Improving Barotropic Tide Modeling in MPAS-Ocean and Estimating Changes in Future Tides

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E3SM Webinar

December 7, 2023

Funding provided by the DoE Integrated Coastal Modeling project (ICOM)

Importance of Tides

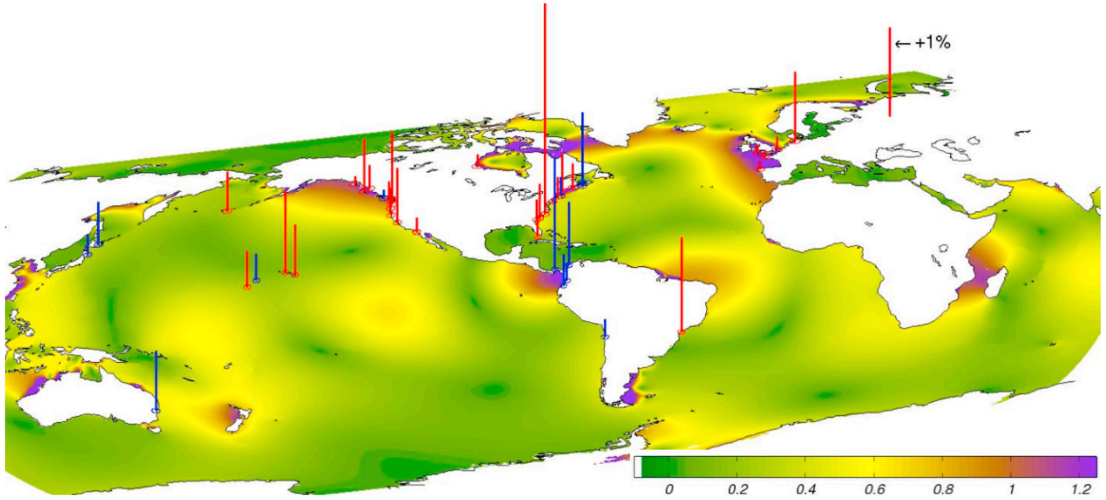


Figure 1. Fractional trends in M_2 amplitude. The reference bar on the Eurasian continent shows a trend of 1% decade^{-1}. Red (blue) bars denote positive (negative) trends. Color contours provide the tidal amplitude in m (TPXO.7.2) [*Egbert et al.*, 1994].

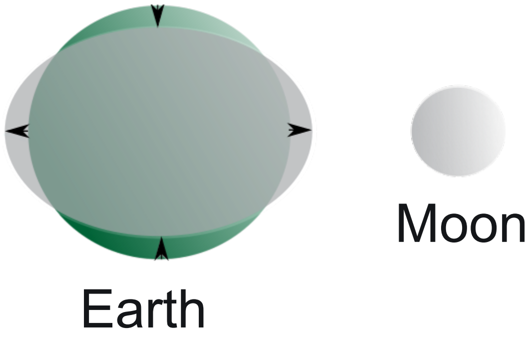
Müller, M., Arbic, B. K., and Mitrovica, J. X. (2011), Secular trends in ocean tides: Observations and model results, J. Geophys. Res., 116, C05013, doi:10.1029/2010JC006387.

Observed tides are not constant
They can be influenced by things like:

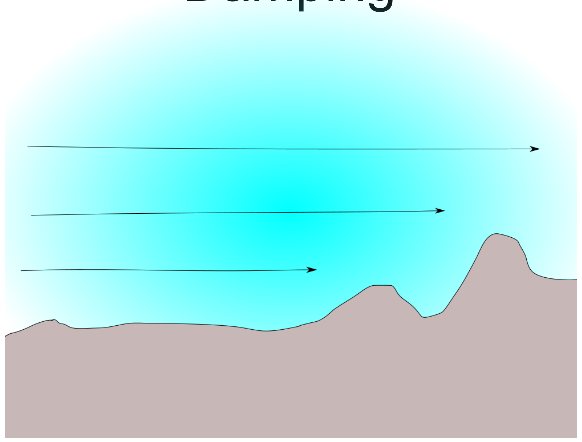
- Tectonics
- Water depth
- Shoreline position
- Seabed roughness
- Extent of sea ice coverage
- More…

Including Tides in Models

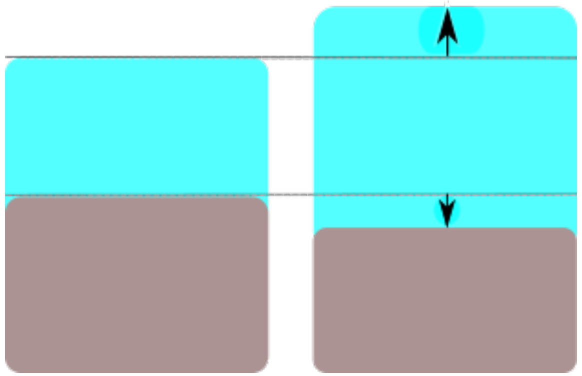
Astronomical forcing
(sun and moon)



Damping

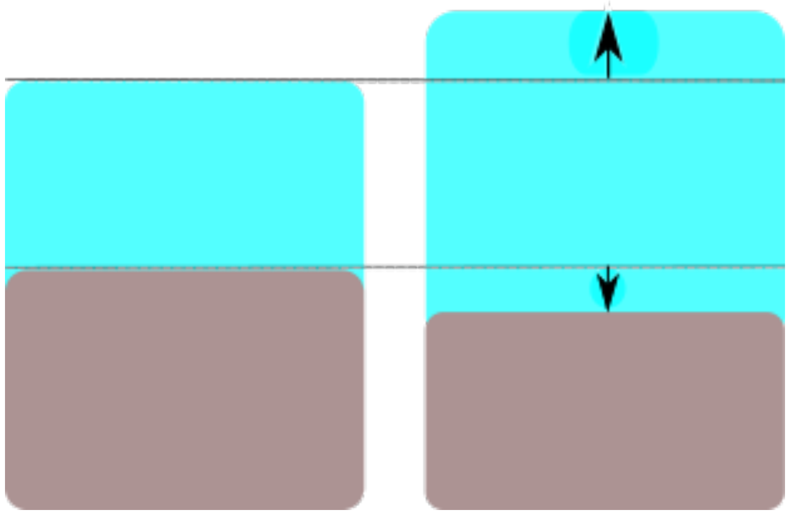


Self-Attraction and Loading



Self-Attraction and Loading (SAL)

Mass changes in the ocean water column lead to deformation of the Earth's crust



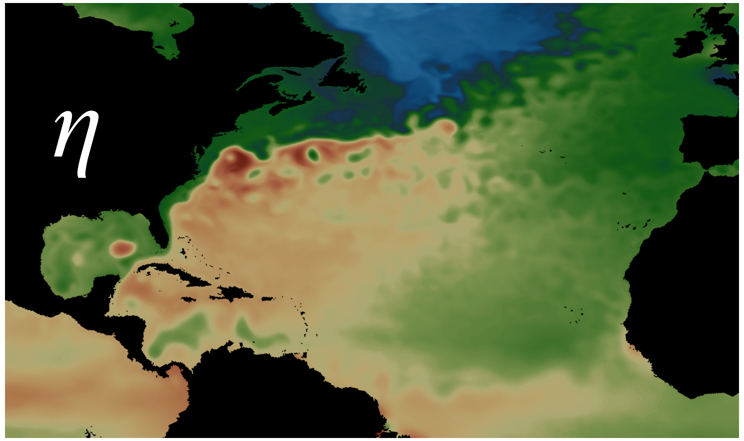
SAL accounts for:

