On improving the accuracy of the barotropic tides in a global ocean circulation model

James Richman, Hans Ngodock, Alan Wallcraft and Jay Shriver
Naval Research Laboratory
Stennis Space Center, MS

Innocent Souopgui
University of Southern Mississippi
Stennis Space Center, MS

Brian Arbic
University of Michigan
Ann Arbor, MI

This work described in Ngodock et al. (2015) Ocean Modelling, submitted

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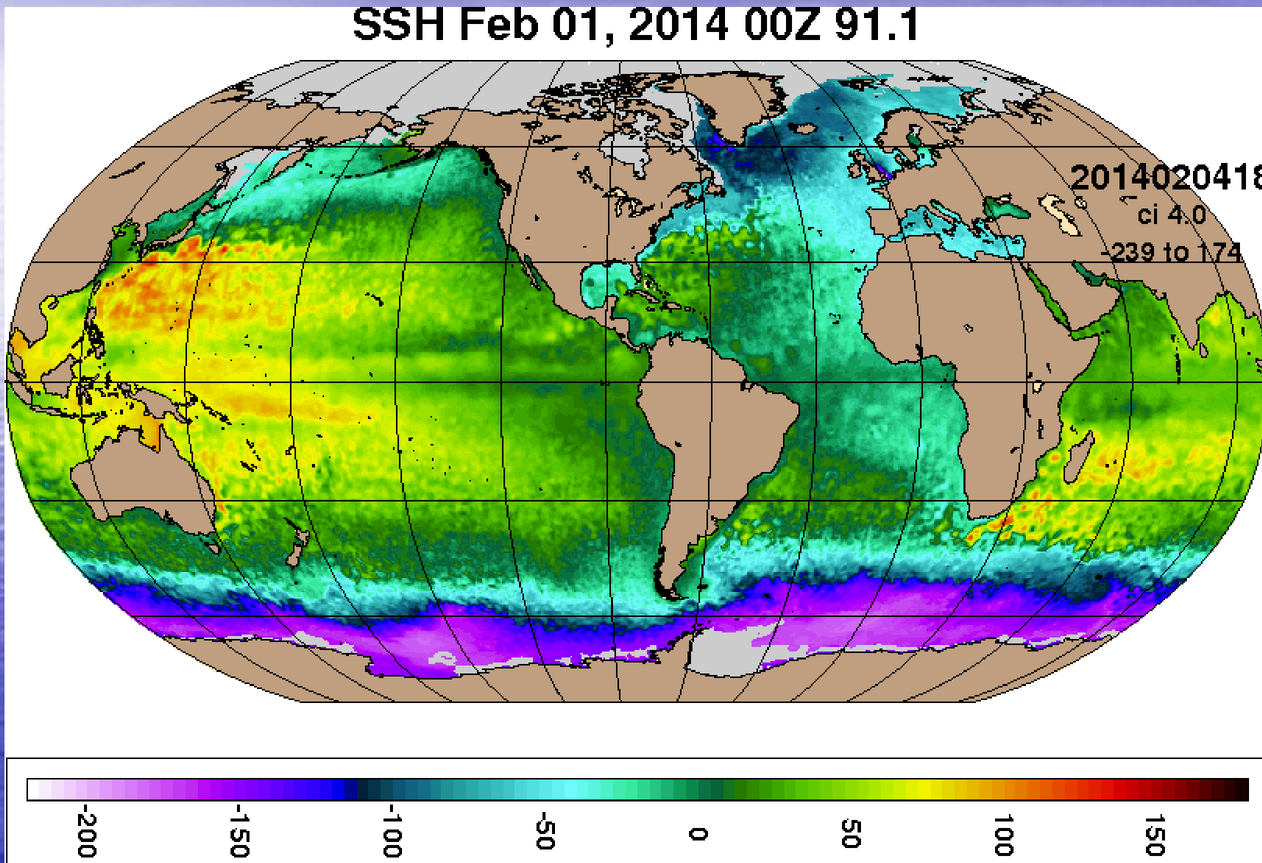
Global HYCOM Ocean Forecast Model



The Sea Surface Height (SSH) from the operational global model for the past year is shown in the animation.

A snapshot of the model "analysis," which is a statistical blending of the numerical model and observations, is shown for each day.

In operation, a 7 day forecast is provided each day. Forecasts provide boundary conditions for regional models

In Arbic's talk, he described results we obtained when we changed the global model to embed tidal forcing and generate internal tides and internal waves

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How well do we know the tides?

