Seafloor Topography and Ocean Tides from Satellite Altimetry

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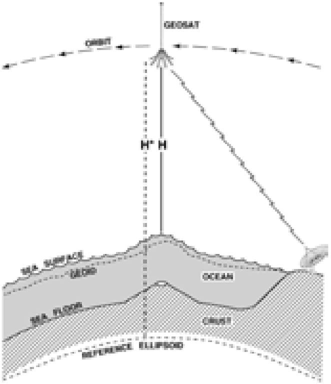
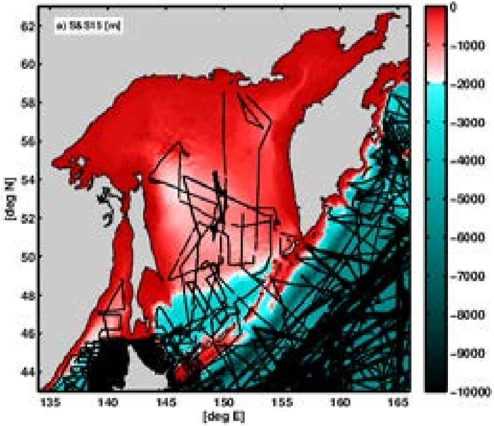
Outline

1. Motivation and methodology
2. Assembling the pieces:
   – topography, altimeter data, and their error models
3. An idealized identical twin experiment
4. Results for Sea of Okhotsk
5. Discussion

Motivation: uncertain topography in some areas

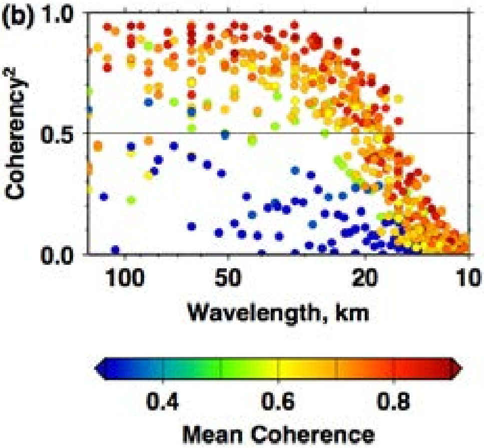
Smith and Sandwell (JGR 1994)





- nearly global coverage
- complex relationship between topography and gravity

Motivation: uncertain topography in some areas



Marks and Smith, Radially symmetric coherence between satellite gravity and multibeam bathymetric surveys, *Mar. Geophys. Res.*, 33(3), 223-227, 2012.

Objective

To assimilate altimetric observations into a dynamical model for tides in which bottom topography is a control variable.

Precedents:

- Storm surge modeling on the European shelf (Lardner et al).
- Topography from SSH assuming large-scale dynamics (Losch and Wunsh).
- Topography from tidal currents, SSH (Hirose; Mourre et al).

Methodology

The approach builds on OTIS, the Oregon State Tidal Inversion System, developed by Egbert and Erofeeva.

$$-i\omega U + f \times U + gH\nabla\eta + C_d|u_f|U/H = -gH\nabla\Phi^{astro} + \lambda^U \quad (1)$$

$$-i\omega\eta + \nabla \cdot U = 0 \quad (2)$$

$$H = H_0 + \lambda^H \quad (3)$$

Minimize a weighted integral of squared misfits to dynamics and data,

$$J(H, U, \eta) = \int \lambda^U C_{UU}^{-1} \lambda^U + \int \lambda^H C_{HH}^{-1} \lambda^H + \sum_{data} \frac{\epsilon^2}{\sigma^2}.$$

Methodology

Technical developments:

- Inter-constituent coupling (same H at each tidal frequency).
- Separate representers for obs. of Re/Im parts (H is real-valued).
- New spatial covariance models for H.
- Picard iteration for nonlinearity.
- Optimizations for large multi-core machine (64 cpus, 256GB RAM).

Where might this approach work?

Requirements for success:

- Accurate tidal SSH ($\sigma_\eta \approx 1\%$)
- H less accurate than η ($\sigma_H \approx 10\%$)
- Accurate barotropic dynamics:
  - no baroclinic tide
  - no wetting and drying
  - bottom drag not too influential

This talk focusses on the Sea of Okhotsk, where tides are large, altimetry is plentiful, and topography is uncertain.