- Deformation of the Earth's crust
- Changes in self-gravitation of the deformed Earth
- Changes in self-gravitation of the ocean mass

SAL impacts

- Tidal amplitudes by ~10%
- Non-tidal motions (e.g., storm surges)

Governing Equations



SAL is ~10% sea-surface height

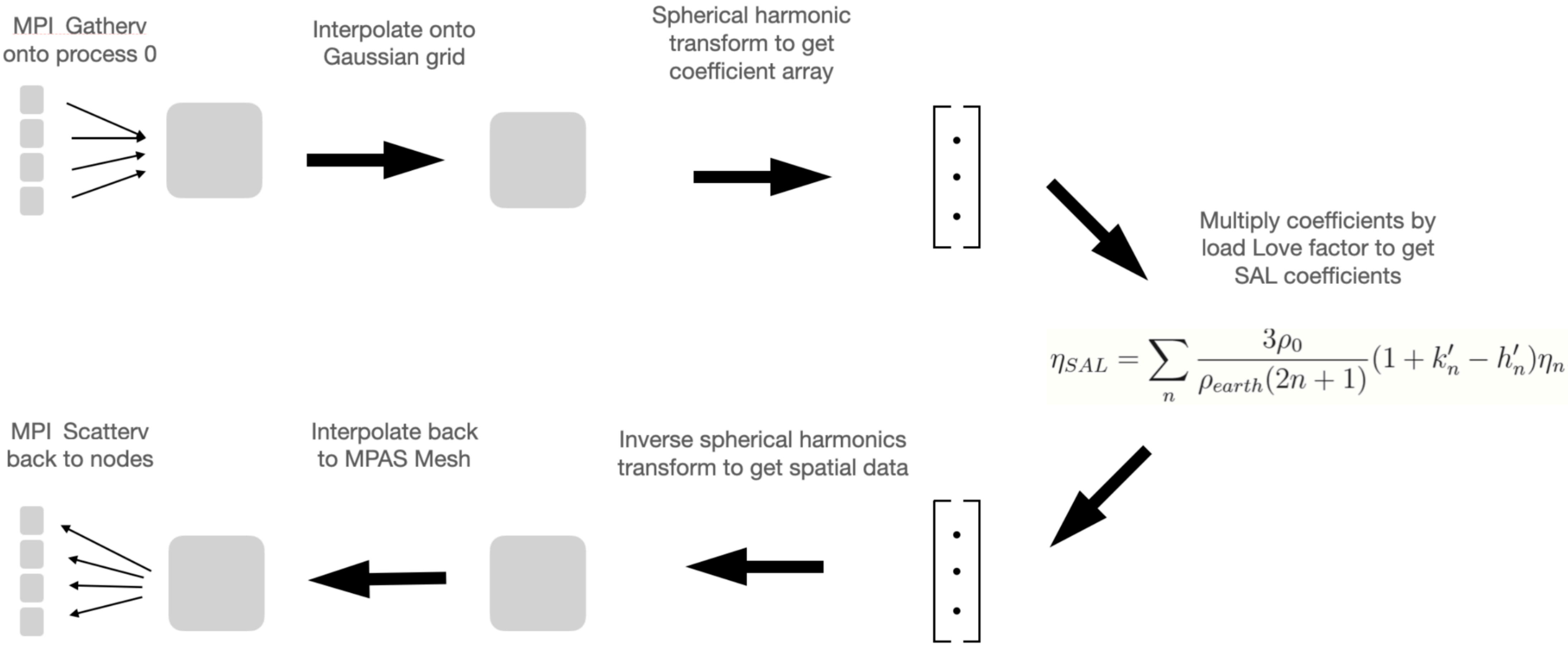
Self-Attraction and Loading

$$\frac{\partial \mathbf{u}}{\partial t} + (\nabla \times \mathbf{u} + f\mathbf{k}) \times \mathbf{u} = -\nabla K - g\nabla(\eta - \eta_{EQ} - \boxed{\eta_{SAL}} - \chi \frac{\mathscr{C}\mathbf{u}}{H} - \frac{\mathscr{C}_D|\mathbf{u}|\mathbf{u}}{H},$$

$$\eta_{SAL} = \sum_n \frac{3\rho}{\rho_{earth}(2n+1)} \underline{(1 + k_n' - h_n')\eta_n}$$

- 1 = gravitational self-attraction of ocean
- k’n = gravitational self-attraction of deformed Earth
- h’n = deformation of solid Earth due to mass loading from ocean
- These values are derived from solid Earth models
- Acts as a smoothing operator and reduces amplitude by ~1/10

Self-Attraction and Loading (SAL) Calculation



MPI_Gatherv onto process 0

Interpolate onto Gaussian grid

Spherical harmonic transform to get coefficient array

Multiply coefficients by load Love factor to get SAL coefficients

$$\eta_{SAL} = \sum_n \frac{3\rho_0}{\rho_{earth}(2n+1)}(1+k'_n-h'_n)\eta_n$$

Inverse spherical harmonics transform to get spatial data

Interpolate back to MPAS Mesh

MPI_Scatterv back to nodes

Can compare this to the “scalar” approximation: $\eta_{SAL} = \beta\eta$

Simulations

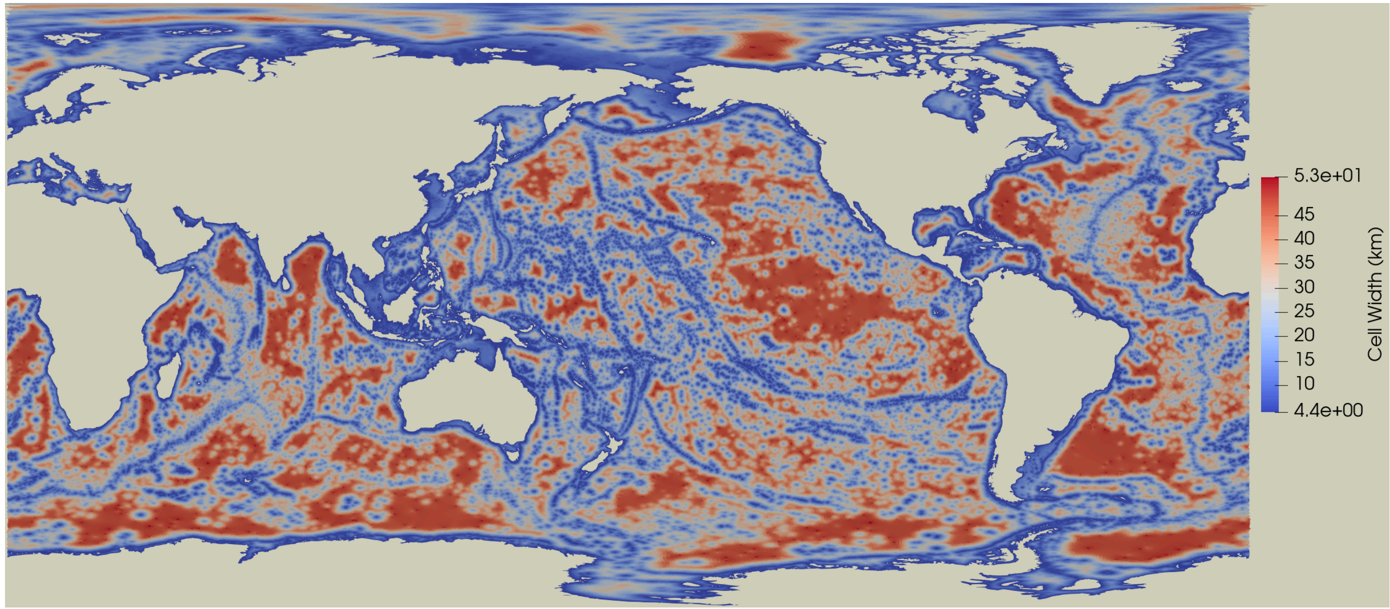
Main Comparisons:

- Scalar vs. Inline SAL
- Variable resolution vs. quasi-uniform mesh
- SAL update frequency

Mesh	Avg. Cell Width (km)	# Cells
Icosohedron 7	64	163, 842
Icosohedron 8	32	655,362
Icosohedron 9	16	2,621,442
Icosohedron 10	8	10,485,762
Variable Resolution	45 to 5	2,359,578

All runs are in a single-layer setup

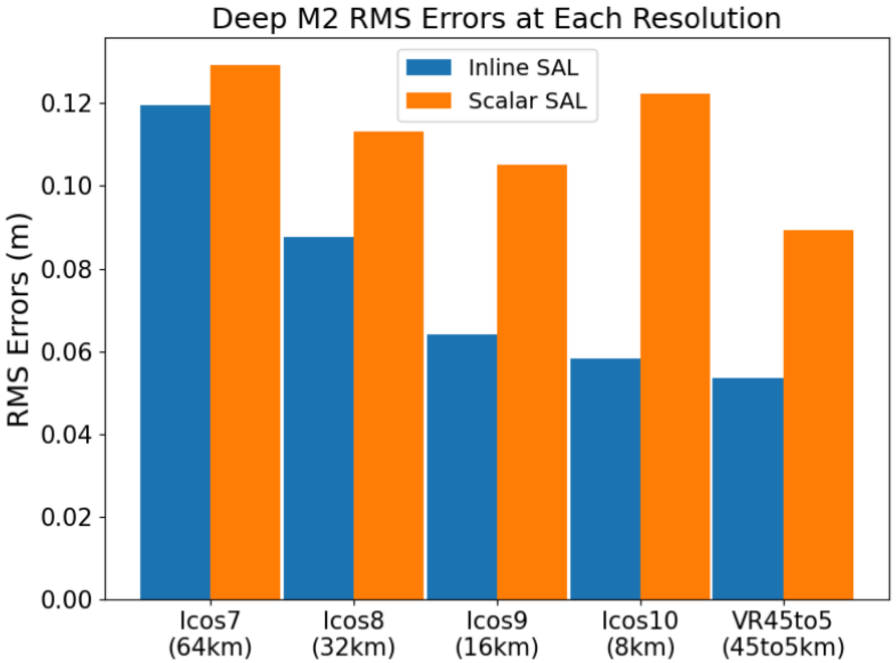
Variable Resolution Cell Width, 45 to 5km

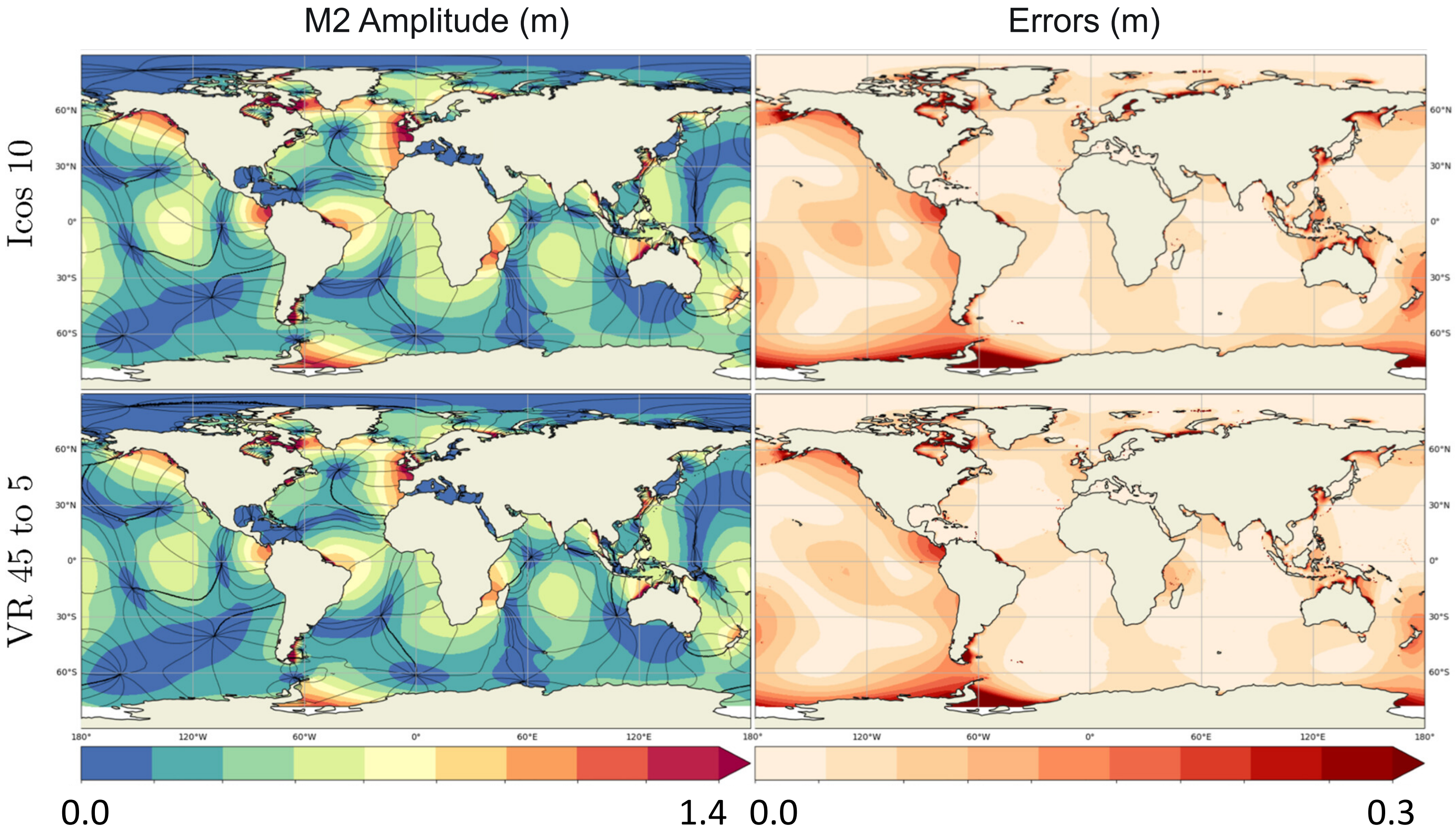


Increased resolution in:

- Areas of large topographic gradients
- Shallow regions

Tidal Errors





- Comparison to benchmark tidal dataset TPXO8
- Reduced error from:
  - Inline Self-Attraction and Loading
  - Variable Resolution Mesh

