Ocean self-attraction and loading (SAL) and internal tides dissipation implementation within an unstructured global tide-surge model

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Contents

- Context: BASE Platform project
- Introduction GTSM model
- SAL and Internal tides dissipation
  - Physical process
  - Parameterization
  - Numerical implementation in DELFT3D-FM
- Sensitivity tests
- Discussion
- Future work

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BASE Platform

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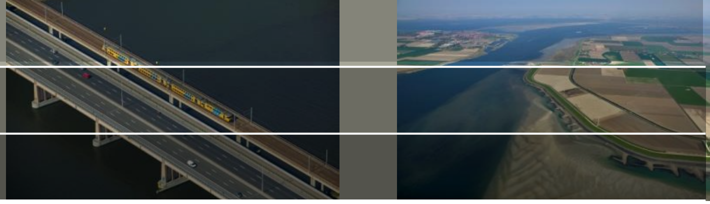
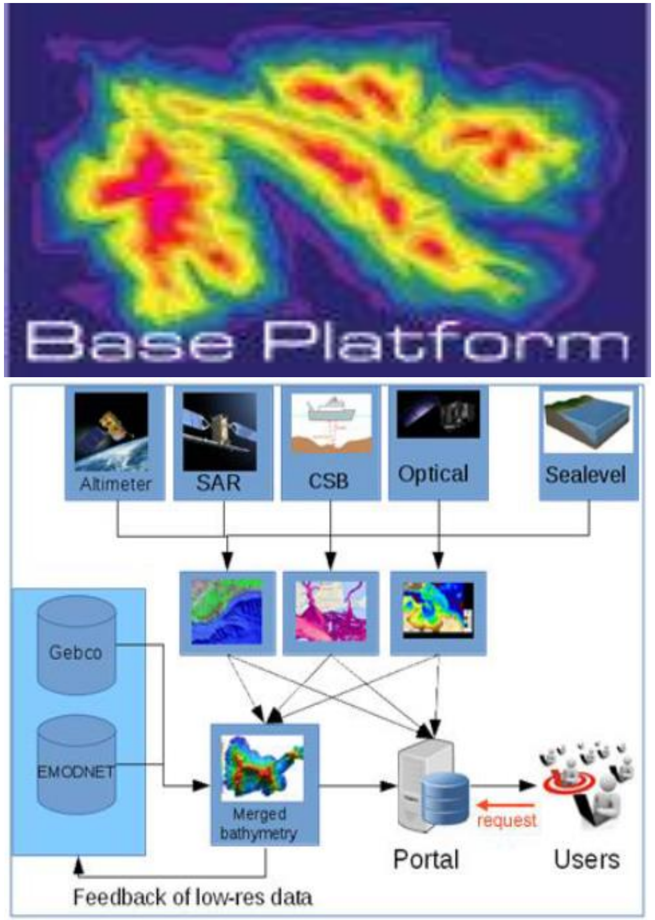
BASE- Platform



- 2 year project funded by the European Union's Horizon 2020 research and innovation programme (No 687323)
- Objective: set up an online platform for up to date bathymetry data for the whole globe
- Deltares' role: Develop a global hydrodynamic model to correct depth data from different sources for dynamic variation of the sea level

GLOBAL TIDE SURGE MODEL (GTSM)



Concept of data flows and interaction. Synergy of techniques for retrieving bathymetric data

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Global Tide Surge Model (GTSM)

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Model description

- Global unstructured, depth averaged model in spherical coordinates.
- Courant grid: Local grid refinement based on depth. Use of triangles and rectangles. Maximum resolution on coast down to 5 km; Most of the domain is around 50 km
- Bathymetry: GEBCO 1/60 degree resolution
- Periodic boundary conditions (“No boundaries” situation).

- Tidal motion induced by Tide Generating Forces (Including solid earth tide or Earth elasticity factor) on a 1 degree resolution grid.

From regional to global models

- Tide generating potential equation added to the governing equations:

$$\frac{\partial \mathbf{u}}{\partial t} + \frac{1}{h}\left(\nabla \cdot (h\mathbf{u}\mathbf{u}) - \mathbf{u}\nabla \cdot (h\mathbf{u})\right) \quad = \quad -g\nabla\left(\xi - \xi_{EQ}\right) + \nabla \cdot \left(\nu\left(\nabla \mathbf{u} + \nabla \mathbf{u}^T\right)\right) + \frac{\tau}{h}$$

- Two physical processes that are not negligible at a global scale:
  - Self attraction and loading (SAL)
  - Tidal dissipation through generation of internal tides.

Self Attraction and Loading (SAL)

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SAL – Physical explanation

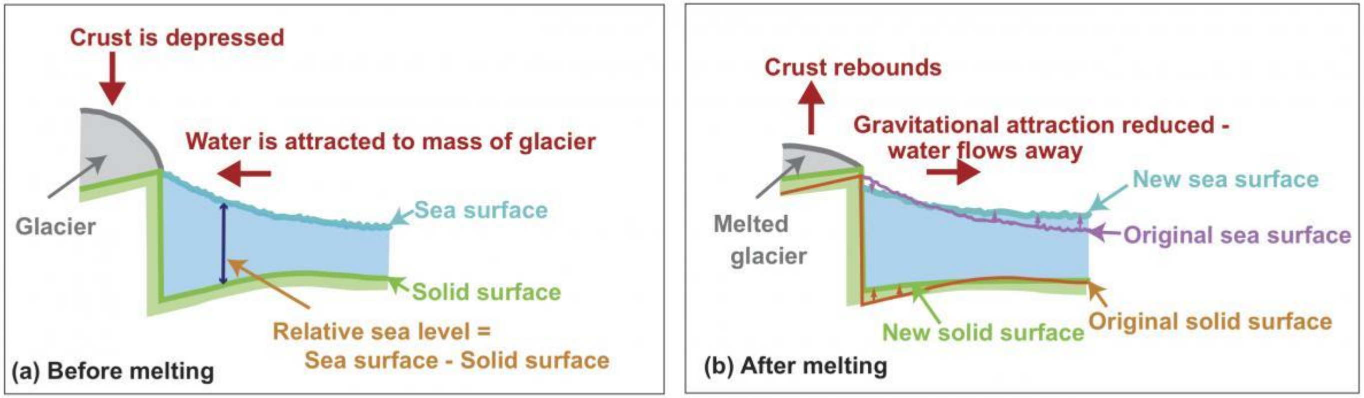
SAL is the sum of **three** effects:

Deformation of the seafloor under the weight of the column of water (Earth is a elastic body)

Redistribution of Earth mass changes the gravitational field

} LOADING

Gravitational attraction induced by the mass of the ocean on the ocean itself — SELF ATTRACTION