- In a recent paper by Detlef Stammer with 26 coauthors, 7 state-of-the-art barotropic tide models were compared to observations
  - Deep water errors ~0.5 cm M_2 and 1 cm for 8 major tides
  - Continental Shelf errors ~3.5 cm M_2 and 5 cm for 8 major tides
  - Coastal errors ~ 5 cm M_2 and 7 cm for 8 major tides
  - Arctic errors ~ 5 cm M_2 and 7 cm for 8 major tides
  - Differences between models smaller than differences relative to gauges

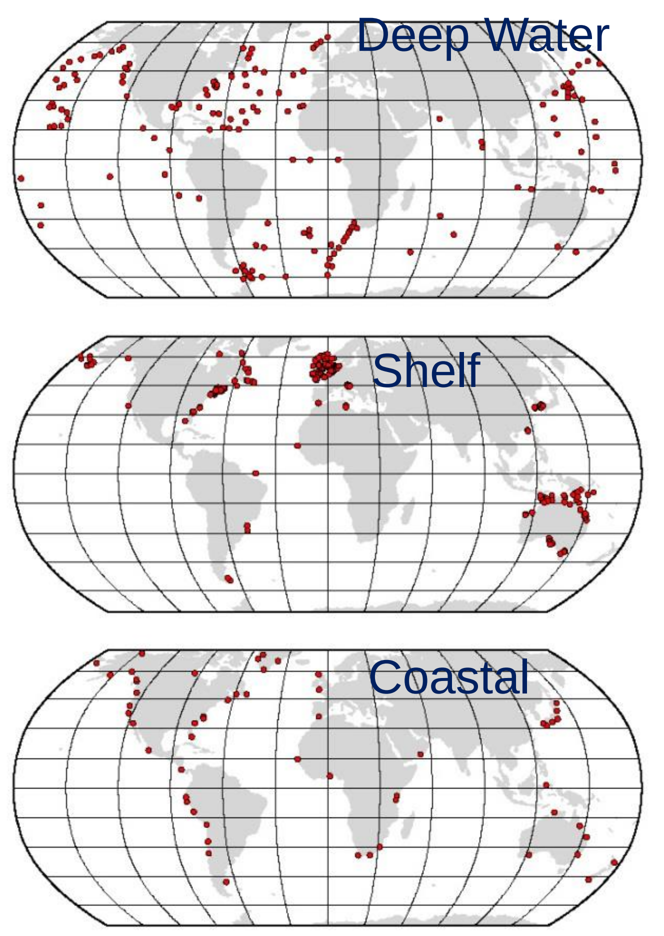
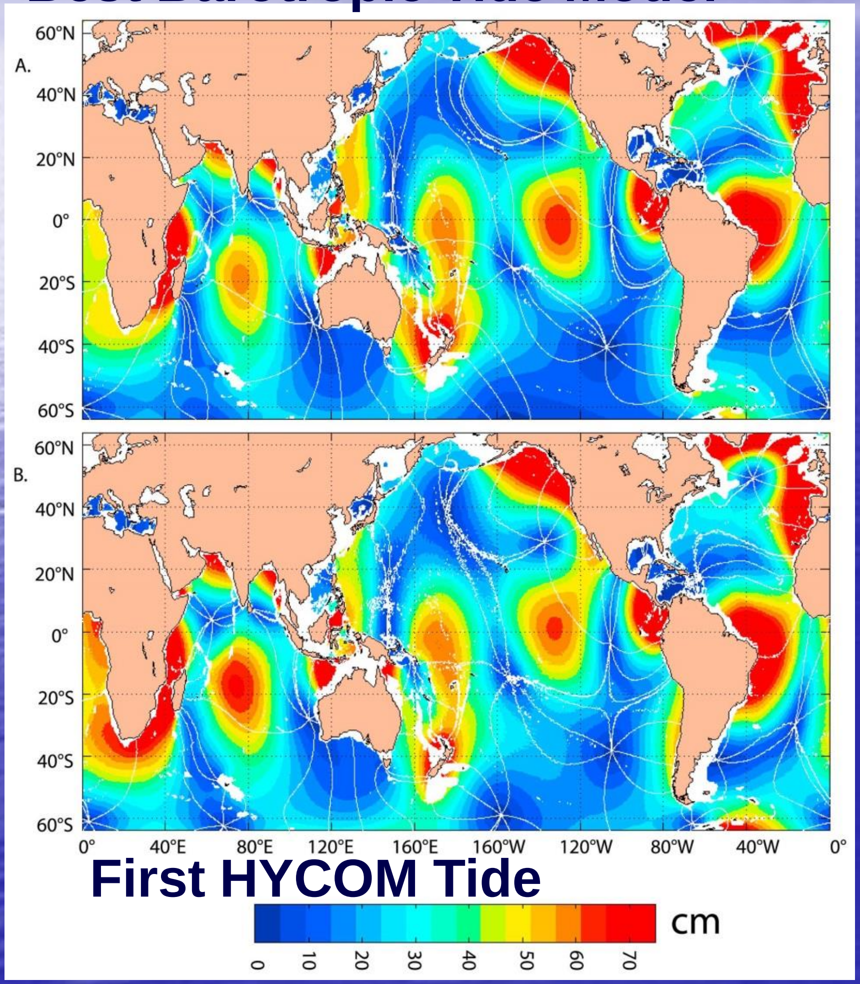


Figure 2. Station locations for the "ground truth" tidal data used in section 4. (top) Deep-water stations. (middle) Shelf stations. (bottom) Coastal stations.

