

Unconstrained global simulations of ocean tides up to degree 3 for satellite gravimetry

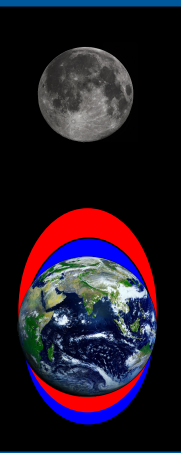
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Supplementary Material vEGU2021





Degree-3 tides

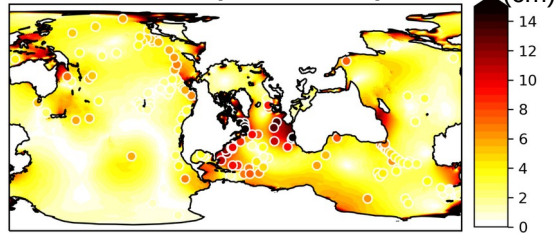
The tidal potential is not **symmetric** but exhibits pronounced **asymmetry** described in first order by degree-3 terms of spherical harmonic decomposition.
(3M00, M1, 3M02, 3MK2, M3)

Barotropic Tidal Modeling

Purely hydrodynamic tidal model TiME is upgraded and optimized for M2 partial tide.

$$\overline{rms} = 3.39 \text{ cm}$$

M2 RMS (TiME-FES14)



global simulation of degree-3 Tides

Validation:

(A) Tide gauge stations (TG) by M. Hart-Davis @ DGFI

$$RMS_{\zeta} = \sqrt{(\zeta_{obs}(t) - \zeta_{mod}(t))^2}$$

(B) Supraconducting Gravimeter constituents (SG) by H. Wziontek @ BKG

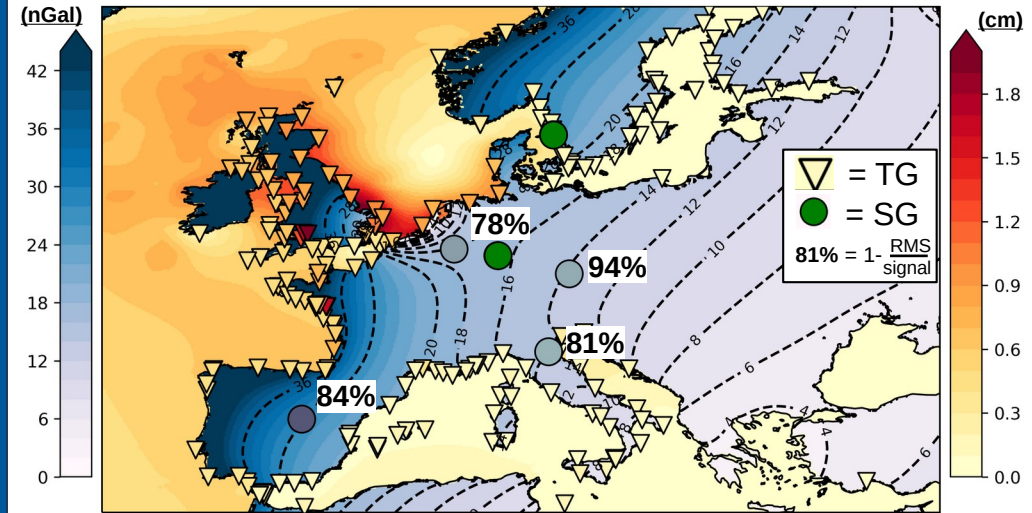
$$RMS_g = \sqrt{(g_{obs}(t) - g_{mod}(t))^2}$$



(OSG-030, Wettzell, Germany)

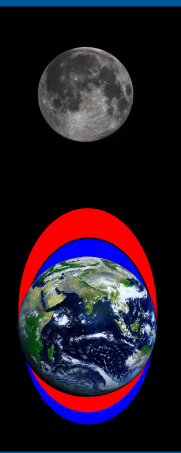


M1 ocean tide and gravity tide amplitude in Europe



Results:

- (A) Tidal solutions **match empirical estimates** (Ray,2020)
- (B) **50-60% of the TG-signal** is predicted by simulations
- (C) Degree-3 Load-tide signal at SG-stations can be precisely modeled at **levels over 80%**
- (D) Ensemble of Degree-3 tides can induce **relevant aliased signal** into GRACE-FO solutions



Degree-3 tides
 The tidal potential is not **symmetric** but exhibits pronounced **asymmetry** described in first order by degree-3 terms of spherical harmonic decomposition.
 (3M00, M1, 3M02, 3MK2, M3)

global simulation of degree-3 Tides

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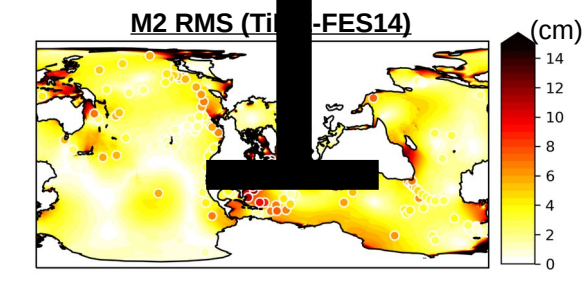
$$RMS_g = \sqrt{(g_{obs}(t) - g_{mod}(t))^2}$$



