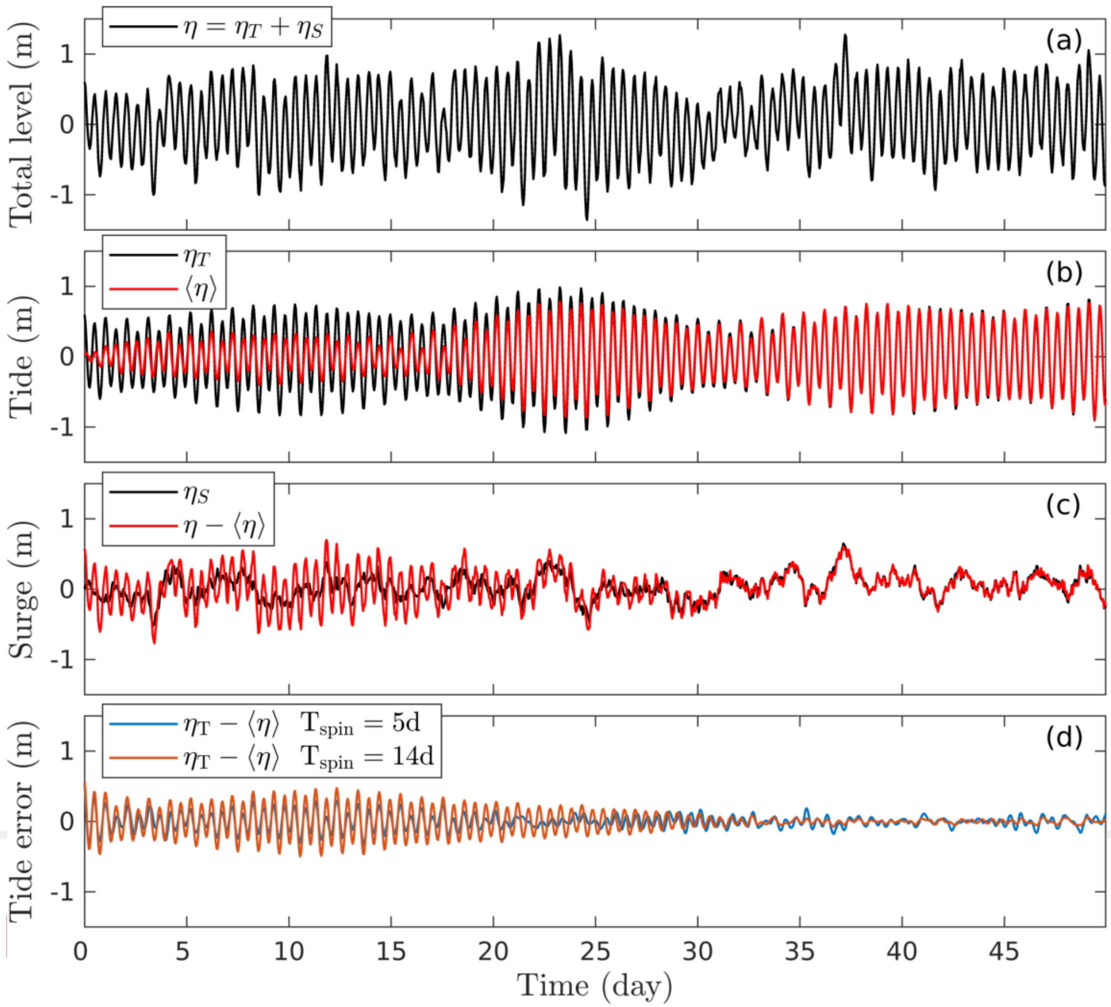
GDRS: Global Deterministic Reforecast System (GEPS-reforecast control member)

DESIGN OF EXPERIMENTS
(Tide-only, Surge-only, coupled tide-surge run)

		Tidal potential	Full forcing	S_2 signal removed	Nudging U	Nudging η
		η_A	$(\boldsymbol{\tau}_s, p_a)$	$(\boldsymbol{\tau}'_s, p'_a)$	$\lambda\langle \boldsymbol{u}_{obs} - \boldsymbol{u}\rangle$	$\lambda\langle \eta_{obs} - \eta\rangle$
Tide only	$\mathrm{Run}_{\mathrm{T}}$	✓				
	$\mathrm{Run}_{\mathrm{Tn}}$	✓			✓	
	$\mathrm{Run}^{*}_{\mathrm{Tn}}$	✓				✓
Surge only	$\mathrm{Run}_{\mathrm{S}}$		✓			
	$\mathrm{Run}_{\mathrm{S'}}$			✓		
Coupled	$\mathrm{Run}_{\mathrm{TS}}$	✓	✓			
	$\mathrm{Run}_{\mathrm{TnS}}$	✓	✓		✓	

Tidal Nudging (λ, κ)

- κ controls the width of the nudged bands and the spin-up time of the filter.
- Conceptually similar to applying a tidal analysis over a sliding window, and increasing κ is equivalent to reducing the window length.



