The mean dynamic topography of the ocean:

Applications for local geopotential measurements

Chris W. Hughes *(University of Liverpool and NOC, Liverpool)*

… and many collaborators

IAG WG2.1 Meeting, Hannover, 15 May 2017

National Oceanography Centre
NATURAL ENVIRONMENT RESEARCH COUNCIL

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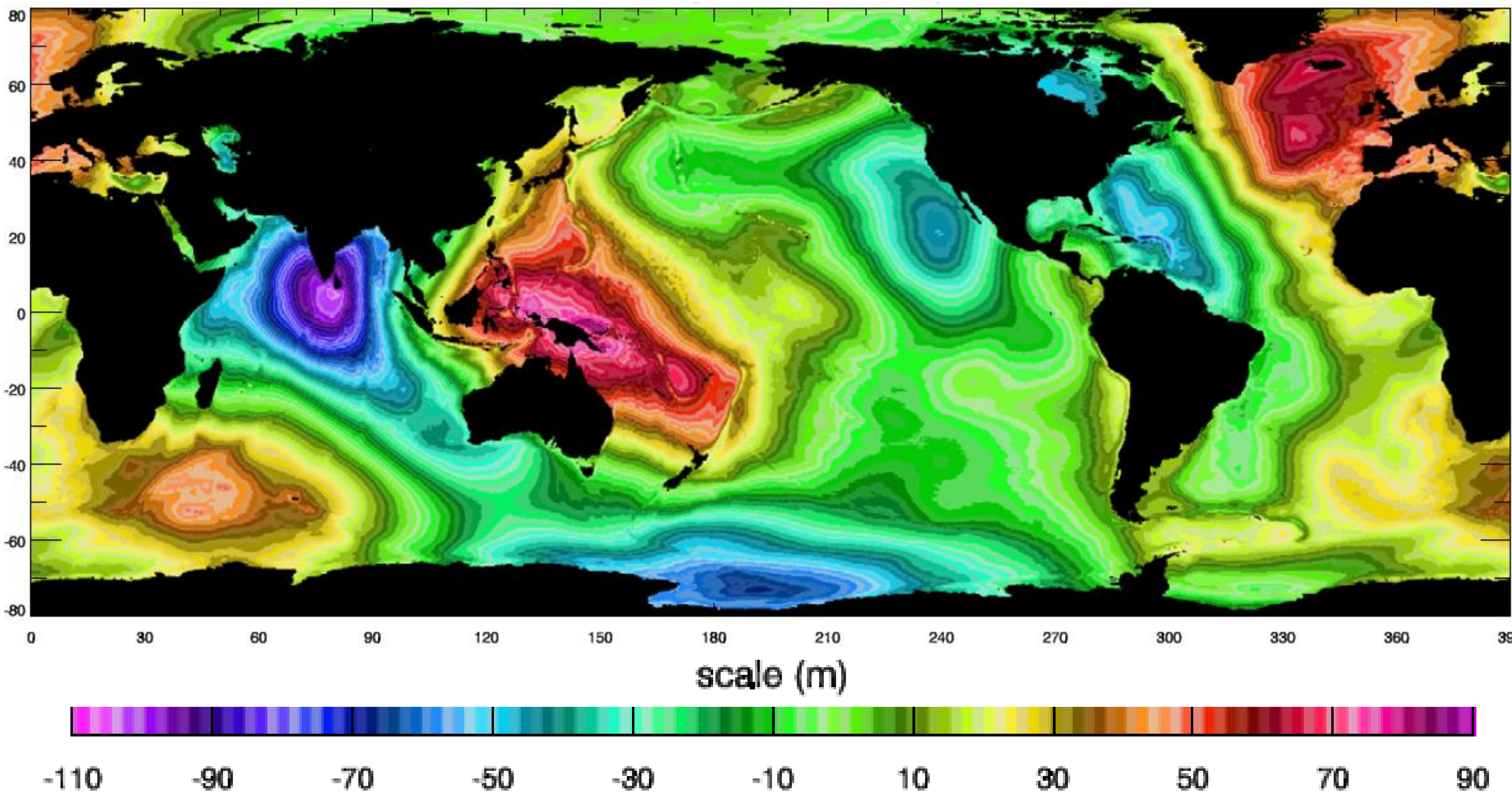
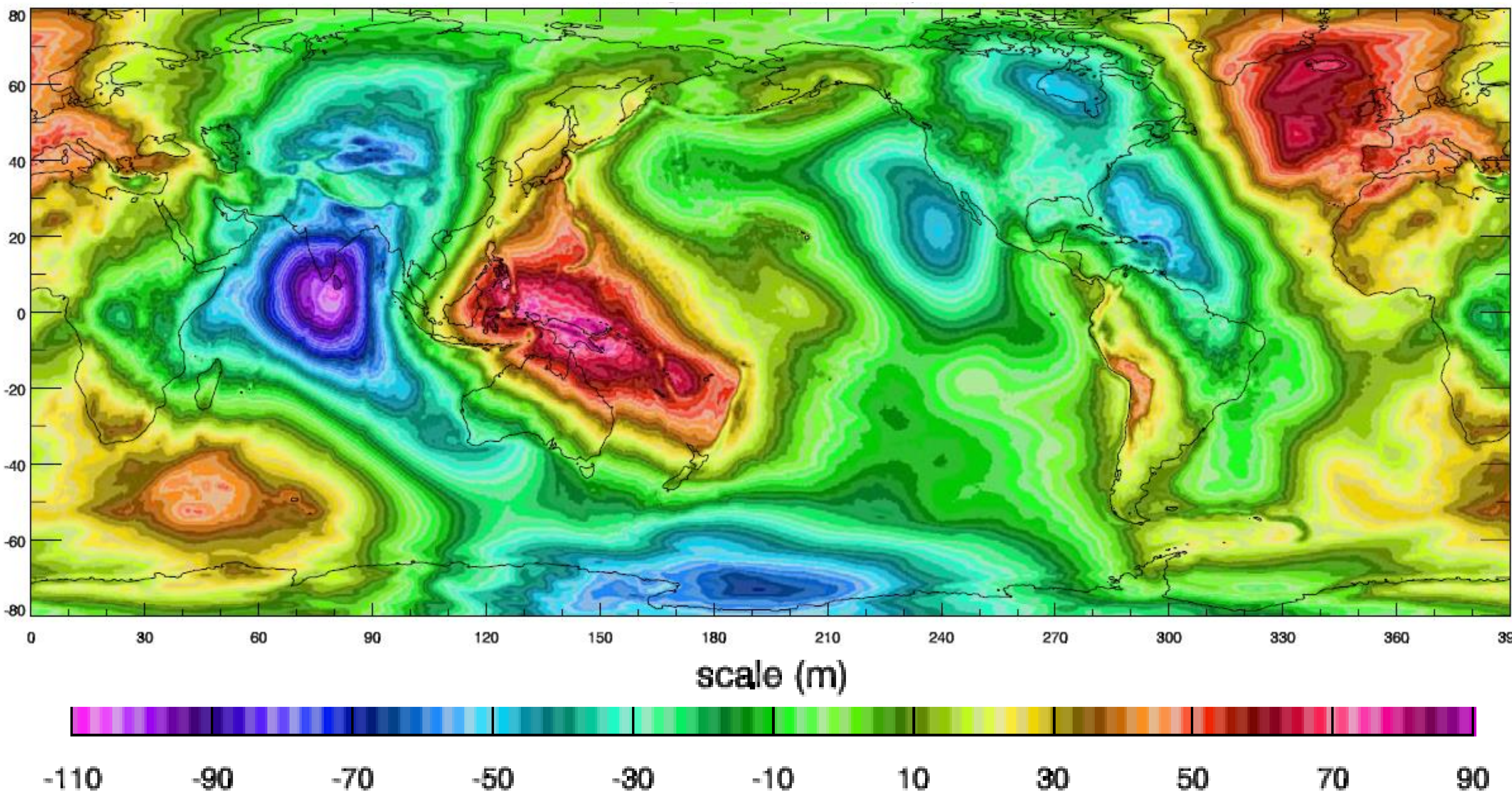
Height of the sea surface above the reference ellipsoid