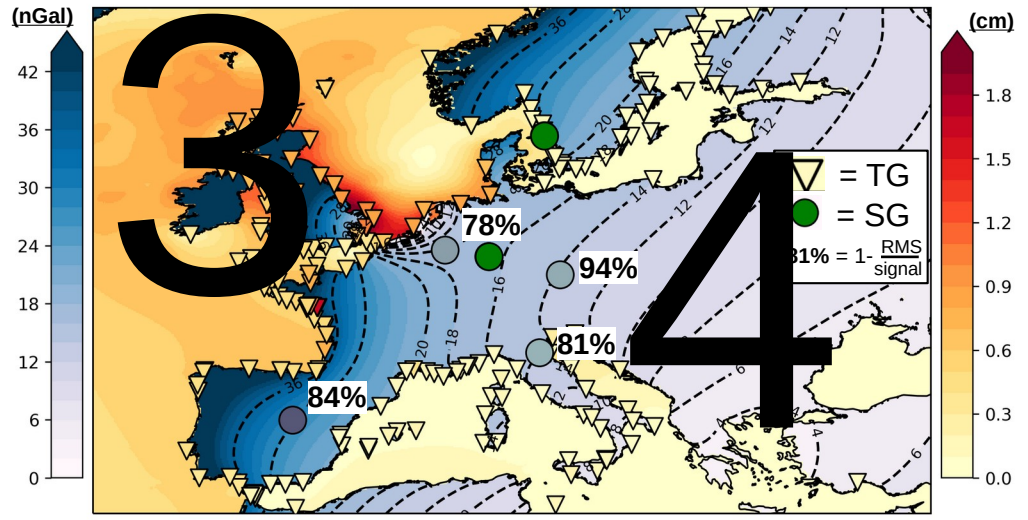
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Barotropic Tidal Modeling
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Display Layout

Goal: Use a barotropic, purely-hydrodynamic tidal model to accurately simulate minor tidal excitations (including degree-3 contributions) that can be employed for gravimetric purposes (de-aliasing)

1) Improved Barotropic Tidal Modeling

- Model Development (M2)
 - Performance for minor tides
- What are the characteristics of the employed model?
 - How does it perform for major tides?
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2) Third Degree Tide-Raising Potential

- What are the characteristics of the degree-3 tide-raising forces?

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4) Global Degree-3 gravity tide solutions

- How can we derive global gravity tide solutions ?

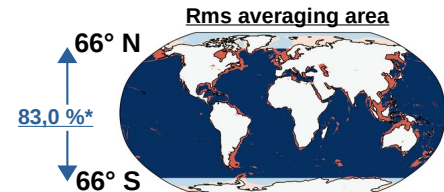
Model Development (M2 tide)

TiME (Weis, 2008)

- Barotropic tidal model
- Resolution: 1/12°
- Temporal finite differences
- Two-fold resolution reduction towards North Pole
- Gebco-Bathymetry
- Polar cap to avoid singularity
- Mainly shallow-water dissipation
- Local SAL-Parametrization

upgrades:

- + Updated bathymetric map (Schaffer, 2016)
- + Pole rotation scheme (Gooding, 2010)
- + Topographic Wavedrag (Nycander, 2005)
- + Non-local SAL-handling (Schindelegger, 2018)



* % of total ocean surface

$$RMS_{\zeta} = \sqrt{(\zeta_{obs}(t) - \zeta_{mod}(t))^2}$$

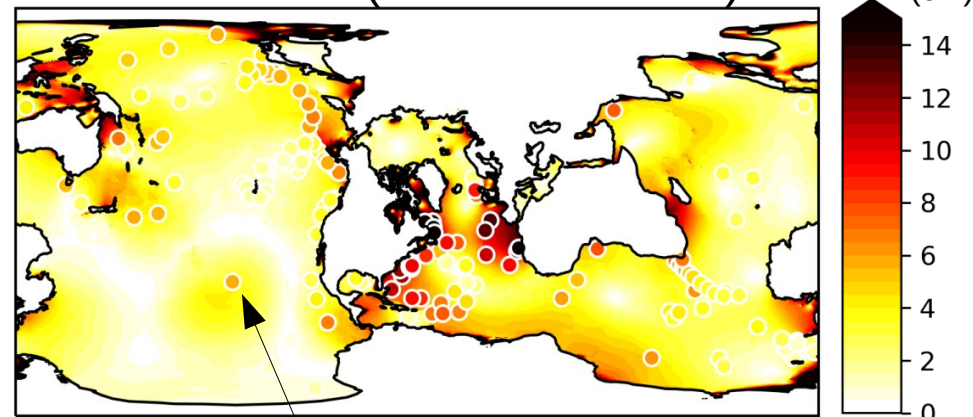
M2 rms = 3.39 cm (TiME21)

Model characteristics:

