Ocean tide loading – where we are standing

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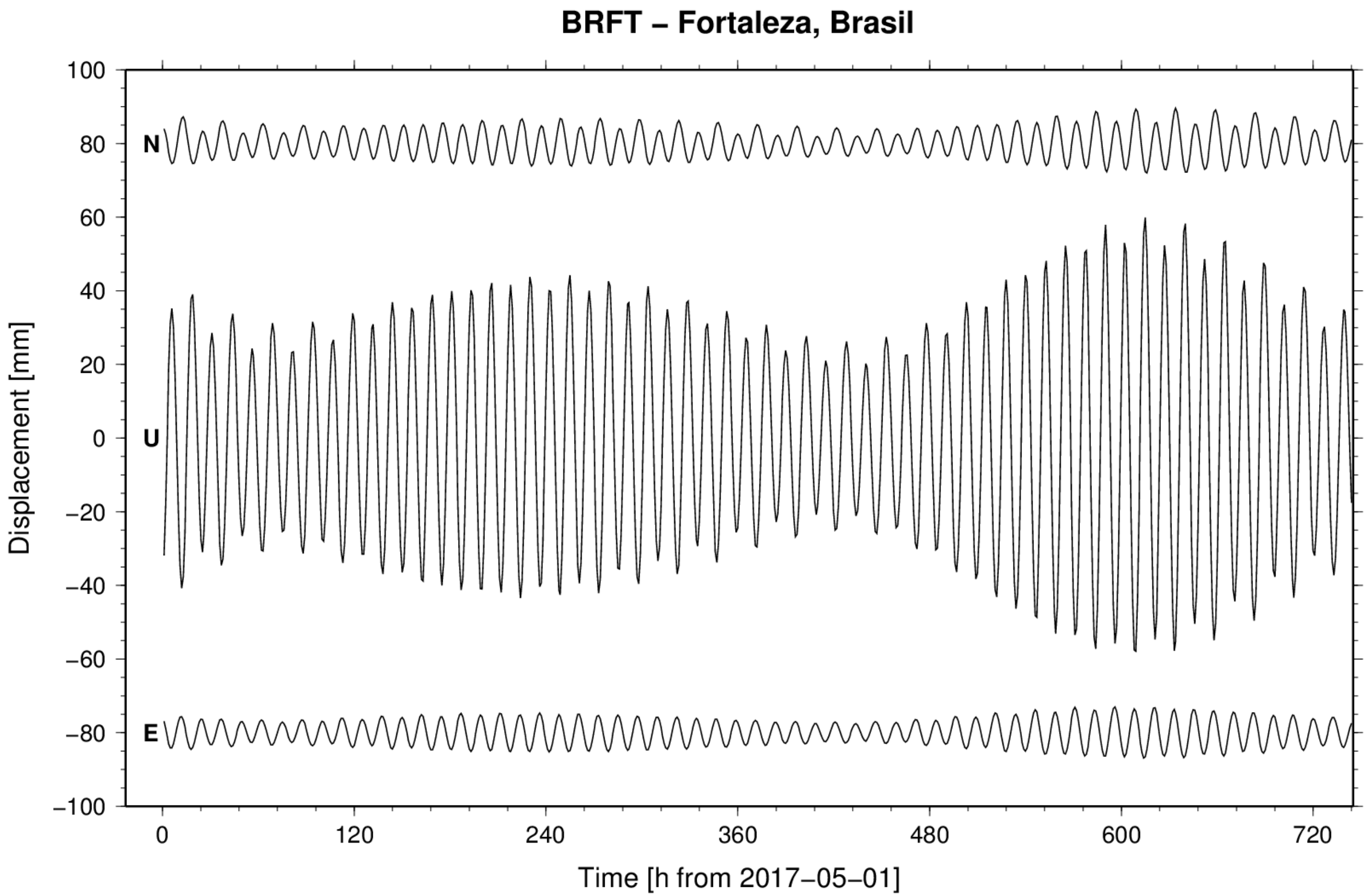
Overview


BRFT – Fortaleza, Brasil
N
U
E
Displacement [mm]
100
80
60
40
20
0
−20
−40
−60
−80
−100
0
120
240
360
480
600
720
Time [h from 2017−05−01]

Overview

- Ocean Tide Models – a short review
- – higher and higher spatial resolution

- Ocean Loading parameters – lengthier calculations
- – looking for smarter solutions

- Testing methods & options – gridding (no kidding!)
- – complex Greens functions, anelastic
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- Verifying – GNSS time series
- – complex Greens functions, anelastic
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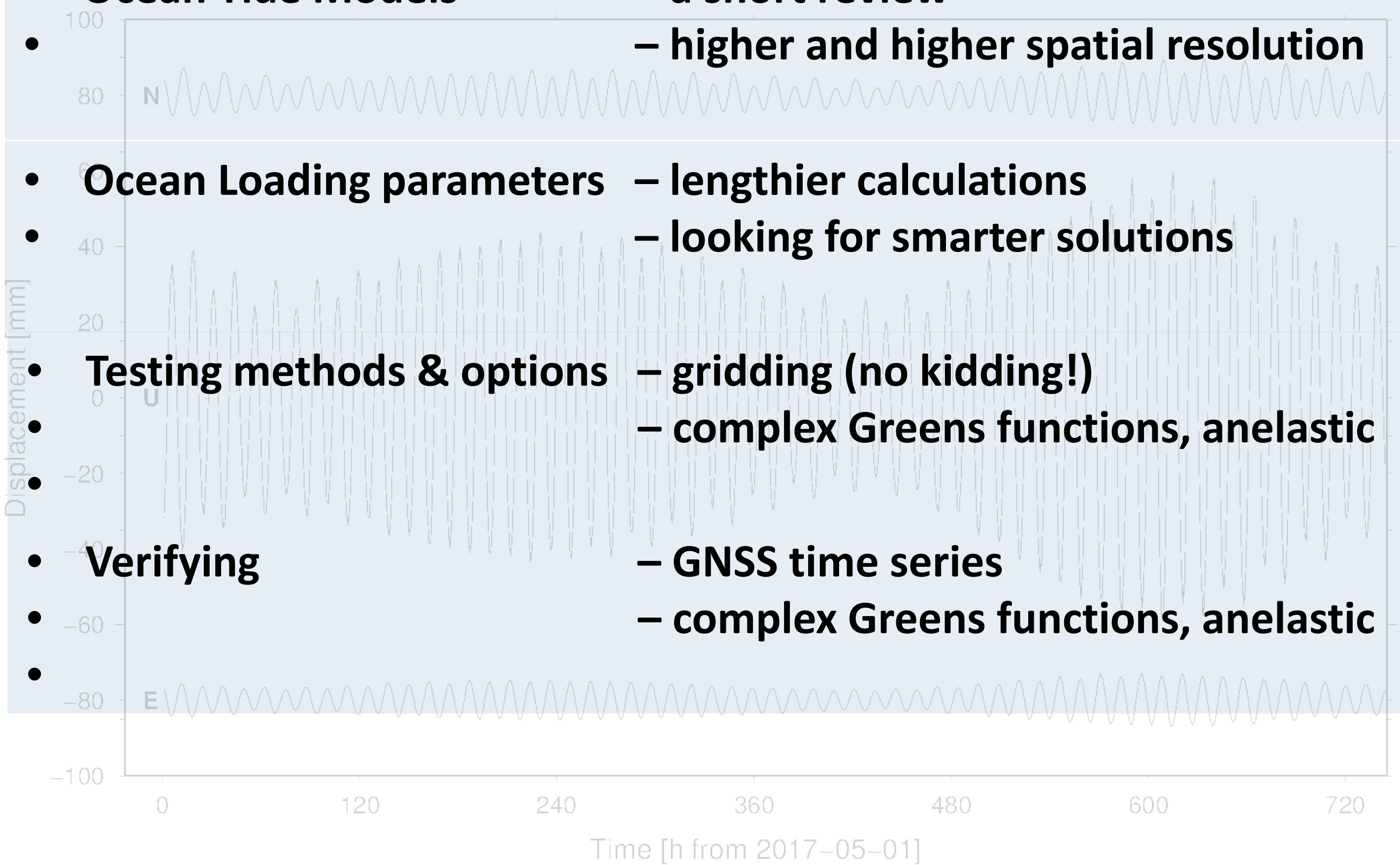


Time line

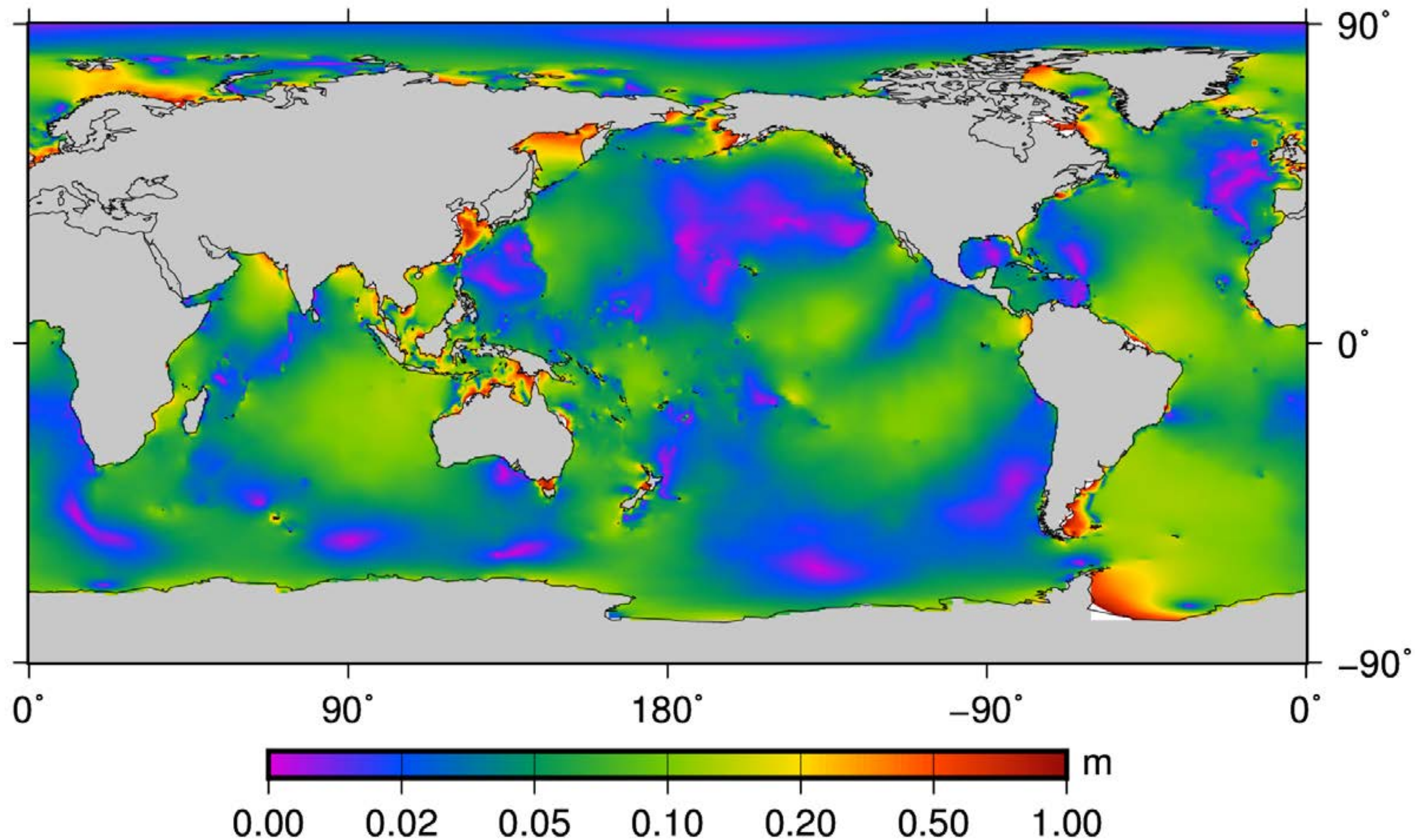
- The number of tide constituents has generally been growing (long-period eventually missing)