Assembling the pieces: Topography

Question: What topography to start with? How to describe its spatial error covariance?

There are errors in the bathymetric data at control points. Smith (1993) and Marks and Smith (2008) note:

- positional errors, pre-GPS navigation
- sound speed errors
- blunders

In lieu of a complete error model, intercompare gridded topographies.

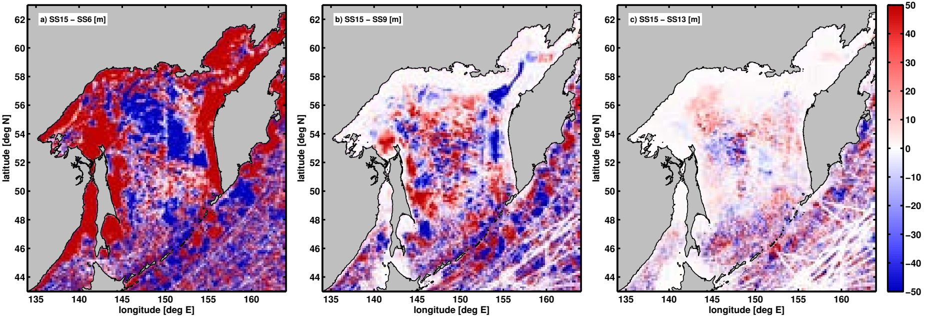
Assembling the pieces: Topography

Comparison of gridded topography to JAMSTEC multibeam bathymetry [m].

source	mean	std	mean Δ	std Δ
SS15	1079	160	0.8	4.9
SS11	1097	165	19	71
ETOPO1	1111	157	33	79
DBDB2v30	1080	168	1.7	63
GEBCO	952	111	-127	84

Assembling the pieces: Evolution of SS over time

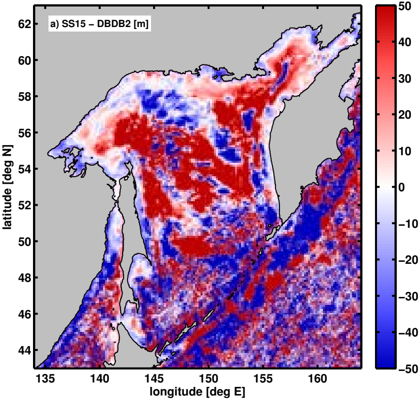
SSv15 - SSv6 (1997) | SSv15 - SSv9 (2007) | SSv15 - SSv13 (2011)



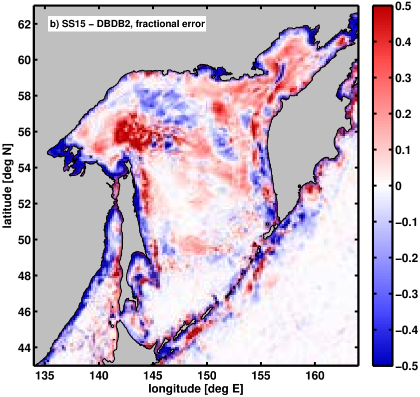
RMS differences reduced from 180m to 20m over time.

Assembling the pieces: DBDB2 versus SSv15

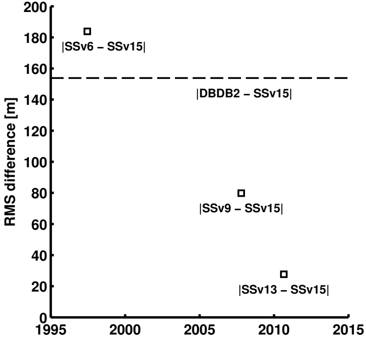
SS15 - DBDB2
RMSD=155 m

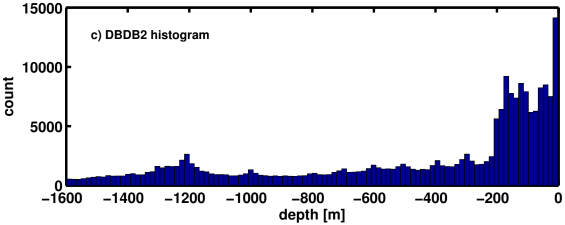


Fractional
Difference



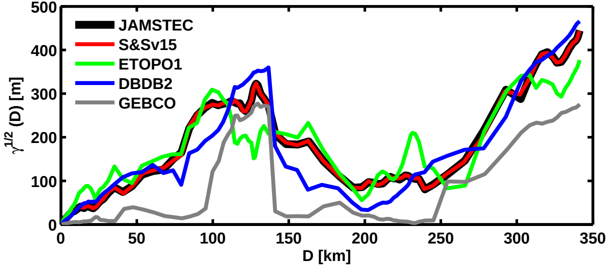
Assembling the pieces: DBDB2 versus SSv15