- 910 GW wave drag (deep ocean) dissipation
- Accuracy on comparable level as modern data-unconstrained models

Results are displayed on rotated num. grid

RMS (TiME21-FES14*)



Tide gauge stations (Ray, 2013) mean rms = **4.83 cm**

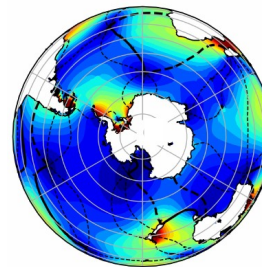
*FES2014: (Lyard, 2014, updated)

Model Development (M2 tide) - Retrospect

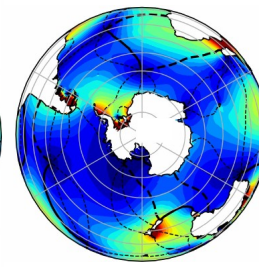
New setting	Previous setting	RMS-improvement / other benefit
rtopo2-bathymetry	gebco2014-bathymetry	-3.10 cm
no wave drag dissipation	Nycander-wavedrag	-4.64 cm
Local SAL-handling	Spectral treatment to $l=1024$	-2.03 cm
Pole-rotation scheme	Arctic Pole cap	No Arctic numerical artifacts

All upgrades were crucial to produce results at maximum possible accuracy

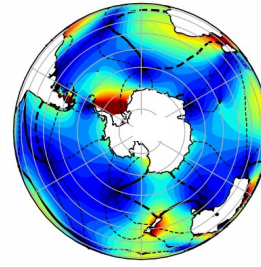
rtopo2 (TiME21)



FES14

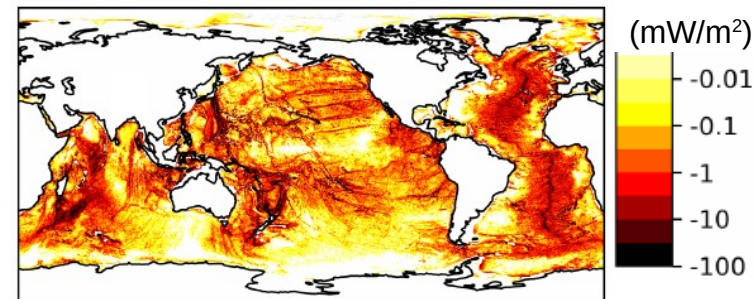


gebco2014 (TiME21)



→ RMS-increase as result of Antarctic shelf-blocking

Energy dissipation by wave drag = 910 GW



→ dissipation concentrated at bathymetric features

Publication: Sulzbach et. al., JGR : Oceans, under revision

Performance for additional partial tides

- Export model setting derived for M2 tide experiments to additional partial tides
- Compare results in terms of admittance Z (normalized ocean response)
 - **Relative accuracy only decreases moderately for simulated minor tides**

RMS(cm)*	K2	nue2	K1	Q1
FES14	0.15	0.09	0.23	0.14
TiME21	0.43	0.18	1.32	0.25

* at open ocean tide gauges compiled by (Ray, 2013)

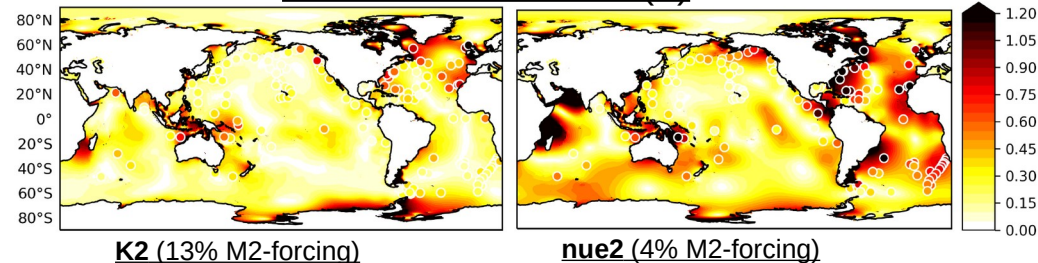
- “Accuracy gap” to FES14 decreases for tides with smaller excitation amplitudes (minor tides)
 - **Q: Can there be situations, where TiME can perform more accurate than data-constrained models?**

Admittance function/
normalized response:

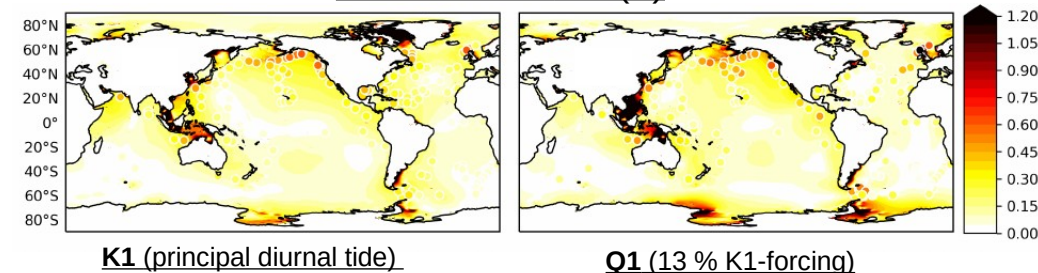
$$Z_{lm}(\phi, \lambda, \omega_n) = \frac{\zeta_{lm}^n(\phi, \lambda)}{A_{lm}^n} g_0$$

ocean tide ←
excitation amplitude ←

Semidiurnal tides rms(Z)