- Schwiderski (1980) included 11 species, 3 long-per., 4 diurnal, 4 semi-diurnal. This has set a kind-of standard for loading calculations

Model	avail	resol	rem
Schwiderski	1980	1	
TPXO.5	1994	2	
CSR3	1994	2	
CSR4	1994	2	
FES94.1	1994	2	
FES95.2	1995	2	
GOT4.x	1994	2	
FES98	1998	4	
FES99	1999	4	
GOT99.2b	1999	2	
NAO.99b	2000	2	
GOT00.2	2000	2	
FES2004	2004	8	
TPXO.7.0	2004	4	year uncertain
AG06	2006	4	
TPXO.6.2	2002	4	
TPXO.7.1	2007	4	year uncertain
EOT08a	2008	8	
TPXO.7.2	2009	4	year uncertain
DTU10	2010	8	
EOT11a	2011	8	
TPXO-Atlas	2011	30 (6)	
OSU12	2012	4	
FES2012	2012	16	
Hamtide	2014	8	
FES2014b	2014	16	

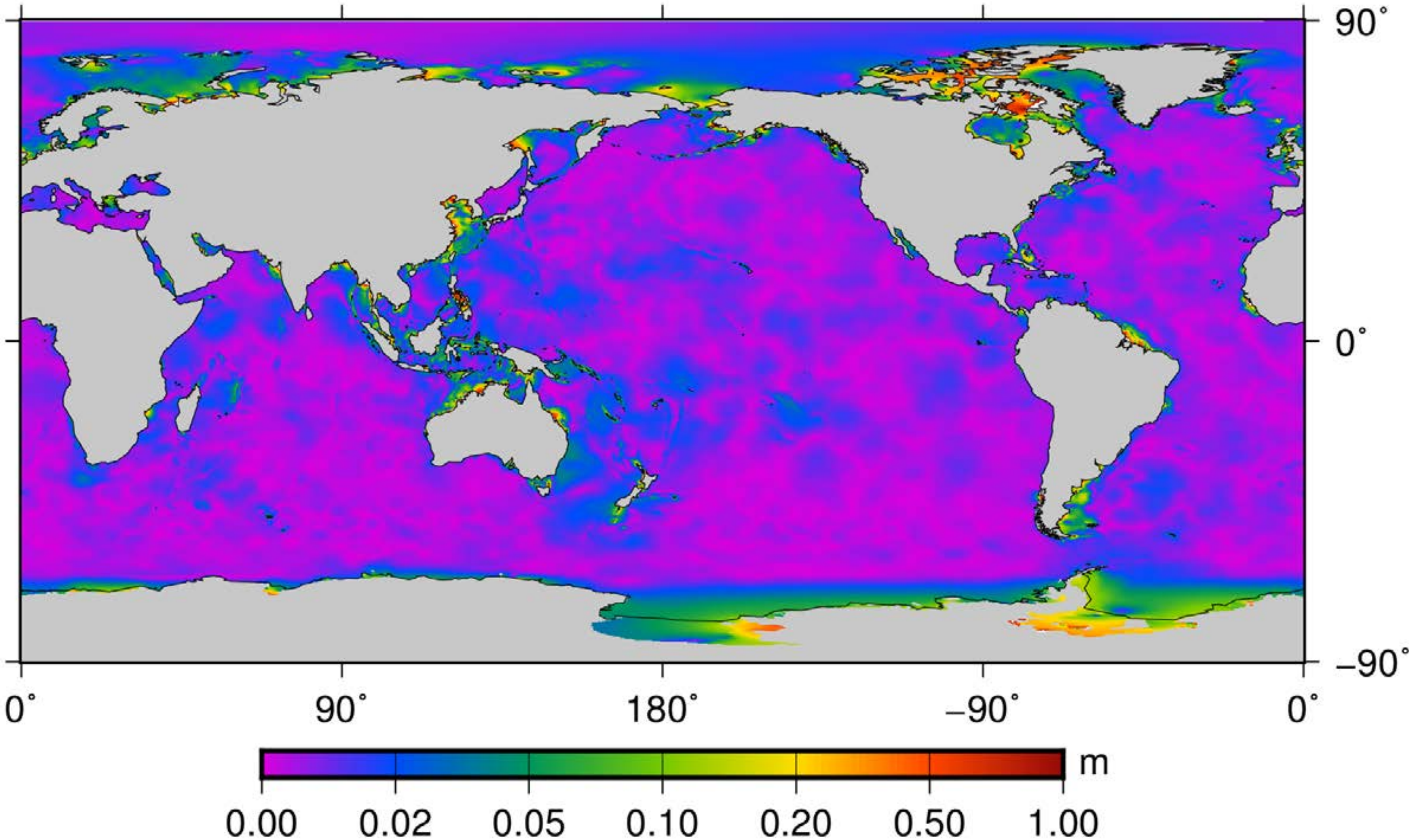
Progress in ocean tide models

Vector difference in M2 for Schwiderski – FES94.1



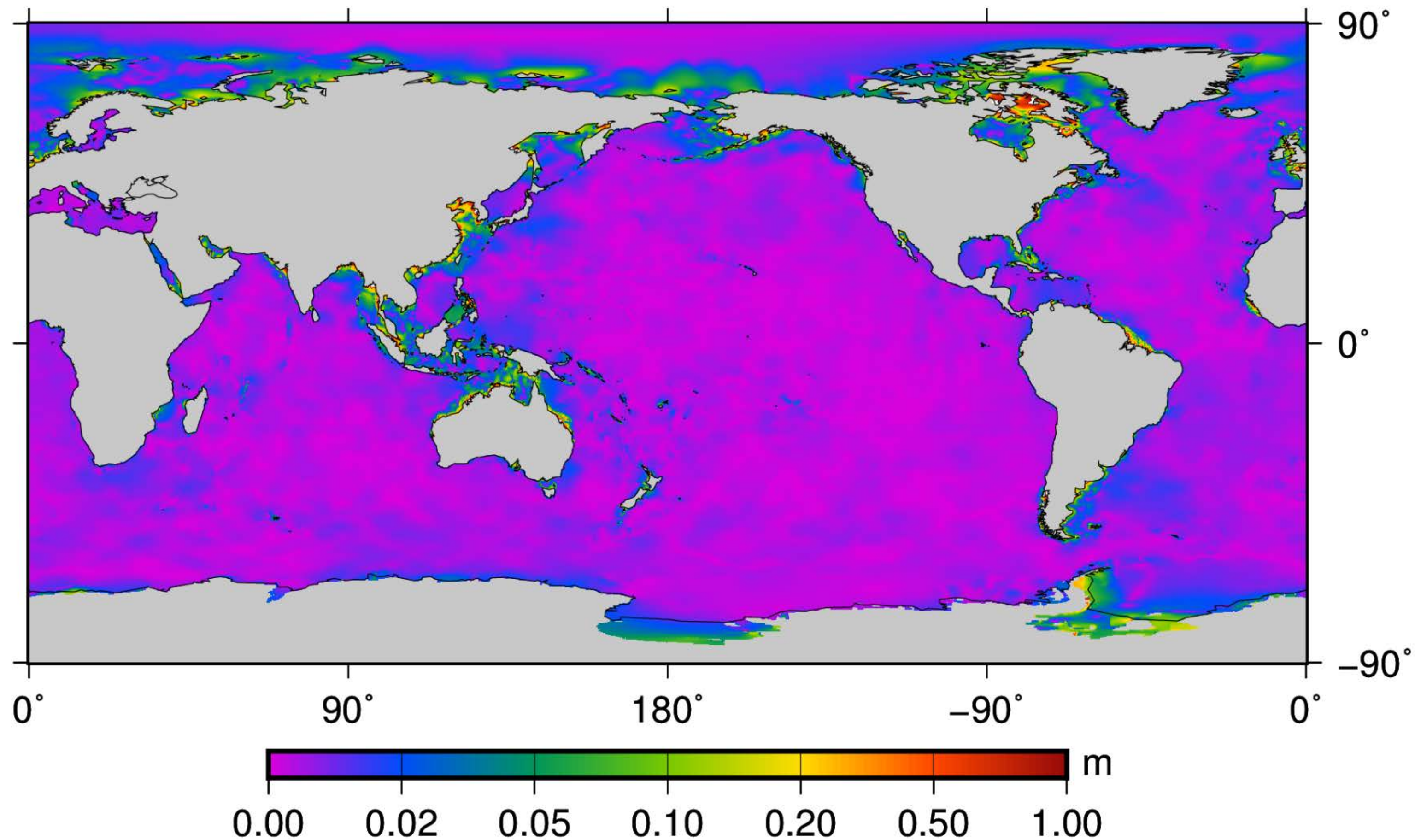
Progress in ocean tide models

Vector difference in M2 for GOT00.1 – FES2004



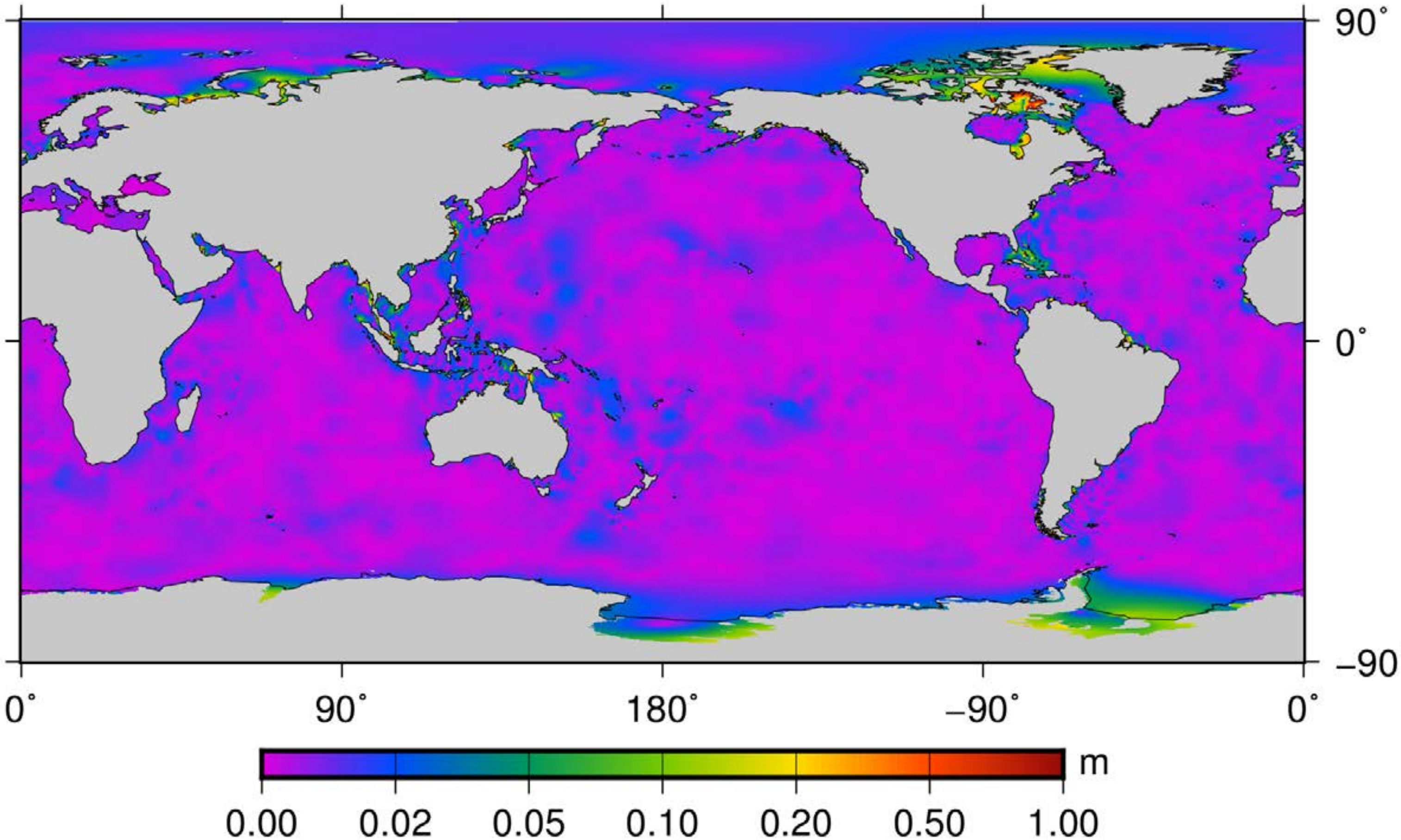
Progress in ocean tide models

Vector difference in M2 for TPXO7.2 – GOT4.7



Progress in ocean tide models

Vector difference in M2 for FES2012 - FES2014b



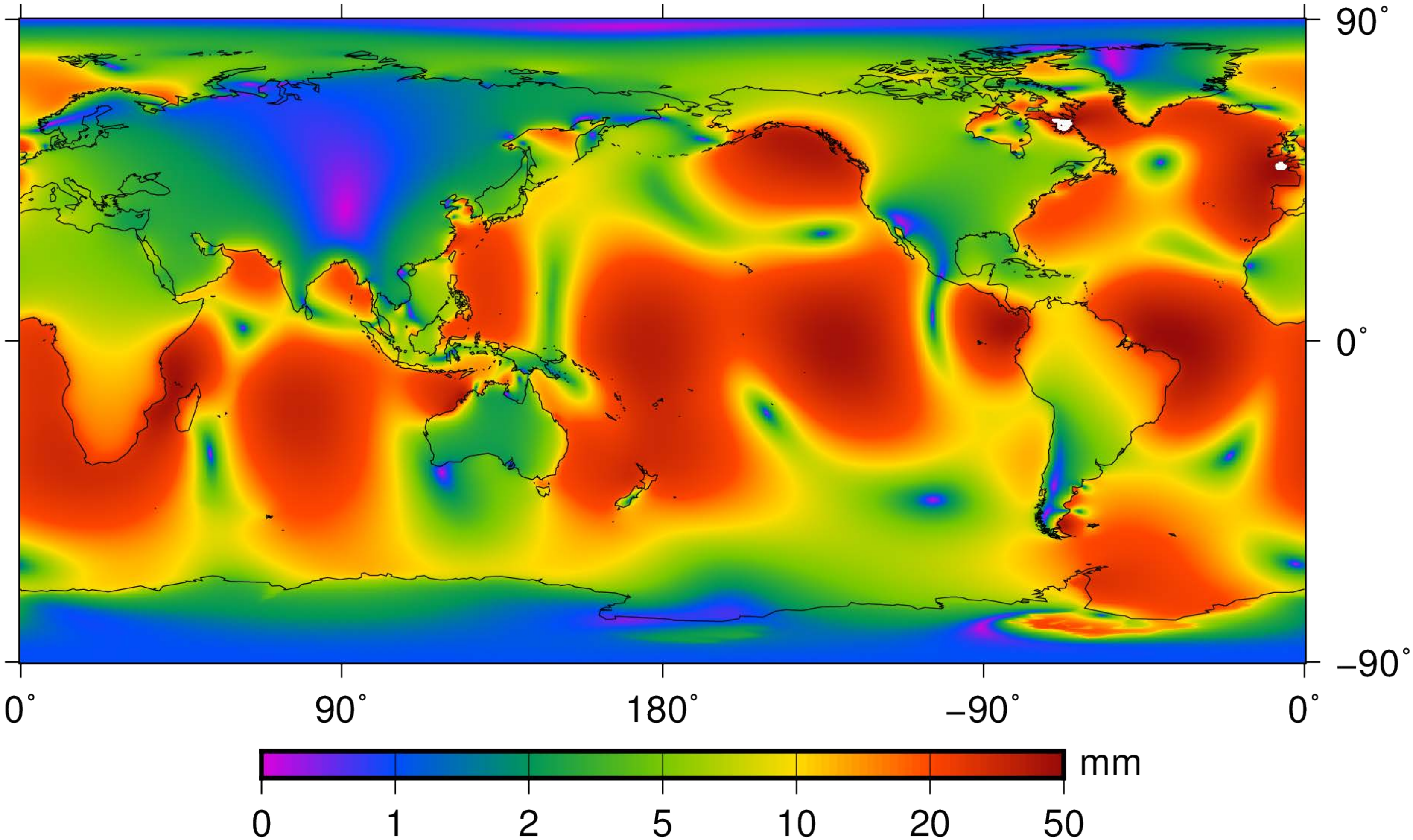
Problems, solutions, and new problems

- In 2002, a web service was launched with automated processing. Calculates 3-D displacements, gravity (and tilt)