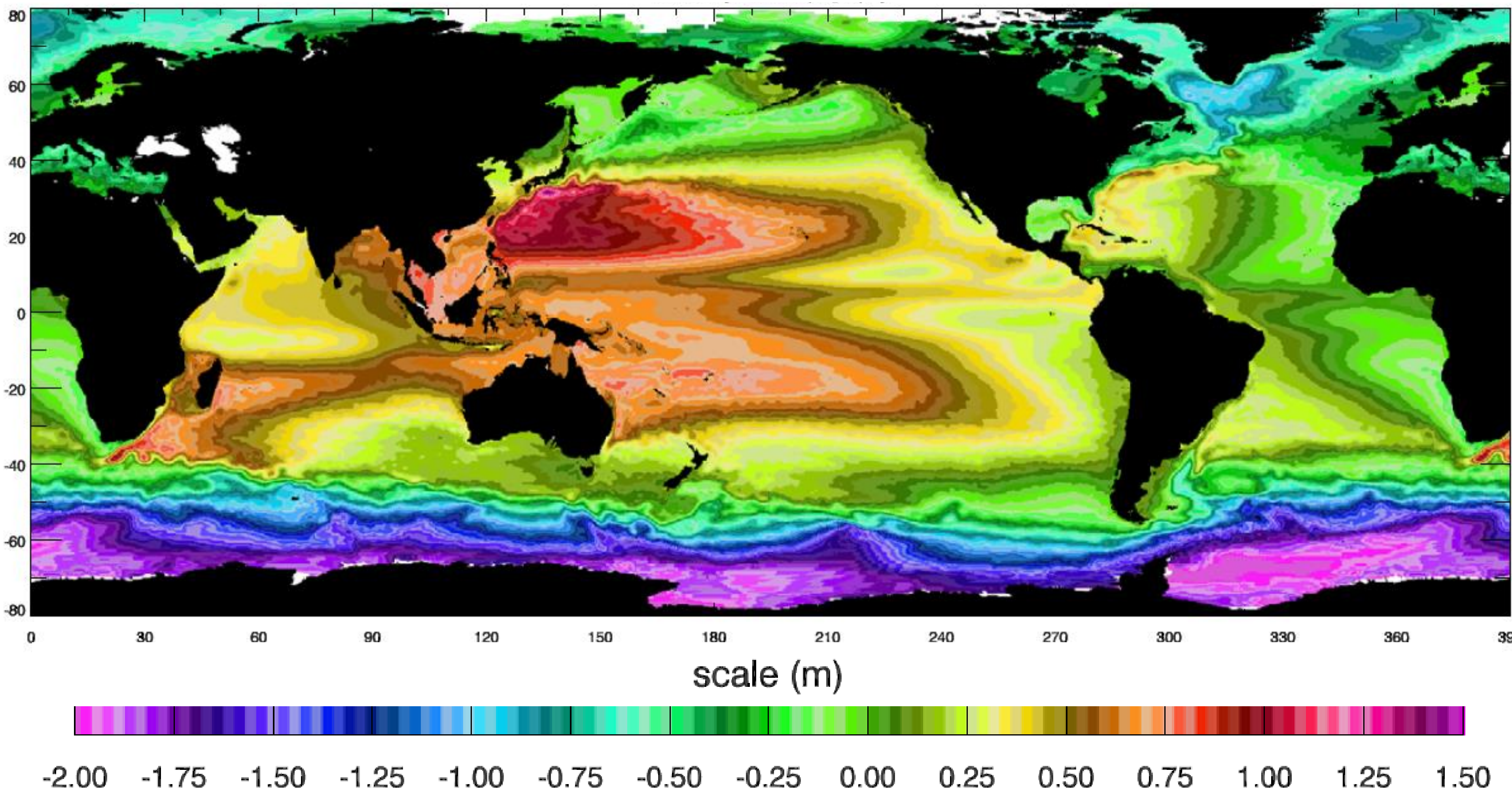


Height of the geoid above the reference ellipsoid

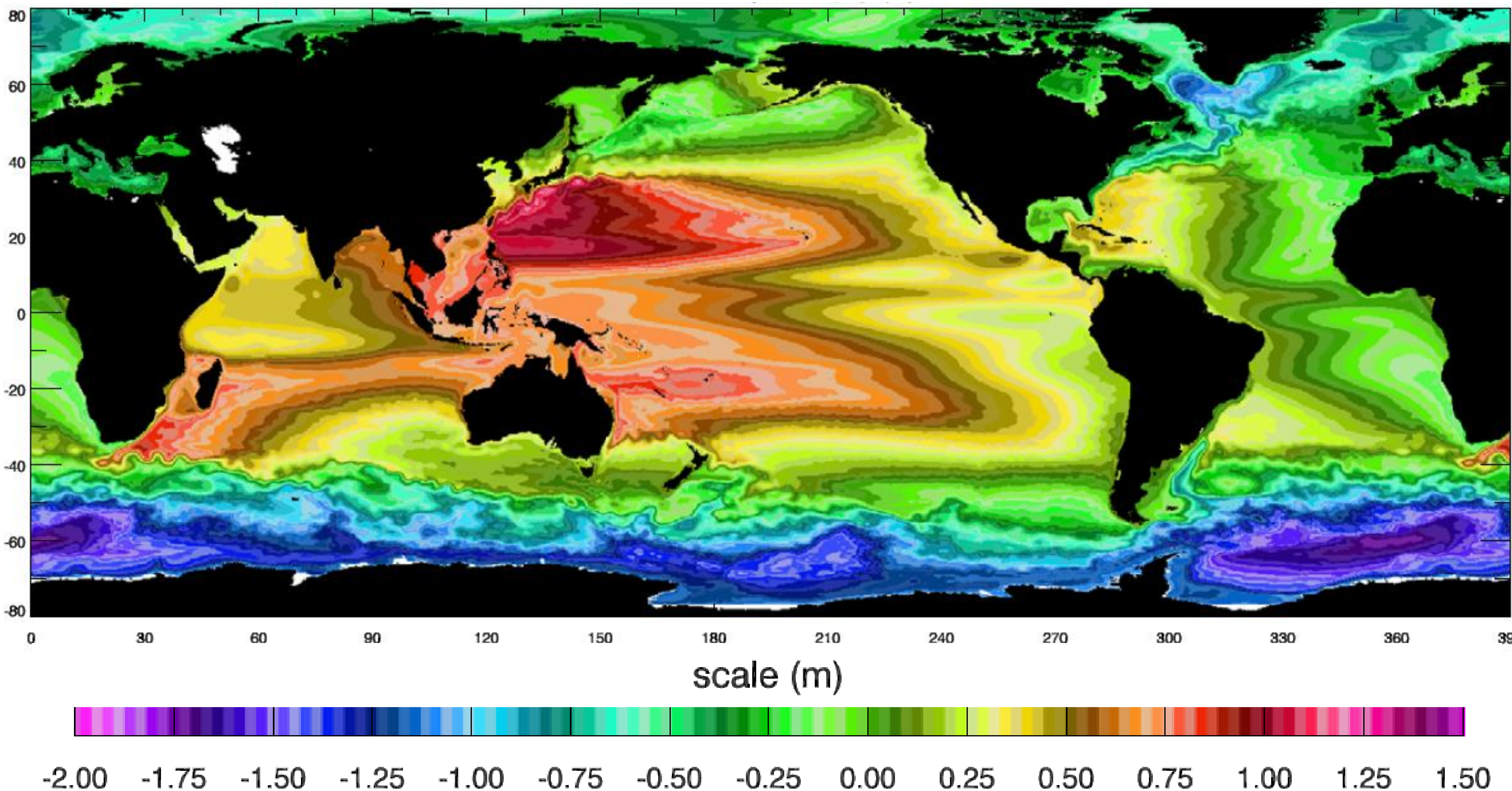


The shape of the geoid dominates the shape of the ocean,
with a range of almost 200 m relative to the reference ellipsoid

Ocean dynamic topography (sea surface height minus geoid)



Ocean dynamic topography (from an ocean model)



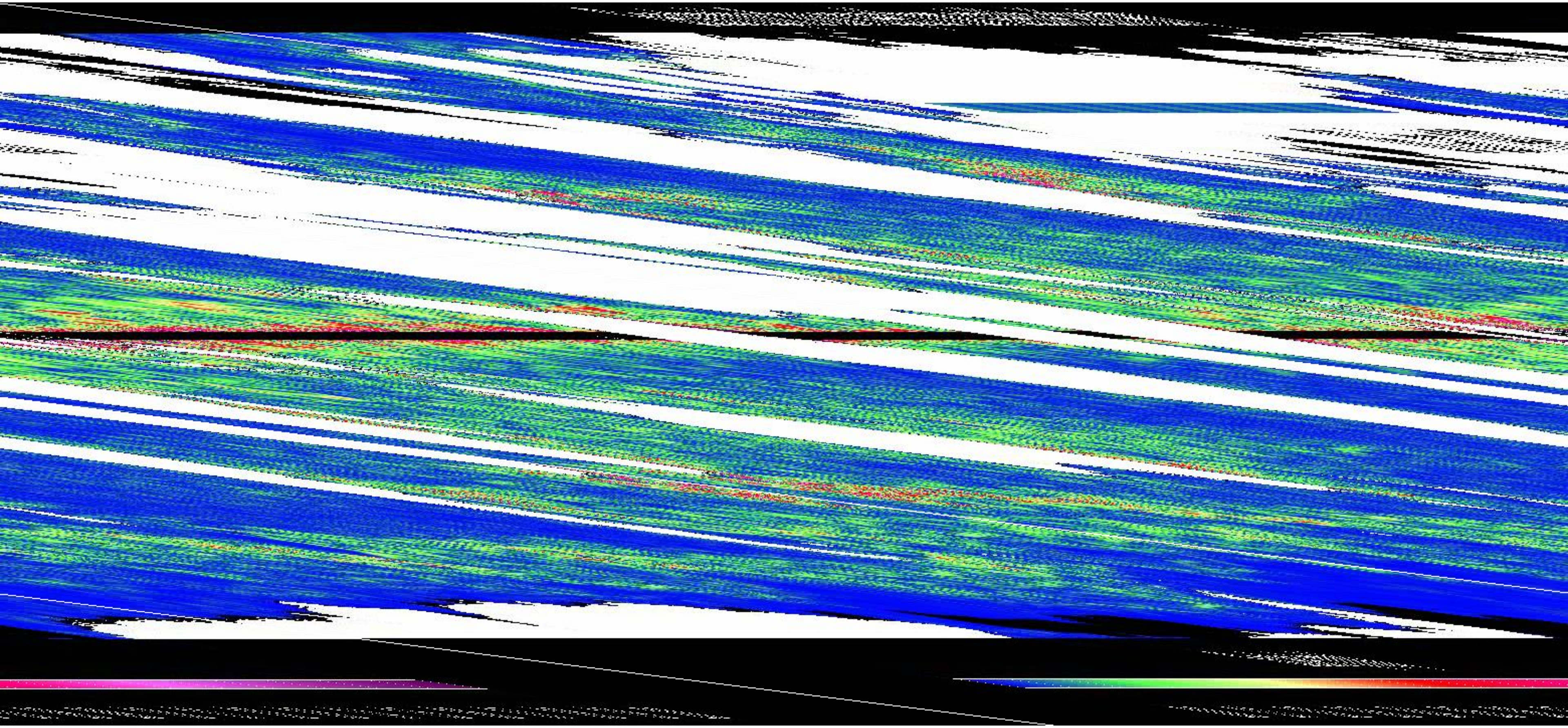
Geostrophic balance

$$\boldsymbol{u} = \frac{\nabla W \times \nabla p}{2\rho g \Omega \sin\phi}$$

We know density ρ, g, Earth rotation rate Ω latitude ϕ to good accuracy.

The sea surface is a surface of constant pressure (we make an “inverse barometer” correction for atmospheric pressure).

We need to know either how geopotential W varies along a p surface (the dynamic topography) or how p varies along a geopotential surface, to obtain geostrophic currents $\boldsymbol{u}$.



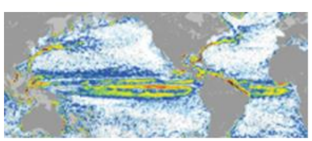
Problem solved? No.

- To make this comparison, we have to smooth the SSH, resulting in a smoothed version of the MDT. We rely on patchy in-situ gravity measurements to fill in the small scales.
- The place where sea level has the most direct societal impact is at the coast. Only tide gauges measure exactly at the coast, and they make a point measurement – no smoothing is possible

Mean dynamic topography at tide gauges… why?

- Flooding results from sea level at the coast. Only tide gauges measure sea level precisely at the coast.
- We want to know whether local dynamics affects sea level significantly, and how open-ocean dynamics affects the coast. For long-term prediction (centuries) we want to know whether models can get this right.
- The only way to assess the long term is to look at the mean – time series aren't long enough.

GOCE++Dycot

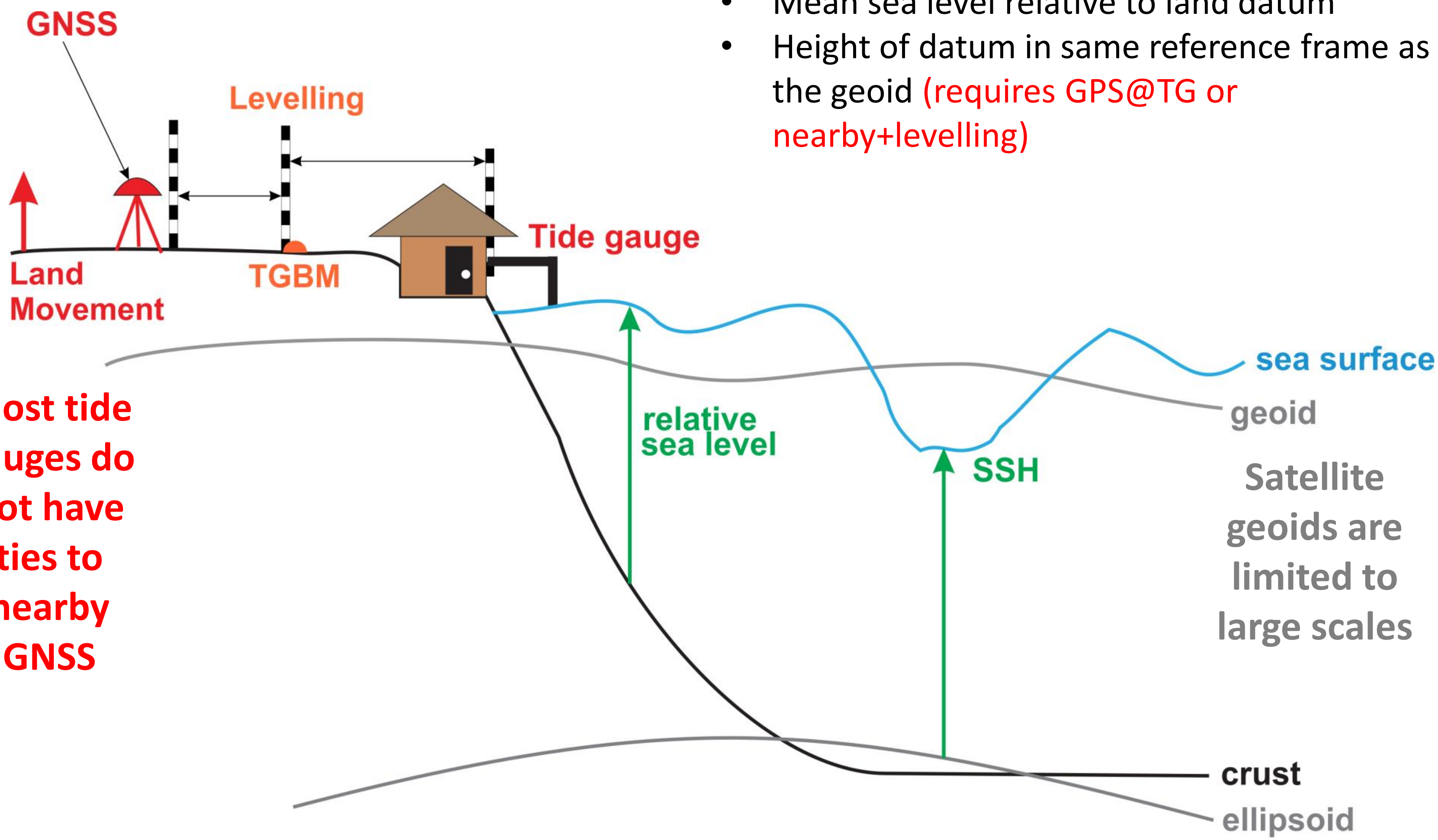


Denmark (DTU), France (La Rochelle)
Germany (TU Darmstadt), UK (Liverpool and Bristol)

Traditional Implementation of a GLOSS CORE Network Site

Mean dynamic topography requires:

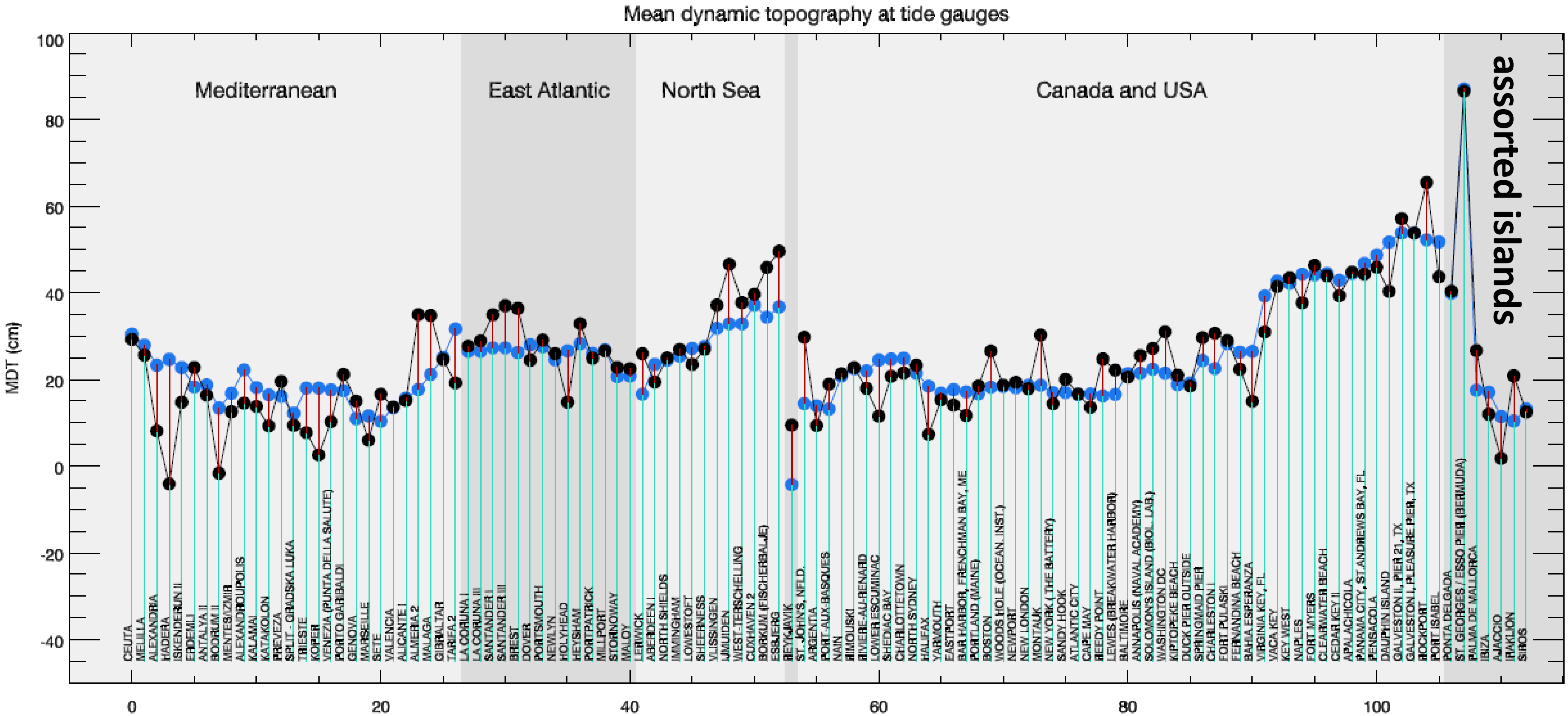
- Geoid (GOCE+GRACE**+local**)
- Mean sea level relative to land datum
- Height of datum in same reference frame as the geoid (requires GPS@TG or nearby+levelling)



Most tide gauges do not have ties to nearby GNSS

Satellite geoids are limited to large scales

Comparing MDT in the N Atlantic and Mediterranean: 113 Tide gauges



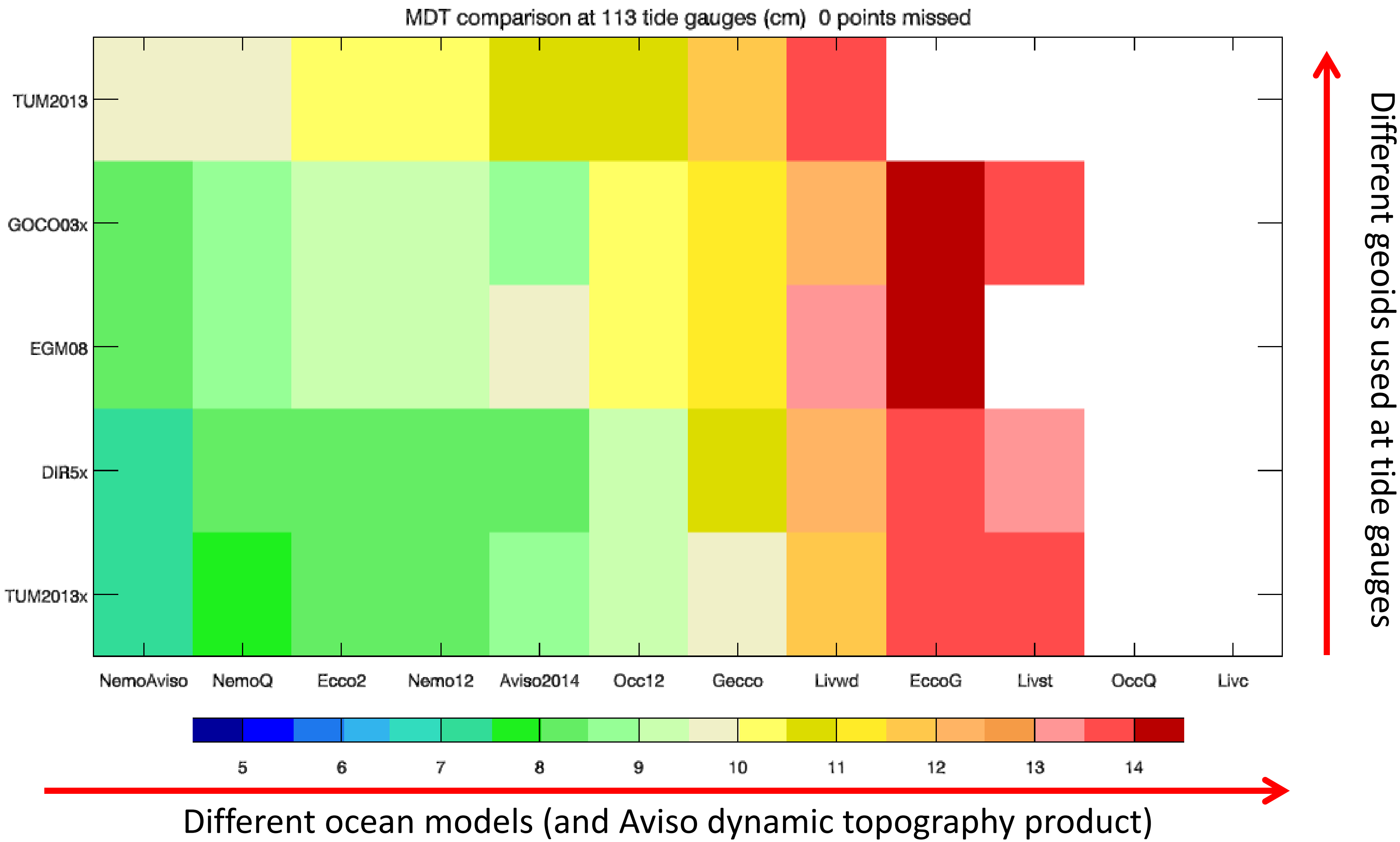
Tide gauge data + GPS position + TUM2013x geoid

(i.e. TUM 2013 extended beyond degree 720 using EGM08)

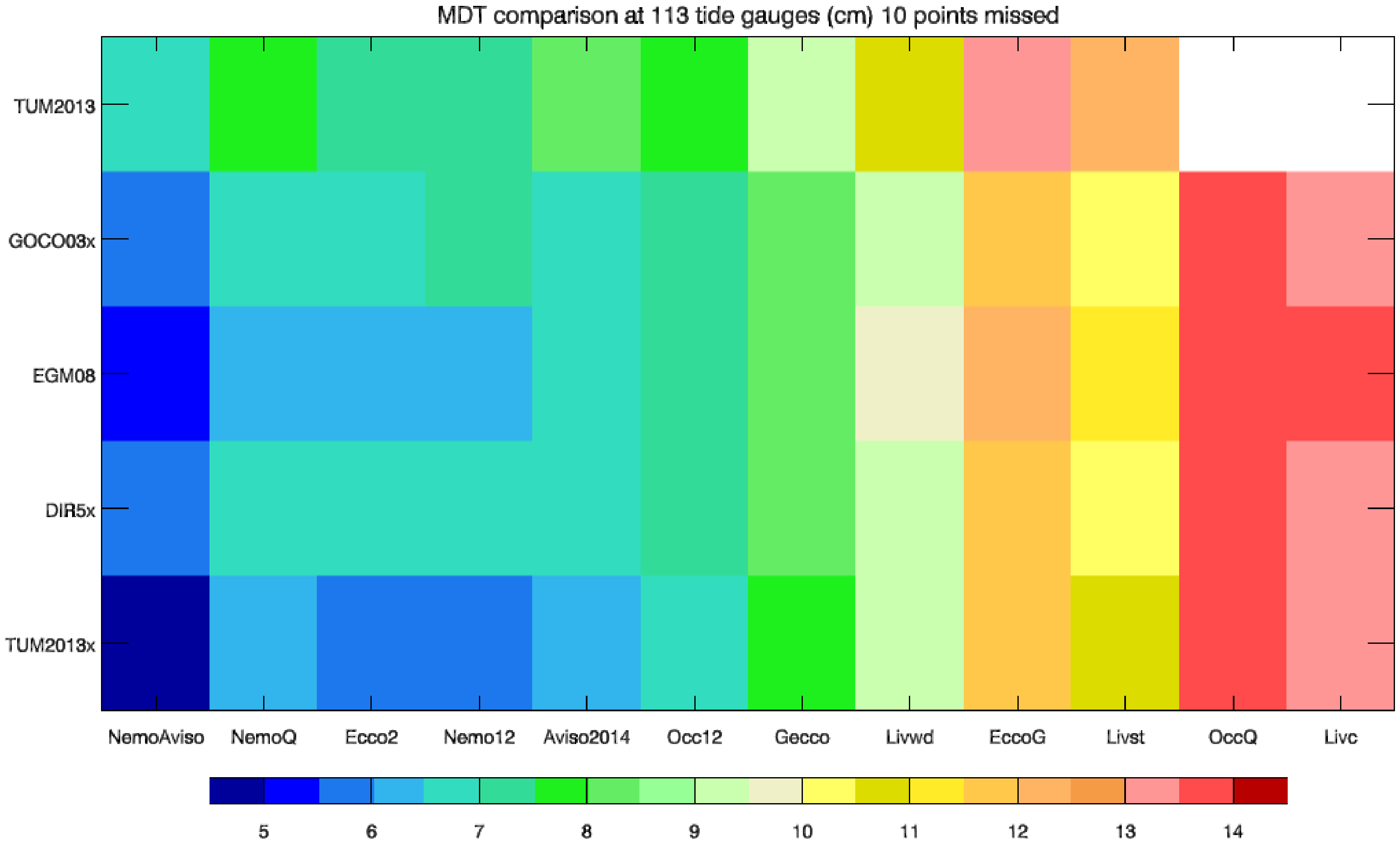
Average of NemoQ, Nemo12 ocean models, and Aviso 2014 MDTs

Hughes, C. W., R. J. Bingham, V. Roussenov, Joanne Williams and P. L. Woodworth, 2015:
The effect of Mediterranean exchange flow on European time mean sea level. *Geophys. Res. Lett.* **42**(2), 466-474. doi: 10.1002/2014GL062654.

Root mean square error, as a function of geoid used and model/MDT product. All tide gauges included.



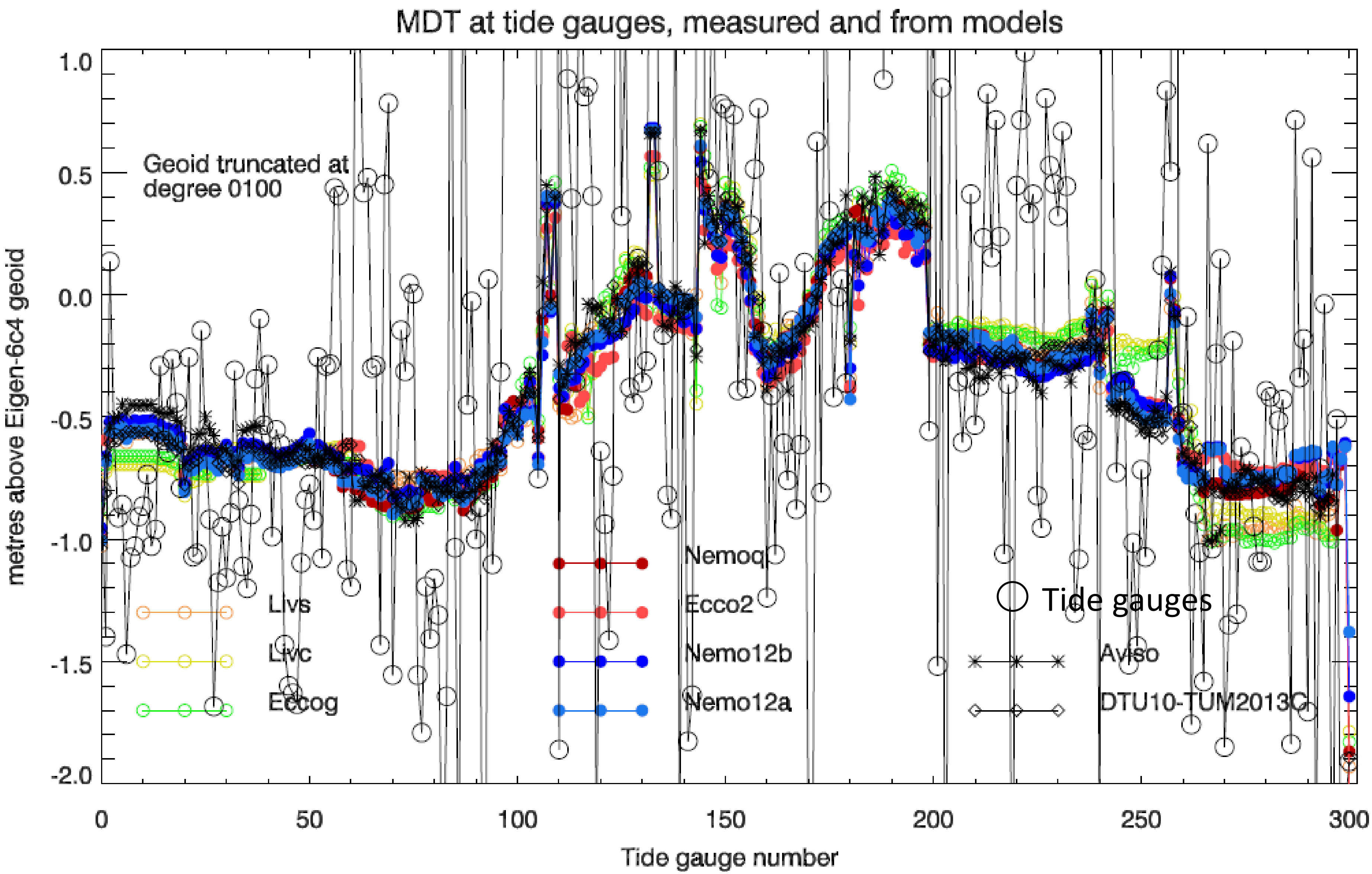
Root mean square error, as a function of geoid used and model/MDT product. "Worst" 10 tide gauges missed out.