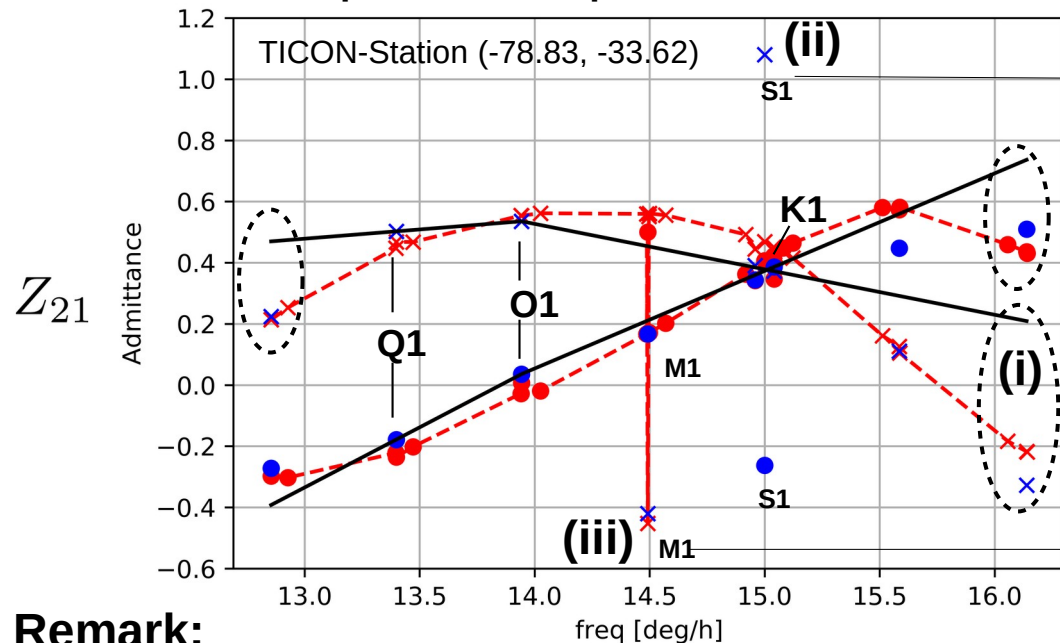


Diurnal tides rms(Z)



Performance for minor tides

- **A:** Some minor tides are hard to determine by satellite data and are derived with linear admittance. As those are prone to extrapolation errors, consider the diurnal admittance function (def. previous slide):



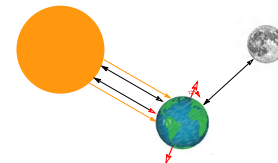
► **radiational excitation**

TICON* tide-gauge-Data (9 partial tides)

TICON linear admittance supported by (Q1,O1,K1)

TiME computation (27 partial tides)

► **Degree-3 tide**



Periodic, differential solar heating causes tidal excitation

X: in-phase-admittance
O: quadrature-admittance

*TICON: (Piccioni, 2019)
augmented by M. Hart-Davis
@DGFI/TUM

Remark:

Linear admittance predictions (**black line**) fail to reliably predict (i) minor tides at the edges of the diurnal band (ii) radiationally contaminated tides (iii) degree-3 tides. Here, unconstrained **TiME-estimates** can correspond to **tide-gauge data** more closely.

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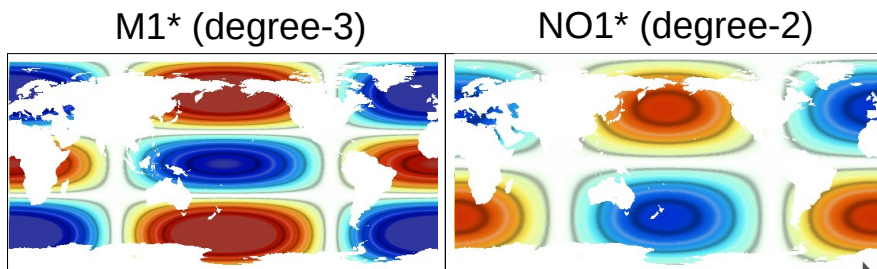
Tide Raising Potential of Degree-3

- **Origin:** The Lunar tidal potential is not symmetric but stronger on the moon-facing side (~ factor 1/60)
 → Corrections to degree-2 potential are described by $l \geq 3$ spherical harmonics (Hartmann and Wenzel, 1995)
- **Problem:** While excitation frequencies are similar (example: table), the excitation patterns differ strongly
 → Tidal response patterns are different and can not be derived by linear admittance assumptions that rely on their similarity (to degree-2 tides)