Assembling the pieces: Comparison of multiple topographies

Variogram along the cruise tracks in central Sea of Okhotsk from JAMSTEC.



Topography: Summary

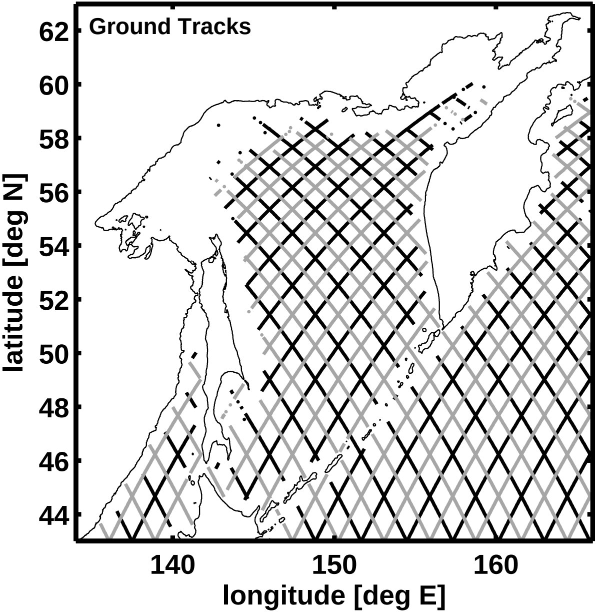
The following topographies were compared:

- Smith & Sandwell v. 6, 9, 11, 13, and 15
- GEBCO
- DBDB2v30
- ETOPO1

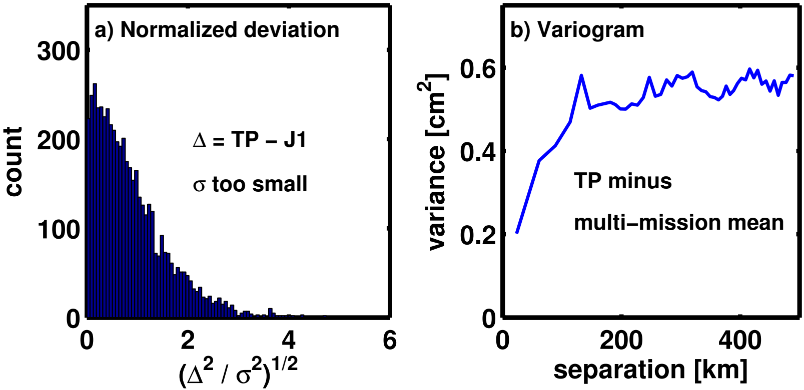
Conclusions:

- SS converging over time.
- DBDB2 and GEBCO are very smooth.
- Use ETOPO1 (hand-edited SSv9) as prior.
- Build topo. error model from DBDB2 minus SSv15.

Assembling the pieces: Altimetry



Assembling the pieces: Altimetry



Inflate σ from harmonic analysis by 30%.
Use data from cross-overs.