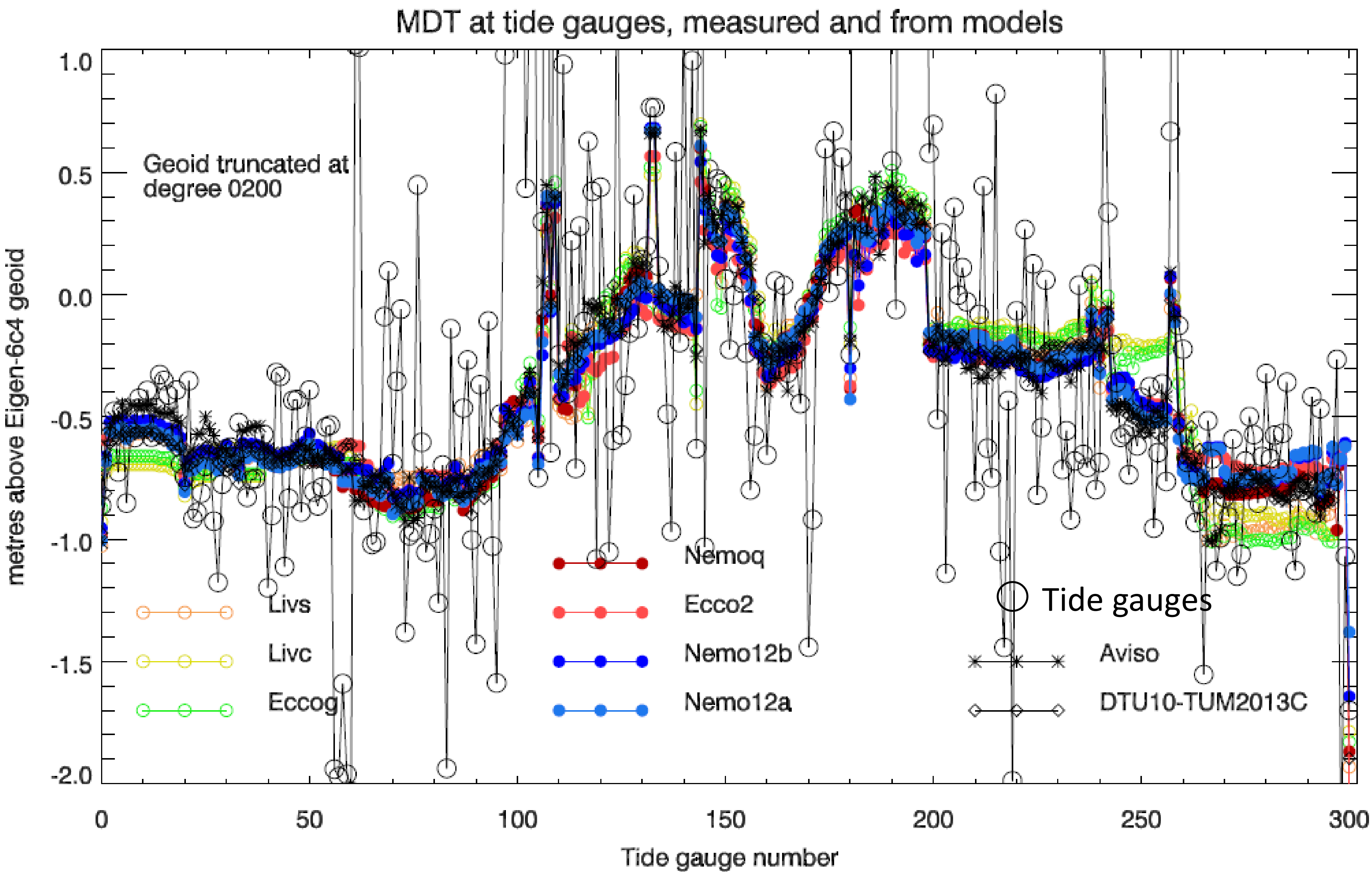


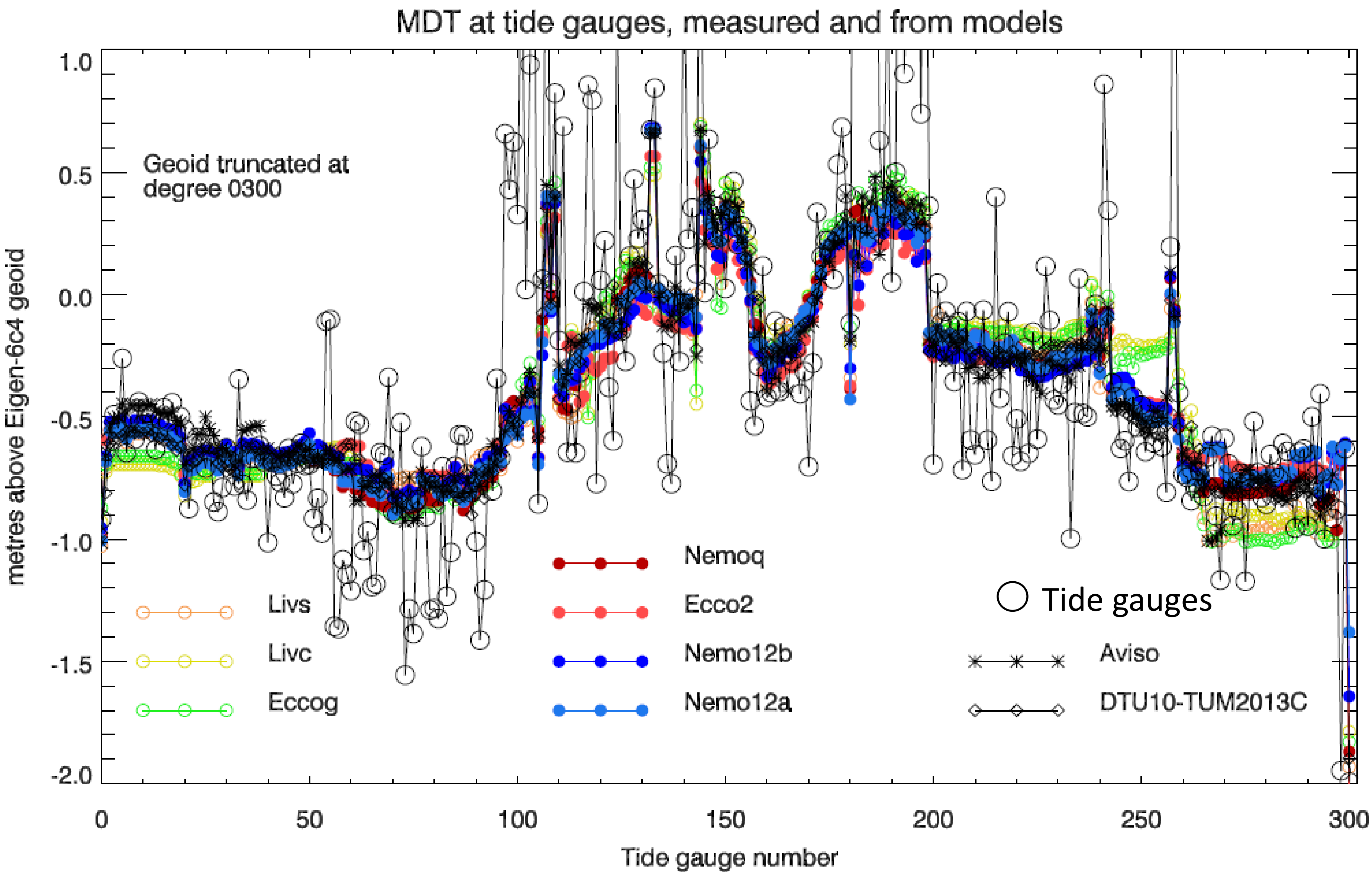
Down to 5-6 cm RMS error (combined error of tide gauges and models)

Preliminary results (work in progress)

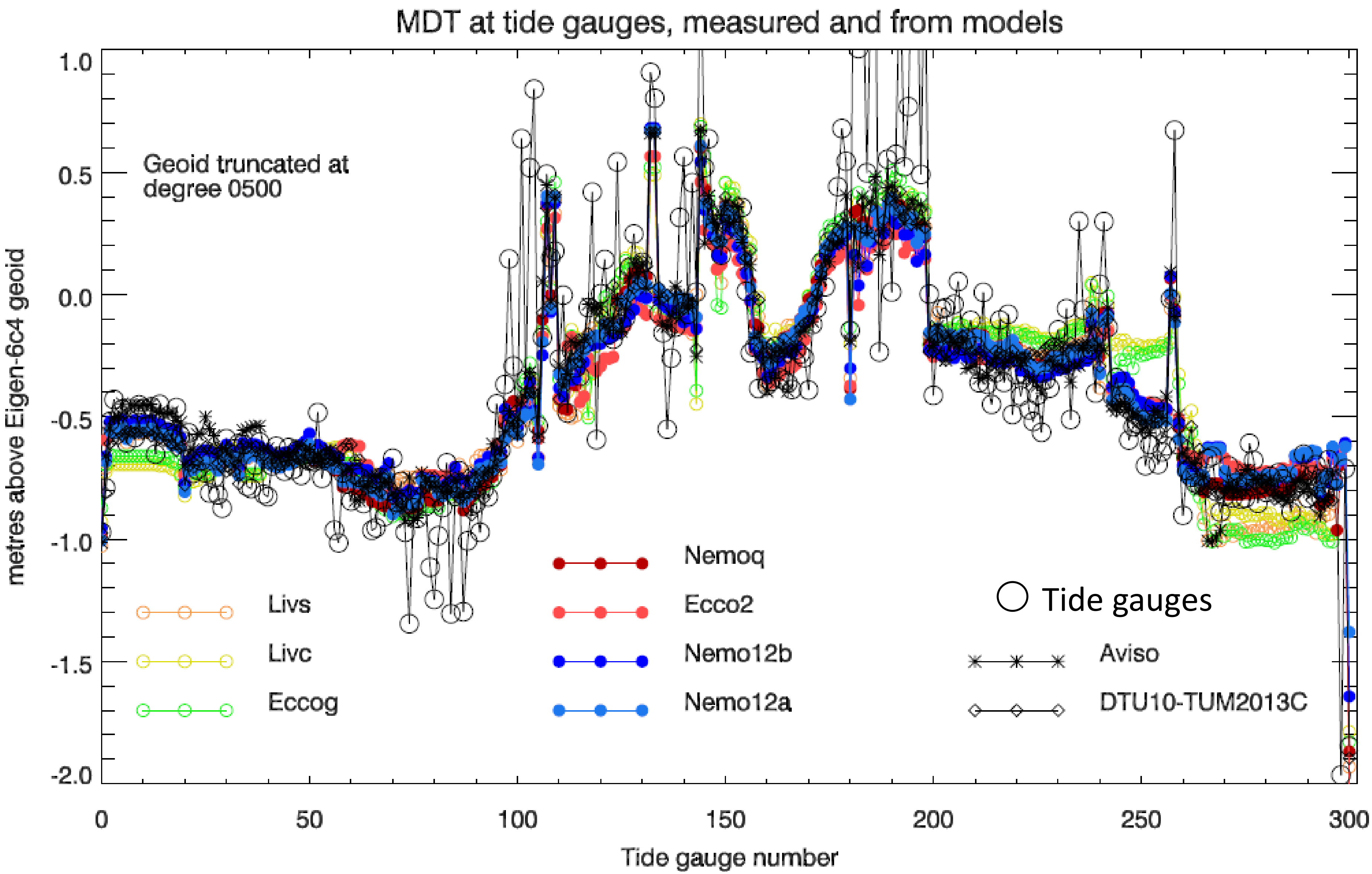
- From ESA-funded GOCE++ Dycot project
- With Philip Woodworth, Médéric Gravelle, Guy Wöppelmann, Rory Bingham, Mick Filmer,Will Featherstone and Luciana Fenoglio-Marc
- 300 tide gauges with GPS ties
- Using the Eigen6c4 geoid to degree 2192
- Satellite gravity information contributes to between degree 200 and 300, higher degrees rely on local gravity data
- Compared with a range of ocean models at the same points