Computational Scaling

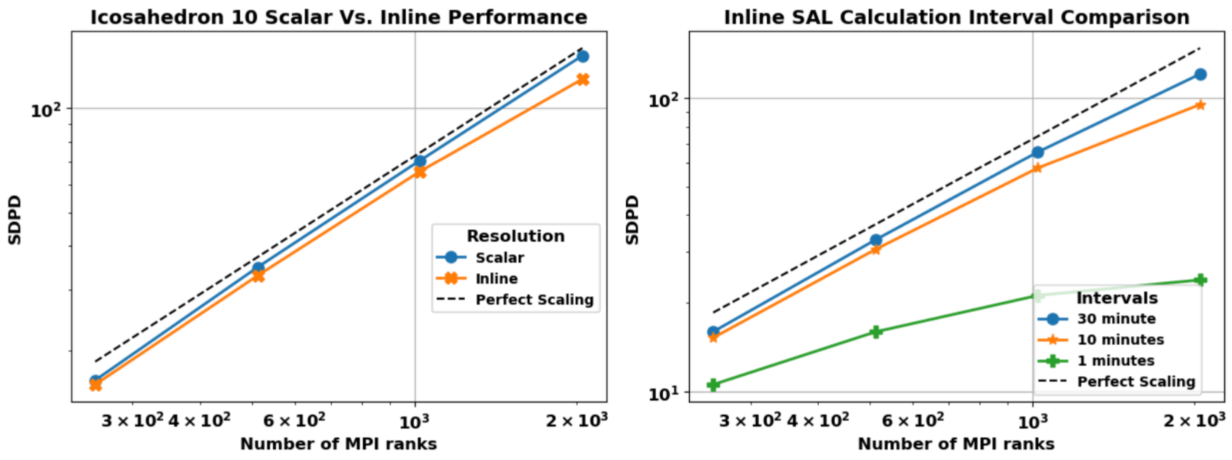
- Computational improvements from:
  - New SAL has excellent scaling up to 2000 MPI ranks
  - Updating Self-Attraction and Loading term in 10-30 minute intervals
  - Variable Resolution down to 5km is almost as fast as Icos9 (16km)

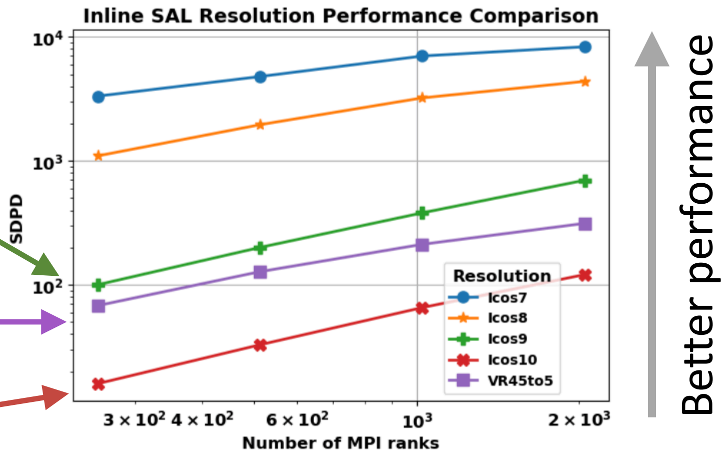
Global M2 Tidal Error

Calculation Interval	30 min.	10 min.	1 min.
Icosahedron 8 RMSE (cm)	8.8	8.4	8.4
Icosahedron 9 RMSE (cm)	6.4	6.4	6.5
VR 45 to 5 km RMSE (cm)	6.1	6.1	6.4

lowest error

Simulated Days Per Day vs. Number of Ranks





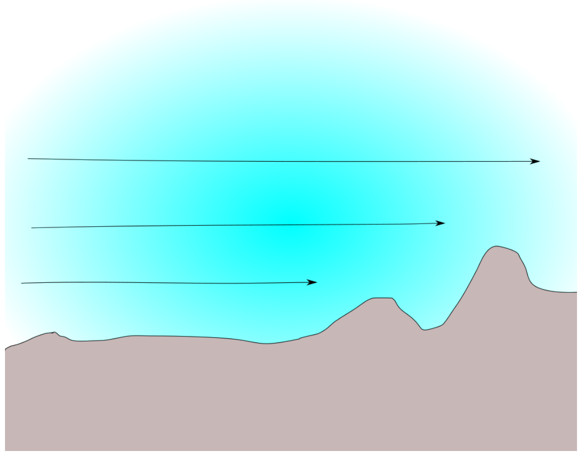
Icos9 (16km)

VR (45 to 5km)

Icos10 (8km)

Topographic Wave Drag

- The ocean consists of stratified density layers
- As tides flow over rough topography, it creates waves in the layers
- Energy dissipates as these waves form and break
- The dissipation happens at small spatial scales
- For a single-layer model at 5km (minimum) resolution, we cannot directly resolve the physics
- Instead, the dissipation is parameterized



Topographic Wave Drag

- We compare two scalar-based schemes and one tensor-based scheme

Jayne and St. Laurent

$$\mathcal{C}_{JSL} = \frac{\pi}{L}\hat{H}^2 N_b$$

Zaron and Egbert

$$\mathcal{C}_{ZAE} = \Gamma H(\nabla H)^2 \frac{N_b \bar{N}}{8\pi^2\omega}$$

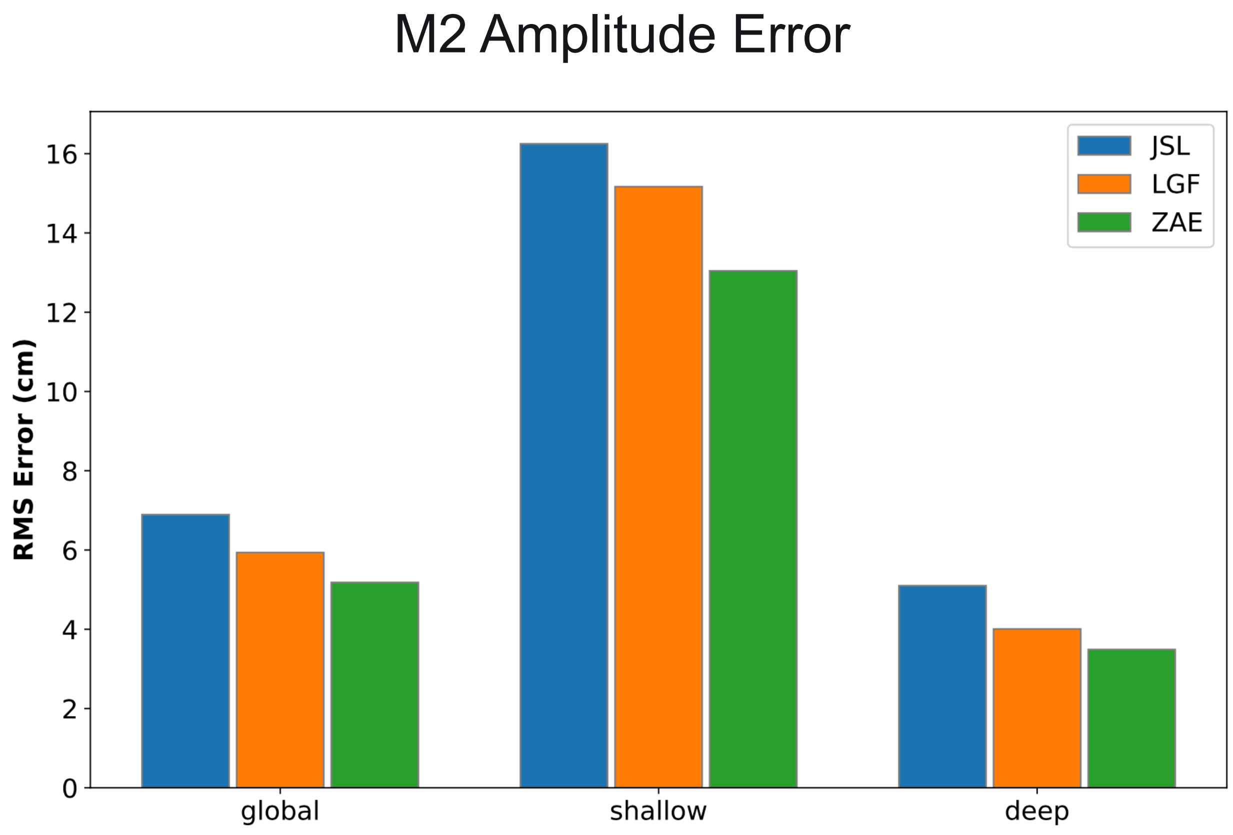
Local Generation Formula

$$\mathbb{C}_{LGF} = \frac{\left[(N_b^2-\omega^2)(N_m^2-\omega^2)\right]^{1/2}}{4\pi\omega}\begin{pmatrix}(\nabla_\lambda H)^2 & \nabla_\lambda H \nabla_\phi H \\ \nabla_\lambda H \nabla_\phi H & (\nabla_\phi H)^2\end{pmatrix}$$