η_s : surge (AR1 model)

η_T : tide (8 constituents)

<> : tidal filter

$$T\_spin = \kappa^{-1} \Delta t$$

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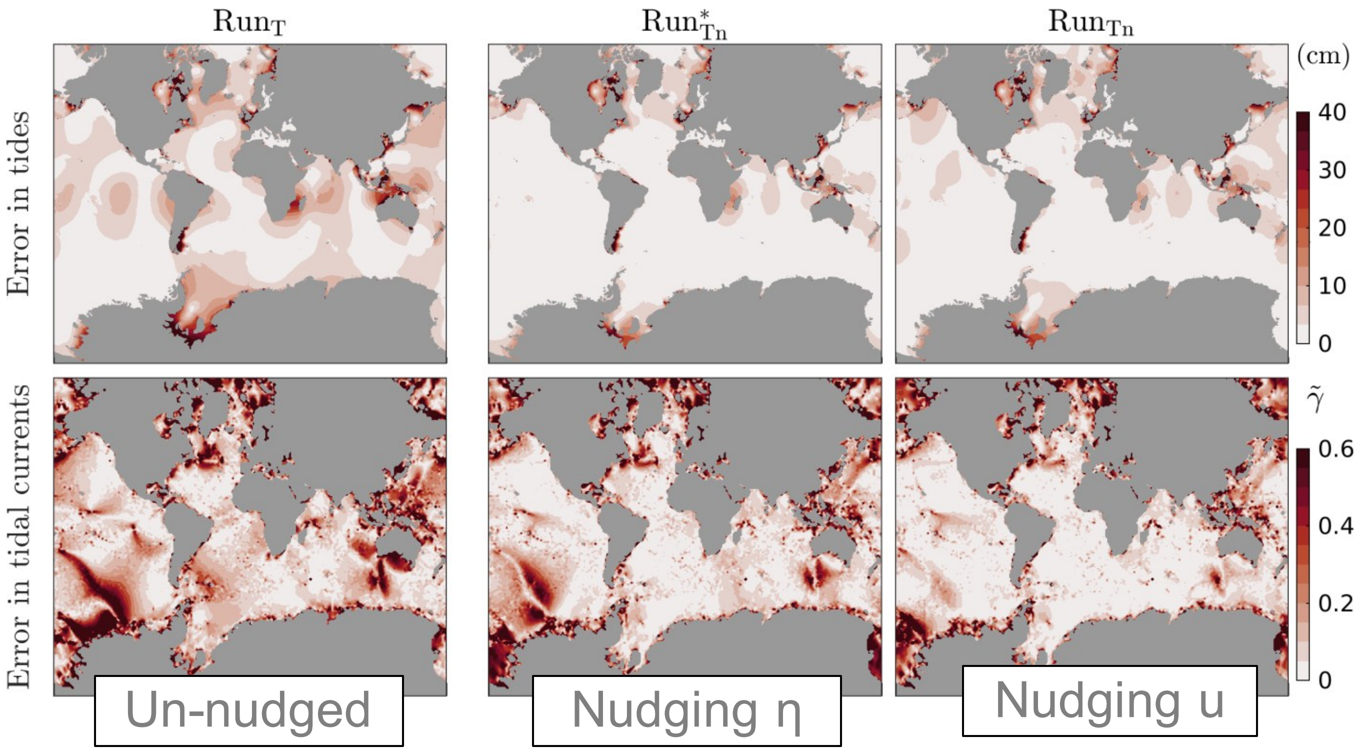
Nudging u VS. Nudging η
Comparison with TPXO8 for M2 tide (top) and tidal current (bottom)