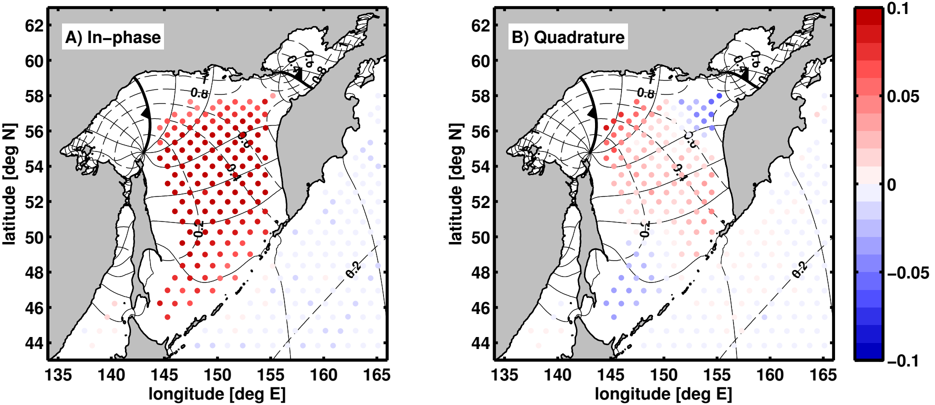
Application to the Sea of Okhotsk

- Approx. 3km resolution
- M_2, S_2, K_1, and O_1
- Quasi-linear drag, $C_d|u_f|U/H$, following Snyder et al (1979)
- Open boundary conditions from TPXO7.2-ATLAS

Tide Model	RMSE [cm]
TPXO7.2-Atlas	1.3
DBDB2	12
ETOPO1 ($C_d = 1.5 \times 10^{-3}$)	5.4
ETOPO1 ($C_d = 3.0 \times 10^{-3}$)	6.2

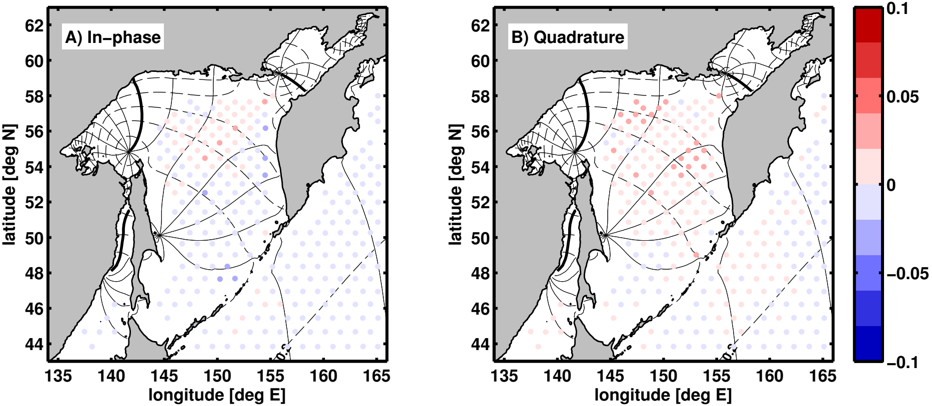
Application to the Sea of Okhotsk

Prior model has large error.



Application to the Sea of Okhotsk

TPXO7.2 fits data within nominal uncertainty.



An identical twin experiment

Purpose: Demonstrate the importance of the error model for the topography.

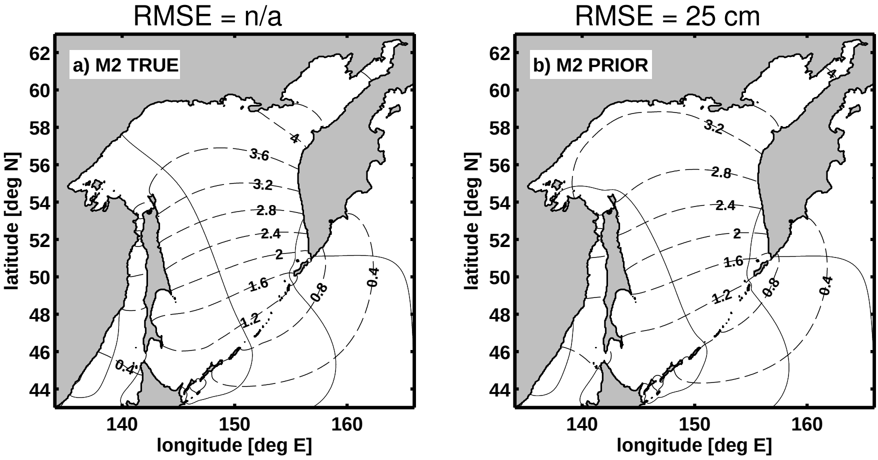
The topography correction, λ^H, is computed from a spatial error covariance model and an adjoint sensitivity, but the latter depends on the η and U fields:

$$\lambda^H(x) = \int C_{HH}(x,y)\left(-g\boldsymbol{\mu}\cdot\nabla\eta + C_d|u_f|\frac{U\cdot\boldsymbol{\mu}}{H^2}\right)dy \qquad (4)$$