MPAS-Ocean momentum eqn:

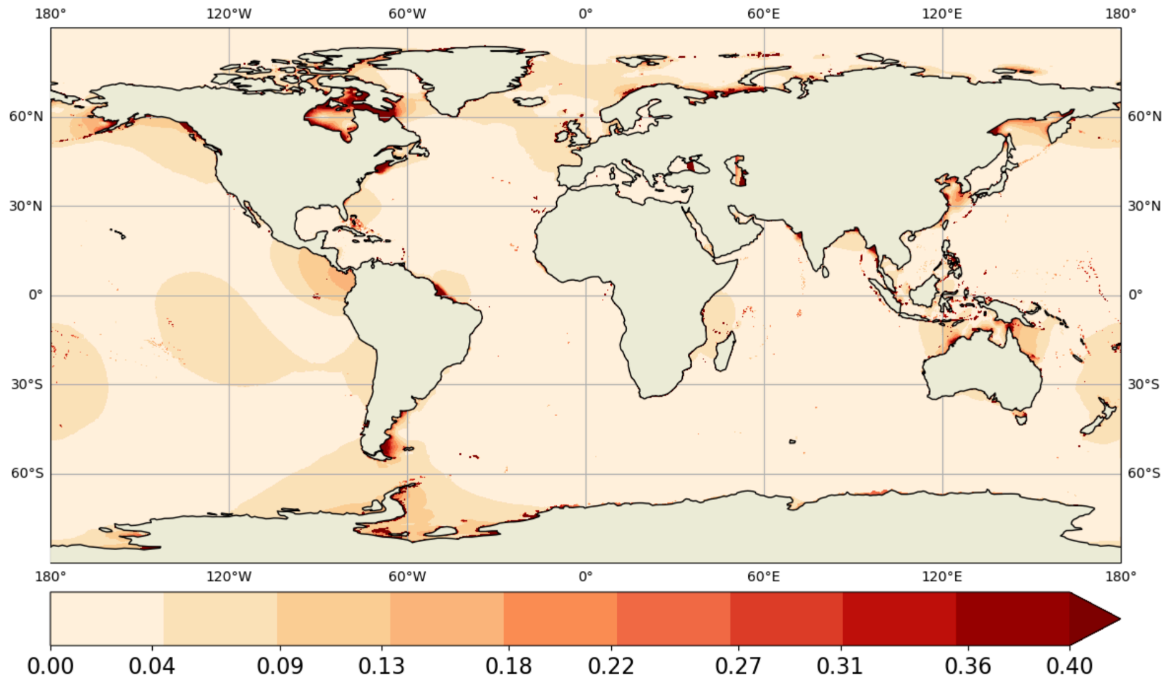
$$\frac{\partial \mathbf{u}}{\partial t} + (\nabla \times \mathbf{u} + f\mathbf{k}) \times \mathbf{u} = -\nabla K - g\nabla(\eta - \eta_{EQ} - \eta_{SAL}) - \chi\frac{\mathscr{C}\mathbf{u}}{H} - \frac{\mathscr{C}_D|\mathbf{u}|\mathbf{u}}{H},$$

Topographic Wave Drag Results



- The scalar-based Zaron and Egbert scheme performs the best in all regions:
  - global (all cells)
  - shallow (100m < depth < 1000m)
  - deep (> 1000m)

Current Best Tidal Errors



Tidal Error (m)

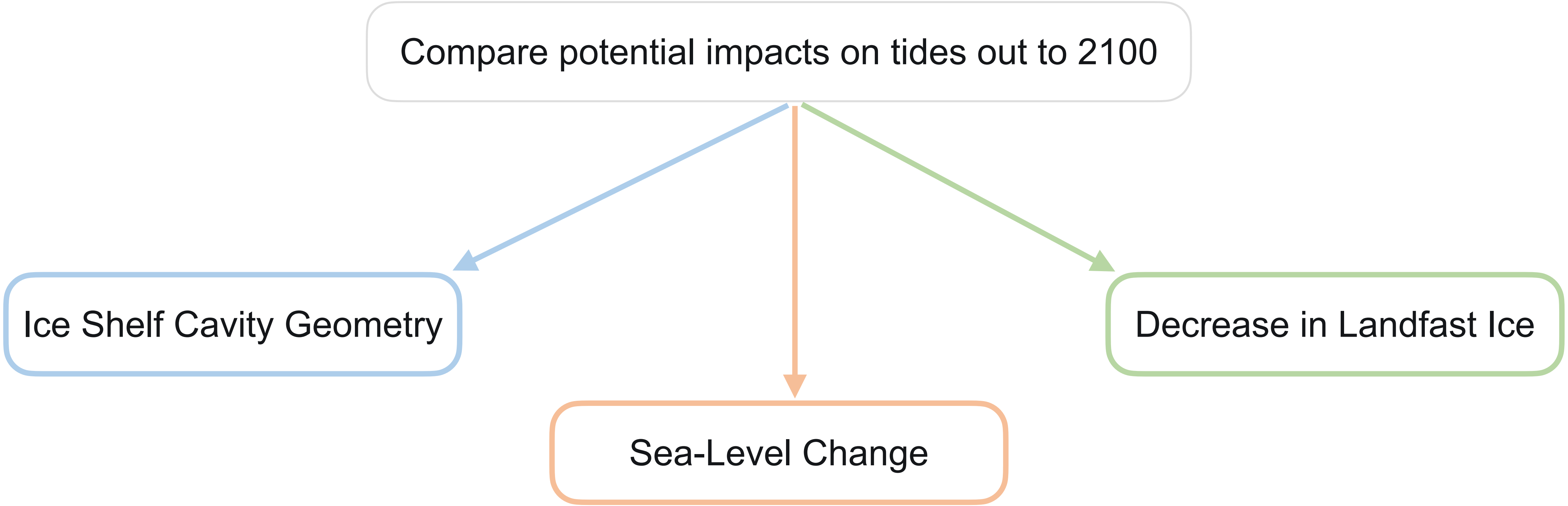
- Deep M2 RMSE of 3.3 cm, which is competitive with other tide models
- Includes improvements in Self-Attraction and Loading calculation from Brus, et al. (2023)
- Includes ice-shelf cavity improvements from Pal, et al. (2023)
- Includes Zaron and Egbert topographic wave drag scheme
- 45-to-5 km mesh with 10-minute SAL intervals

Barton, K. N., et al. (2022). Global barotropic tide modeling using inline self-attraction and loading in MPAS-Ocean. *Journal of Advances in Modeling Earth Systems*, 14.

Brus, S. R., et al. (2023), Scalable self attraction and loading calculations for unstructured ocean tide models, *Ocean Modelling*, 182, 102,160.

Pal, N., et al. (2023), Barotropic tides in MPAS-Ocean (E3SM V2): impact of ice shelf cavities, *Geoscientific Model Development*, 16(4), 1297–1314.