SAL POTENTIAL Φ_{SAL}

Literature values $\approx 10\%$ of Tide

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SAL -Self Attraction

SAL tide:

$$\xi_{EQ} = \frac{\Phi_{\text{eff}}}{g} \text{ with } \Phi_{\text{eff}} = \Phi(1 + k_2 - h_2) \qquad \xi_{SA} = \frac{\Phi_{\text{SA}}}{g}$$

Solid Earth tide

Newton's attraction law: The gravitational potential at a location p induced by a point mass m at a location q

$$V(\mathbf{p}) = \gamma \frac{m}{\overline{\mathbf{pq}}}$$

Depth << Radius

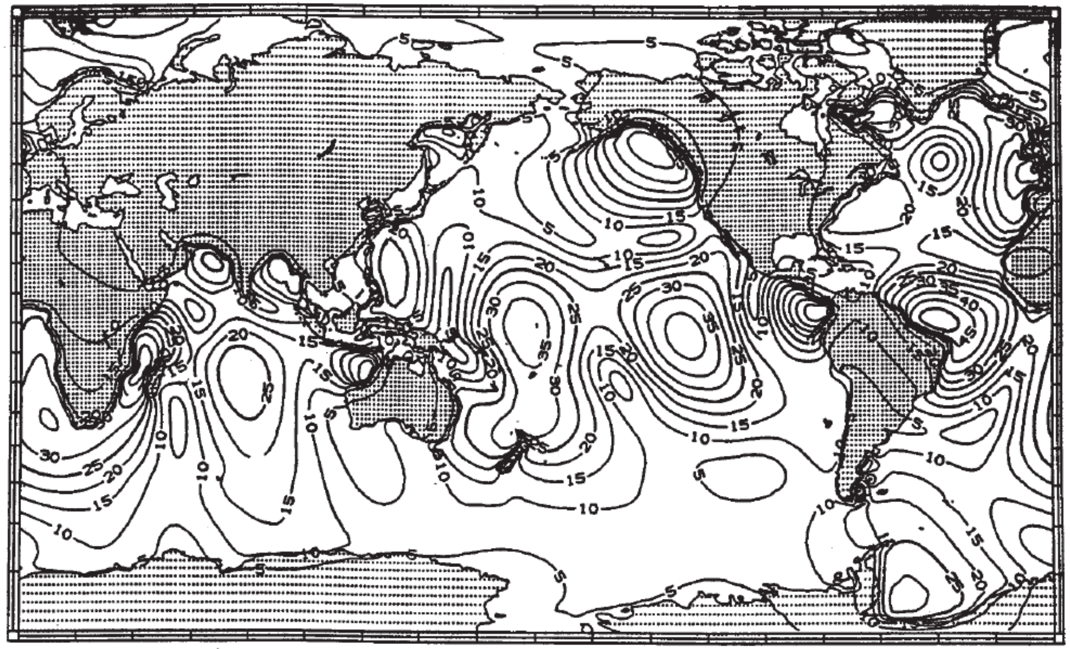
$$V(\mathbf{p}) = \gamma \int\int_S \frac{\sigma(\mathbf{q})}{\overline{\mathbf{pq}}} dS$$

$\sigma(q)$: the surface mass density at location q and S the surface of the spherical shell.

Full 2D convolution computationally expensive →Spherical harmonic function series (Camille le Coz); accuracy depends on grid size.

SAL - Loading

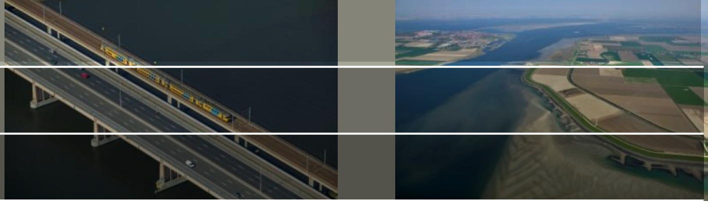
Load tide in spherical harmonics function series, given by Love numbers (h_n', k_n') for bottom displacement and induced gravitational potential change.



Amplitude map in millimeters of the M2 load tide (Schrama, E., (2007))

n	$-h_n'$	$-k_n'$
1	0.295	0
2	1.007	0.309
3	1.065	0.199
4	1.069	0.136
5	1.103	0.103
6	1.164	0.093
8	1.313	0.079
10	1.460	0.074
18	1.952	0.057
30	2.411	0.043
50	2.777	0.030
100	3.127	0.016

SAL- Implementation in FM



SA + Loading in spherical harmonics:

$$\xi_{SAL} = \frac{\Phi_{SA}(1+k_n{}'-h_n{}')}{g}$$

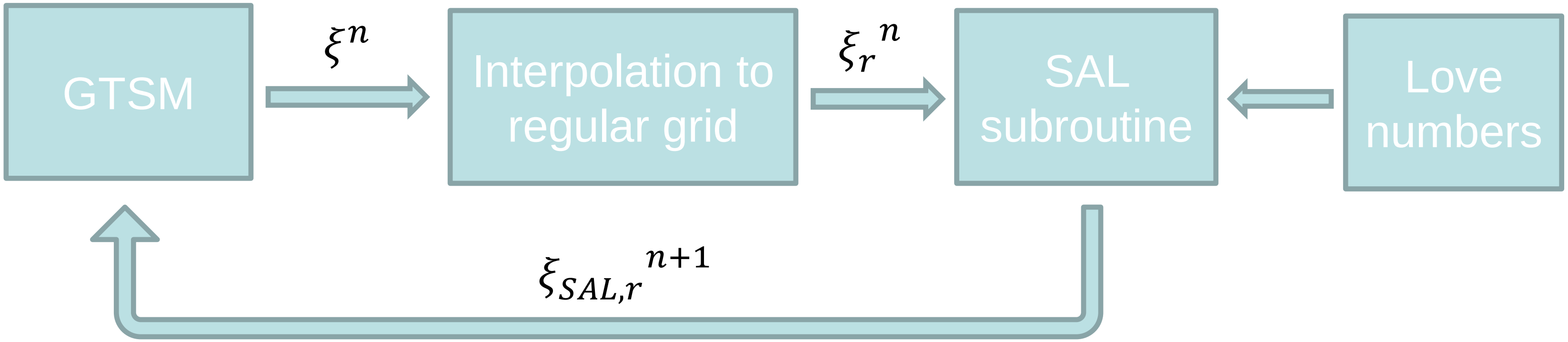
$$\frac{\partial \mathbf{u}}{\partial t} + \frac{1}{h}\left(\nabla\cdot(h\mathbf{u}\mathbf{u}) - \mathbf{u}\nabla\cdot(h\mathbf{u})\right) = -g\nabla\left(\xi - \xi_{EQ}\right) + \Phi_{SAL} + \nabla\cdot\left(\nu\left(\nabla\mathbf{u} + \nabla\mathbf{u}^T\right)\right) + \frac{\tau}{h}$$

$$\frac{\partial \mathbf{u}}{\partial t} + \frac{1}{h}\left(\nabla\cdot(h\mathbf{u}\mathbf{u}) - \mathbf{u}\nabla\cdot(h\mathbf{u})\right) = -g\nabla\left(\xi - \xi_{EQ} - \xi_{SAL}\right) + \nabla\cdot\left(\nu\left(\nabla\mathbf{u} + \nabla\mathbf{u}^T\right)\right) + \frac{\tau}{h}$$