- Tide models at this time have been resolving coastlines only roughly, thus high-resolution coastline refinement (quad-tree algorithm and GMT full-resolution coastlines) were incorporated.
- Requests served (e.g. 2016):
  - 1156 different users, **7,332** requests, 113,682 geographic locations — probably non-unique, but many users compare a range of models for their observing stations. 8 × 8 models need **1 – 2 h walltime/request.**
- Since 2014, high-resolution models 1/16 x 1/16 degrees became available – not any more feasible with the existing software.
- Since earlier this year, requests for loading effects from the high-resolution models are processed at SEGAL/UBI-IDL

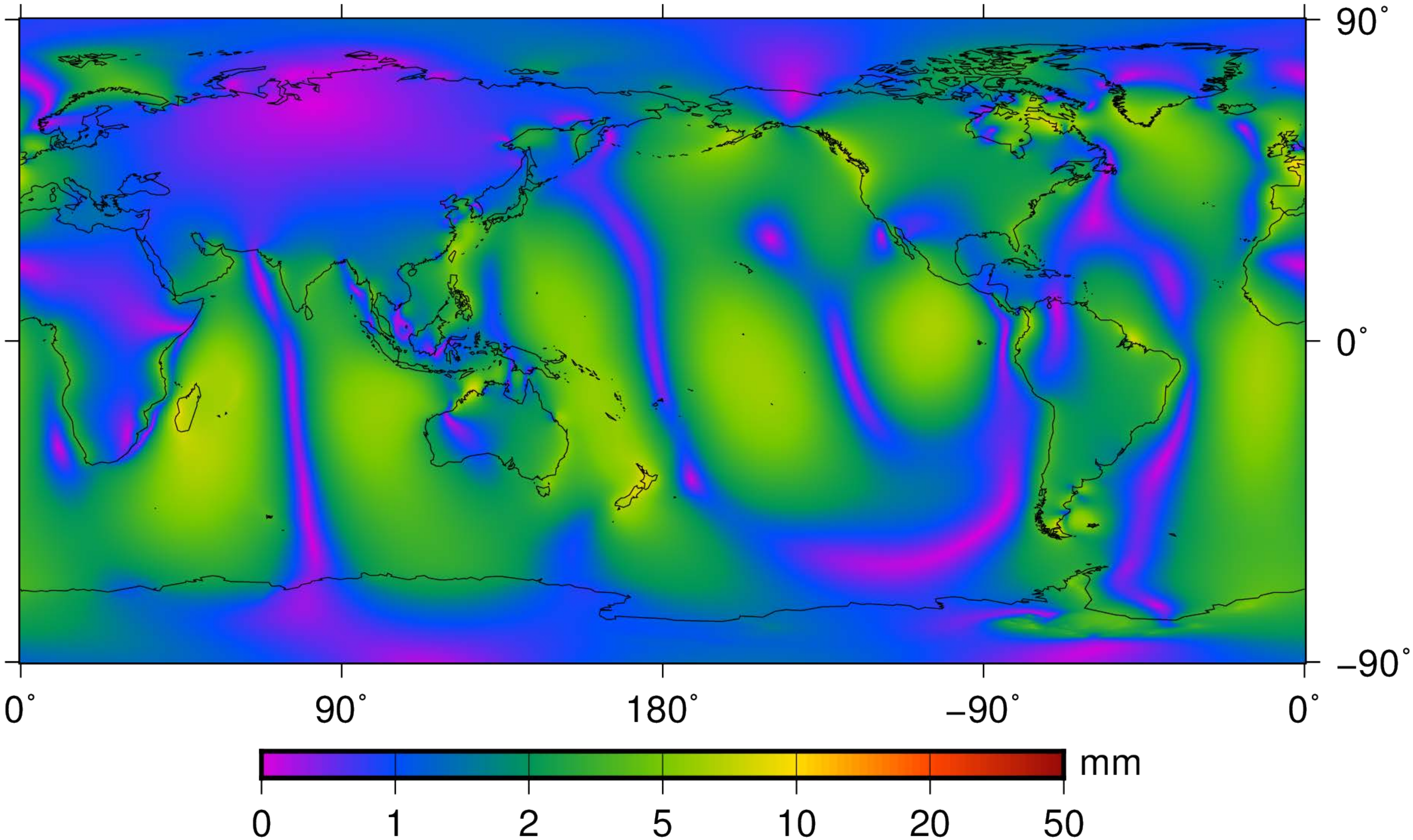
Reducing the number of OTL values

- OTL varies fast near coast but smoothly in open ocean.
- Therefore, more OTL values are needed near the coast than in open ocean to guarantee good accuracy everywhere.
- This is achieved using quadtree approach which divides each cell into 4 smaller cells recursively when it is close to the coastline.
- We obtain a reduction of a factor 25 in the number of OTL values we need to compute for a global map.
- For OTL maps shown: finest grid spacing is 0.125 degree (can still be lowered), largest spacing is 1 degree.