Magnitude of differences in complex amplitude

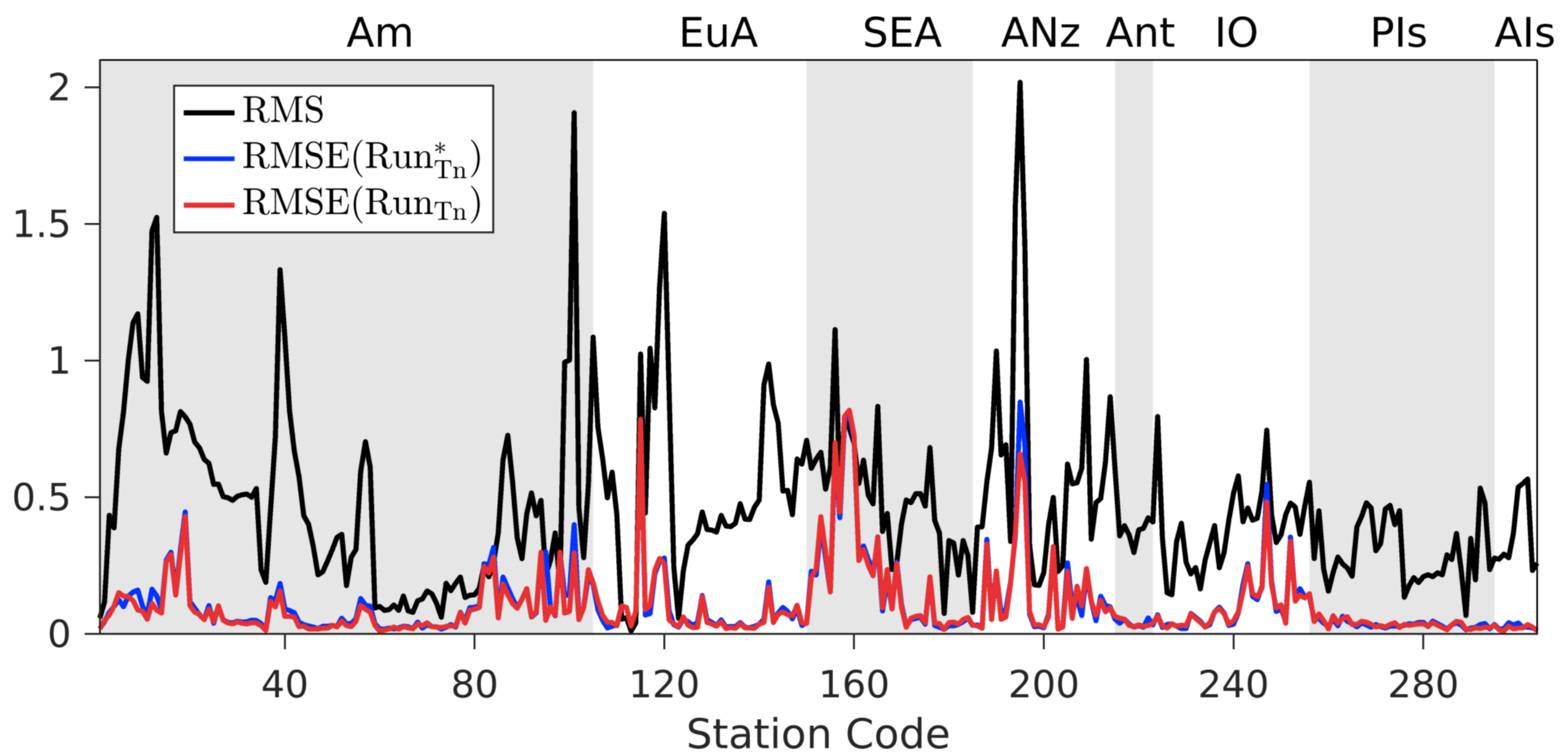
$$|Z_{obs} - Z_{mod}|$$

$$\tilde{\gamma}^2 = \frac{\int_0^p |\tilde{\mathbf{u}}_{obs}(t) - \tilde{\mathbf{u}}_{mod}(t)|^2 dt}{\int_0^p |\tilde{\mathbf{u}}_{obs}(t)|^2 dt}$$



As nudging η violates mass conservation which may create inconsistency between η and u, a fair comparison is to compare simulated tidal currents (bottom panel)

Nudging u VS. Nudging η
(Comparison with tide gauge data)



Overall, the comparison of tidal currents from TPXO8 and tides at gauges demonstrate that nudging u is the best approach.

Predicting the tides

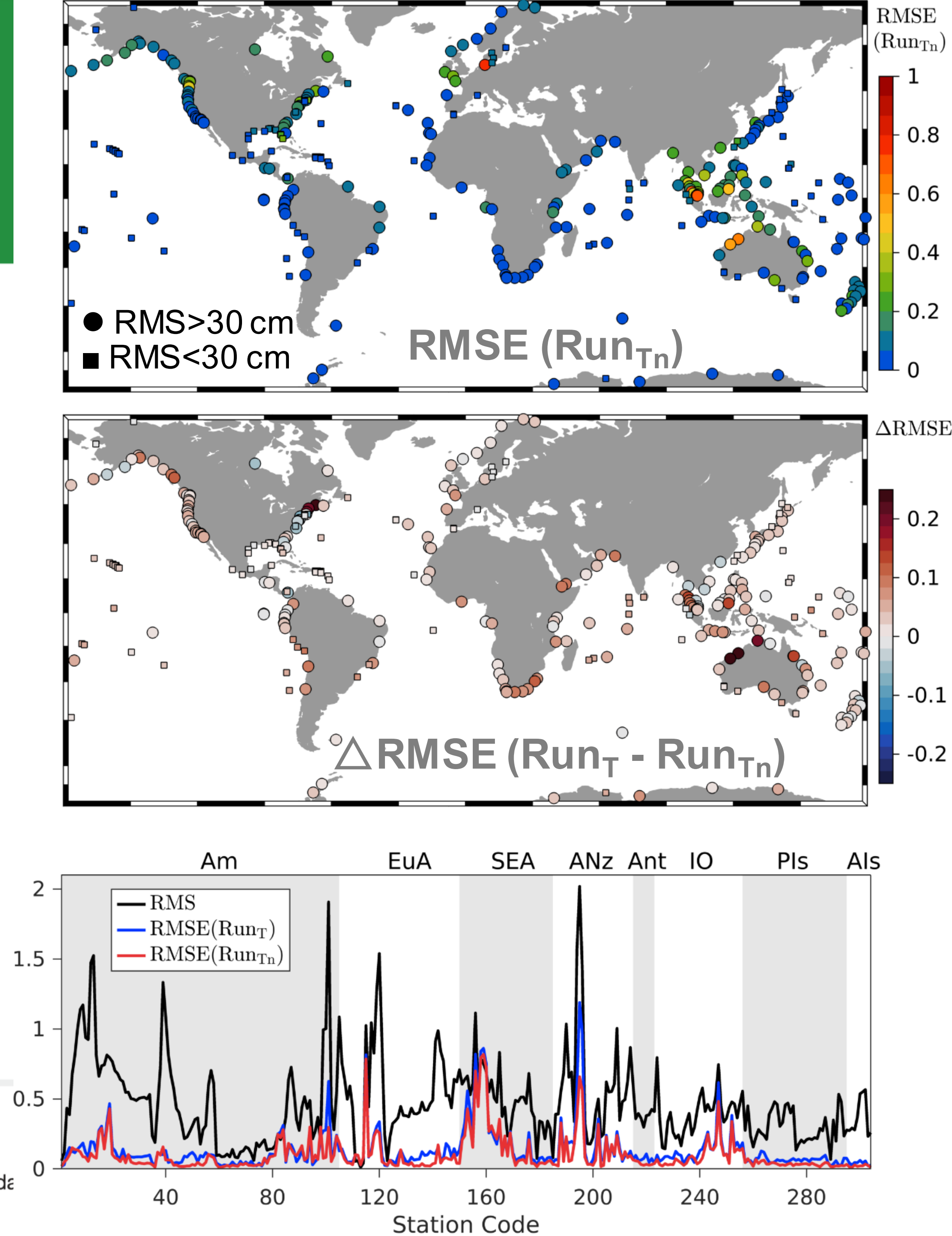
- RMS_{50}: median of RMS values for observed tides at 304 gauges.
- $RMSE_{50}$: median of RMSE values for runs without and with tidal nudging