Estimation of Future Tides



Compare potential impacts on tides out to 2100

Ice Shelf Cavity Geometry

Sea-Level Change

Decrease in Landfast Ice

Simulations

- Future cases based on *Shared Socioeconomic Pathways*
- Two Ice-Shelf Cavity cases from SSP5-8.5
    - AE03 — Largest changes
    - AE05 — Moderate changes
- Sea-level changes are consistent with ISC changes
- Landfast ice is seasonal, with future scenarios having no ice in the “summer” hemisphere

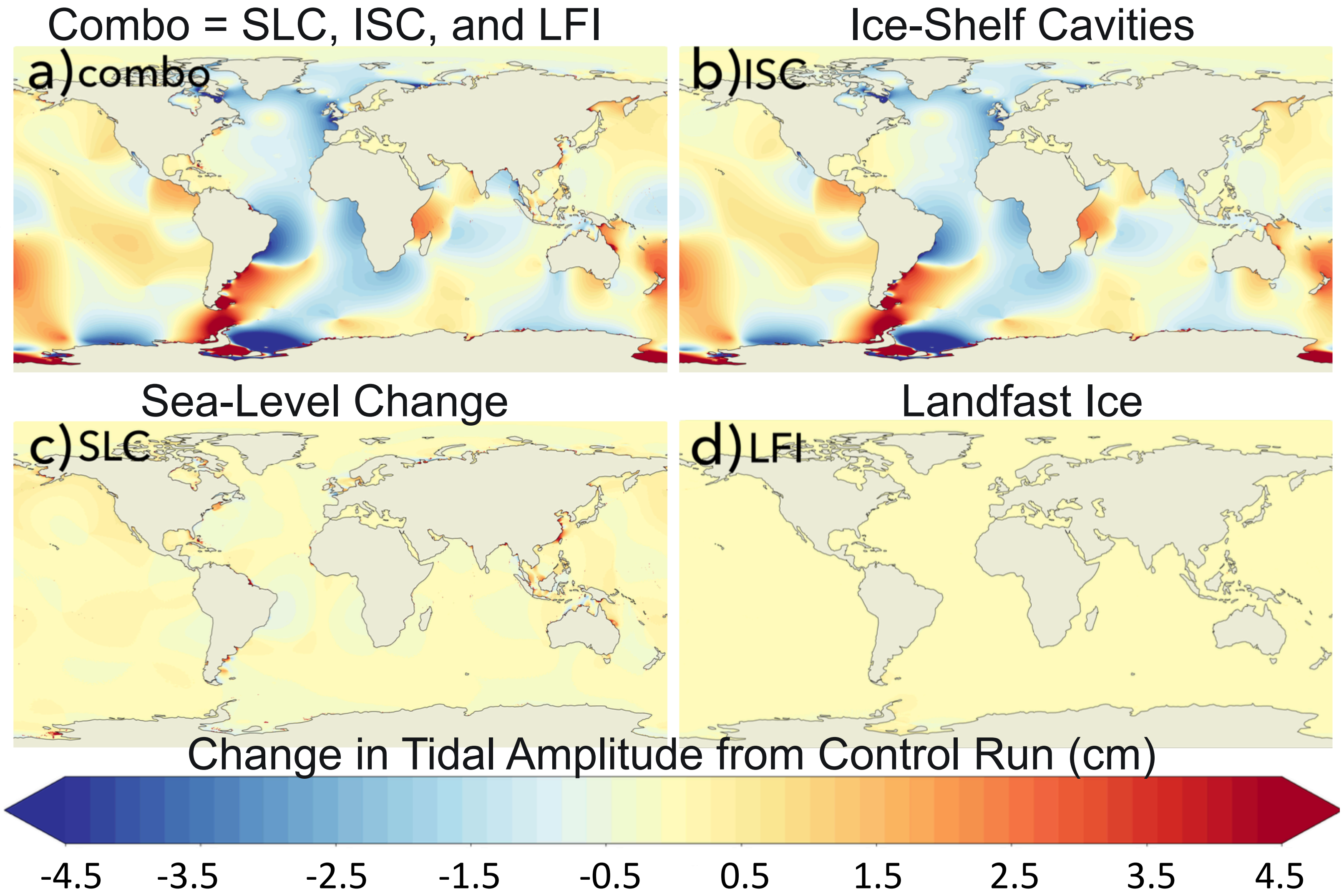
Name	**Ice Shelf Cavities**	**Sea Level Change**	**Landfast Ice**
ctrl2015M	2015 CTRL	2015 CTRL	CTRL March
ctrl2015S	2015 CTRL	2015 CTRL	CTRL September
isc2060ae05	2060 AE05	2015 CTRL	CTRL March
isc2060ae03	2060 AE03	2015 CTRL	CTRL March
isc2100ae05	2100 AE05	2015 CTRL	CTRL March
isc2100ae03	2100 AE03	2015 CTRL	CTRL March
slc2060ae05	2015 CTRL	2060 AE05	CTRL March
slc2060ae03	2015 CTRL	2060 AE03	CTRL March
slc2100ae05	2015 CTRL	2100 AE05	CTRL March
slc2100ae03	2015 CTRL	2100 AE03	CTRL March
lfi2100M	2015 CTRL	2015 CTRL	Future March
lfi2100S	2015 CTRL	2015 CTRL	Future Sept.
comb2060M	2060 AE03	2060 AE03	Future March
comb2060S	2060 AE03	2060 AE03	Future Sept.
comb2100M	2100 AE03	2100 AE03	Future March
comb2100S	2100 AE03	2100 AE03	Future Sept

Ice Sheet and Sea Level datasets provided by: Holly Han, Sophie Coulson, Matthew Hoffman, Luke Jackson, Roelof Rietbroek, and Michael Schindelegger