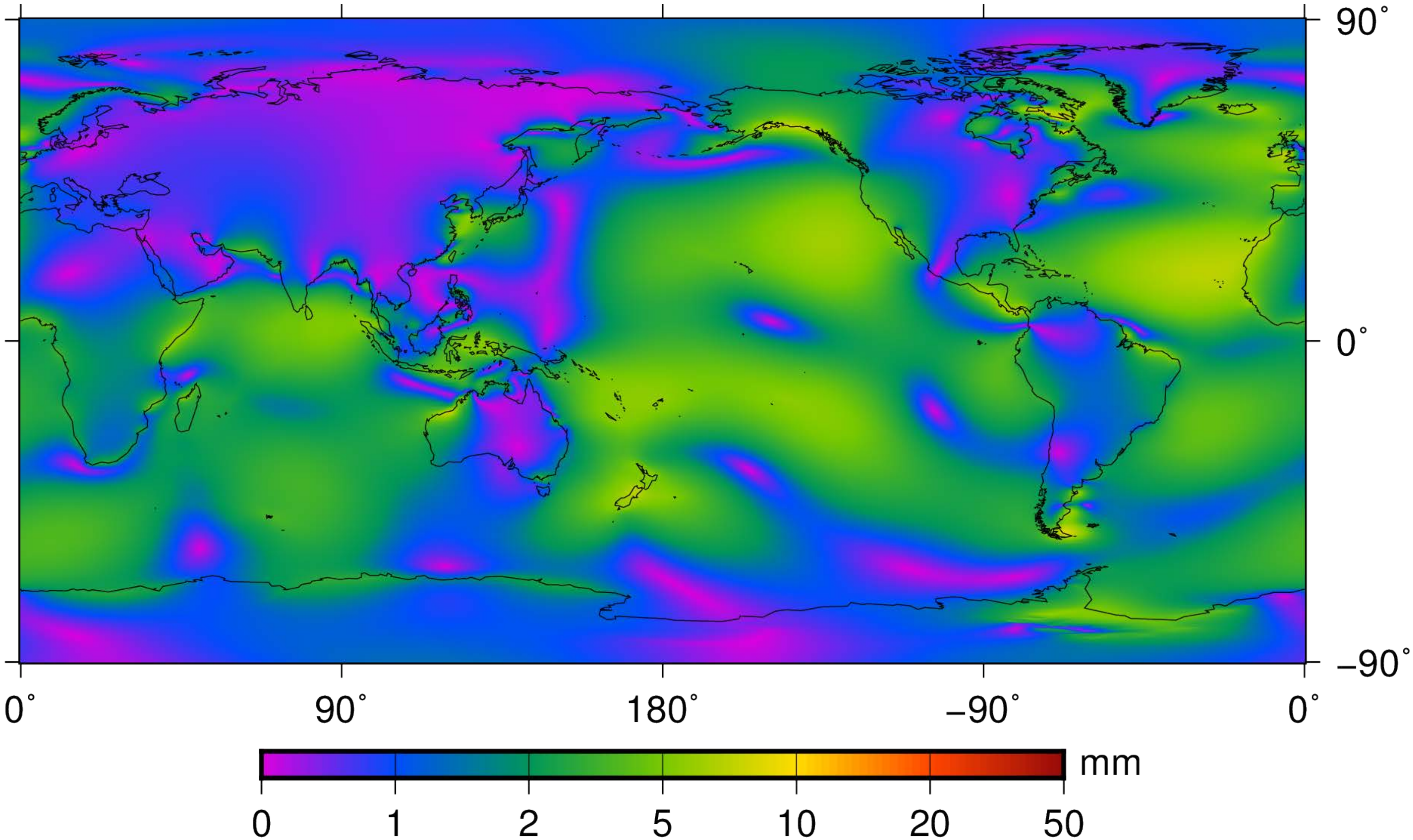
FES2014b at reduced grid resolution ¼ × ¼ deg
but augmented with high resolution coastlines
M2 vertical loading, PREM