	O_1 K_1 P_1 Q_1	M_2 S_2 N_2 K_2	S_2	All
RMS_{50}	0.143	0.365	0.118	0.416
$RMSE_{50}$ Run_T	0.028	0.077	0.035	0.086
$RMSE_{50}$ Run_{Tn}	0.023	0.040	0.013	0.053

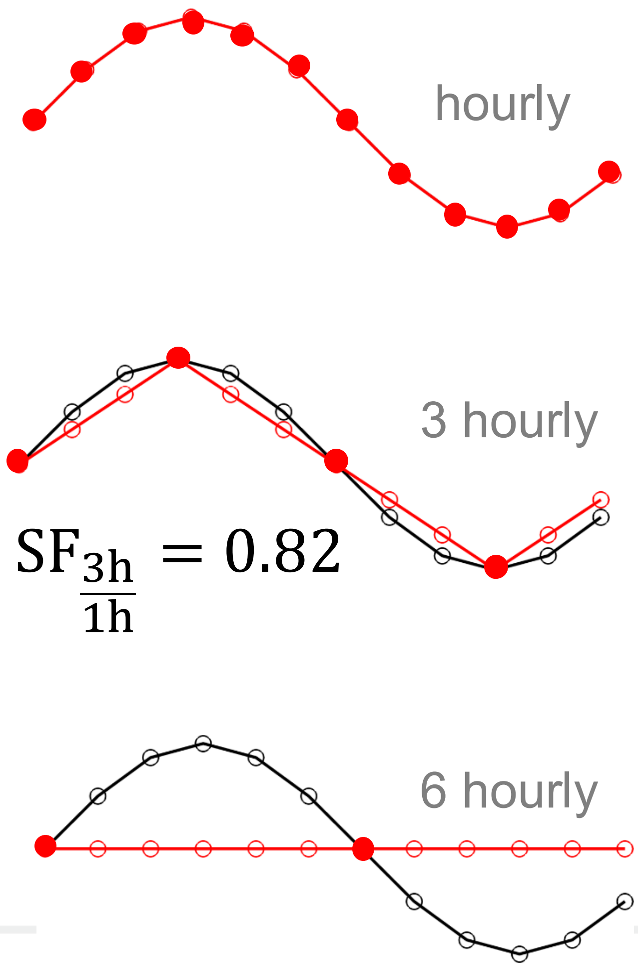
The impact of nudging is most drastic for S_2. One reason is that Run_{Tn} includes rS_2 through the nudging to TPXO8, consistent with tide gauge data which also include this rS_2 signal.

Predicting the tides

- Tidal nudging improves the model skill at 82% of the 304 stations, and reduces the average RMSE by 23% (from 0.13 m to 0.10 m).
- Comparable to data-assimilative model FES2012 in terms of average RMSE (Muis et al., 2016)