Other implementations (β approximation) :

$$\xi_{SAL} = \beta\xi + Const \quad with\ \beta = 0.9 \rightarrow \qquad -g\beta\nabla(\xi - \xi_{EQ})$$

Sequence:



Tidal dissipation through generation of internal tides (IT)

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IT dissipation – Physical explanation

Barotropic tidal dissipation sources:

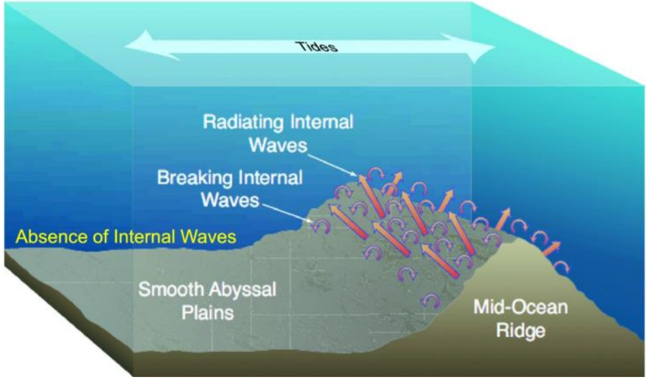
- Bottom friction (dominant in shallow waters)
- Generation of internal waves when flowing over rough topography in stratified oceans (dominant in deep waters)

Internal tides (or *Baroclinic* tides) are generated as the barotropic tides move stratified water up and down a sloping topography, which induces buoyancy forces that generate oscillation of isopycnals.

ρ of 2 surfaces at interface is similar → Large displacements

Baroclinic energy:

- Dissipates locally (high order mode waves)
- Radiates out into the ocean (low order mode waves)



Internal tides signal of sea surface in the strait of Gibraltar

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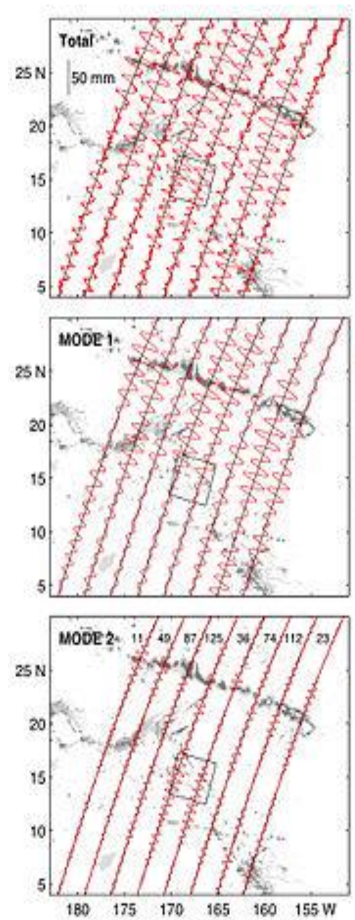
IT dissipation – Physical explanation

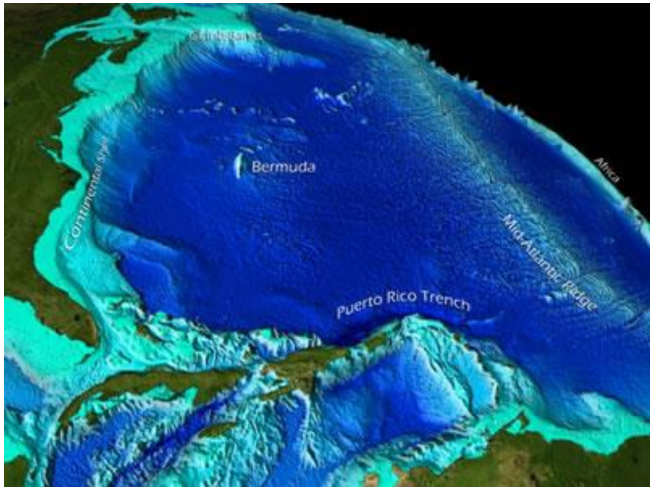
Dissipation =f (Stratification, bathymetry gradient, cross-slope flow)

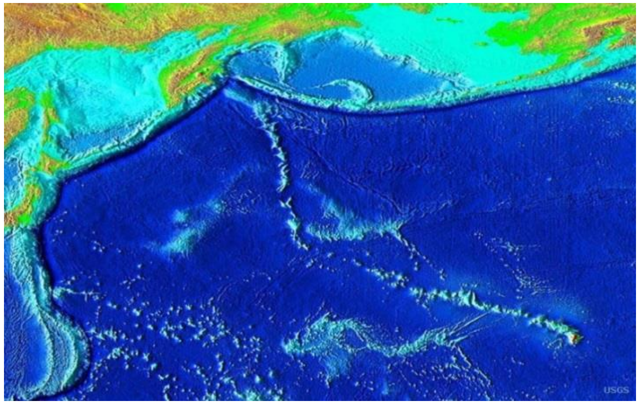
Internal tides generation locations:

- Mid-ocean ridges and trenches (e.g. Mid-Atlantic Ridge)
- Continental shelves (e.g. Bay of Biscay)
- Island chains (e.g. Hawaiian Ridge)