Modeling tides in the global model

Best Barotropic Tide Model

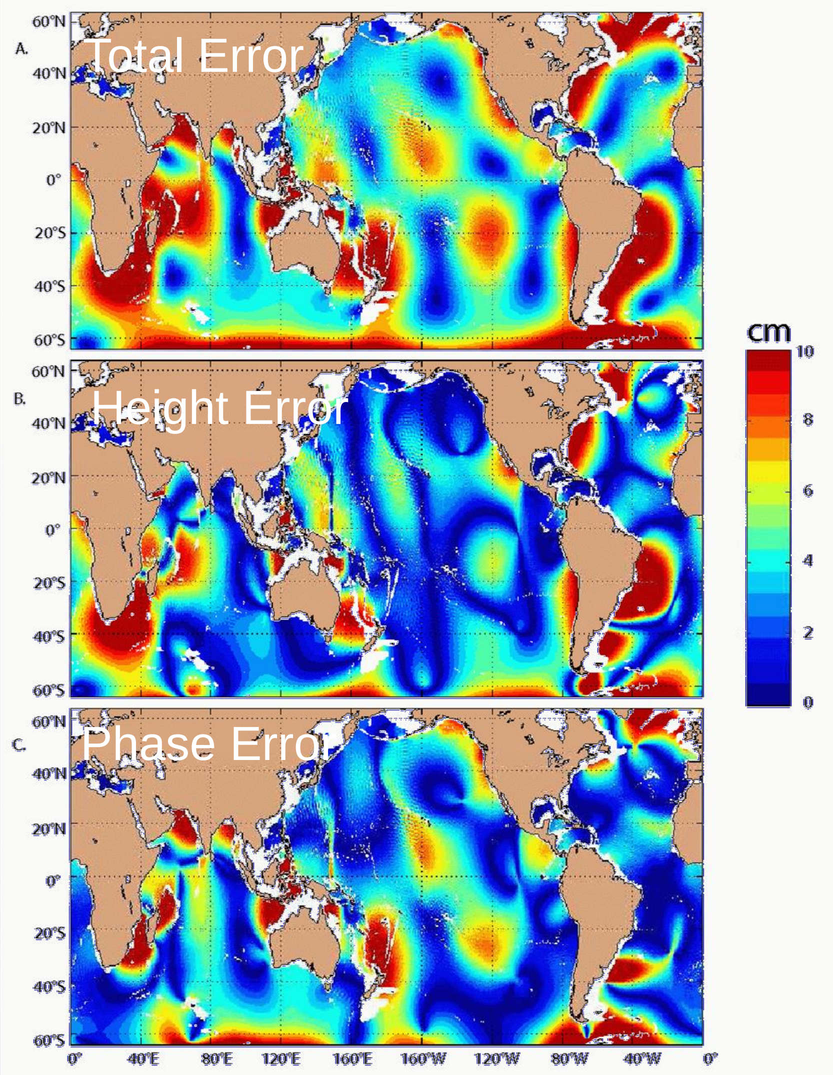


From Shriver et al. (2012)

- The circulation model is modified to include
  - Gravitational Potential of the Sun and Moon
    - 8 leading constituents
    - M_2, S_2, N_2, K_2 semidiurnal tides
    - K_1, O_1, P_1, Q_1 diurnal tides
  - Self Attraction and Loading (SAL) due to the deformation of the ocean and solid earth
    - Scalar approximation in initial simulation
  - Topographic wave drag to parameterize effects of internal wave generation and breaking
    - Coarse resolution Garner (2005) wave drag in initial simulation

Initial simulation M_2 RMS Error 7.0 cm

Accuracy of Model Barotropic Semidiurnal Tide



The model tidal amplitude can be compared to the amplitude from the state-of-the-art barotropic tide model TPXO