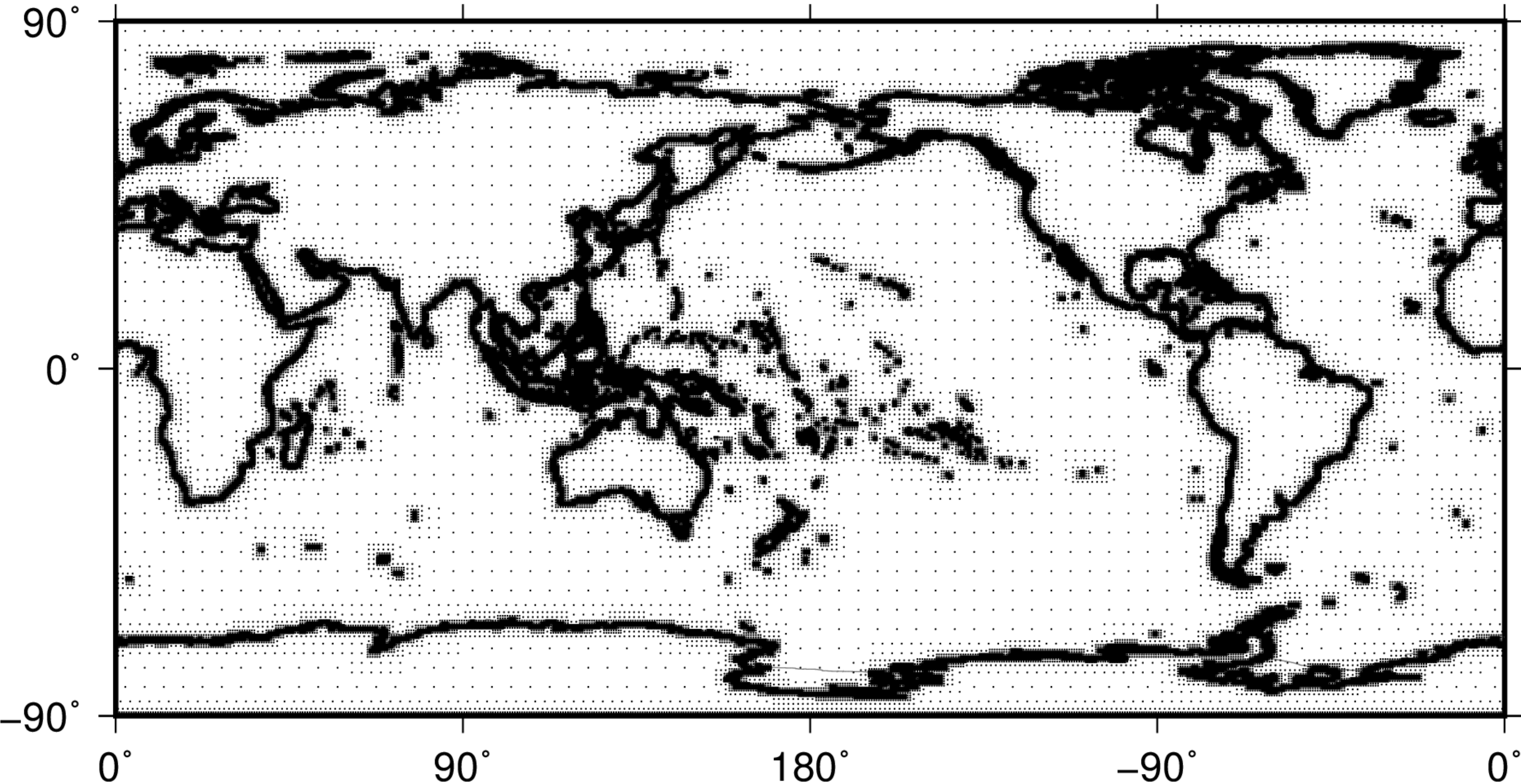
M_2 East-West loading



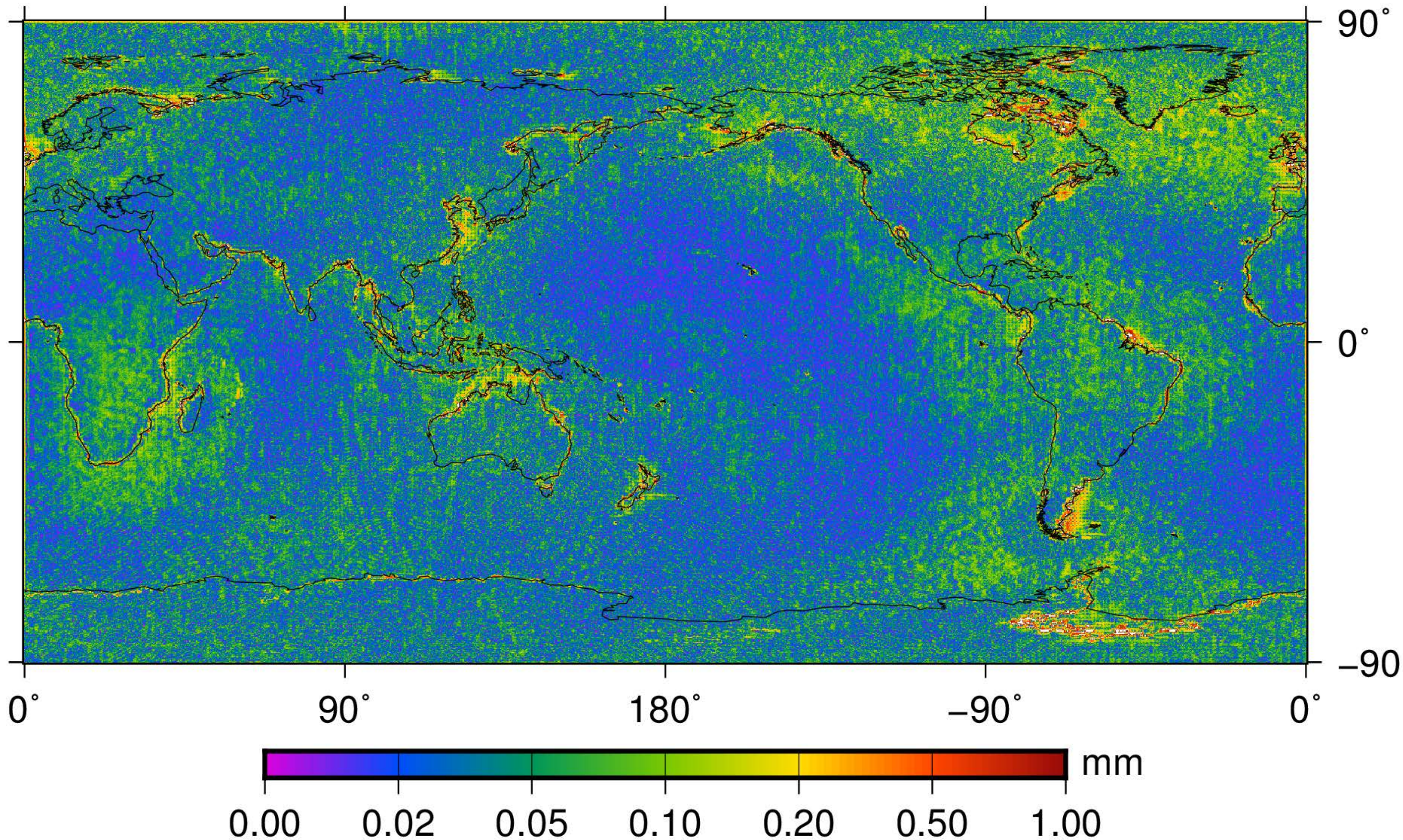
M_2 North-South loading



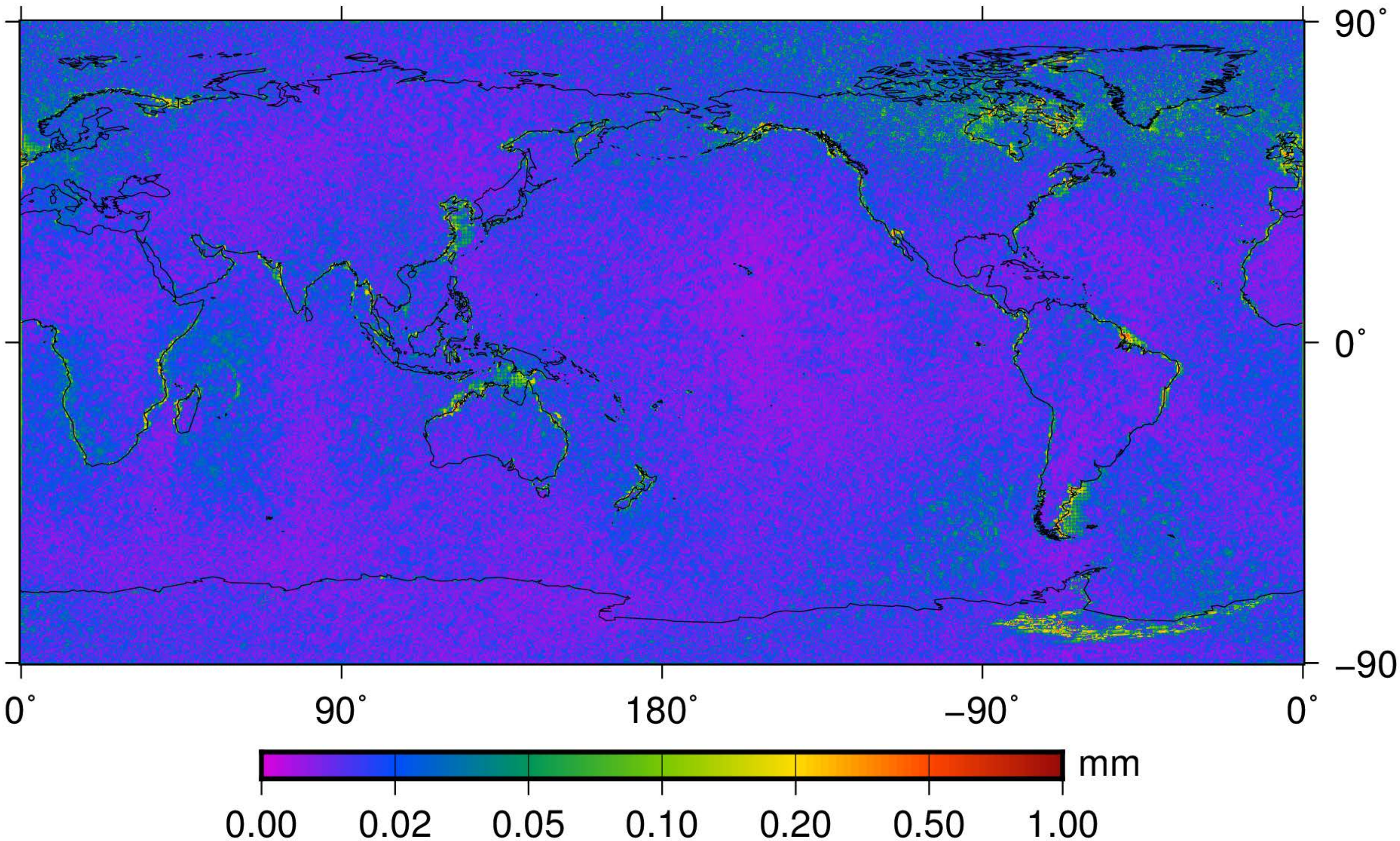
Example of quadtree grid



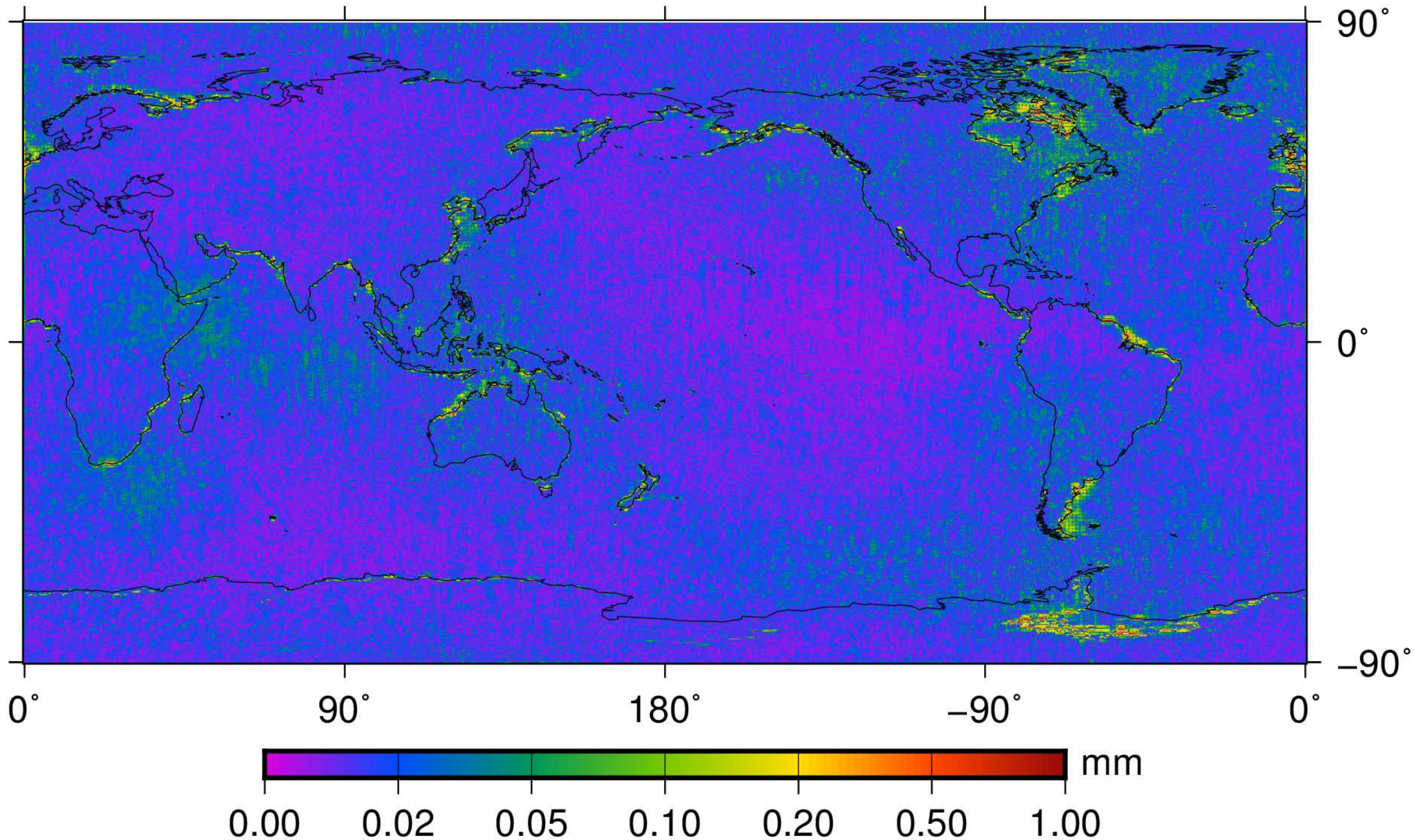
Difference OTL regular ¼ × ¼ grid versus quadtree grid (M_2 Up)



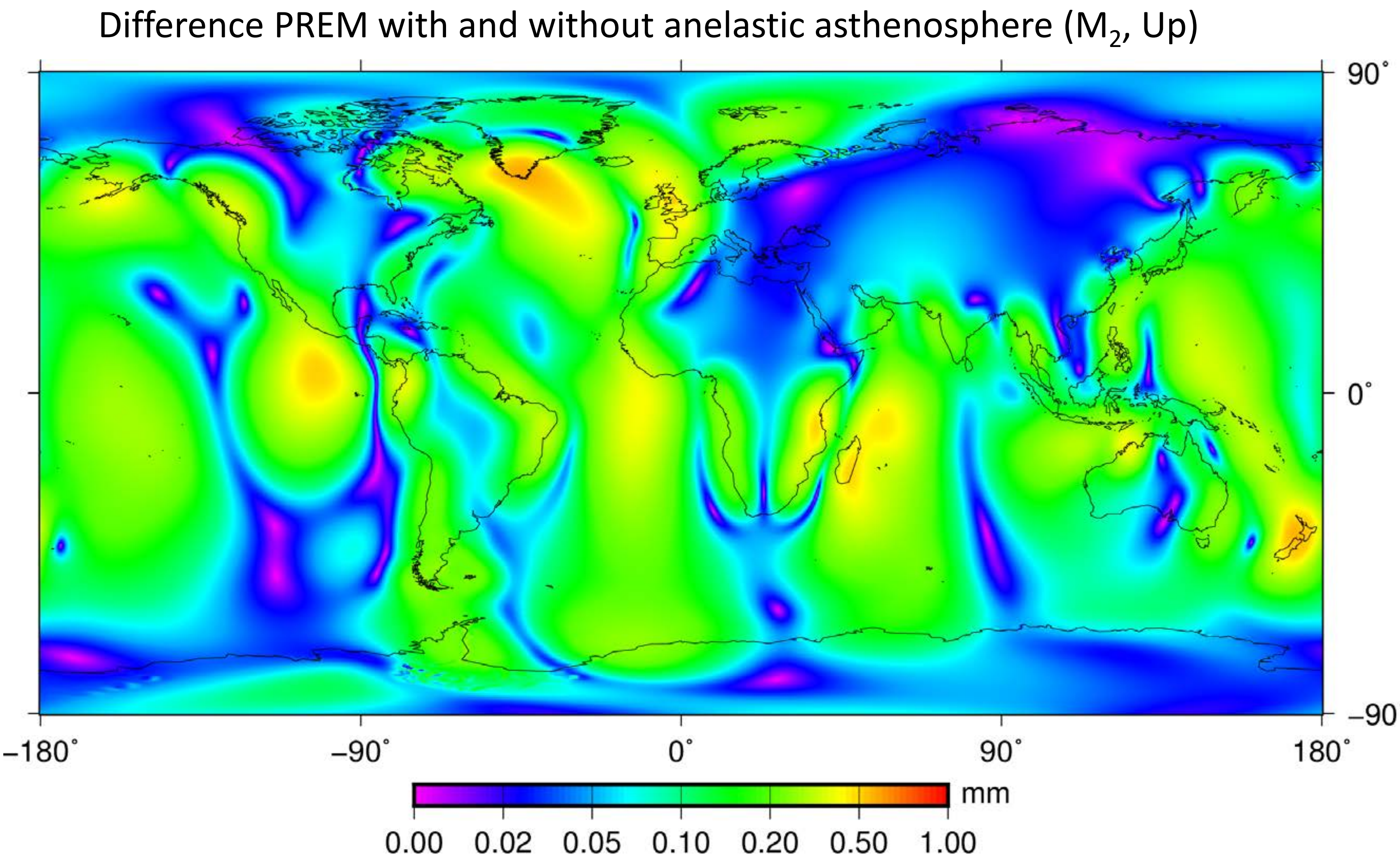
Difference OTL regular ¼ × ¼ grid versus quadtree grid (M_2 East-West)