Literature values: $\approx 1TW$

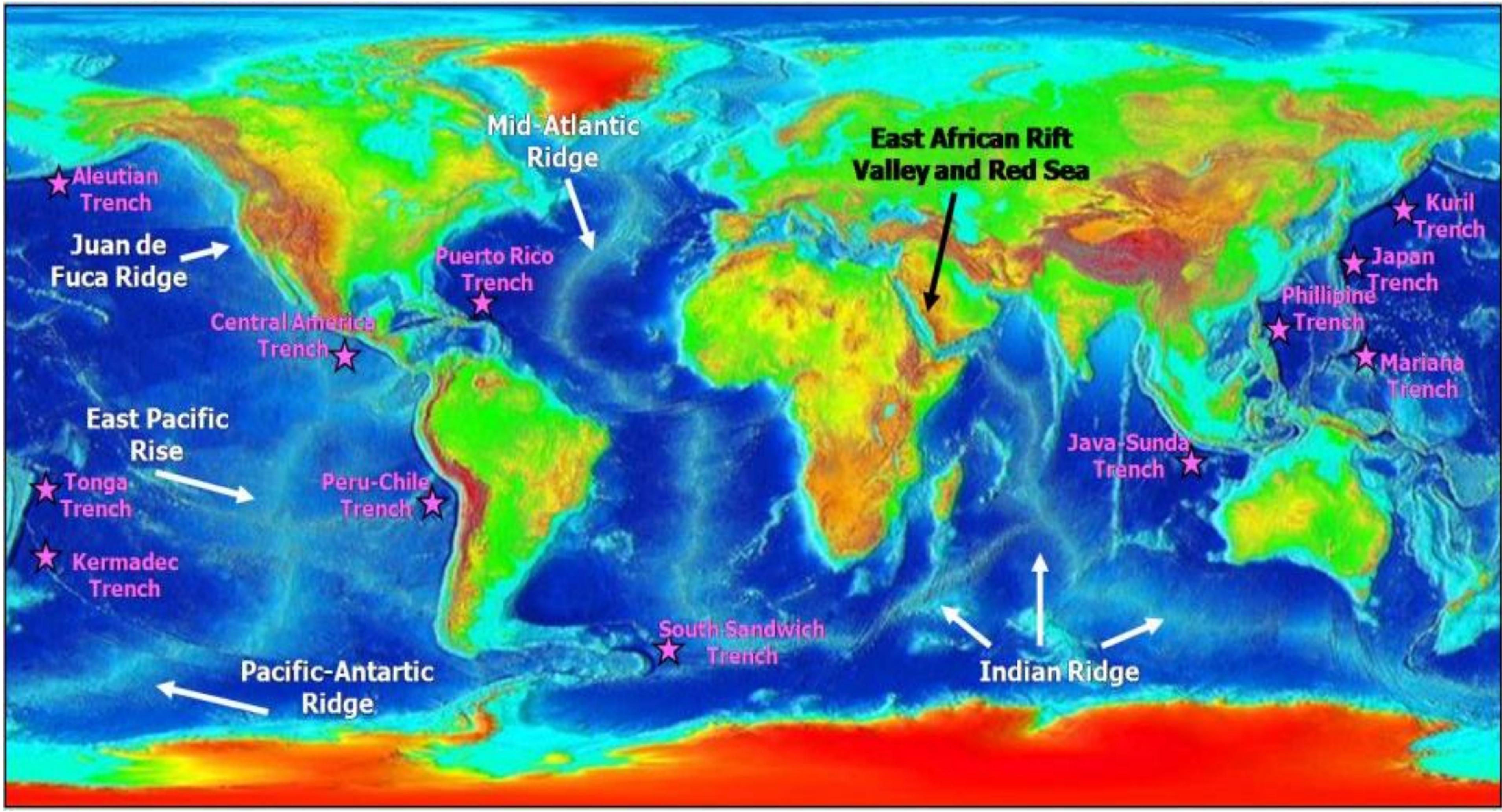






Left: baroclinic amplitudes from altimetry in the Hawaiian Ridge. Right: Examples of sites with strong internal tides generation.

IT generation potential zones



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IT dissipation- Implementation in DELFT3D FM

Formulation (C.Maraldi et. Al.(2011)):

$$\tau_{IT} = C\rho\kappa^{-1}N(\nabla h \cdot u)\nabla h$$

$$\tau_{IT} = C_{IT}(\nabla h \cdot u)\nabla h$$

N: Brunt–Väisälä frequency
κ : Wavenumber characterizing bathymetry
C : Tuning parameter

Brunt–Väisälä frequency (or *Buoyancy frequency*):

$$N = \sqrt{-\frac{g}{\rho_0}\frac{\partial\rho}{\partial z}}$$

$$\frac{\partial\rho(s,T)}{\partial z} = \frac{\partial\rho}{\partial s}\frac{\partial s}{\partial z} + \frac{\partial\rho}{\partial T}\frac{\partial T}{\partial z}$$

2DH model:

MyOcean monthly (T,S)maps

↓

Depth averaged *N*

Remarks:

- MyOcean model doesn't include tides→ Fictitious stratification in SW
- Formulation recommended for deep waters (d>200m)

myOcean

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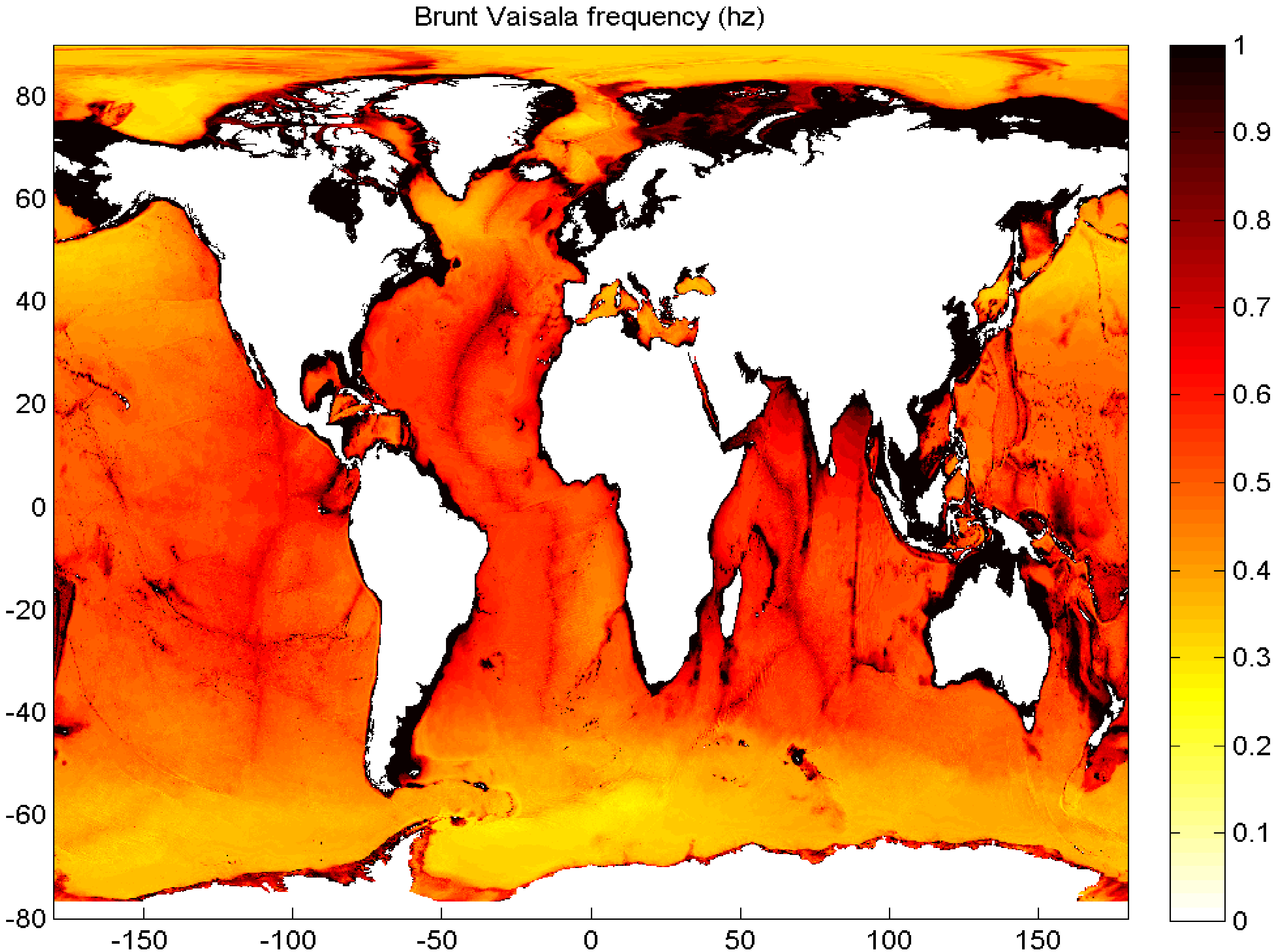
Brunt–Väisälä frequency