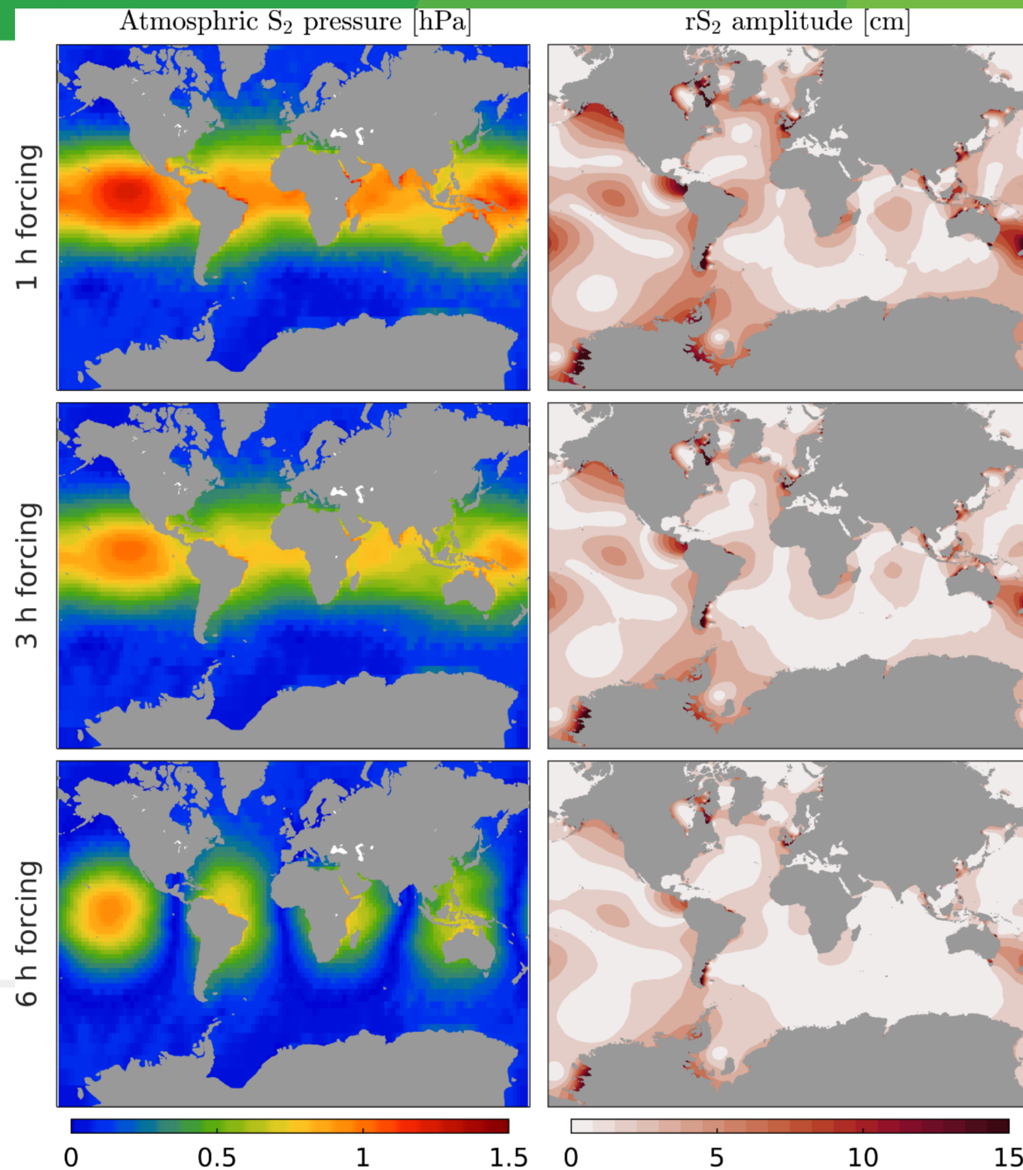


Sea level response to S_2 air pressure and need for hourly forcing



$$SF_{\frac{3h}{1h}} = 0.82$$

$$SF_{\frac{6h}{1h}} = 0.82|\sin(\varphi)|$$



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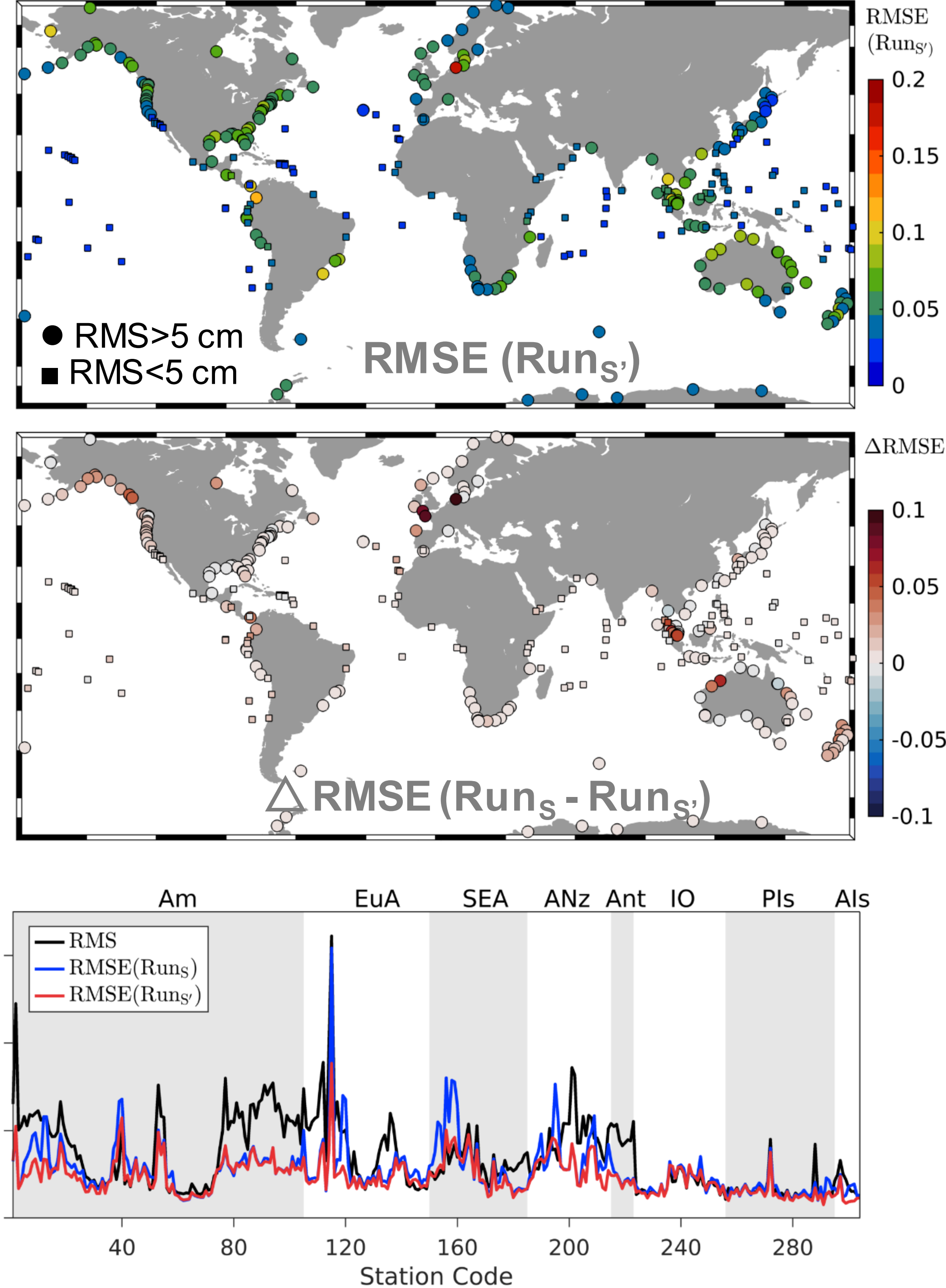
Predicting the surges