MDT at tide gauges, measured and from models
Geoid truncated at degree 0100
metres above Eigen-6c4 geoid
Tide gauge number
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
0
50
100
150
200
250
300
Livs
Livc
Eccog
Nemoq
Ecco2
Nemo12b
Nemo12a
Tide gauges
Aviso
DTU10-TUM2013C

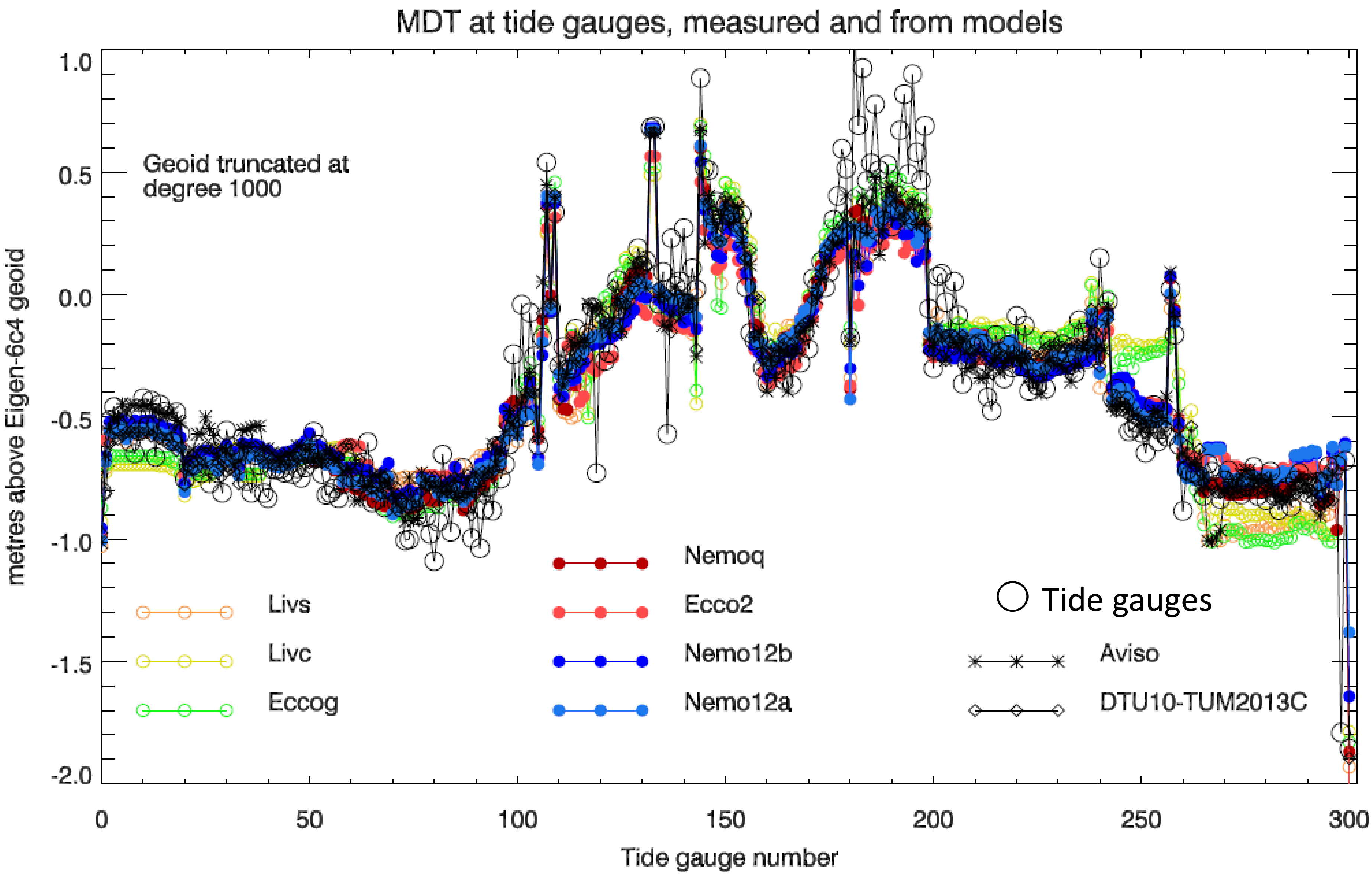

MDT at tide gauges, measured and from models
Geoid truncated at degree 0200
metres above Eigen-6c4 geoid
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
0
50
100
150
200
250
300
Tide gauge number
Livs
Livc
Eccog
Nemoq
Ecco2
Nemo12b
Nemo12a
Tide gauges
Aviso
DTU10-TUM2013C



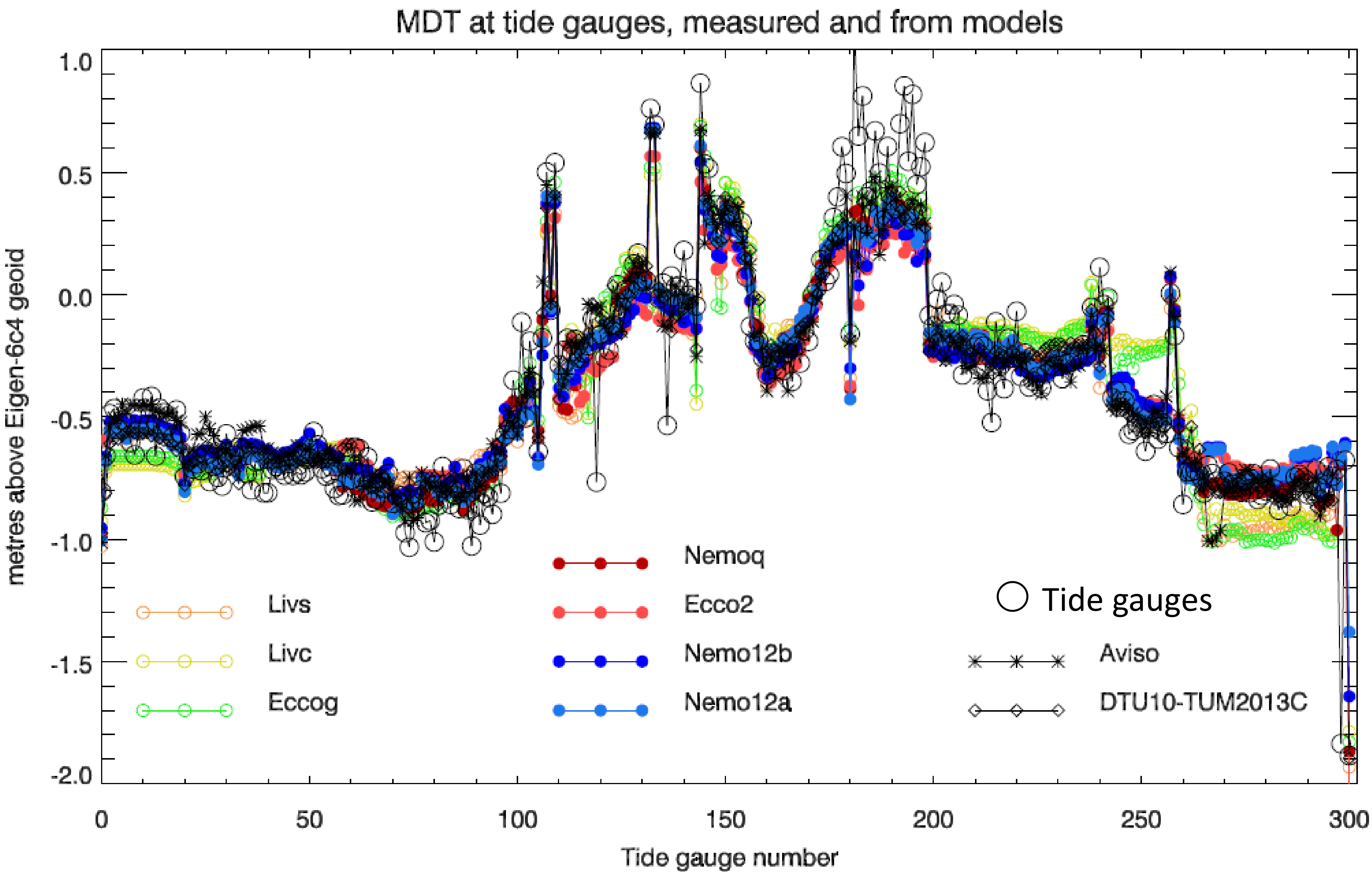
MDT at tide gauges, measured and from models
Geoid truncated at degree 0300
metres above Eigen-6c4 geoid
Tide gauge number
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
0
50
100
150
200
250
300
Livs
Livc
Eccog
Nemoq
Ecco2
Nemo12b
Nemo12a
Tide gauges
Aviso
DTU10-TUM2013C

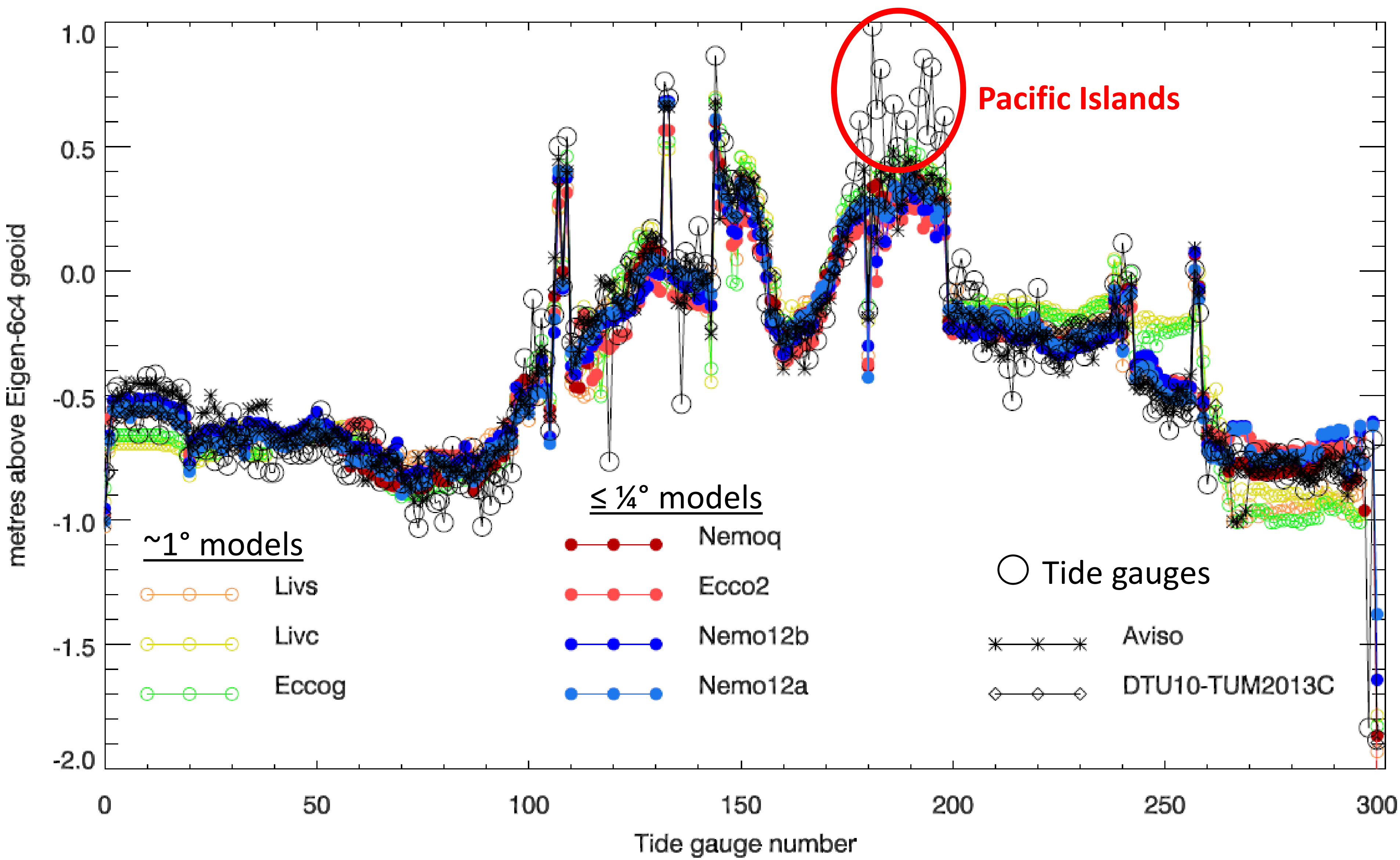


MDT at tide gauges, measured and from models
Geoid truncated at degree 0500
metres above Eigen-6c4 geoid
Tide gauge number
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
0
50
100
150
200
250
300
Livs
Livc
Eccog
Nemoq
Ecco2
Nemo12b
Nemo12a
Tide gauges
Aviso
DTU10-TUM2013C