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Sensitivity tests

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Tests overview

Model setup:

- Forcing only tidal potential to isolate effects of SAL and IT dissipation.
- Observation stations: UHSLC tide gauge data (297) and FES2012 for open ocean (347)

Simulation period	25-Dec-2006 / 01-Feb-2007
Spin-up time	7 days
Time step	150 seconds
Friction coefficient	• Manning: 0.028 uniform • Chézy: 62.657 uniform
Gravity	Uniform $9.81\ m/s^2$

SAL testing:

- Simulation without SAL
- Simulation with $\beta = 90\%$ approximation
- Simulation with SAL

We look at:

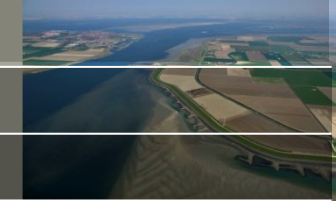
Effect on modeled water levels and computational times

IT dissipation testing:

- $C = 200 \cdot 10^{-5},\ \kappa = 2\pi/10km$ uniform
- Simulation with τ_{IT} in full globe
- Simulation with τ_{IT} in $d > 200\ m$

Effect on modeled water levels and dissipated energy values

SAL results – Water levels



Effect of $\beta = 90\%$ approximation :

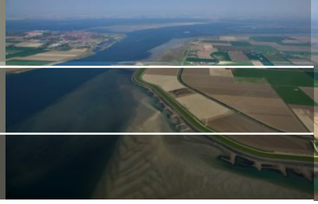
No SAL:

group name	#stations	#values	avg(res)	std(res)	relstd(res)	relrange	obsrange	correlation	time-error
tide-gage	297	1326105	-0.103	0.565	123.6%	153.7%	0.49	0.59	-31.85
arctic_ocean	40	178560	0.014	0.107	139.4%	152.2%	0.08	0.46	-10.66
north_atlantic	30	133920	-0.000	0.328	106.6%	135.0%	0.31	0.61	-44.91
south_atlantic	31	138384	-0.017	0.324	162.9%	212.7%	0.25	0.70	-25.55
indian_ocean	43	191952	-0.082	0.333	119.5%	157.8%	0.30	0.66	-55.97
southern_ocean	68	303552	0.001	0.426	171.6%	212.3%	0.25	0.60	-42.52
north_pacific	65	290160	0.038	0.374	102.8%	127.9%	0.35	0.63	-41.73
south_pacific	70	312480	0.024	0.390	160.4%	177.4%	0.26	0.43	-43.82
total	347	1549008	0.002	0.343	139.9%	169.1%	0.26	0.57	-39.32

***β* approximation**:

group name	#stations	#values	avg(res)	std(res)	relstd(res)	relrange	obsrange	correlation	time-error
tide-gage	297	1326105	-0.102	0.420	89.2%	153.9%	0.49	0.83	-3.83
arctic_ocean	40	178560	0.010	0.104	135.8%	172.3%	0.08	0.62	28.73
north_atlantic	30	133920	0.000	0.243	81.5%	162.4%	0.31	0.93	-5.50
south_atlantic	31	138384	-0.019	0.237	104.8%	183.2%	0.25	0.87	-6.00
indian_ocean	43	191952	-0.093	0.173	66.1%	144.3%	0.30	0.92	13.55
southern_ocean	68	303552	-0.002	0.290	116.4%	194.6%	0.25	0.88	0.34
north_pacific	65	290160	0.044	0.198	58.3%	134.8%	0.35	0.93	-9.61
south_pacific	70	312480	0.028	0.209	90.5%	169.6%	0.26	0.91	-17.61
total	347	1549008	0.001	0.212	92.2%	165.7%	0.26	0.87	-1.31

Substantial improvement in both amplitudes and phases

SAL results – Water levels

SAL implementation *vs* β approximation:

β approximation:

group name	#stations	#values	avg(res)	std(res)	relstd(res)	relrange	obsrange	correlation	time-error
tide-gage	297	1326105	-0.102	0.420	89.2%	153.9%	0.49	0.83	-3.83
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total	347	1549008	0.001	0.212	92.2%	165.7%	0.26	0.87	-1.31

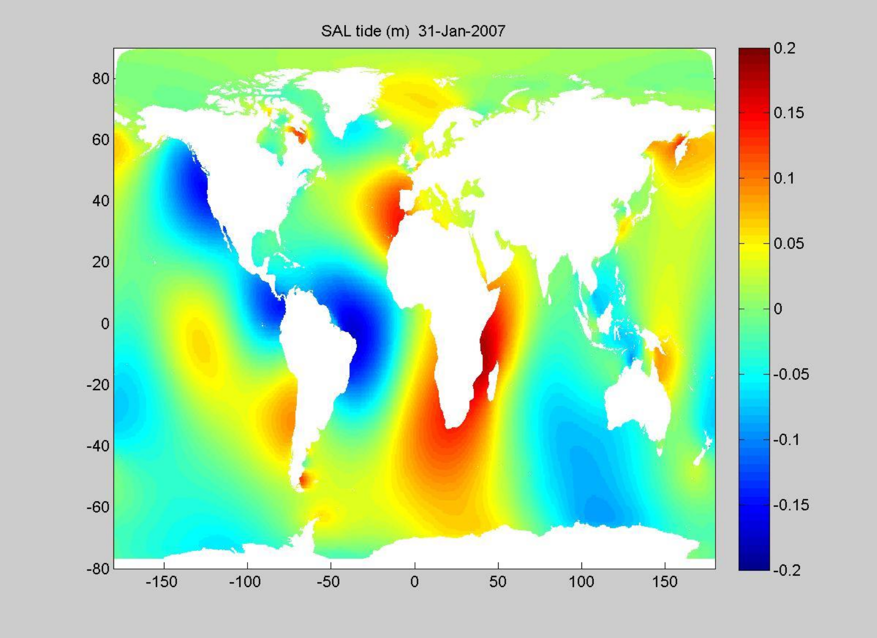
SAL (spherical harmonics):