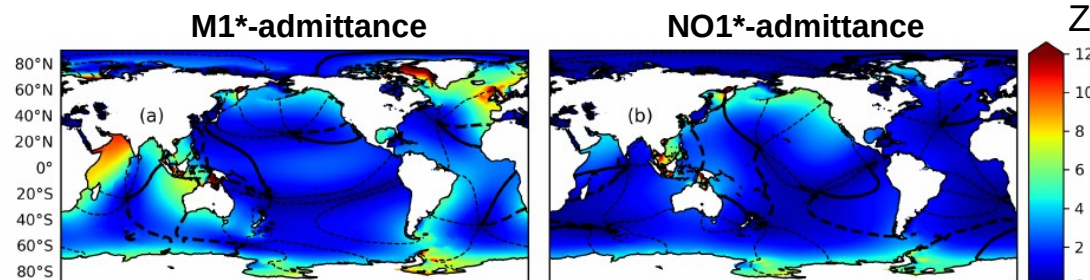
$$V_{tid}(\phi, \lambda, t) = \sum_{l=2} \sum_{m=0}^l \bar{Y}_{lm}(\phi, \lambda) \sum_n A_{lm}^n e^{i\omega_n t}$$

Doodson	$f \left[\frac{deg}{h} \right]$	l	m	amp $\left[\frac{mm^2}{s^2} \right]$	name
155.455	14.48741	2	1	1.448964e+04	LK1
155.555	14.49205	3	1	7.832888e+03	M1
155.655	14.49669	2	1	4.028717e+04	NO1

Degree-3 tides have to be simulated explicitly!



Excitation-pattern



Ocean response pattern

* naming after HW95-catalogue, M1 and NO1 are part of the M1-wavegroup (e.g. Ray,2020, where notation differs)

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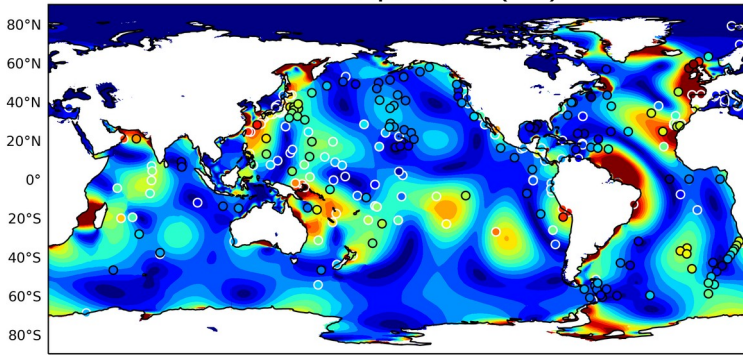
Validation of Degree-3 Tides

- Export the derived M2 model parameters for global degree-3 simulations
- Open ocean subset of TICON² (134 stations):
→ Validate degree-3 tides and compare to mean tidal signal at tide gauge-stations (TGs)

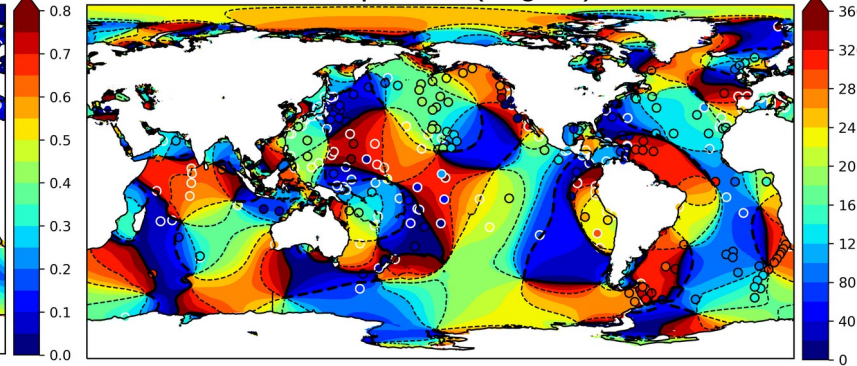
tide	M1 ²	3MK2 ²	3MO2 ²	M3 ²	M3 ¹	RSS ²
RMS (cm)	0.10	0.09	0.09	0.13	0.09	0.21
signal (cm)	0.15	0.20	0.26	0.29	0.23	0.46
RMS/signal	66%	45%	35%	45%	39%	46%

→ A high fraction of the ~0.5cm-signal is depicted (FES14 M2-accuracy:~0.3cm)

M3-amplitudes (cm)



M3-phases (degree)



¹ 151 TGs (Ray,2013) ●

² 134 TGs provided by M. Hart-Davis @DGFI ○

Degree-3 signal has the same magnitude as M2 residuals.