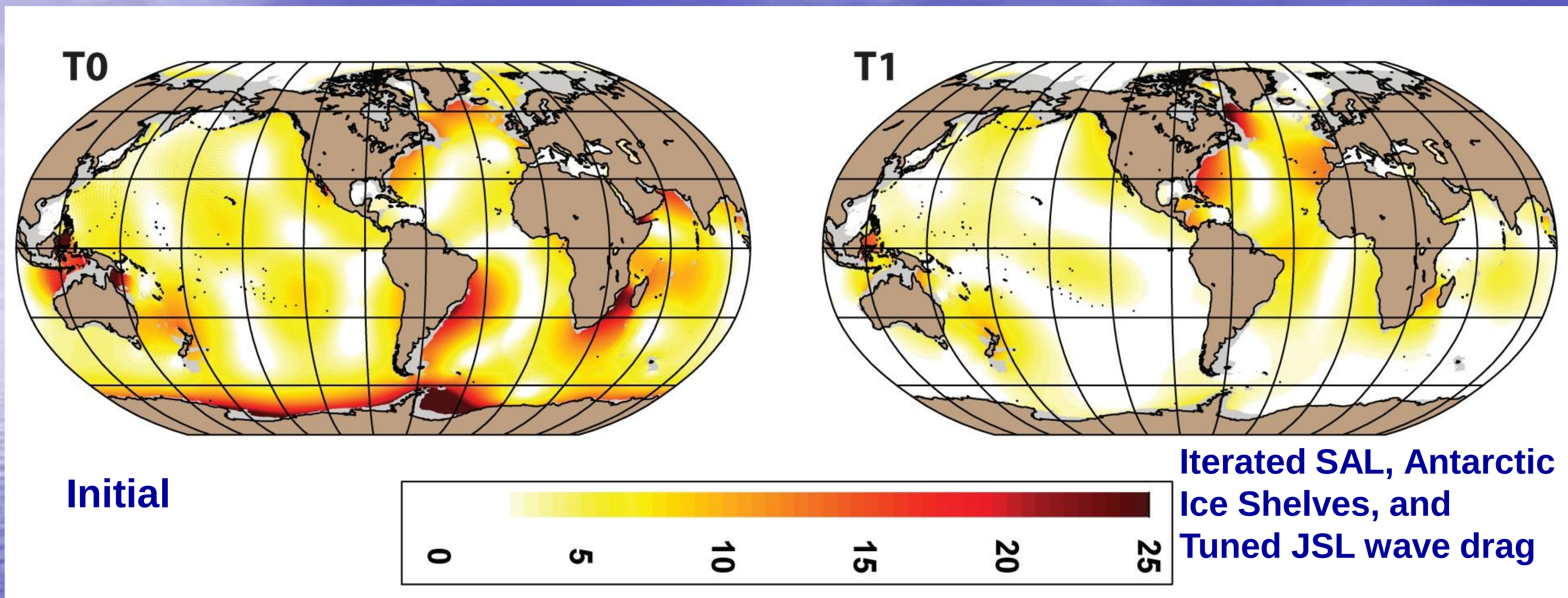
The tidal amplitude is characterized by a height and timing (phase)

The model M_2 tidal error over the ocean is 7 cm rms approximately evenly split between height and phase errors

The height errors are largest in the Atlantic and Southern Ocean

Important phase errors occur in the Pacific

Improving the tides in a global ocean circulation model



- The initial tidal simulation identified several issues
  - SAL poorly modeled
  - Wave drag needed tuning, replaced Garner (2005) drag with Jayne and St. Laurent (2001) wave drag
  - Tidal resonances with Antarctic ice shelves need to be included
- New simulation addressing these issues leading to a reduced rms error of 4.4 cm
- Good, but not at acceptable forecast levels

A new approach to correcting the model

- Best Barotropic Tide Models assimilate data to get an accurate state
  - Techniques used in barotropic tide models can't be used in the global ocean model
  - We need a continuous, concurrent forecast of the tide not a one time state estimate
- We borrow from the traditional data assimilation to make a correction to the model forcing
  - Augmentated State Ensemble Kalman Filter (ASEnKF)

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Kalman Filter State Estimation

- Ocean model dynamics—state variable **X**

$$\frac{\partial \mathbf{X}}{\partial t} = F(\mathbf{X}) + f$$

- Observations—**Y** [Observation error ε (covariance C_ε)]

$$\mathbf{Y} = H\,\mathbf{X} + \varepsilon$$

- Analysis—$\mathbf{X}^a$

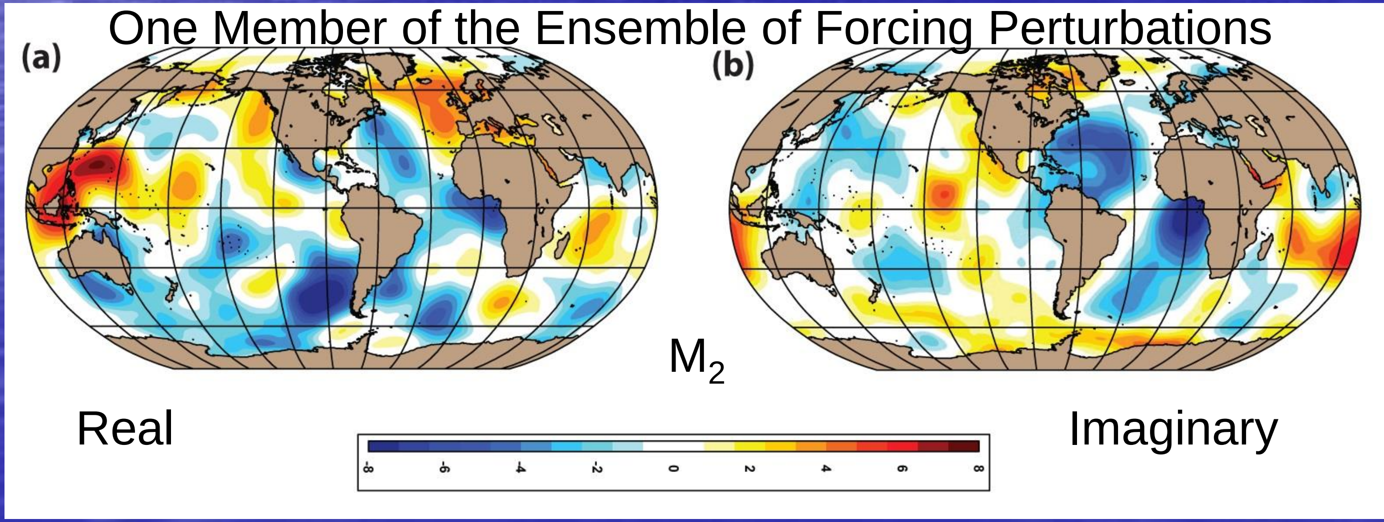
$$\mathbf{X}^a = \mathbf{X} + \mathbf{B}\,HT\,(H\mathbf{B}H^T + C_\varepsilon)^{-1}\,(\mathbf{Y} - H\,\mathbf{X})$$