group name	#stations	#values	avg(res)	std(res)	relstd(res)	relrange	obsrange	correlation	time-error
tide-gage	297	1326105	-0.100	0.279	60.4%	125.1%	0.49	0.87	0.07
arctic_ocean	40	178560	0.009	0.078	104.2%	156.9%	0.08	0.75	22.17
north_atlantic	30	133920	-0.002	0.166	58.6%	135.2%	0.31	0.93	3.27
south_atlantic	31	138384	-0.020	0.144	63.4%	147.3%	0.25	0.93	1.89
indian_ocean	43	191952	-0.103	0.129	48.6%	131.4%	0.30	0.95	13.78
southern_ocean	68	303552	-0.005	0.180	72.5%	156.6%	0.25	0.93	2.77
north_pacific	65	290160	0.049	0.115	34.8%	113.6%	0.35	0.96	-4.73
south_pacific	70	312480	0.034	0.116	51.7%	133.1%	0.26	0.94	-3.23
total	347	1549008	0.001	0.133	59.9%	138.0%	0.26	0.92	3.72

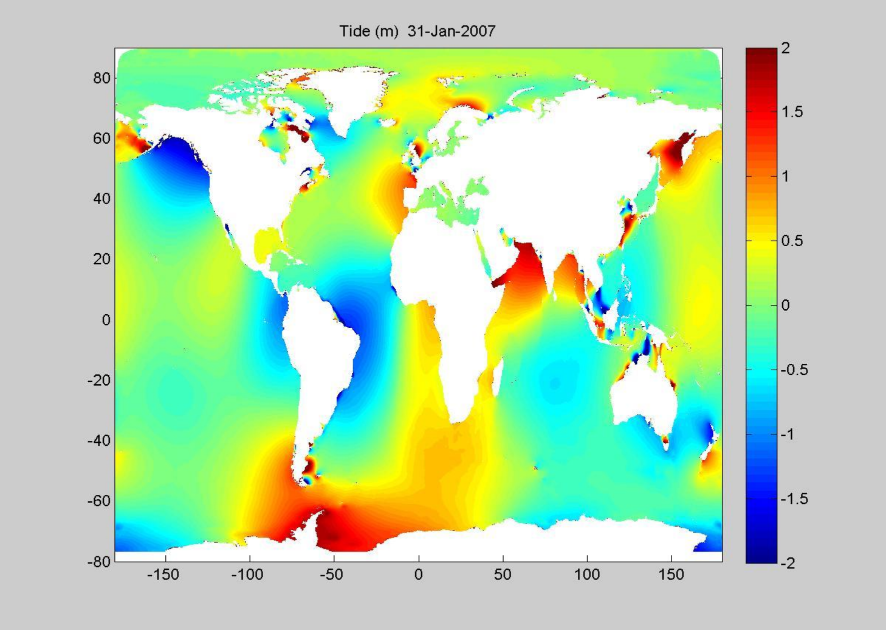
Further considerable improvement in both amplitudes and phases

SAL results – SAL tide spatial distribution

SAL tide



Tide



Uniform $\beta = 90\%$ approximation too simplistic


SAL results – Computational times

Run	Number of cores	Computational period	Computational time (Wallclock)
Without SAL	8 (2x4)	38 days	4.18 h
With SAL	8 (2x4)	38days	4.29 h

- No clear increase of computational time relative to no SAL case.
- Considerable improvement (~ 60 %) on predicted tide relative to no SAL case

IT dissipation results –Water levels

No IT dissipation (SAL included):

group name	#stations	#values	avg(res)	std(res)	relstd(res)	relrange	obsrange	correlation	time-error
tide-gage	297	1326105	-0.100	0.279	60.4%	125.1%	0.49	0.87	0.07
arctic_ocean	40	178560	0.009	0.078	104.2%	156.9%	0.08	0.75	22.17
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total	347	1549008	0.001	0.133	59.9%	138.0%	0.26	0.92	3.72

IT dissipation (SAL included):

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southern_ocean	68	303552	0.007	0.172	68.8%	153.7%	0.25	0.94	5.78
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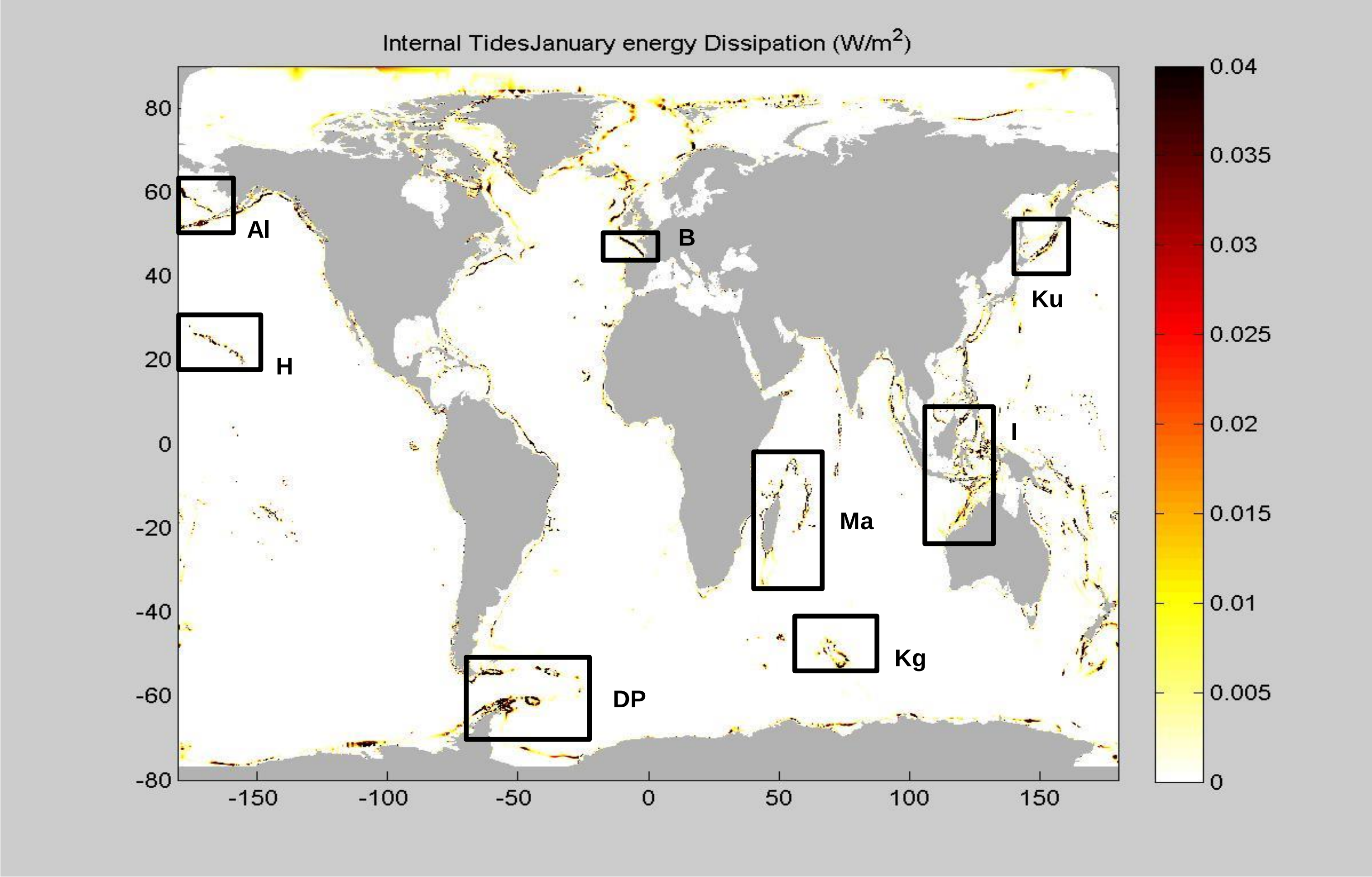
south_pacific	70	312480	0.000	0.107	47.7%	131.0%	0.26	0.95	-3.54
total	347	1549008	0.000	0.126	57.0%	136.2%	0.26	0.93	4.10