Compare empirical results of Ray (2020)

Gravity Tide Modeling and Analysis

- Tidal elevations and information about the solid earth structure encoded in load Love numbers (LLNs, here: Wang (2012) - PREM) can be used to estimate global gravity solutions at sea level (Merriam, 1980)

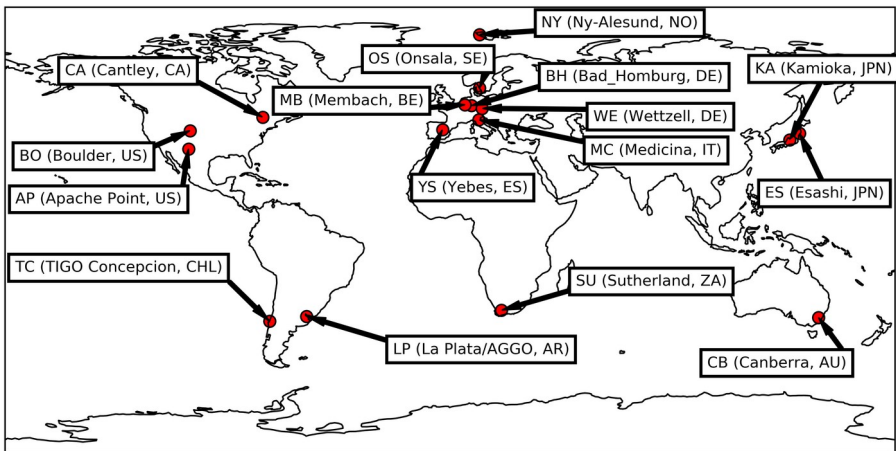
$$\delta g_L^n(\phi, \lambda) = g_0 \frac{3\rho_{sw}}{2a\rho_{se}} \left(\zeta^\omega(\phi, \lambda) + \sum_{l, |m| \leq l}^{l_{max}} \frac{4h_l - 2k_l(l+1) - 1}{2l+1} \zeta_{lm}^\omega Y_{lm}(\phi, \lambda) \right)$$

Seawater mean density $\rightarrow 3\rho_{sw}$
 Surface gravity $\rightarrow \delta g_L^n(\phi, \lambda)$
 Gravity tide $\rightarrow \delta g_L^n(\phi, \lambda)$
 Solid earth mean density $\rightarrow 2a\rho_{se}$
 Load Love numbers $\rightarrow 4h_l - 2k_l(l+1) - 1$
 Sea surface elevation $\rightarrow \zeta^\omega(\phi, \lambda)$
 Spherical harmonic functions $\rightarrow Y_{lm}(\phi, \lambda)$
 Spherical harmonic coefficient of sea surface elevation $\rightarrow \zeta_{lm}^\omega$
 The sum is truncated at $l=2048$

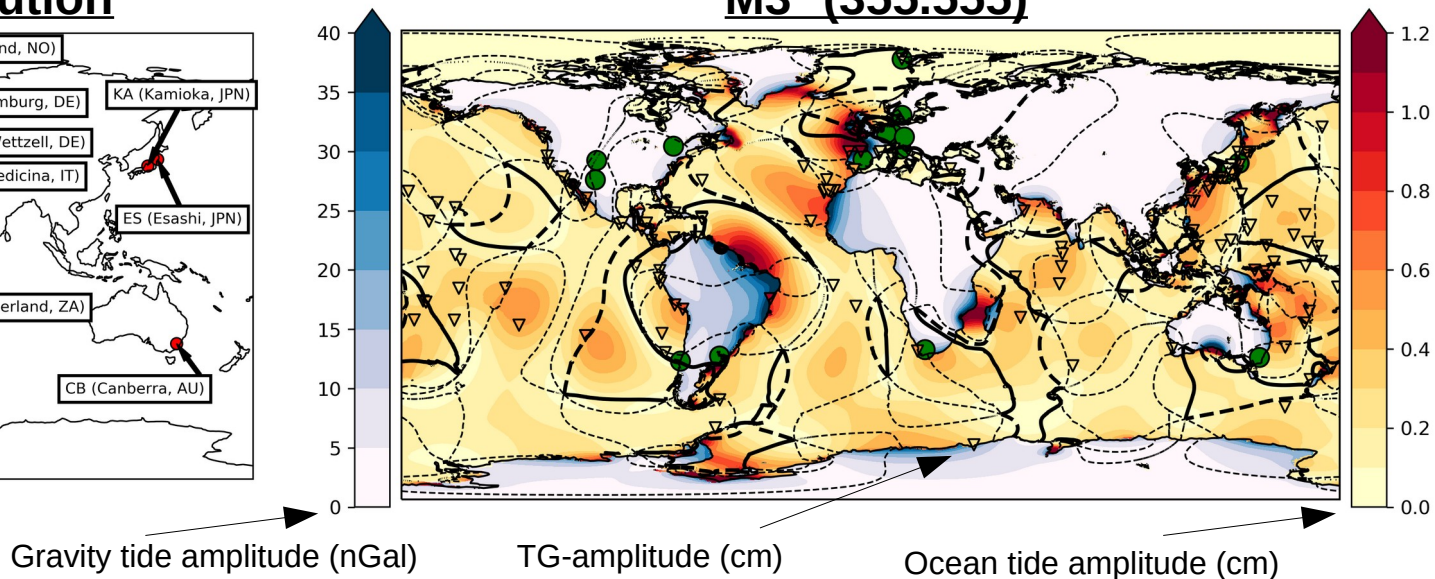
- As superconducting gravimeters (SGs) are often placed near coasts at finite height we use the loading program nloadf (Agnew, (2012): SPOTL) to derive local modeled gravimetric constituents
- Analysis of gravity time series is performed with Eterna-x V81 (author: Klaus Schüller *) which allows hypothesis-free modeling of tidal wave groups belonging to potential functions of different degrees (work in progress, Hartmut Wziontek @ BKG)
- The analysis is based on long records provided by IGETS **), Level 3, or station operators. We acknowledge the processed times series contributed by M. Van Camp (MB), E. Antokoletz (LP), O.C.D. Omang (NY), H.-G. Scherneck (OS) and C. Voigt (SU)