Difference OTL regular ¼ × ¼ grid versus quadtree grid (M_2 North-South)

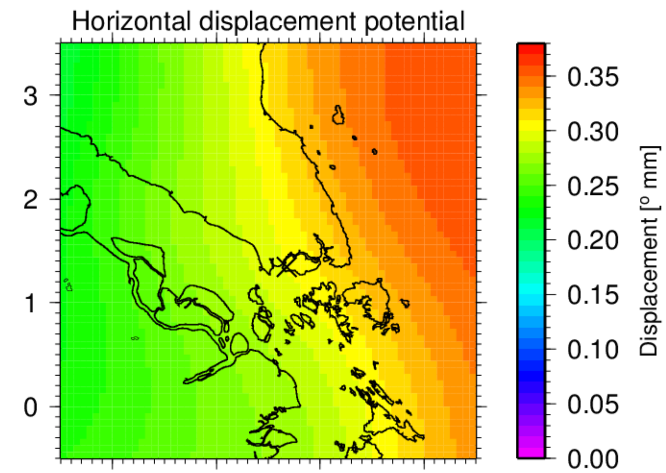


Effect of Green's function



Working on a fast and precise solution, presenting: The mapping algorithm

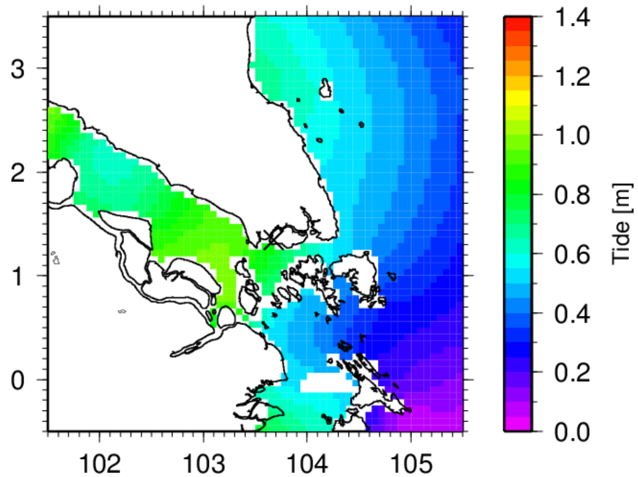
- **FES0216 at full resolution 1/16 × 1/16 deg**
- **Complex-valued Green's function**

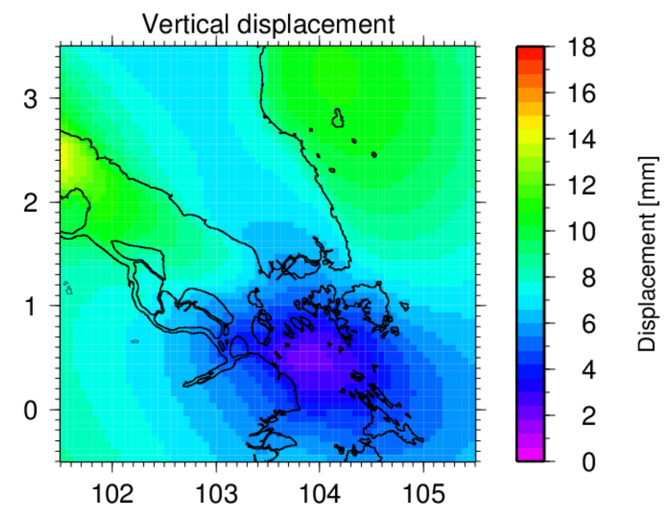


Tide model: FES2014b M_2

Load model: PREM anelastic

Site NTUS





The mapping algorithm

- Loading Greens kernel function, PREM earth
- Radial displacement $G_u = \sum_{n=0}^{\infty} h'_n \, P_n \, (\cos\vartheta)$
- Tangential displacement "potential" $G_p = \sum_{n=0}^{\infty} \, l'_n \, P_n \, (\cos\vartheta)$
- Anelasticity, $Q \sim \omega^{-0.3}$ => complex-valued Greens
- Semi-fast convolution (FFT along latitude rings, util. circular correlation)
- Utilizing hemispherical symmetry
- Utilizing load <-> field point symmetry and that Greens are even functions
- Wall-time: 90 minutes for a 1/16 × 1/16 global tide model
- East and North components from gradients (polynomial, local triangle)

Slow: $u_{ij} = \frac{G}{a\,g} \sum_{kl} G_p\left(\vartheta_{ijkl}\right) m_{kl}$ Fast: $\tilde{\boldsymbol{u}}_{jl} = \frac{G}{a\,g} \, \mathbf{FCOST}\left\{\boldsymbol{G}_{u,jl}\right\} \mathbf{FCFT}\{\boldsymbol{m}_l\}$

transforms, latitude rings j and l:
fast cosine and fast complex Fourier

Local interpolation on grid, M=3,

up: $u = P(x, y) = \sum_{\mu+\nu=M} u_{\mu\nu} x^{\mu} y^{\nu}$ north: $d_n = \sum_{\mu+\nu=d} \mu \, p_{\mu\nu} x^{\mu-1} y^{\nu}$

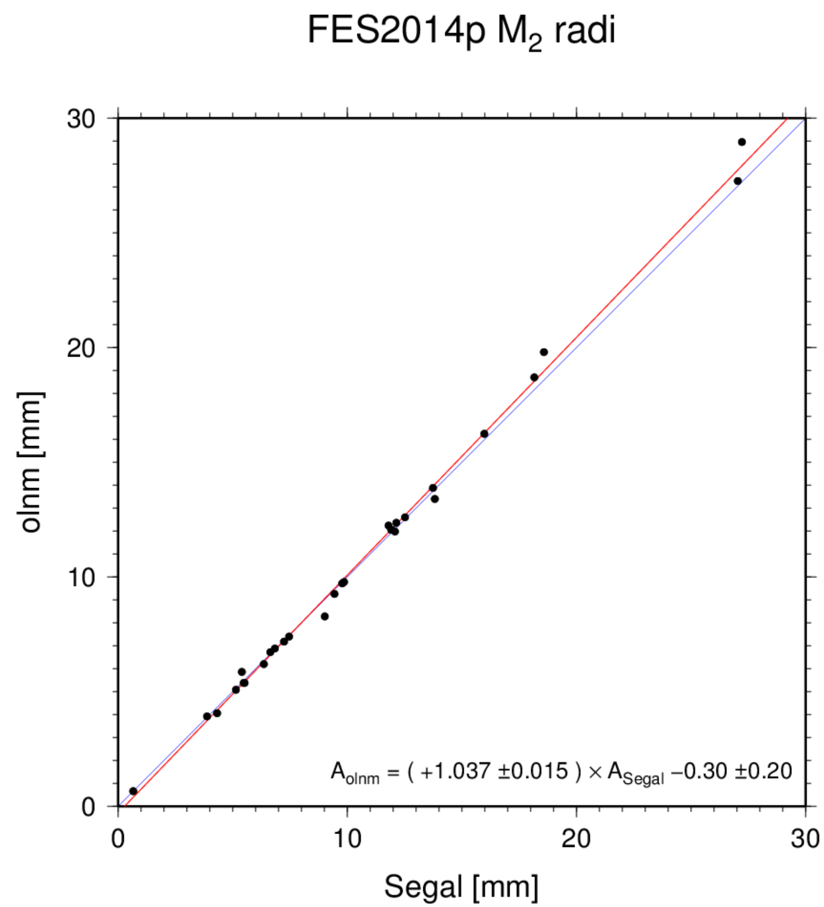
east: $d_e = \sum_{\mu+\nu=d} \nu \, p_{\mu\nu} x^{\mu} y^{\nu-1} / \cos\beta$

Comparison 1: Grid <-> explicit w. coast

- The 30 stations of Penna et al., 2008 (all near coasts + Wettzell).
- **Segal**: Ocean loading service, high resolution coastlines.
- **olnm**: interpolation on the global grid.
- Error of fit (1 σ): 0.6 mm
  Max. discrepancy: 1.5 mm (this is only for M_2 and radial displacement).
- Will amount to at least 1 mm σ, 3 mm max. with the usual 11 tides.

→ Rule of thumb: 10% accuracy, not good enough.

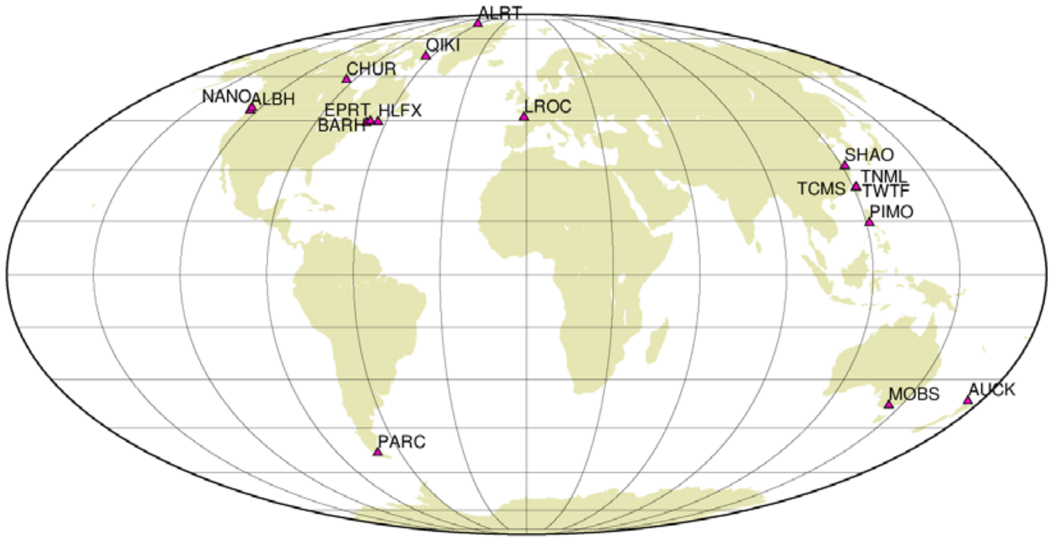
→ Envisage a combination of this method with regional resolution of coastline, which will be a fast process.