Water levels prediction improved

IT dissipation results –Dissipation rates



Al: Aleutians islands/trench

B:Bay of Biscay

DP: Drake Passage/Scotia Sea

H:Hawaii

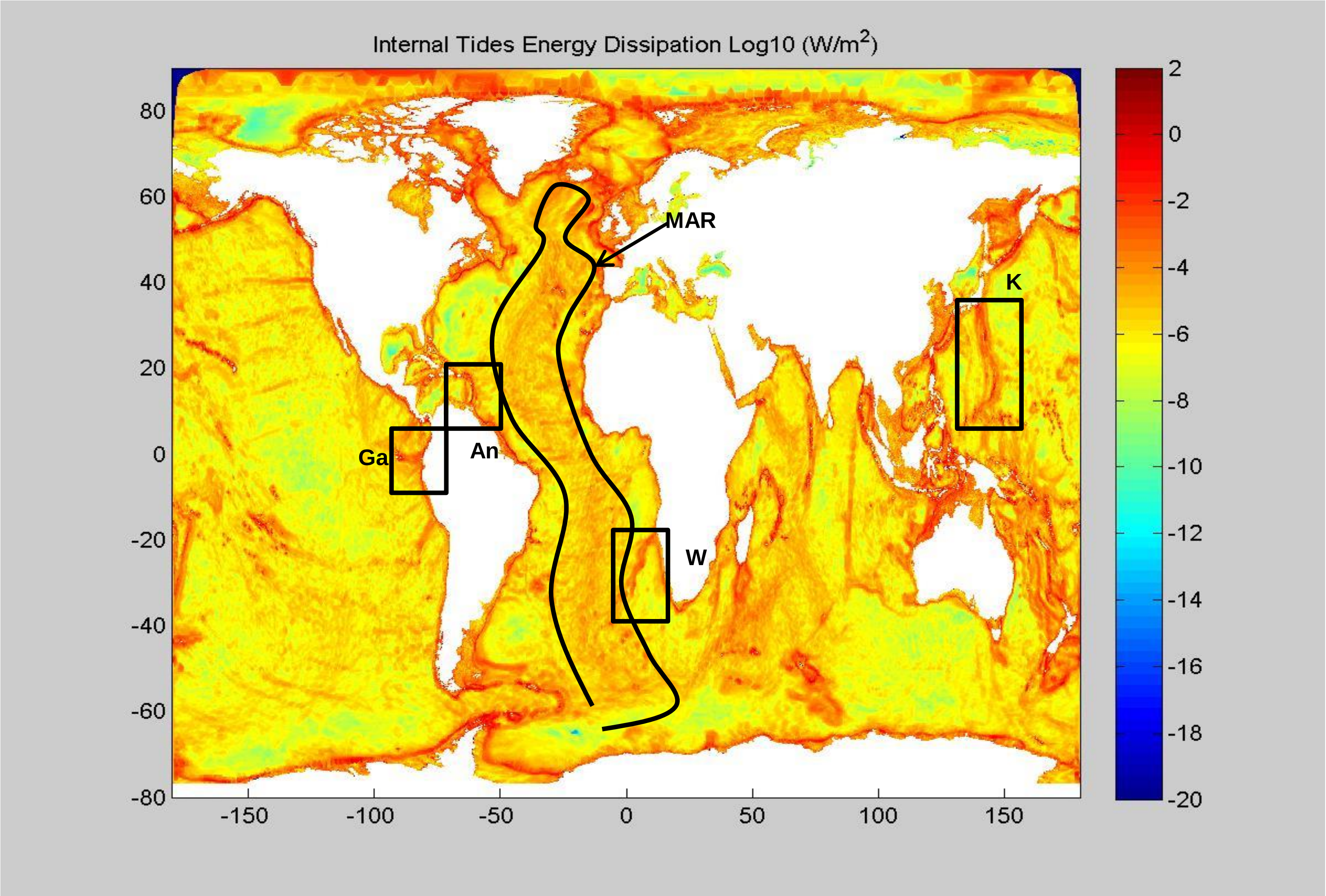
I: Indonesia

Kg: Kerguelan Plateau

Ku: Kuril islands/trench

Ma: Madagascar

IT dissipation results- Dissipation rates



An Antilles

G:Galapagos

K:Kyushu/Palu Ridge

MAR:Mid-Atlantic ocean ridge

W: Walvis Ridge
Kg: Kerguelan

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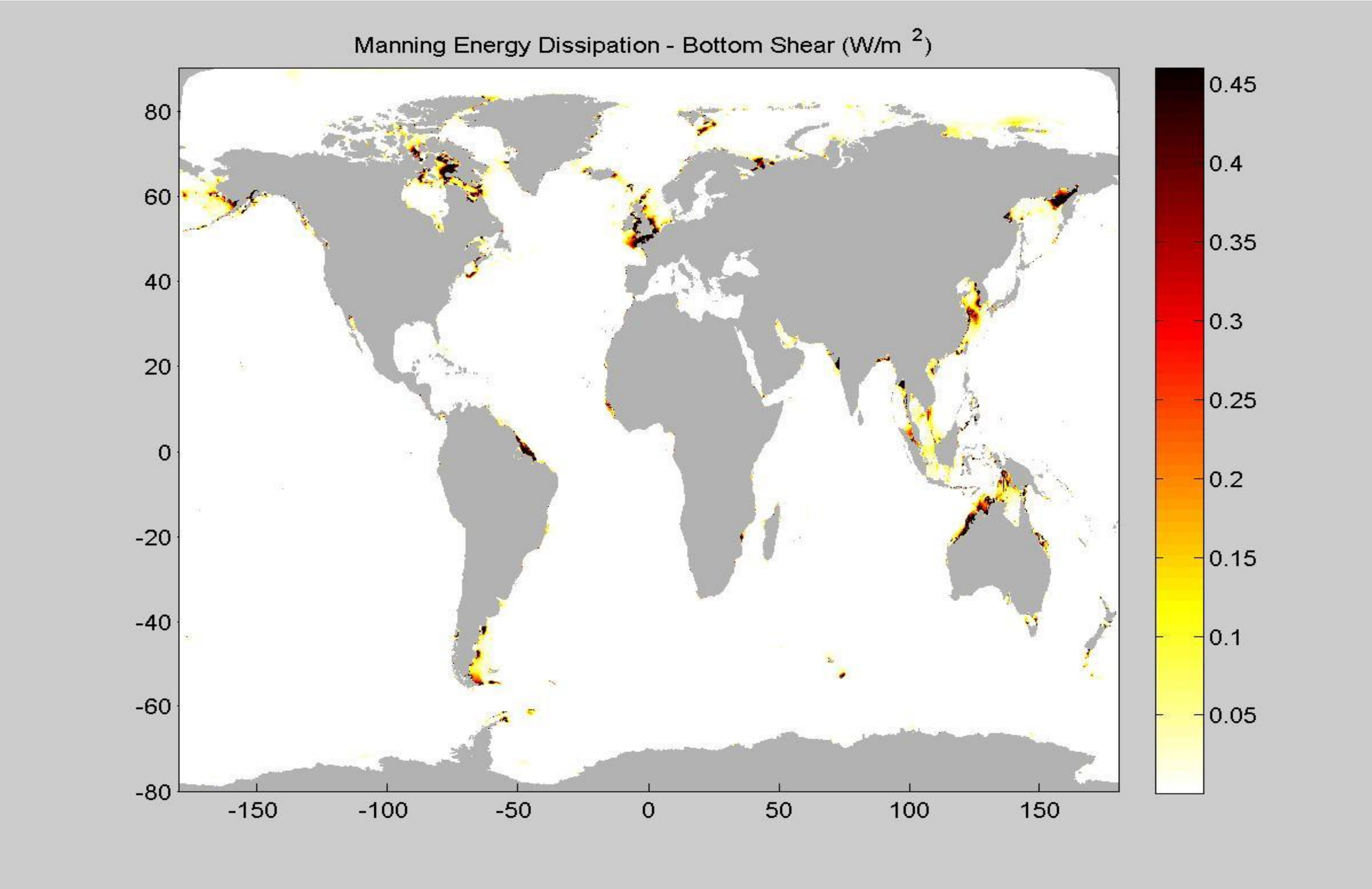
Bottom Friction - Dissipation rates



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Overview of modeled dissipation rates

Dissipation type	Value (TeraWatts)
IT dissipation (Full Globe)	1.1171
IT dissipation $(d > 200m)$	0.8783
Bottom friction dissipation (Manning)	3.0727
Bottom friction dissipation (Chézy)	3.6076

- IT dissipation close to literature values $(\approx 1TW)$
- Manning (depth dependent) << Chézy; Slightly better water levels for Chézy (damped overpredicted amplitudes).
- Preliminary tests; study needed with tuning of C and bottom friction coefficients, some features not represented in bathymetry.

Conclusions - Overall trends of the model

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indian_ocean	43	191952	-0.103	0.129	48.6%	131.4%	0.30	0.95	13.78