*) <http://ggp.bkg.bund.de/eterna/> **) <http://igets.u-strasbg.fr/>

Gravimeter-Distribution



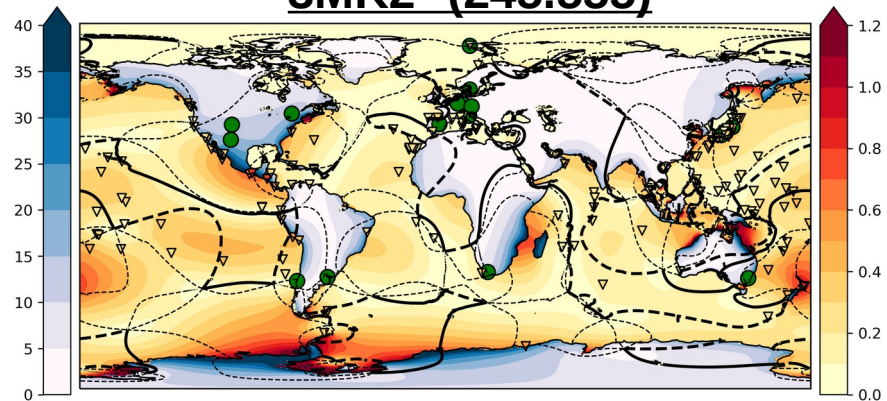
HW95 trivial name $\rightarrow$ **M3* (355.555)** $\leftarrow$ Doodson-Coefficient



- On the following pages global solutions for ocean and gravity tides are presented
- Phase information is overlain in 60 ° increments (**Fat** = 0°; [**Fat**, dashed] = 60°)
- Please note that phases can be unsteady at coasts (ocean tide vs. gravity tide)
- Amplitude at TG- and position of SG-station is shown $\rightarrow$ **preliminary** SG-amplitudes last slide

* naming after HW95-catalogue

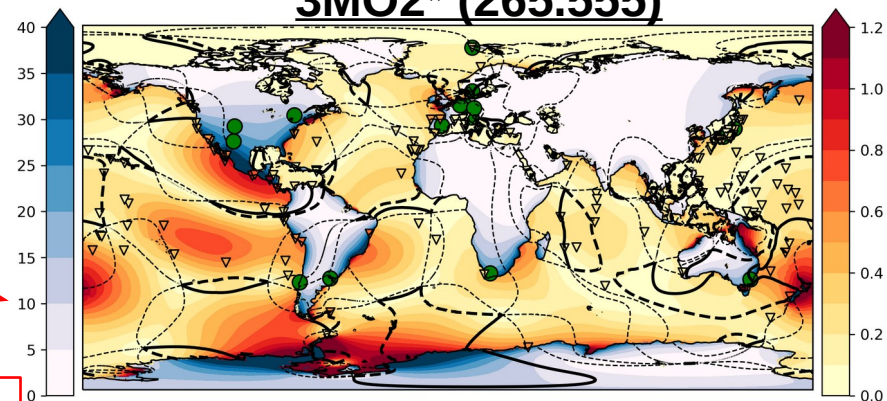
3MK2* (245.555)



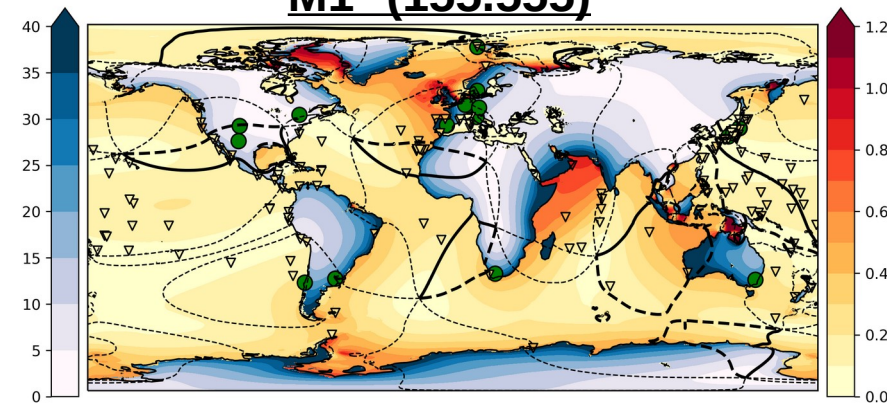
3MO2 -
admittance >
3MK2 -
admittance
(Ray, 2020)

admittance
patterns deviate
from degree-2
tides

3MO2* (265.555)