- rS_2 in Run_S needs to be removed to be consistent with tidal residuals in which rS2 is also removed by t_tide.
- rS_2 is removed by removing the S_2 component from the forcing, which is $Run_{S'}$
- Low frequency (>20 days) signals are filtered out



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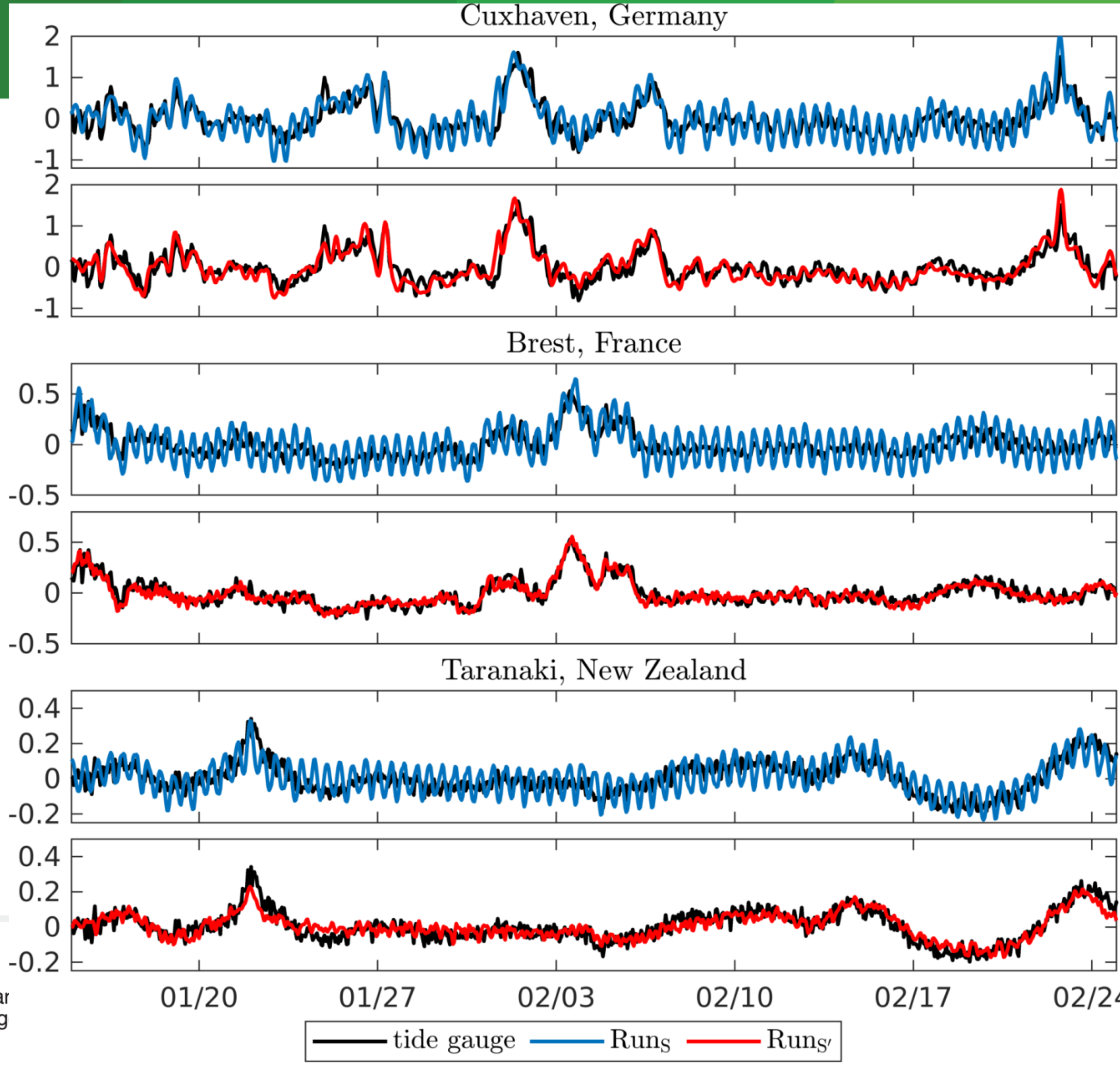
Time series of observed and predicted surge level at three selected stations