southern_ocean	68	303552	-0.005	0.180	72.5%	156.6%	0.25	0.93	2.77
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total	347	1549008	0.001	0.133	59.9%	138.0%	0.26	0.92	3.72

- Both SAL and IT dissipation implementations seem to improve the model response.
- IT dissipation rates seem realistic; further sensitivity tests with tuning parameter.
- Overall trend: **Overprediction** of tide. Chézy slightly better.
- Big time errors:
  - Artic Ocean: Ice drag not included ;seasonal variability.
  - Indian Ocean: Complex tide, complex topography, tidal resonance. Also high dissipation in this area.

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Future work

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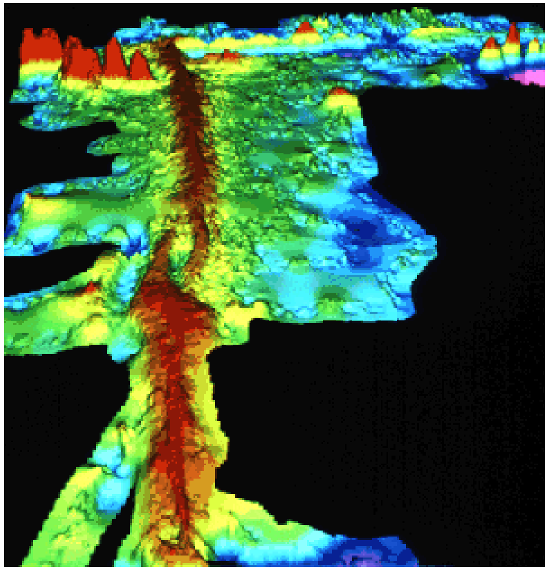
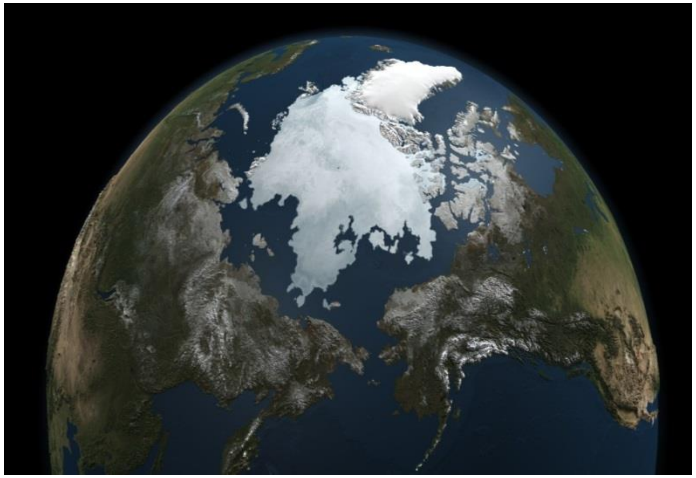
Future work –BASE Project context

- Grid improvement: local refinement for capturing steep topography in deep waters (e.g. Mid-Atlantic Ocean Ridge)
- Recalibration of the model
- Validation including wind-forcing. Wind forcing: ERA-Interim 0.75 degree resolution grid.
- Include IOC(International Oceanographic Committee) tide gauges (real time data)
- Model improvements: baroclinic pressure gradients, ice induced drag near the poles.





Deltares


Thank you
Questions?