Ocean loading coefficients, tangential displacements for tide M2, 30 stations (amplitude [mm], phase [deg])

SITE	EAST			NORTH		
	SEGAL	OLNM	DIFF	SEGAL	OLNM	DIFF
WTZR	(1.901, 258.3)	(1.910, 257.6)	(0.025, 9.086)	(0.358, 131.7)	(0.390, 130.2)	(0.033, 293.936)
ALBH	(5.679, 73.3)	(5.630, 73.3)	(0.049, 73.300)	(1.887, 358.0)	(1.960, 2.1)	(0.156, 242.121)
ALRT	(1.164, 52.4)	(1.180, 52.5)	(0.016, 239.735)	(0.533, 285.9)	(0.490, 285.3)	(0.043, 292.701)
AUCK	(8.395, 159.0)	(8.300, 159.1)	(0.096, 150.331)	(5.297, 202.6)	(5.250, 202.8)	(0.050, 181.312)
BAHR	(1.369, 133.7)	(1.380, 134.4)	(0.020, 10.824)	(1.242, 39.4)	(1.250, 39.7)	(0.010, 258.747)
BAIE	(0.774, 31.0)	(0.780, 29.3)	(0.024, 134.737)	(0.601, 251.6)	(0.650, 245.2)	(0.085, 13.414)
BARH	(3.615, 41.7)	(3.540, 39.9)	(**0.135**, 97.086)	(3.441, 239.9)	(3.410, 239.4)	(0.043, 283.609)
CHUR	(3.467, 52.9)	(3.530, 52.7)	(0.064, 221.830)	(2.505, 347.9)	(2.640, 348.6)	(0.139, 181.356)
EPRT	(3.322, 43.2)	(3.290, 42.3)	(0.061, 101.109)	(3.842, 234.1)	(3.800, 233.8)	(0.047, 259.421)
ESCU	(1.949, 356.5)	(1.940, 355.4)	(0.038, 72.396)	(2.831, 213.6)	(2.780, 212.4)	(0.078, 262.044)
HLFX	(3.450, 321.9)	(3.390, 322.6)	(0.073, 287.397)	(3.505, 167.0)	(3.400, 169.4)	(**0.179**, 114.178)
KUUJ	(1.450, 41.4)	(1.410, 42.6)	(0.050, 5.175)	(0.821, 332.3)	(0.790, 330.9)	(0.037, 4.013)
LROC	(8.879, 273.7)	(8.990, 273.8)	(0.112, 101.747)	(2.415, 211.3)	(2.480, 214.6)	(0.155, 98.201)
MOBS	(3.213, 278.9)	(3.260, 278.9)	(0.047, 98.900)	(2.297, 224.7)	(2.230, 225.0)	(0.068, 214.819)
NANO	(5.819, 75.4)	(5.800, 75.3)	(0.022, 103.437)	(1.930, 8.3)	(1.950, 7.6)	(0.031, 138.108)
NTUS	(1.763, 51.5)	(1.800, 49.1)	(0.083, 166.670)	(1.227, 82.5)	(1.210, 83.8)	(0.032, 24.736)
PARC	(5.108, 348.2)	(5.190, 348.7)	(0.094, 197.172)	(4.481, 50.0)	(4.470, 50.5)	(0.041, 335.980)
PIMO	(4.401, 280.9)	(4.400, 281.4)	(0.038, 192.642)	(1.541, 266.6)	(1.510, 266.5)	(0.031, 271.459)
QIKI	(1.430, 305.8)	(1.470, 307.6)	(0.061, 175.416)	(3.812, 140.9)	(3.770, 140.5)	(0.050, 172.917)
RESO	(2.534, 86.9)	(2.550, 87.3)	(0.024, 315.063)	(0.861, 109.4)	(0.850, 108.3)	(0.020, 165.039)
SHAO	(2.240, 12.1)	(2.300, 12.4)	(0.061, 203.455)	(2.896, 157.6)	(2.950, 157.0)	(0.062, 307.753)
SHE2	(2.325, 344.8)	(2.360, 344.2)	(0.043, 129.474)	(3.086, 227.1)	(2.960, 222.7)	(**0.264**, 286.421)
TCMS	(7.348, 284.2)	(7.250, 284.6)	(**0.110**, 256.927)	(3.526, 72.4)	(3.440, 71.4)	(0.105, 107.156)
TNML	(7.348, 284.2)	(7.250, 284.6)	(**0.110**, 256.927)	(3.526, 72.4)	(3.440, 71.4)	(0.105, 107.156)
TWTF	(7.140, 284.2)	(7.090, 284.5)	(0.062, 247.661)	(3.401, 69.0)	(3.360, 68.1)	(0.067, 120.878)
UNBJ	(2.167, 21.0)	(2.150, 18.3)	(0.103, 100.164)	(3.293, 232.6)	(3.230, 231.7)	(0.081, 271.269)
APPL	(7.864, 300.6)	(7.920, 301.0)	(0.079, 165.334)	(4.338, 264.4)	(4.360, 267.8)	(**0.259**, 171.229)
GLAS	(3.791, 338.8)	(3.830, 339.5)	(0.061, 209.196)	(2.512, 236.3)	(2.500, 236.0)	(0.018, 283.706)
MALG	(6.711, 339.0)	(6.720, 339.0)	(0.009, 159.000)	(3.963, 255.4)	(3.970, 255.6)	(0.016, 138.680)
NEWC	(0.651, 60.5)	(0.730, 67.4)	(**0.115**, 290.453)	(0.833, 316.4)	(0.880, 319.4)	(0.065, 181.563)

Comparison 2: GNSS



- 3-d time series
- 2011-01 – 2014-09
- low-passed to 1 h smpl.interv.
- noise spectrum balancing with PEF (Burg Maximum Entropy)
- PEF and outlier iteration
- Tamura tide potential
- weighted least-squares

- We used Gipsy v6.3 with the PPP – Precise Point Positioning strategy (Zumberge et al., 1997
- kinematic mode with the following stochastic proprieties:
  - apsig = 2 000 km
  - sigp = 0.001 km/$s^{1/2}$
  - sdelt rate = 300 s
  - smtau = RANDOMWALK
- elevation cut-off 7.5°
  - VMF1GRID (Boehm et al., 2009) mapping function
  - JPL precise orbit & clocks (http://sideshow.jpl.nasa.gov)
  - IGS08 (https://igscb.jpl.nasa.gov/igscb/station/general/igs08.atx) antenna phase center corrections.

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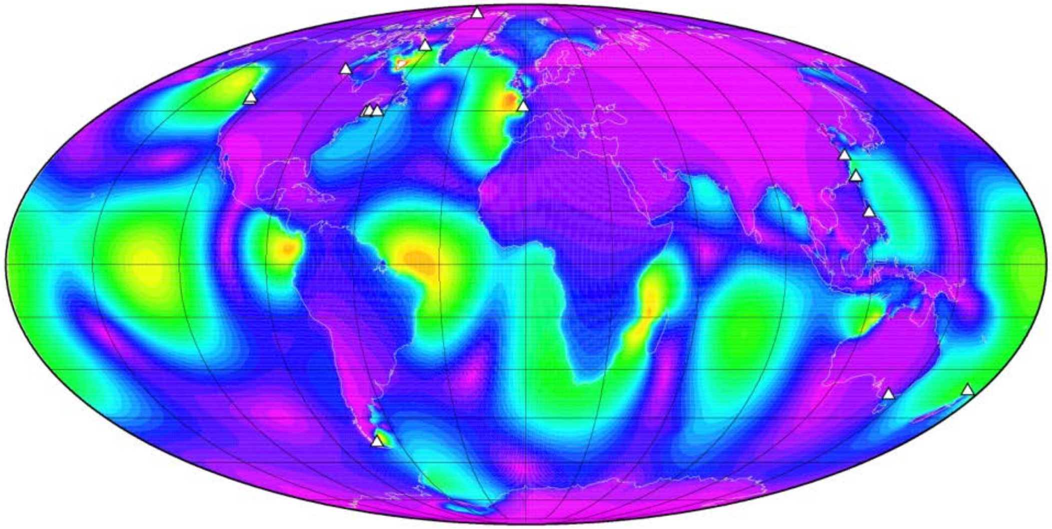

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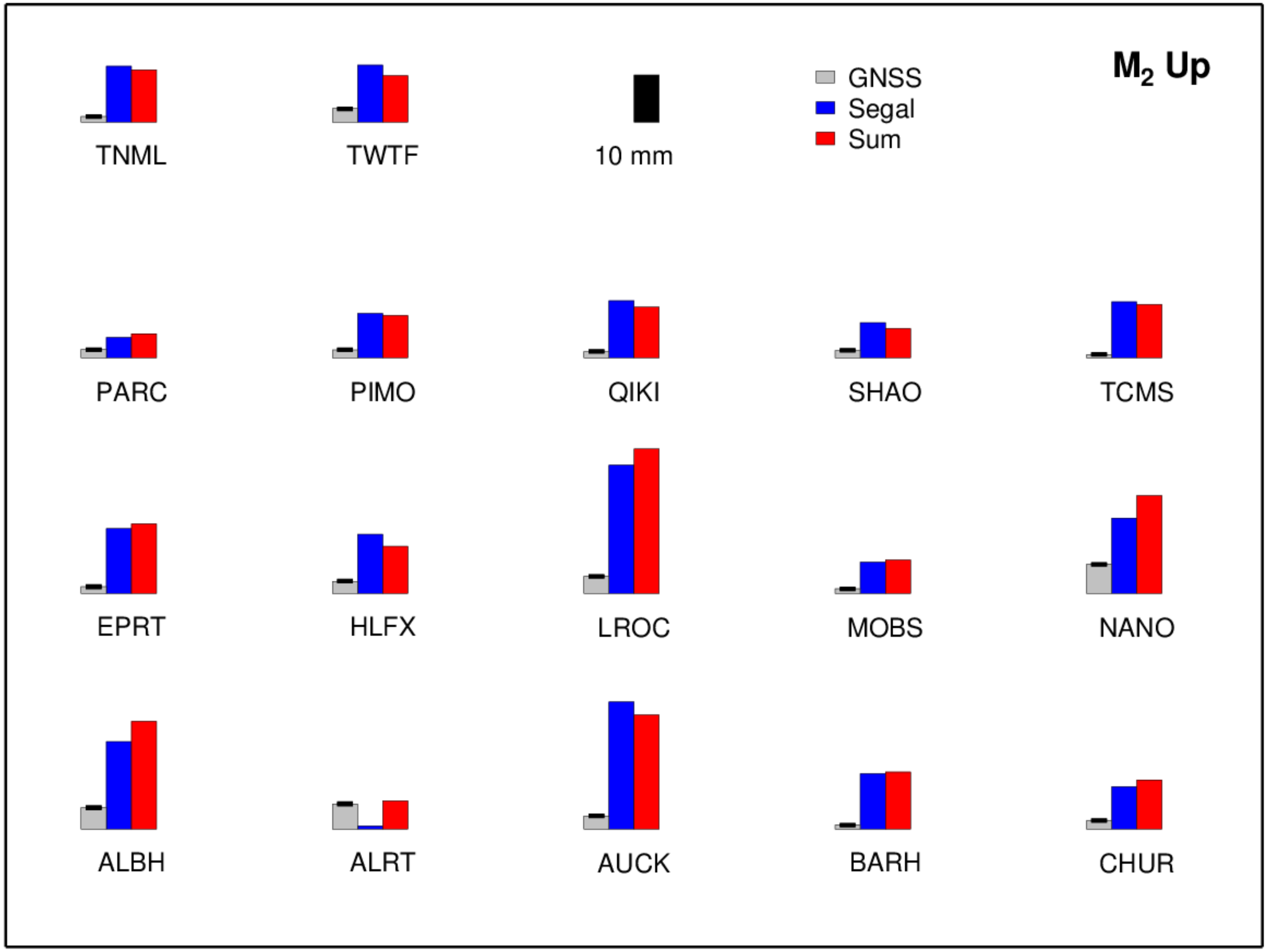