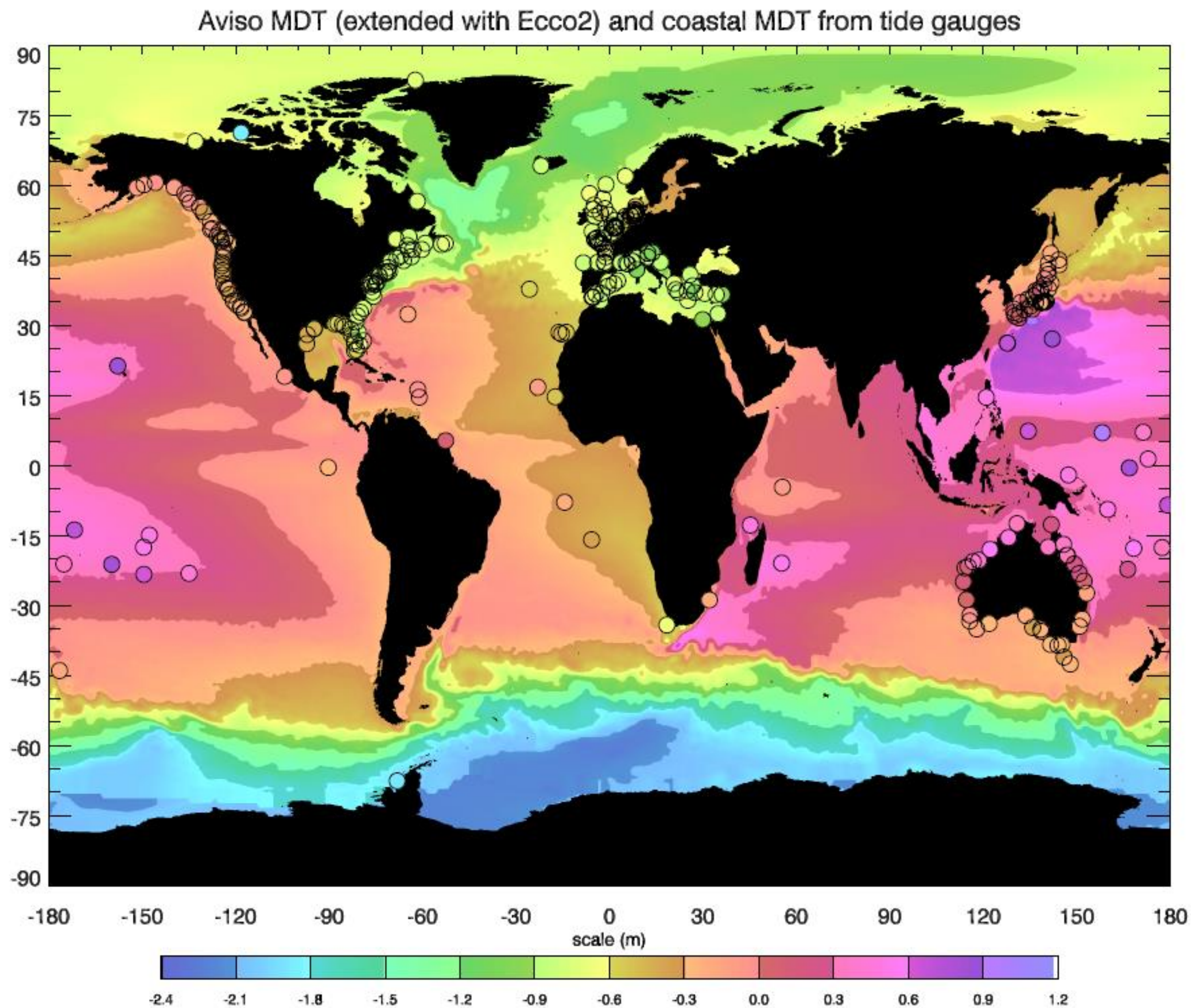


MDT at tide gauges, measured and from models
Geoid truncated at degree 1000
metres above Eigen-6c4 geoid
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
0
50
100
150
200
250
300
Tide gauge number
Livs
Livc
Eccog
Nemoq
Ecco2
Nemo12b
Nemo12a
Tide gauges
Aviso
DTU10-TUM2013C

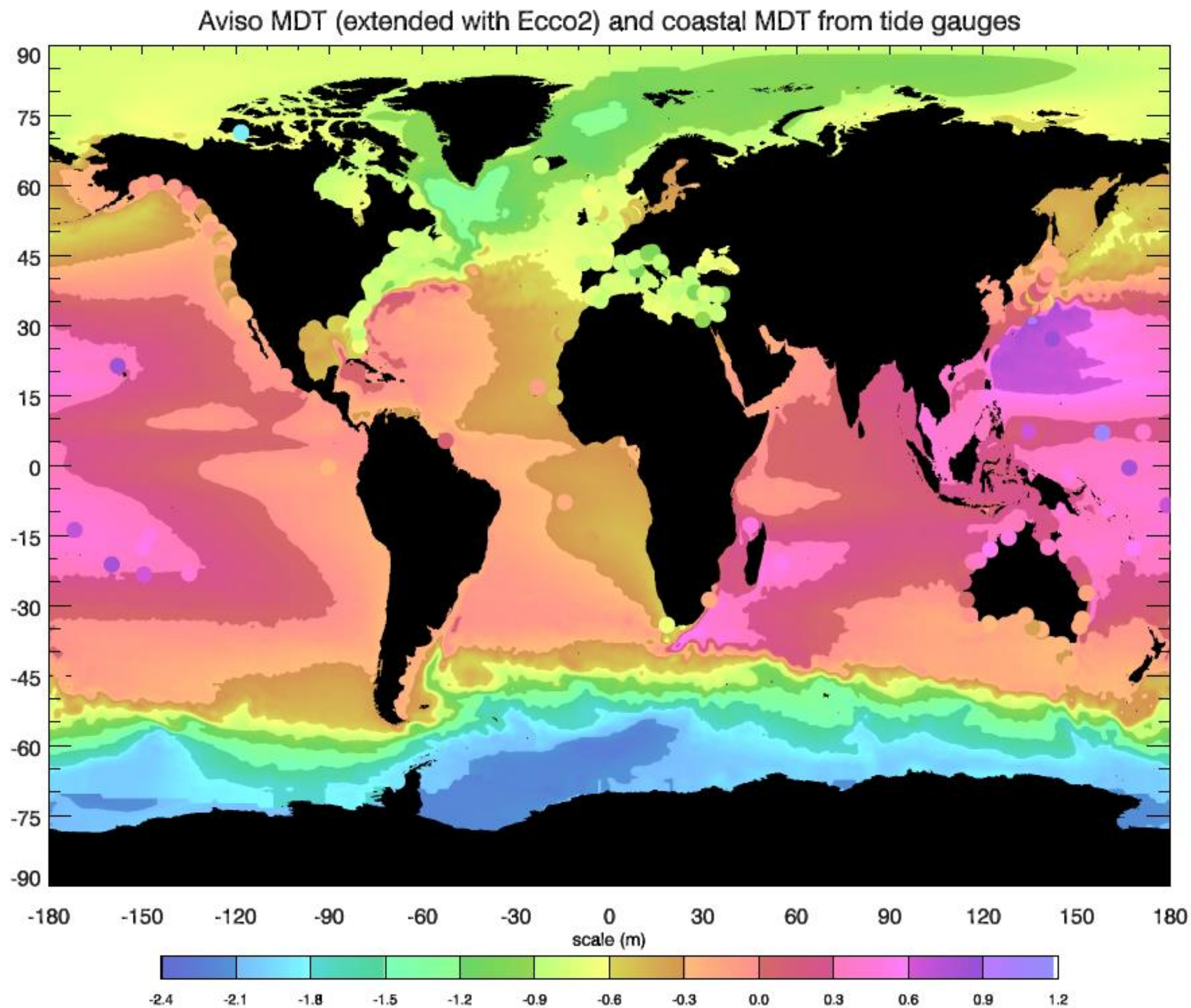

MDT at tide gauges, measured and from models
metres above Eigen-6c4 geoid
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
0
50
100
150
200
250
300
Tide gauge number
Livs
Livc
Eccog
Nemoq
Ecco2
Nemo12b
Nemo12a
Tide gauges
Aviso
DTU10-TUM2013C



Pacific Islands
metres above Eigen-6c4 geoid
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
0
50
100
150
200
250
300
Tide gauge number
~1° models
Livs
Livc
Eccog
≤ ¼° models
Nemoq
Ecco2
Nemo12b
Nemo12a
Tide gauges
Aviso
DTU10-TUM2013C



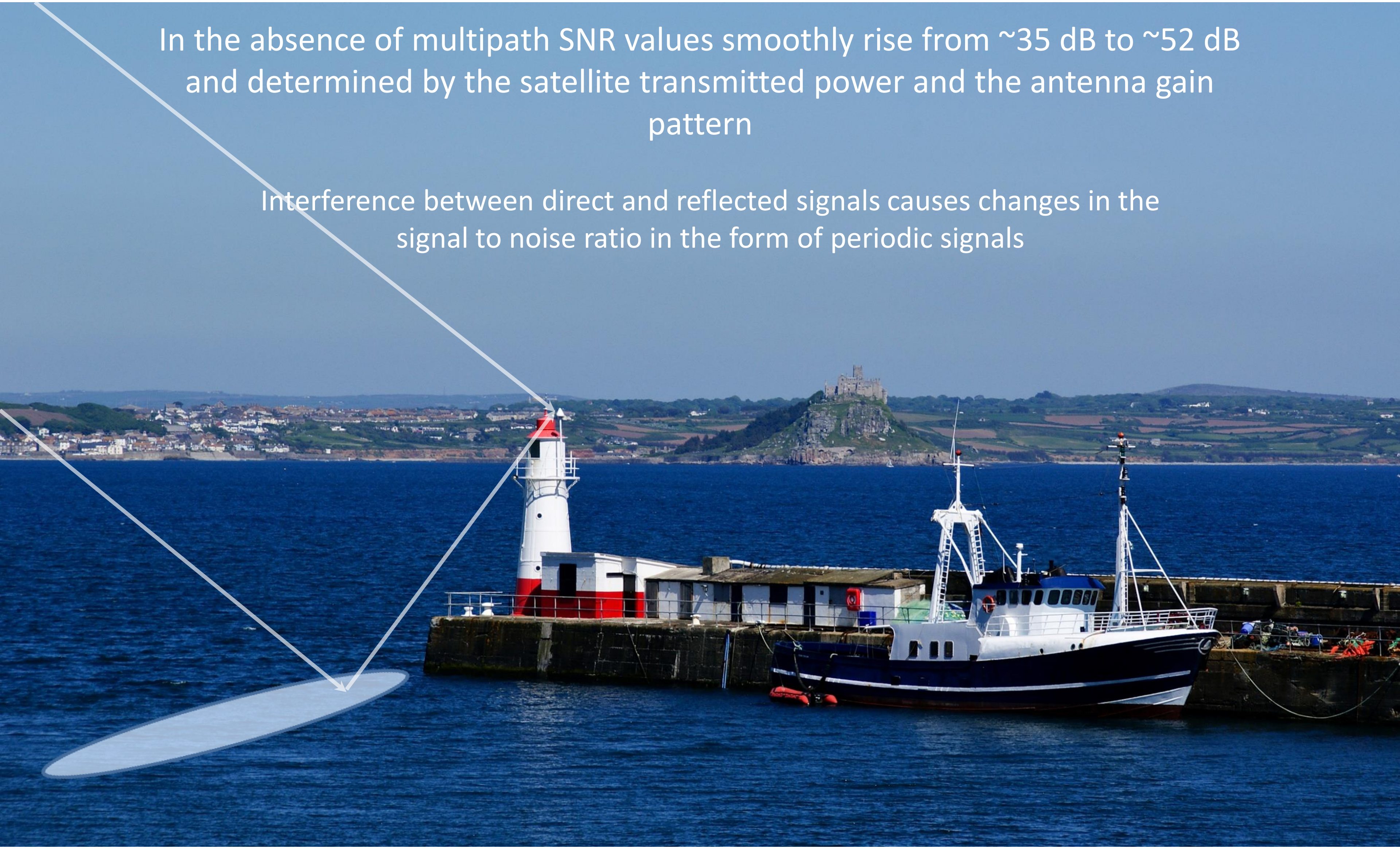
Aviso MDT (extended with Ecco2) and coastal MDT from tide gauges
90
75
60
45
30
15
0
-15
-30
-45
-60
-75
-90
-180
-150
-120
-90
-60
-30
0
30
60
90
120
150
180
scale (m)
-2.4
-2.1
-1.8
-1.5
-1.2
-0.9
-0.6
-0.3
0.0
0.3
0.6
0.9
1.2


Aviso MDT (extended with Ecco2) and coastal MDT from tide gauges
90
75
60
45
30
15
0
-15
-30
-45
-60
-75
-90
-180 -150 -120 -90 -60 -30 0 30 60 90 120 150 180
scale (m)
-2.4 -2.1 -1.8 -1.5 -1.2 -0.9 -0.6 -0.3 0.0 0.3 0.6 0.9 1.2