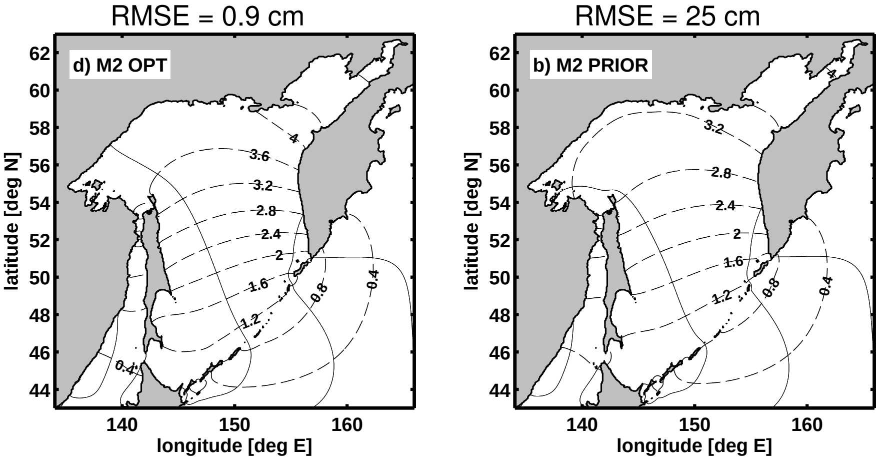
Adjoint sensitivity is dominated by regions where $\nabla\eta$ is large.

(Notation: $x = (\theta, \phi)$ is lat.-lon. coordinate)

An identical twin experiment



An identical twin experiment



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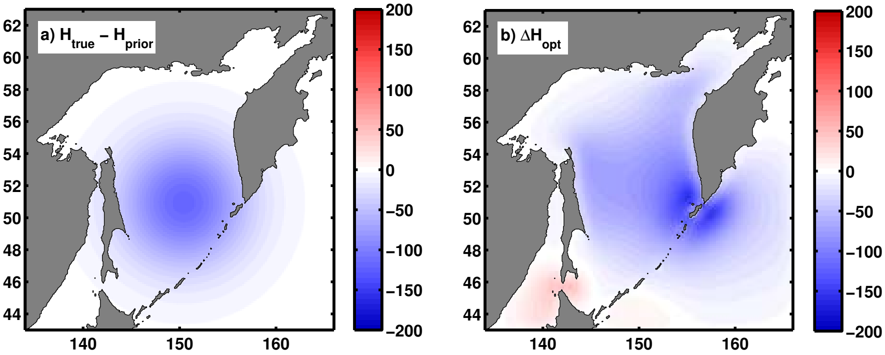
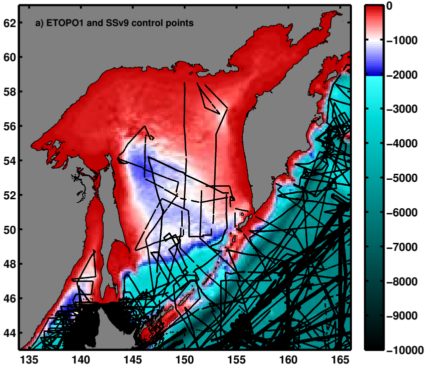


Development of Spatial Error Covariance Model

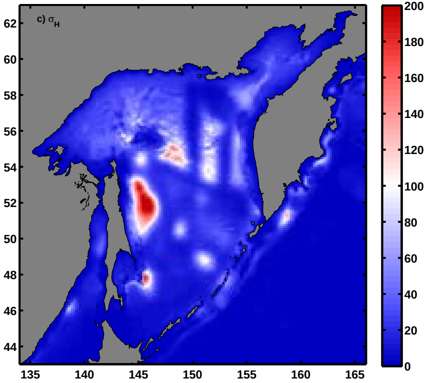
Factorize C_{HH} in terms of a variance and correlation:

$$C_{HH}(x,y) = \sigma_H(x) c_H(x,y) \sigma_H(y) \qquad (5)$$

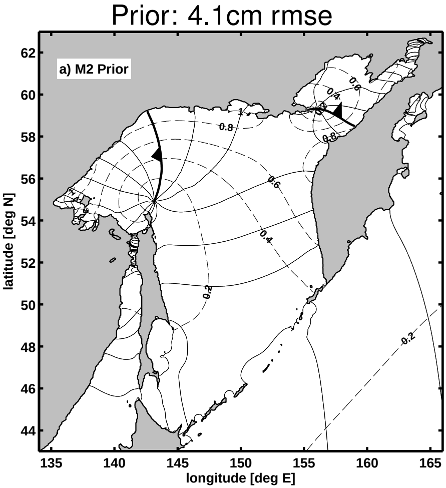
ETOPO1



σ_H

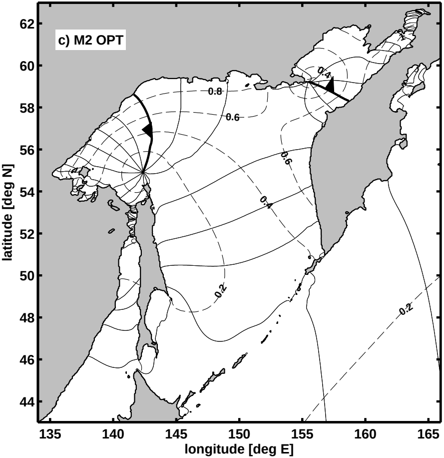


Sea of Okhotsk (ETOPO1 + altimetry)



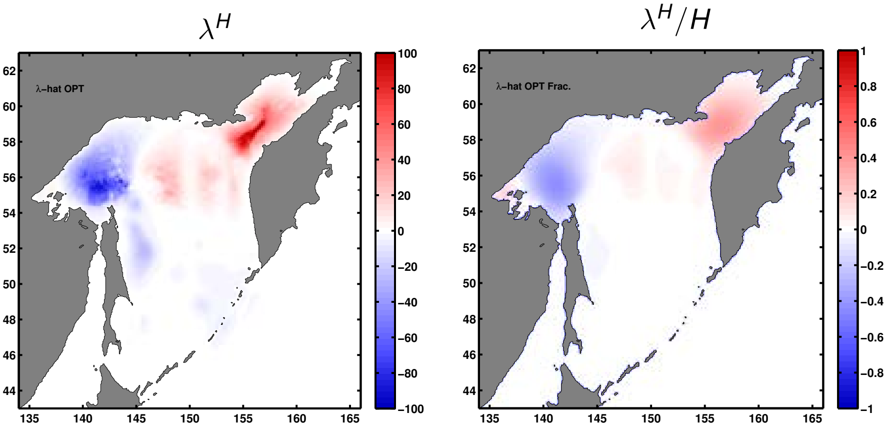
Sea of Okhotsk (ETOPO1 + altimetry)

Optimal: 2.8cm rmse



Topographic adjustments explain about 50% of the SSH error variance.

Sea of Okhotsk (ETOPO1 + altimetry)



Conclusions & Further Questions

Summary:

- Relatively small corrections to bottom topography can explain a significant fraction of the discrepancy between observed and modeled tides.
- The topographic inversion problem is strongly nonlinear.
- Spatial structure of errors in gridded topographies is not well characterized.
- The estimated topography depends strongly on the assumed spatial covariance, C_{HH}.

Questions:

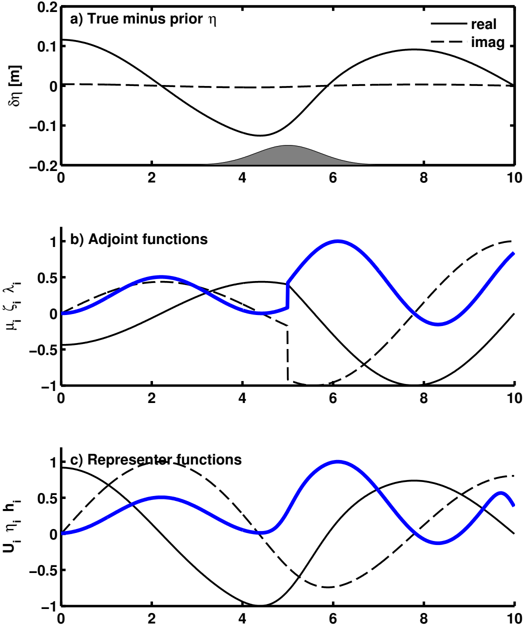
- 1-d idealized experiments show importance of small-scale roughness for de-tuning resonance. What are implications for the first guess?
- Where are other good sites for application?