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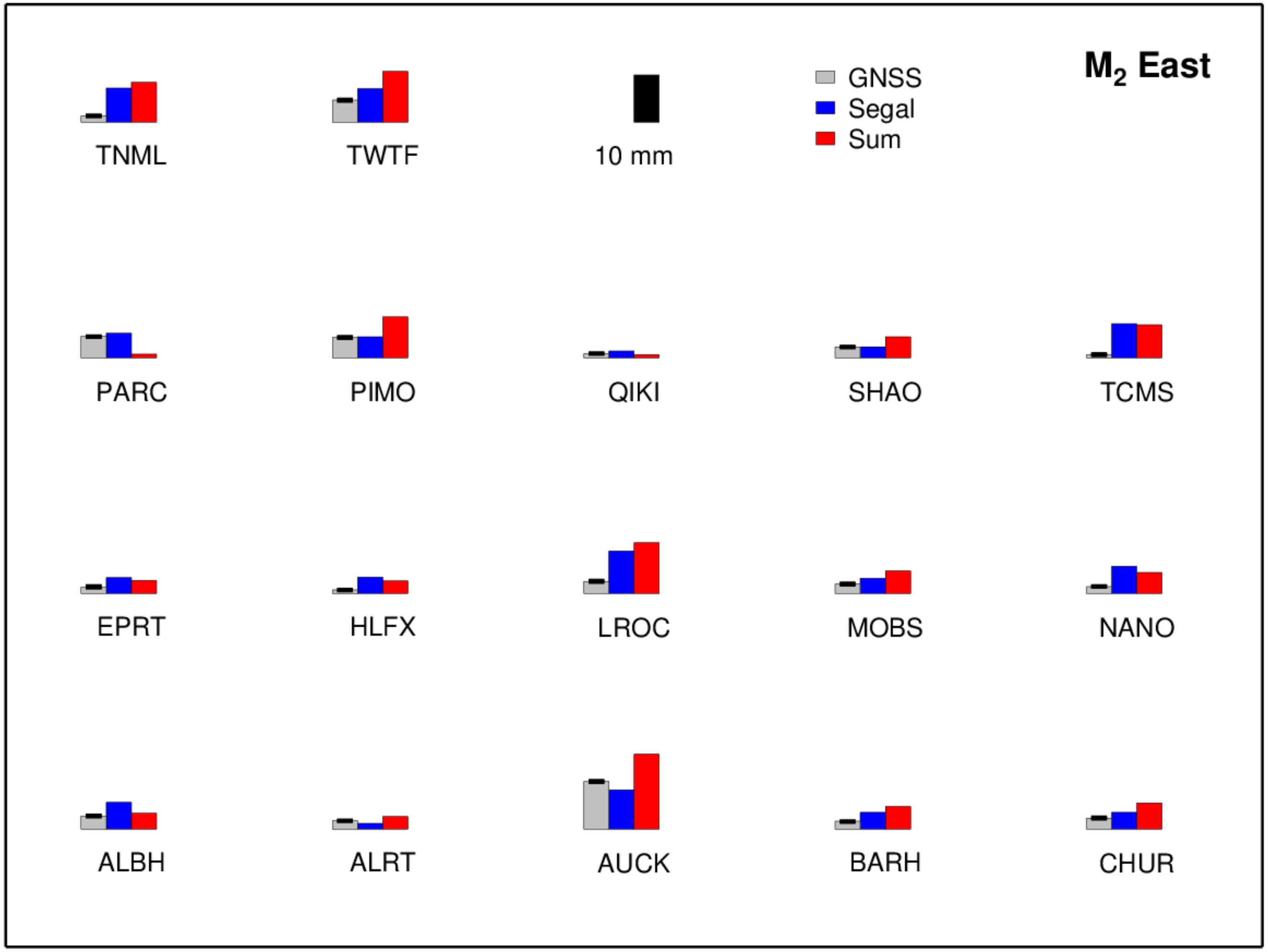

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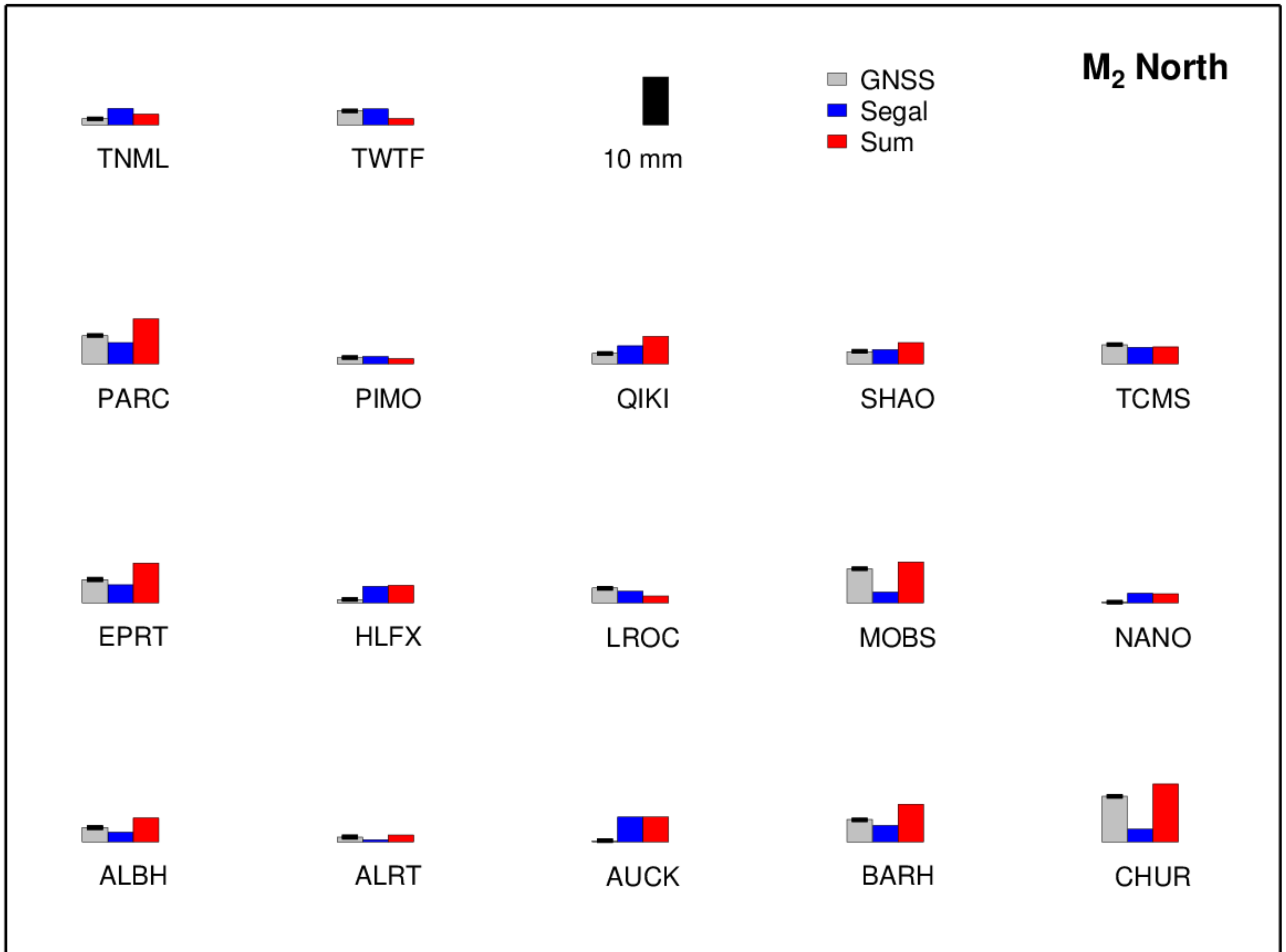

Outlook / Conclusions

- Gridded global displacement data can be disseminated for off-line purpose. Resolution 1/16 x 1/16 deg. Needs 2-D interpolation at users' sites, a relatively fast and simple task.
  - Limited resolution of complicated coastal locations leads to predicition errors (roughly 10% prediction error)
  - Safe at sites at 100 km distance from coasts or beyond.
- If higher accuracy is neeeded, loading service delegates requests involving 1/16 x 1/16 deg. models to Segal for processing.
- We are considering a marriage of the two methods, where the load convolution would only encompasss the differential masses at coasts within a distance of some hundreds of km.
- We are working to add various Green's function options to the ocean tide loading provider.
- Gravimetry is even harder impacted by ocean loading; gravimeters may help to push accuracy of ocean tide loading predictions even further.

The discrepancy between Earth-tide theory and Earth tide observations is mostly the result of the influence of the tides which can easily account for 10%, 20% and 90% of the total Earth tide in gravity, strain and tilt, respectively. These ocean load perturbations can be used to study mantle (in regions where the ocean tide is particularly known), and the ocean tides themselves

W.E. Farrell (1972, Nature)

40 years later ocean tide models and geodetic observation methods have reached accuracy levels where we can study the elastic properties of the earth using OTL!

Back up slide: 5 times more quadtree cells

Difference OTL regular grid versus quadtree grid (M_2 Up)