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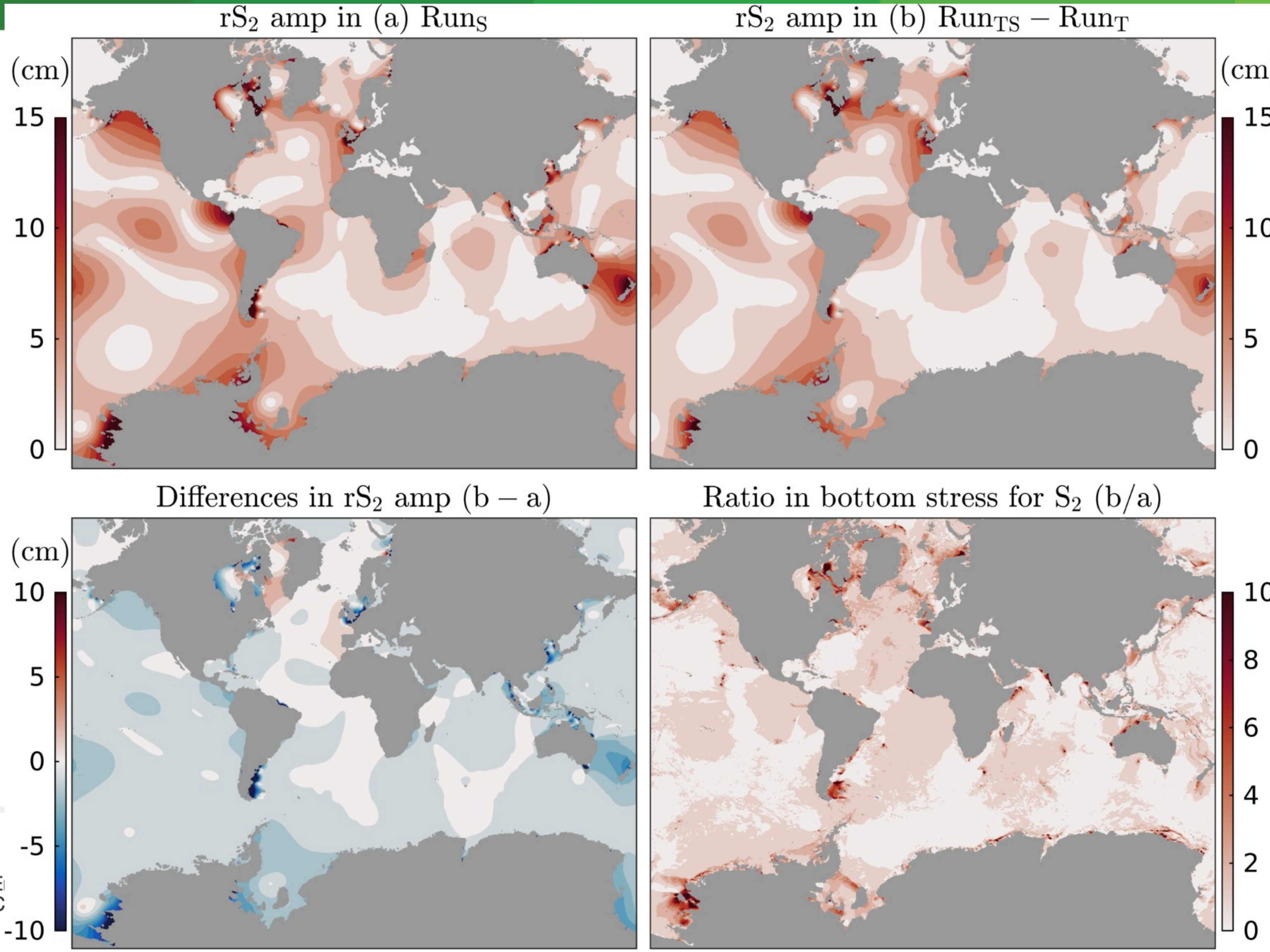
Damping of rS_2 by the gravitational tide

If a current is a combination of tidal components, then bottom friction at a given tidal frequency can be increased by other tidal components