Backup Slides

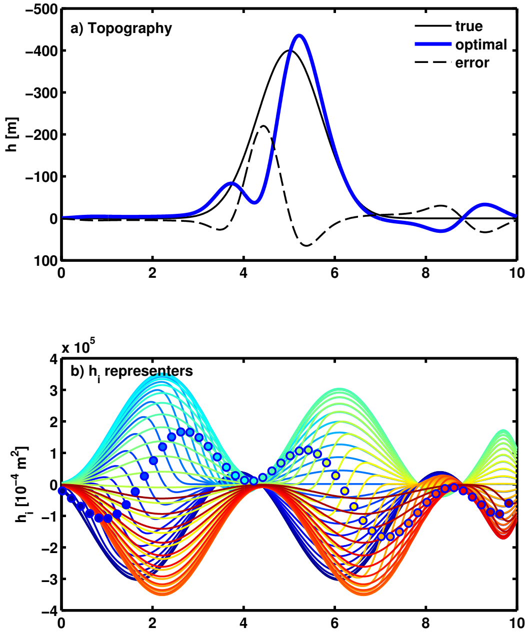
Observability in a 1-d idealized model:

- Nonlinear dependence on first guess.
- No corrections where $|\nabla\eta| = 0$.
- $\longrightarrow$ multiple constituents are required.
- Realizability condition: $\lim \sigma_H / H \to \mathit{const}.$ as $H \to 0$.
- Relative H error is 5 to 10$\times$ relative η error.

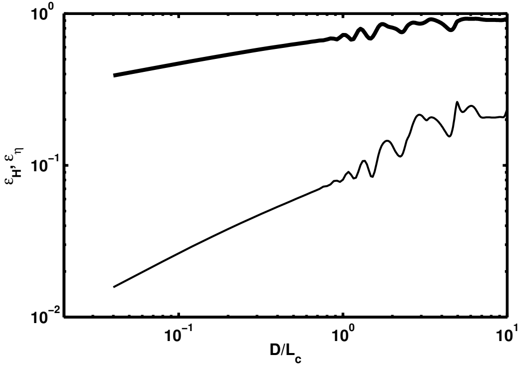
1-d Experiment: isolated bump



1-d Experiment: isolated bump



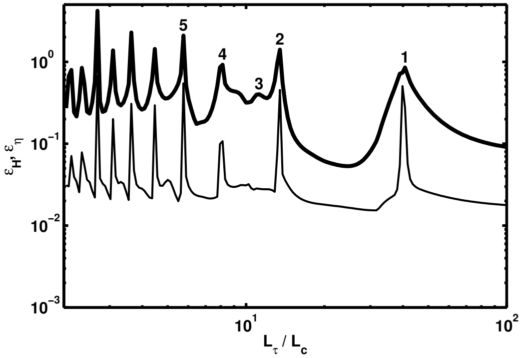
1-d Experiment: isolated bump



ϵ_H and ϵ_η are relative errors in H and η as estimated by data assimilation.

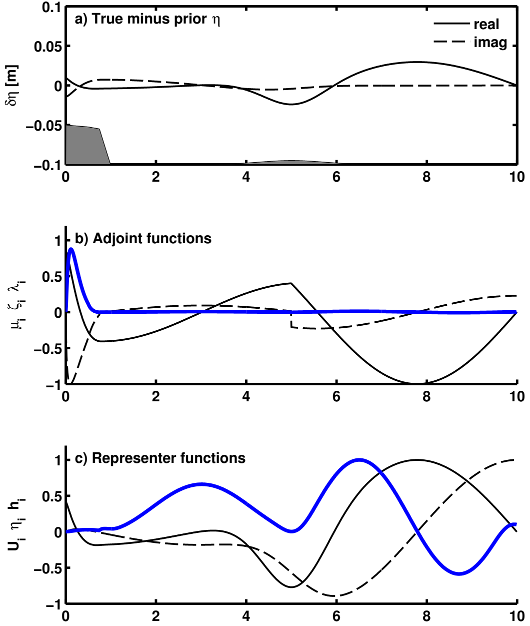
Estimation error decreases as data spacing D goes to zero. L_c is the half-width of the topographic bump.