- Use n-member ensemble of model runs to create background error covariance **B**

$$\mathbf{B} = \frac{1}{N-1}\sum_{n=1}^{N}(\mathbf{X}^n - \bar{\mathbf{X}})(\mathbf{X}^n - \bar{\mathbf{X}})^T$$

Augmentated State Ensemble Kalman Filter (ASEnKF)

- Prediction of tide inside the global circulation model
  - More than an optimal estimate of the barotropic tide
- Augment dynamical model
  - $\frac{\partial}{\partial t}\begin{pmatrix}\mathbf{X}\\ f\end{pmatrix} = \begin{pmatrix}F(\mathbf{X})+f\\ -\rho f\end{pmatrix} + \begin{pmatrix}0\\ u\end{pmatrix}$
- New state variable
  - $Z = \begin{pmatrix}\mathbf{X}\\ f\end{pmatrix}$
- For ensemble, generate a set of random forcing perturbations to drive 3d ocean model—100 members to the ensemble



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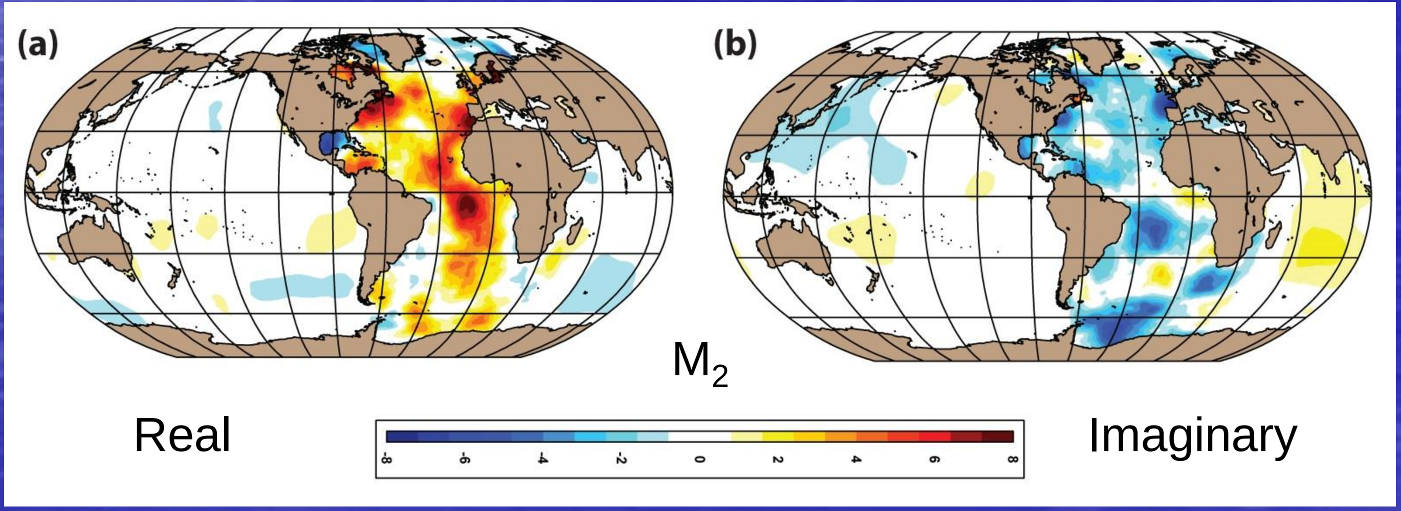
Augmentated State Ensemble Kalman Filter (ASEnKF)

- Solving the Kalman filter on the 3d dynamics is prohibitive, we simplify to
  - $\frac{\partial \mathbf{X}}{\partial t} = F(\mathbf{X}, \langle T_{pot} \rangle + \langle SAL \rangle + \langle f \rangle)$
- where ⟨ ⟩ represents terms defined in frequency space for each constituent and expressed in time for the dynamics
- For the state variable we use SSH_{tidal}

Forcing Correction *f* for the minimal error ASEnKF



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Augmentated State Ensemble Kalman Filter (ASEnKF)

Several Experiments performed where the observation error is changed using the same ensemble

T2 1 cm constant observation error

T3 Spatially varying observation error which varies similar to the error in Stammer et al. (2014)