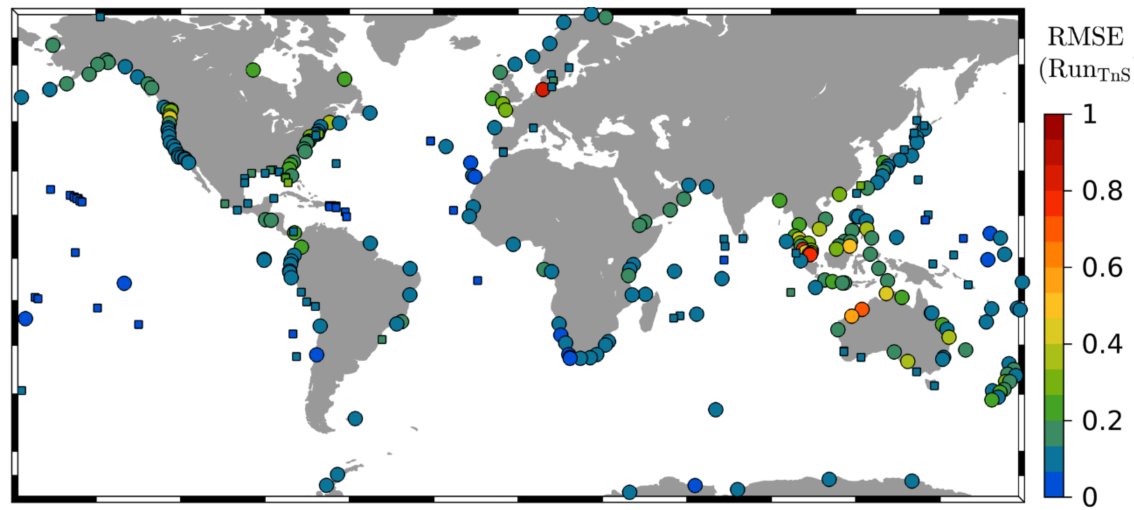
Predicting the total water level

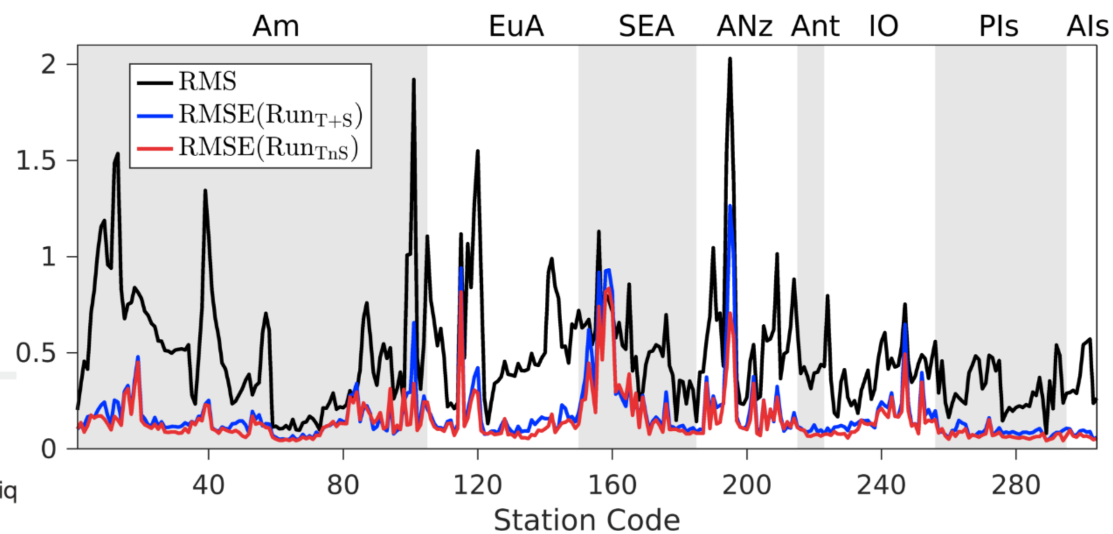
Run_{T+S}	No tidal nudging; No nonlinear interaction
Run_{TS}	No tidal nudging
Run_{Tn+S}	No nonlinear interaction; Double counting of rS_2
Run_{TnS}	Include both tidal nudging and nonlinear interaction

	Unfiltered	Subseasonal $480 > p$	Diurnal $30 > p > 18$	Semi-diurnal $16 > p > 9.6$	
Obs	43.4	42.6	13.8	36.4	Median of RMS
Obs - Run_{T+S}	12.5	10.3	3.3	8.5	Median of RMSE
Obs - Run_{TS}	12.3	10.3	3.2	8.4	
Obs - Run_{Tn+S}	11.2	8.2	2.9	5.7	
Obs - Run_{TnS}	10.7	8.0	2.9	5.1	

Predicting the total water level

- No filter is applied, only the mean is removed.
- RMSE below 0.20 m for 83% of the stations
- The average RMSE in Run_{TnS} is 0.15 m. For comparison, it is 0.17 m in Muis et al., (2016). Note that tide gauges and analysis periods in the two studies are different.





CONCLUSIONS

- Tidal nudging in deep water only is shown to improve tide prediction at the coast.
- Hourly atmospheric forcing is required to resolve the radiational S_2 tide (rS_2).
- rS_2 is subject to strong nonlinear interaction with gravitational tides.
- Due to this nonlinear interaction, it is necessary to use the coupled tide-surge run for global operational forecasting and climate sensitivity studies.