1-d Experiment: isolated bump

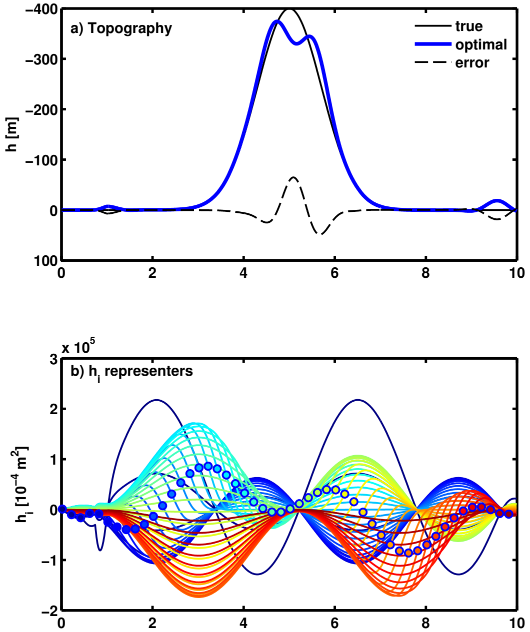


Estimation error varies strongly with tidal wavelength. Errors are worst at near-resonance.

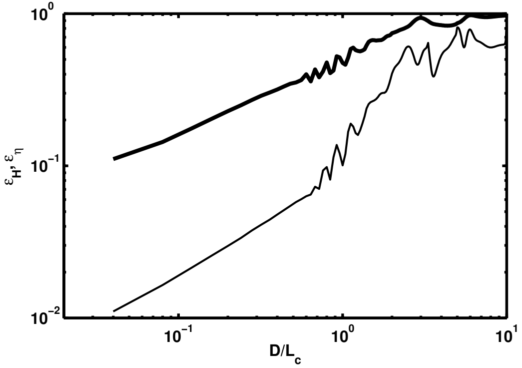
1-d Experiment: shelf + isolated bump



1-d Experiment: shelf + isolated bump

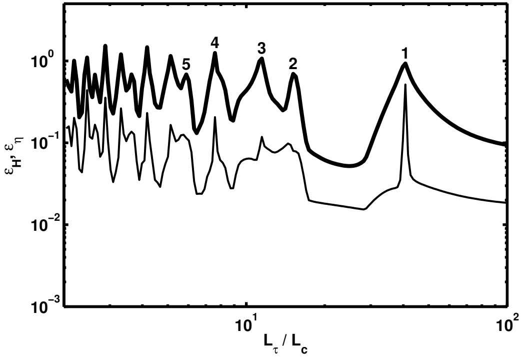


1-d Experiment: shelf + isolated bump

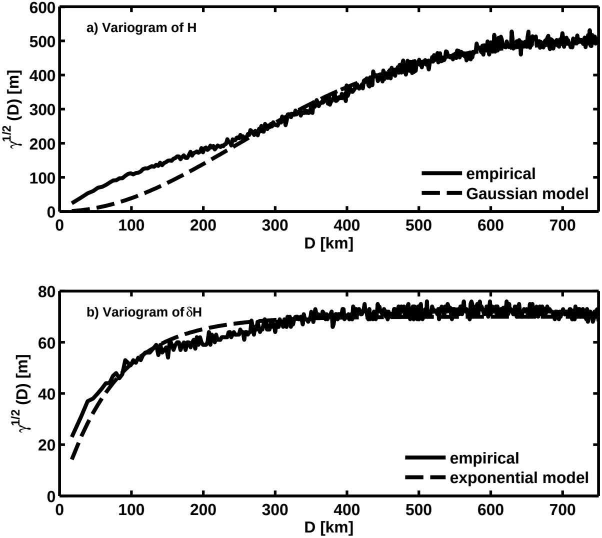


Note: $\sigma_H(x) = \alpha H(x)^p$, with $p > 1$ is required in order to suppress the sensitivity on the shelf.

1-d Experiment: shelf + isolated bump



Error Model for Topography



Topography "error": $\delta H = \text{ETOPO1} - \text{DBDB2}$