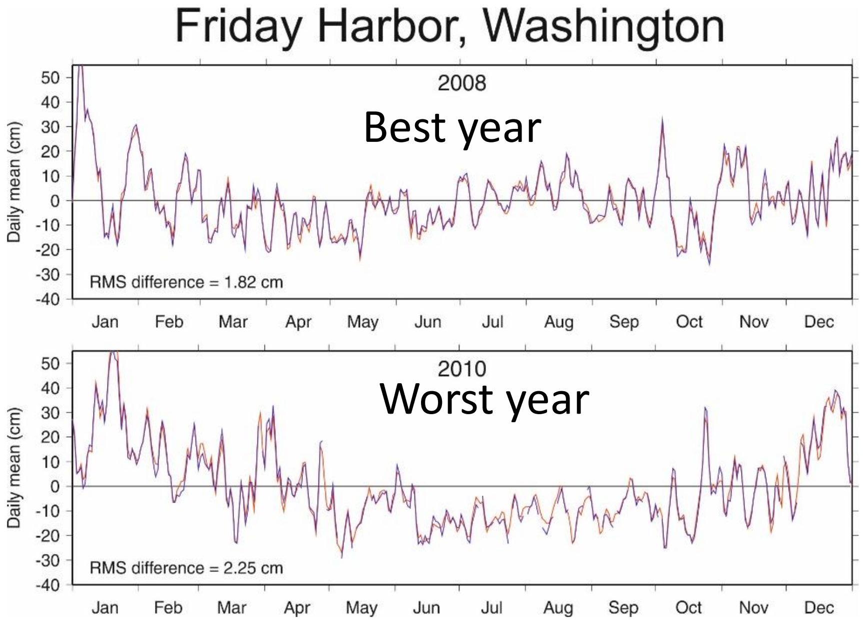
GNSS Multipath Reflectometry

In the absence of multipath SNR values smoothly rise from ~35 dB to ~52 dB and determined by the satellite transmitted power and the antenna gain pattern

Interference between direct and reflected signals causes changes in the signal to noise ratio in the form of periodic signals



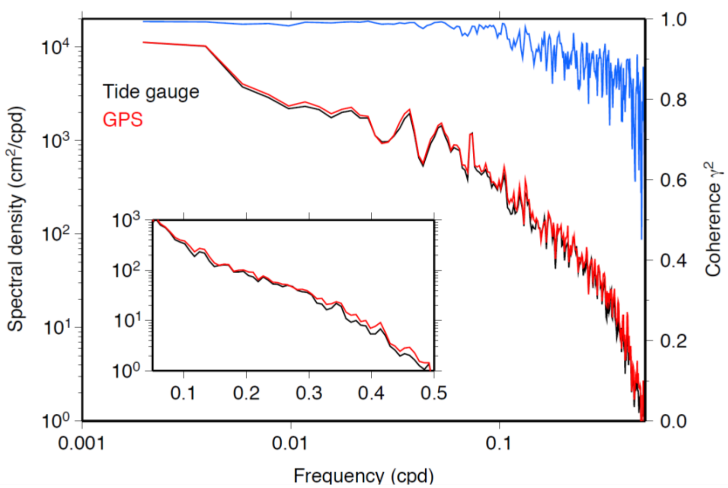
Papers by Kristine Larson, Richard Ray, Simon Williams



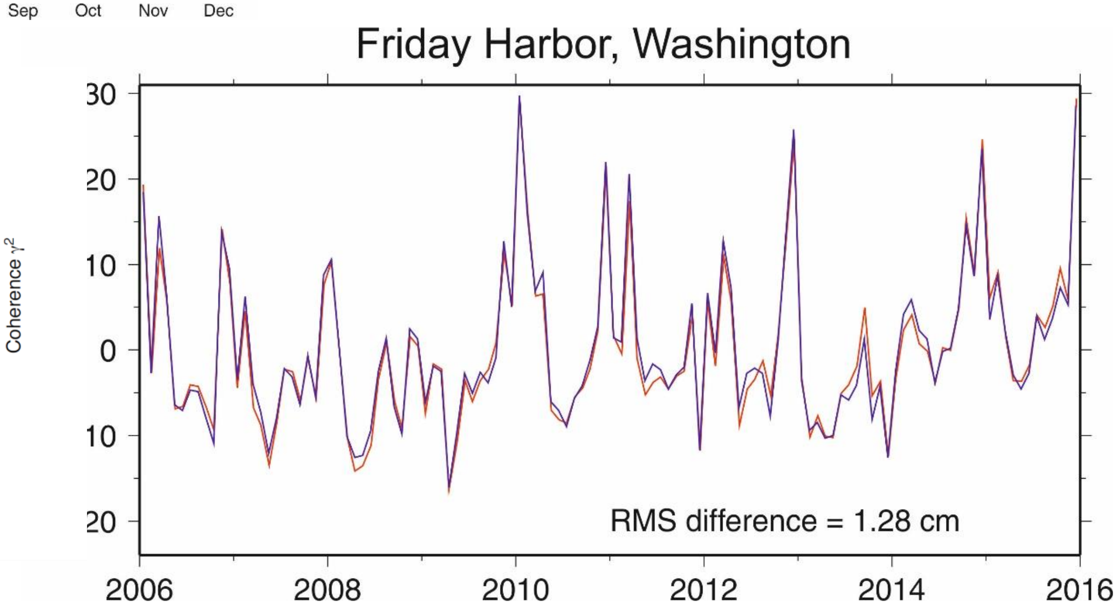
Comparing tide gauge and GPS reflectometry

Daily means

RMS difference about 2 cm



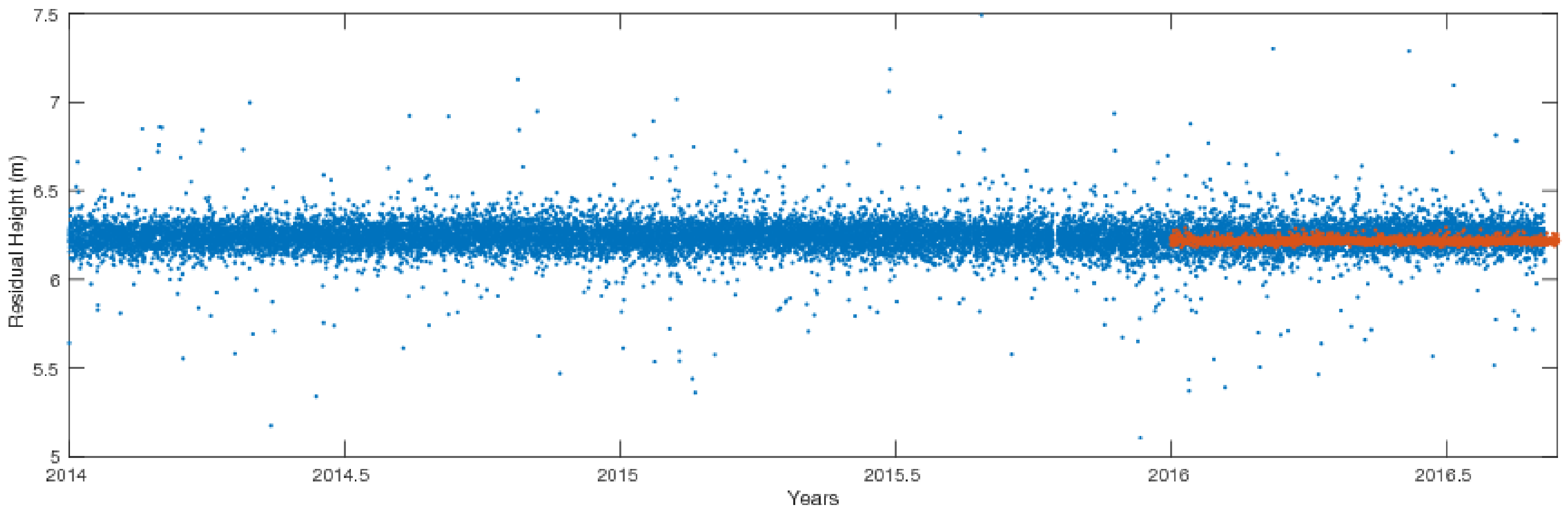
Spectrum shows very small low frequency errors



10 years of **monthly means**
RMS difference close to 1 cm

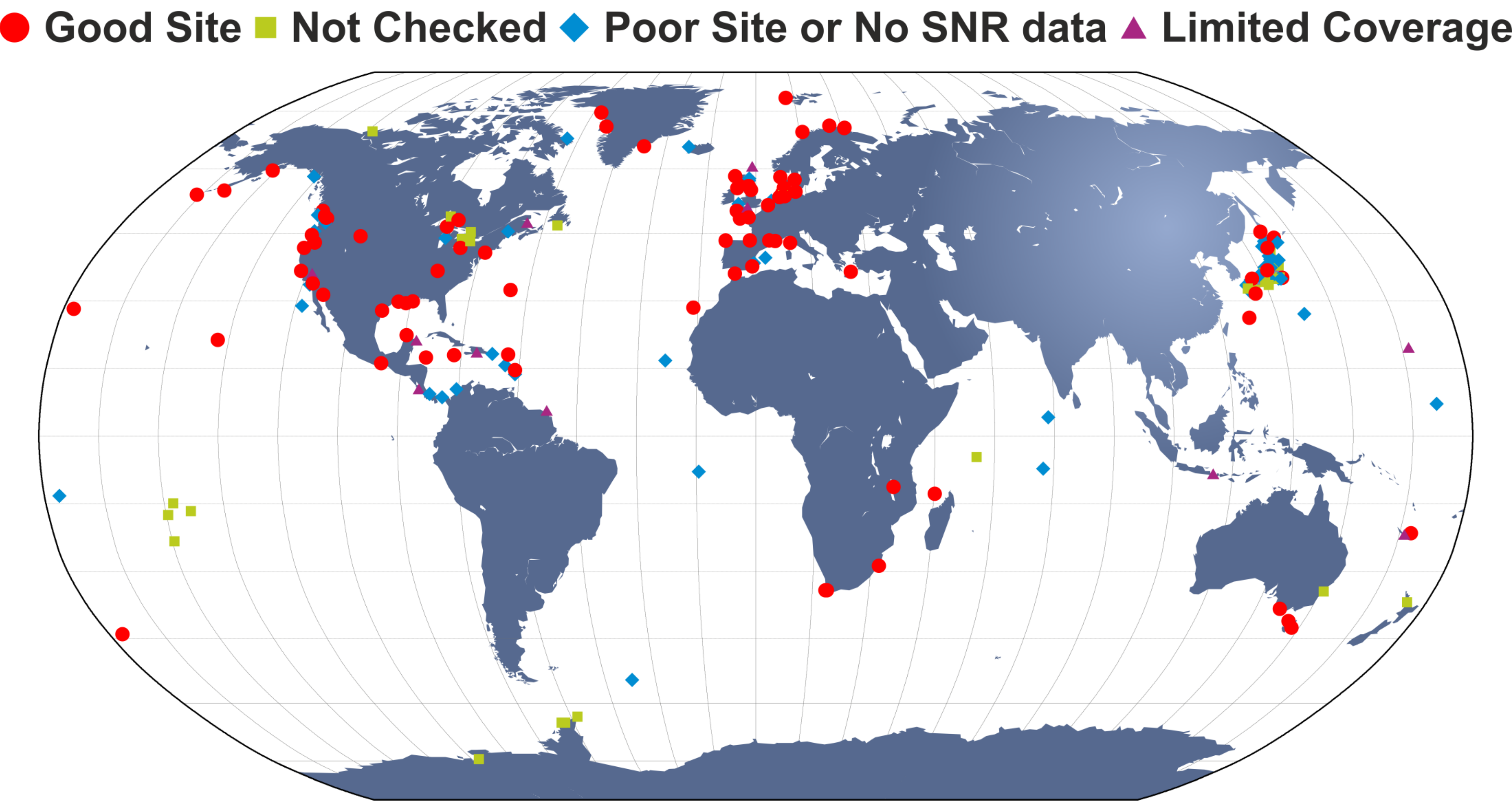
CACC
Crescent City, California
Testing new methods
(L5 signal)

Residual (= L1 error on estimation of tide gauge height from each satellite pass). RMS = 8.6 cm per point (1.6 cm for daily means if 30 independent values per day)



New residual, using L5 instead of L1 and L2
RMS = 1.5 cm
-> 2.7 mm for daily values?