Changes in M2 Amplitude

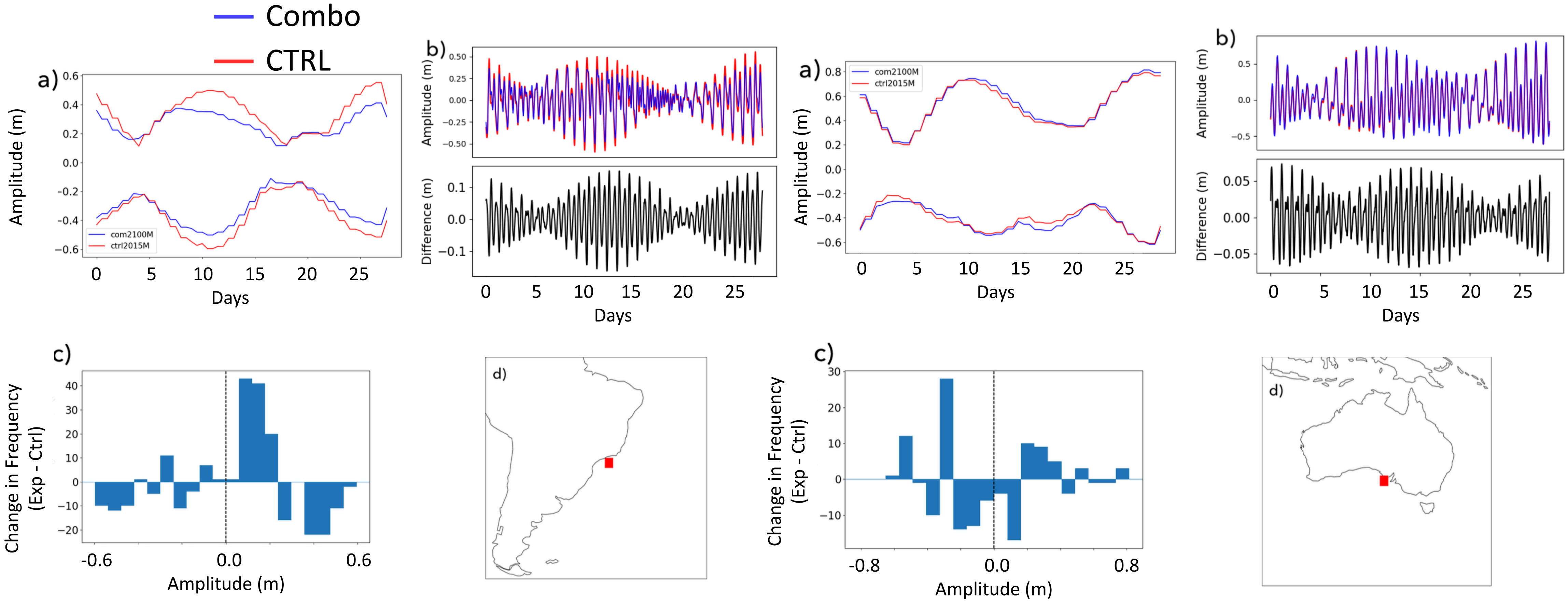
2100, AE03 (“extreme”), March

- Open ocean changes dominated by ice-shelf cavity geometry
- Near-shore changes are dominated by sea-level change
- Landfast ice has minimal impact in simulations



Results At Virtual Tide Gauges

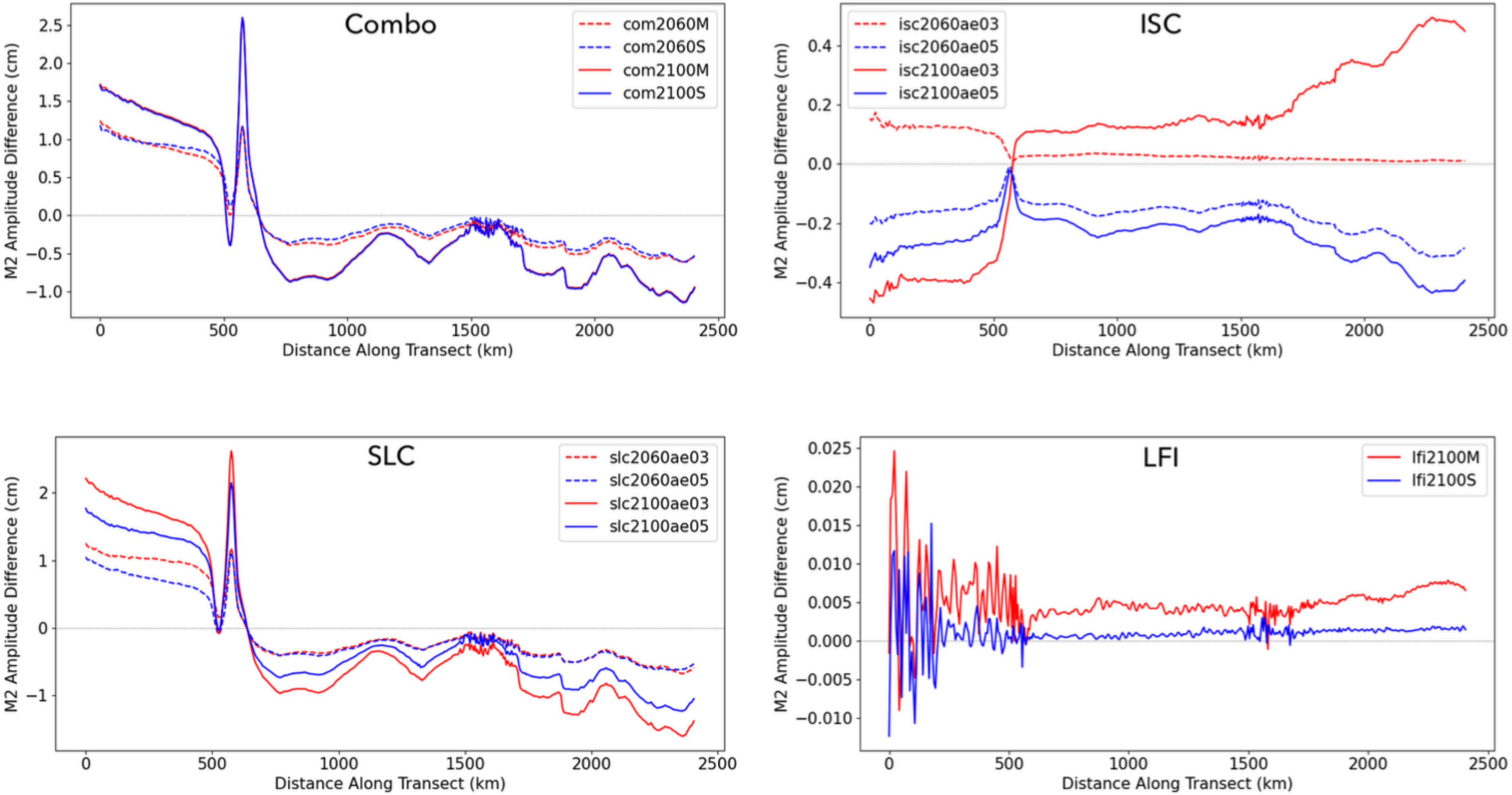
2100, AE03 (“extreme”), March



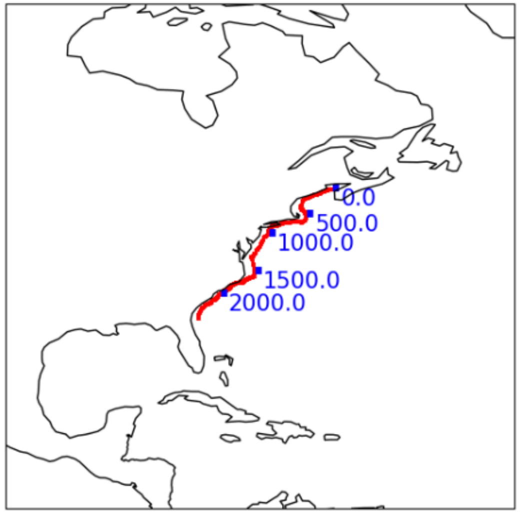
- Measuring total water level simulated in future scenario run
- Tidal ranges can increase or decrease depending on the location
- More changes in frequency of larger tides

Changes “Unraveled” Along Coastline

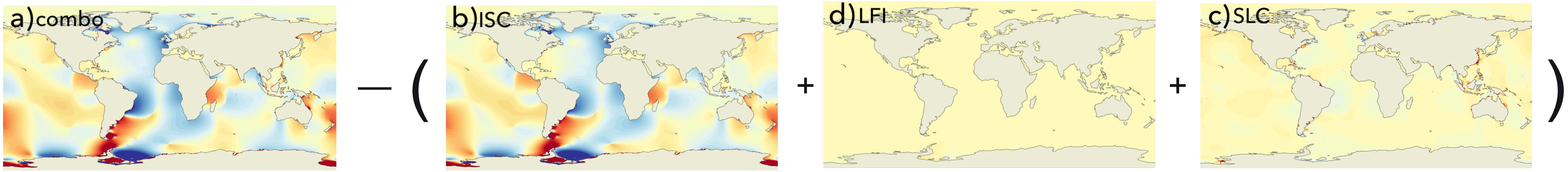
M2 Amplitude difference between control 2015 and experiments



- Ice-shelf cavity geometry impacts can become comparable to sea-level change in some areas
- Sea-level change still generally dominates
- Ice-shelf cavity impacts have large dependence on specific geometry



Nonlinearity of Changes



*Color range top plots: +/- 4.5 cm

- Combo applies ISC, LFI, SLC within one simulation
- How does this differ from the sum of separate simulations?
  - Nonlinearities can get close to 10% of total change
  - Higher resolution in coastal regions would improve results