T4 5 mm constant observation error

T5 Blended Atlantic-only and **T3** solution for rest of ocean

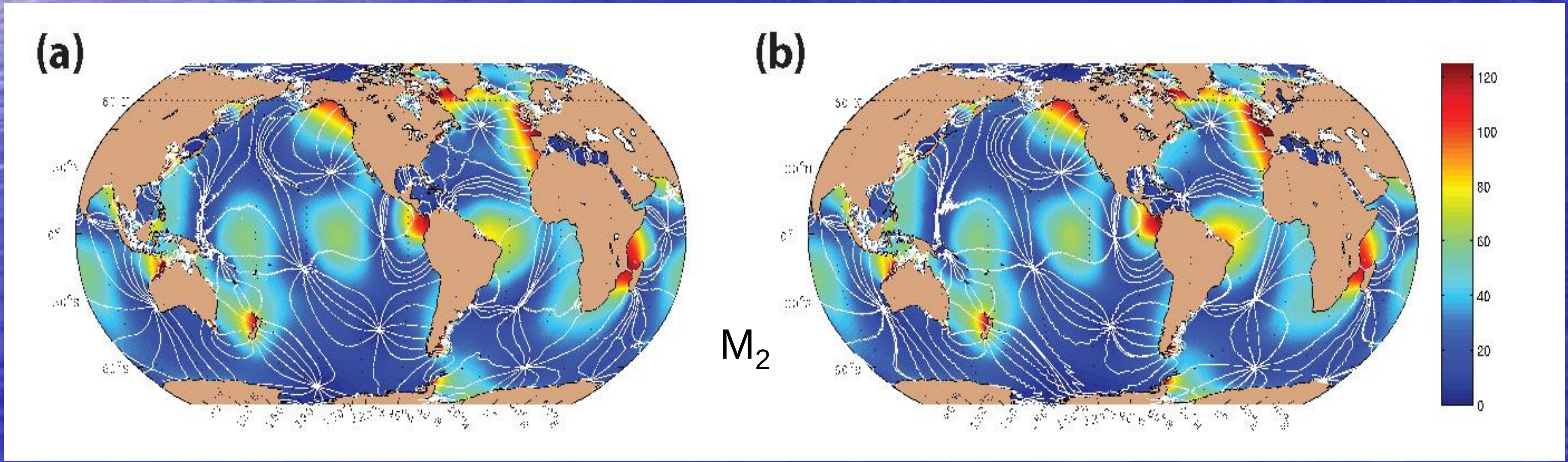
Simulation	Global RMS	Median Global RMS	Atlantic RMS	Median Atlantic RMS	Global excluding Atlantic RMS	Median Global excluding Atlantic RMS
Initial T0	7.0	5.3	6.8	5.6	7.0	4.8
Intermediate T1	4.4	3.2	7.3	7.1	3.5	3.5
1 cm constant observation error ASEnKF T2	2.8	1.7	5.2	5.2	2.0	1.8
Spatially varying observation error ASEnKF T3	3.2	1.6	6.3	6.2	2.0	1.5
0.5 mm constant observation error ASEnKF T4	2.8	1.9	4.6	4.6.5	2.3	1.9
Blended ASEnKF T5	2.6	1.7	4.4	3.8	2.1	1.5

Augmentated State Ensemble Kalman Filter (ASEnKF)

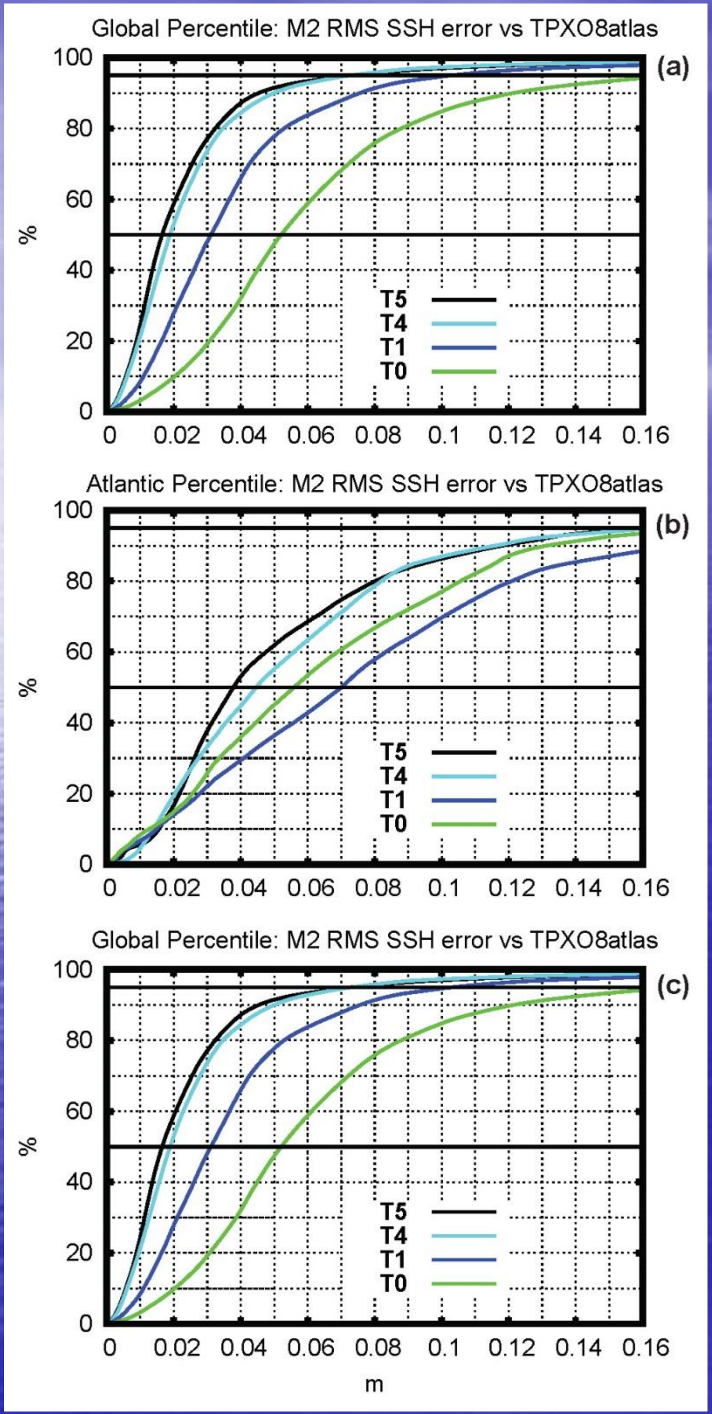
All ASEnKF solutions have a significant reduction in the error relative to TPXO8 compared to the initial simulation **T0** and intermediate simulation **T1**