Current known GNSS water level sites

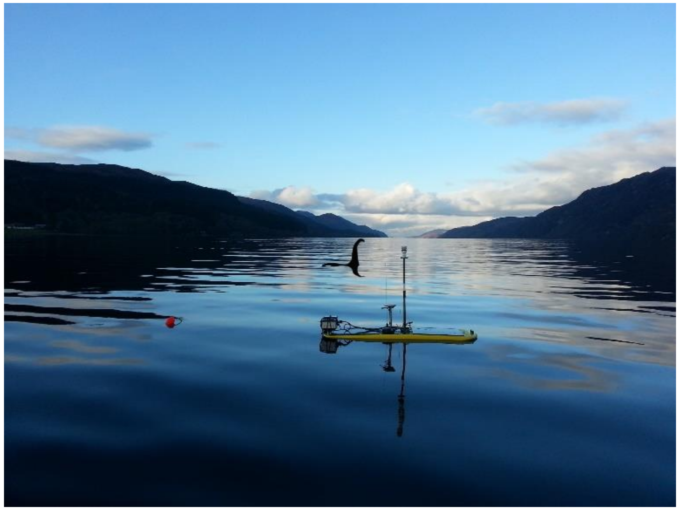


~80 good sites identified so far (only a few processed)

Some are important additions to the GPS@TG dataset (e.g. Greenland, Svalbard, Norway), others provide an independent check of methodology

What else

- Centimetric point geopotentials will help greatly with looking at coastal MDT at tide gauges.
- Could we make the same measurements at sea? Then we could directly measure geostrophic currents across ocean sections



Water Surface Height Determination with a GPS Wave Glider: A Demonstration in Loch Ness, Scotland

M. A. Morales Maqueda

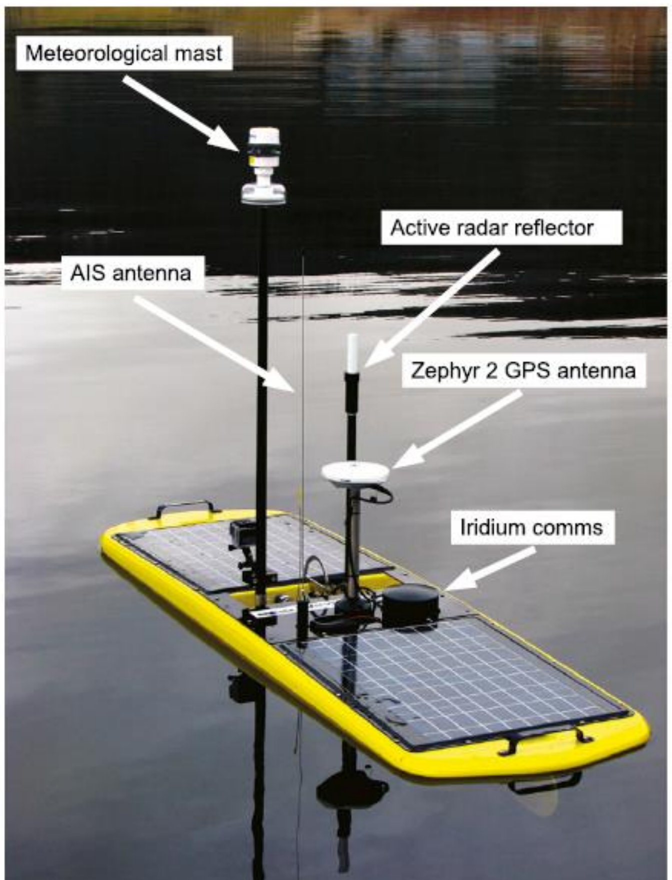
School of Marine Science and Technology, Newcastle University, Newcastle upon Tyne, United Kingdom

N. T. Penna

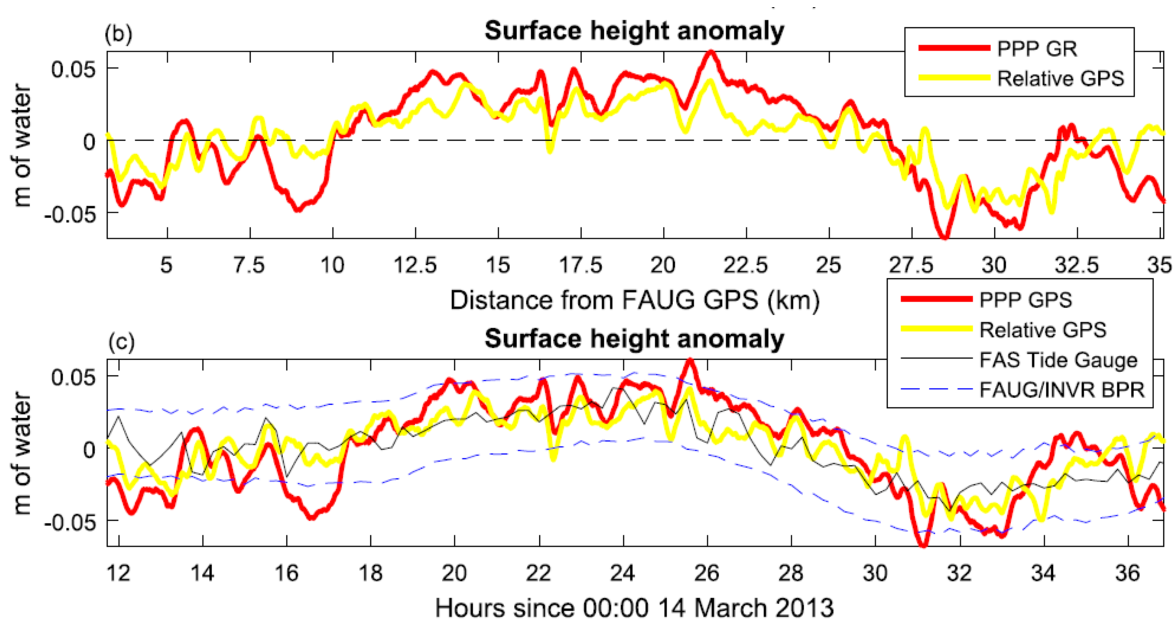
School of Civil Engineering and Geosciences, Newcastle University, Newcastle upon Tyne, United Kingdom

S. D. P. Williams and P. R. Foden

National Oceanography Centre, Natural Environment Research Council, Liverpool, United Kingdom



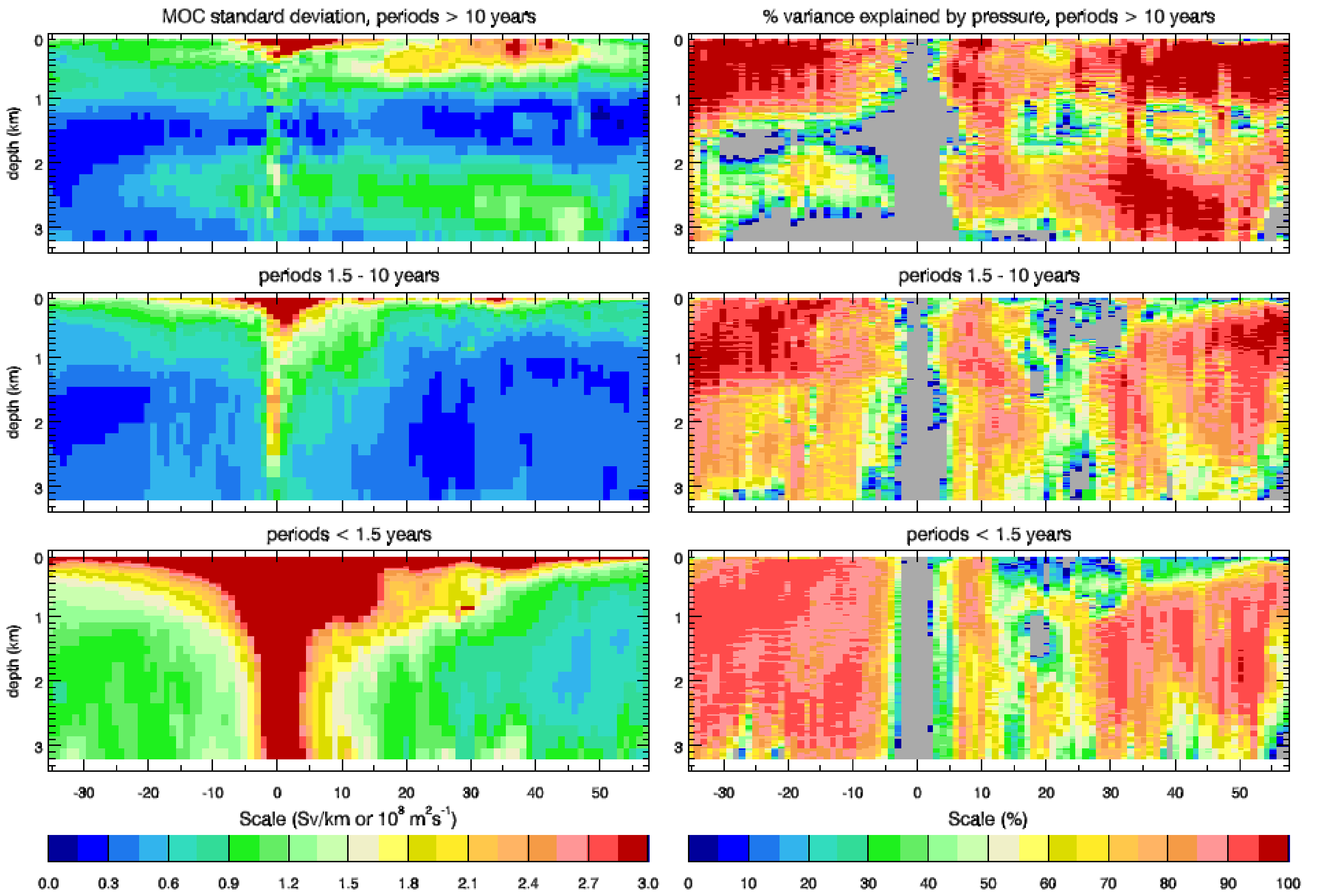
JAOT 2016: Waveglider tested in Loch Ness: ~2cm

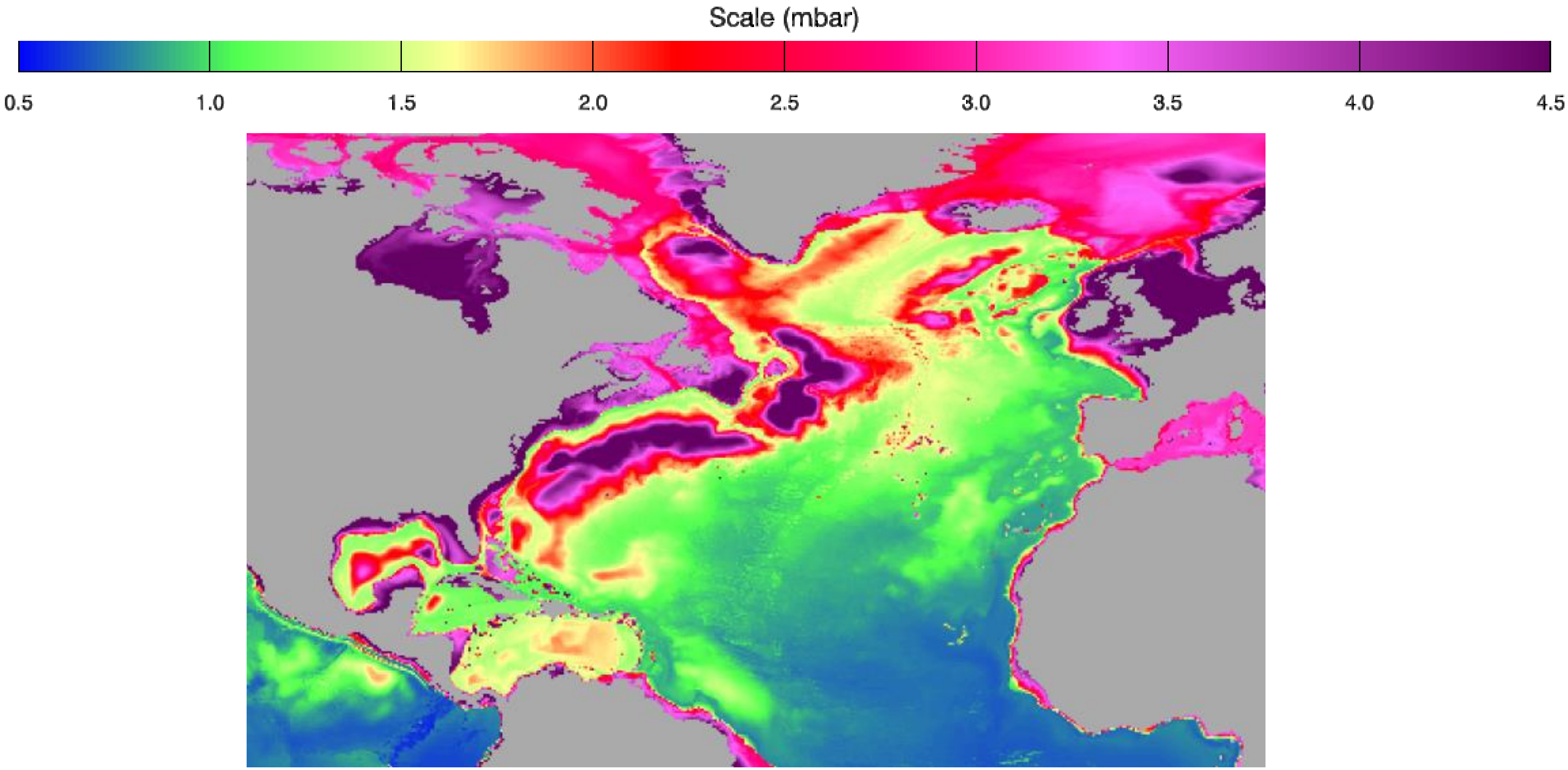


What else

- What about below the surface? A tough, long-term challenge, but centimetric geopotential + centimetric pressure would be extremely valuable.
- Millions are being spent to monitor the Meridional Overturning Circulation, via various indirect methods of inferring pressures on the continental slope

NEMO12 high resolution ocean model, 50 years of simulation: Atlantic MOC





Can’t yet (ever?) be done by satellite – we need to measure the small pressure variations in the thin strip of continental slope, which is surrounded by large variability to either side.

Summary

- We are currently at about 5 to 20 cm accuracy for MDT at tide gauges, centimetric geopotential at points would quickly improve this significantly.
- Pretty much all of large-scale physical oceanography can be thought of as simultaneous determination of pressure and geopotential, with cm accuracy the level that is needed.
- The technology for tide gauges is almost within reach. Other applications are increasingly ambitions, but not impossible in principle.