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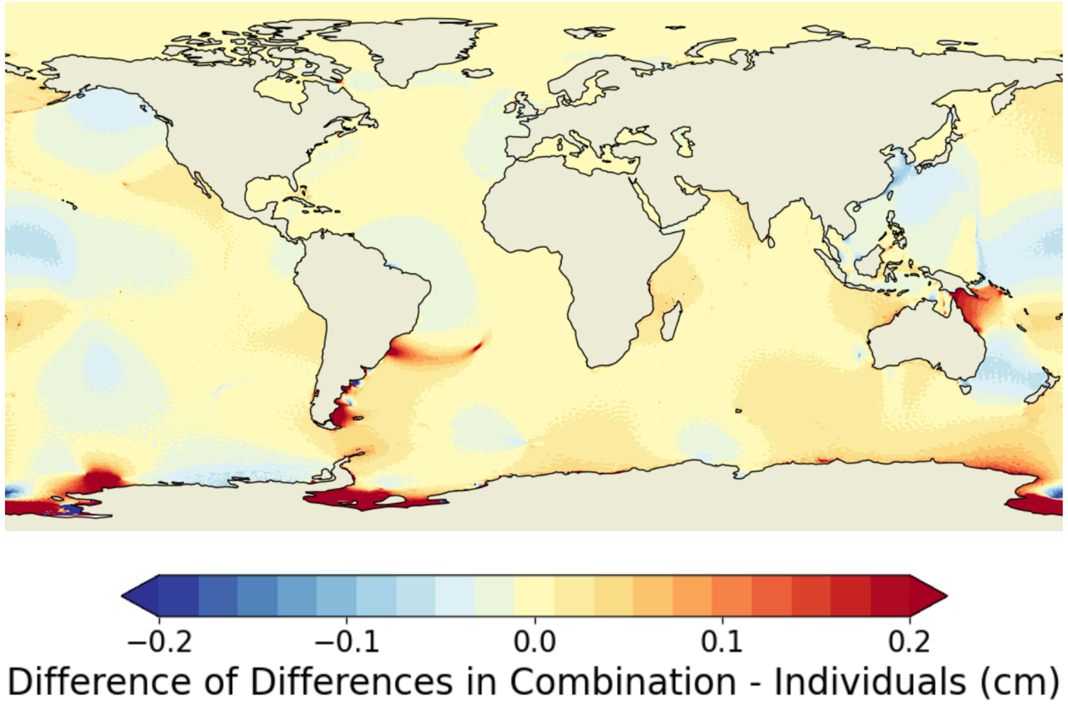
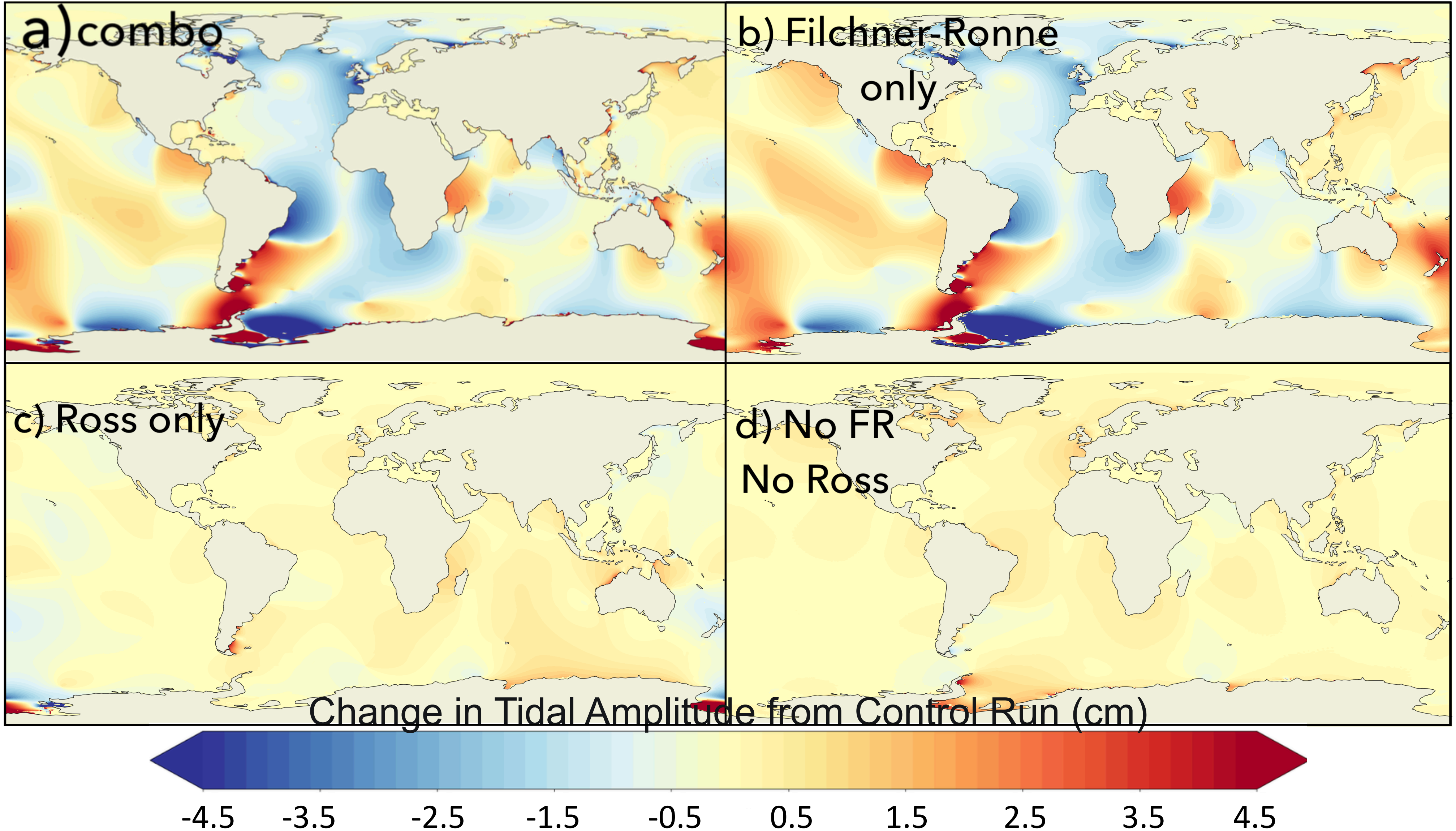


Ice Shelf Cavity Attribution



Conclusions

Adding Tides to MPAS-Ocean

- Self-attraction and loading (SAL), careful selection of topographic wave drag parameterization, and use of a variable resolution mesh can improve tidal performance
- MPAS-Ocean RMS error for deep ocean M2 tides are 3.3 cm, similar to other tidal models
- The MPAS model now has tide modeling capabilities moving forward
- Paper publication: Barton, et al. (2022)

Estimation of Changes in Future Tides

- Ice-shelf Cavity (ISC) geometry has largest impact in the open ocean tides
- Sea-Level Change (SLC) has largest impact near the shore
- ISC impacts can be comparable to SLC impacts in some near-shore regions
- Filchner-Ronne ice shelf responsible for most of ice-shelf cavity impacts on tides

Barton, K. N., Pal, N., Brus, S. R., Petersen, M. R., Arbic, B. K., Engwirda, D., et al. (2022). Global barotropic tide modeling using inline self-attraction and loading in MPAS-Ocean. *Journal of Advances in Modeling Earth Systems*, 14, e2022MS003207. https://doi. org/10.1029/2022MS003207