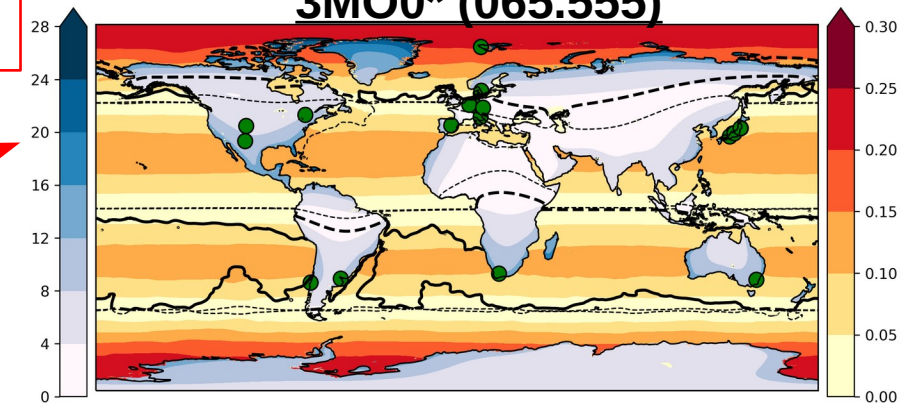


M1* (155.555)

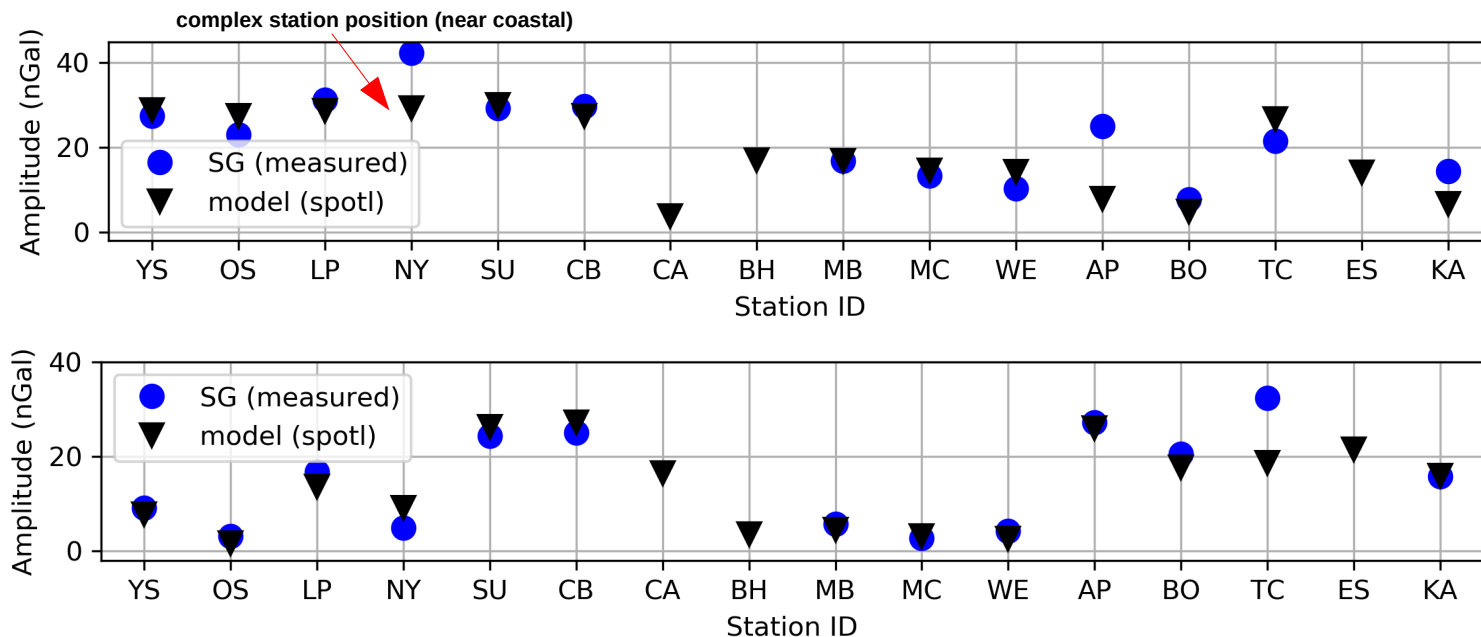


Result close
to equilibrium
tide (period:
~1 month)

3MO0* (065.555)



Gravity Tide Amplitudes at SG-Stations



M1 (155.555)

Missing data-points =
SG-analysis to be conducted

3MO2 (265.555)

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Result: Data-unconstrained tidal models can be used to accurately predict minor tides, that can serve as valuable constraints for satellite gravimetry. Degree-3 tidal signal can cause relevant aliasing and can be detected with superconducting gravimeters, where observations match the modeled signal.

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