- The errors are largest in the Atlantic Ocean
- The difference between the area weighted RMS errors and the median errors suggest that outliers (a few points with very large error) affect the area weighted errors

Maps of the M2 amplitude and phase



Blended ASEnKF **T5** TPXO8



Histograms of the Errors relative to TPXO8

- The errors are largest in the Atlantic Ocean
  - Atlantic histogram differs in shape from global or Pacific
  - Intermediate simulation **T1** performs worse in Atlantic than the initial simulation **T0**
  - Blended soln **T5** performs better than all solns for modest errors in Atlantic
- Global errors are affected by large Atlantic errors
  - For the blended soln **T5**, the 90 percentile error is 1 cm smaller in Pacific compared to global

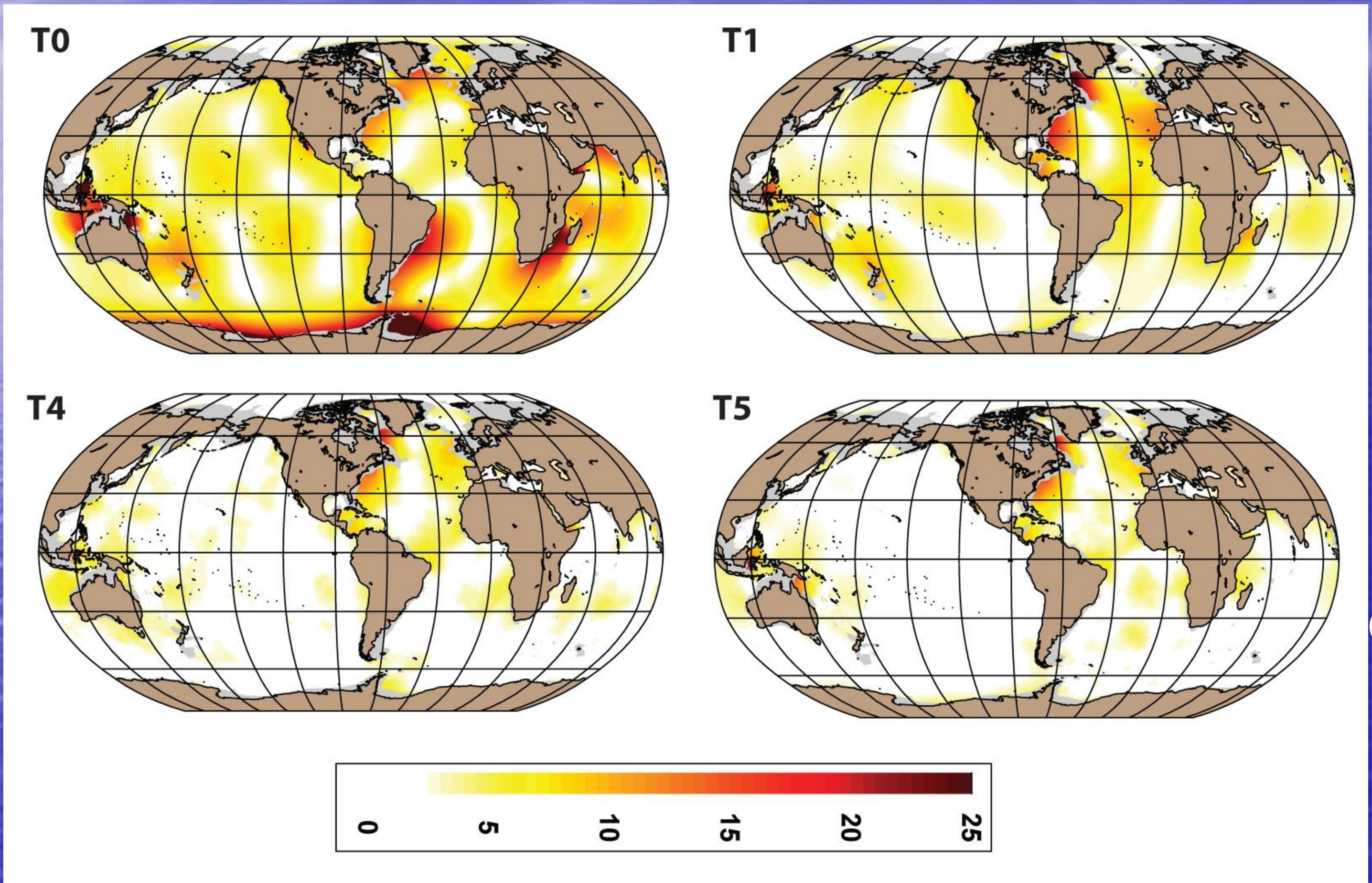
M_2 Error Maps relative to TPXO8

Initial Model

7.0 cm rmse

Iterated SAL Antarctic Shelves JSL drag

4.4 cm rmse



Global ASEnKF With uniform aprior error

2.8 cm rmse

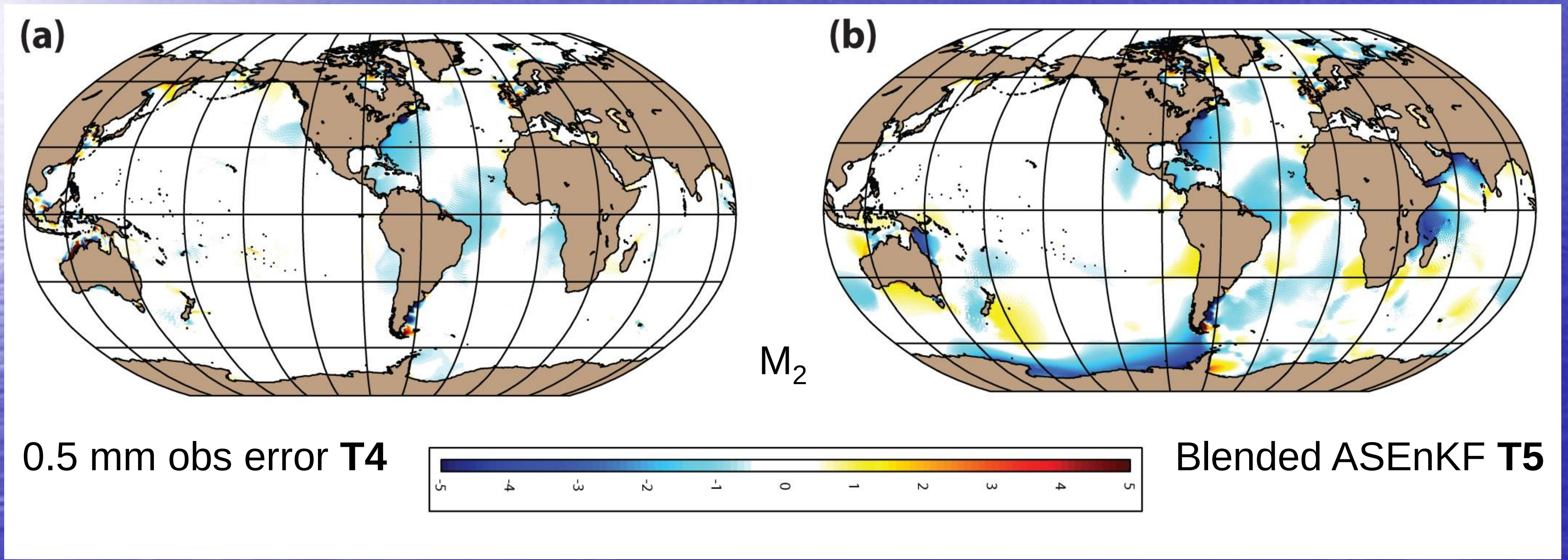
Atlantic Patch Correction

2.6 cm rmse

White areas are regions with RMS error less than 2 cm

Towards a Forecast Quality Global Tidal Prediction

Difference between RMS errors of ASEnKF predicted tide from TPXO8 and the RMS errors of the HYCOM predicted tide from TPXO8



For the extremely small obs error, the predicted tide from the state estimation and the tide from the 3d model with forcing correction are very close. For the blended solution, the 3d model with forcing correction has larger errors than the state estimation prediction, even though this solution had small RMS errors overall.

Performance of ASEnKF

- M_2 Tides with the ASEnKF forcing correction have smaller errors than the initial and intermediate simulations
  - None of the ASEnKF models could reduce the RMS errors to the level of apriori obs error
  - None of the models perform well in the Atlantic or Indonesian Seas
    - Two possible explanations
      - Ensembles generated with large scale perturbations
      - If the ensemble doesn’t contain the error structures then the EnKF can’t make correction
- Way forward
  - Two way nesting with high resolution coastal domains
  - New perturbations with smaller scales