The importance of ocean tides in sea level research using satellite altimetry

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Deltares: Team Hydrodynamics Meeting
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Quick Introduction

Focus areas

- Ocean tide modelling and satellite altimetry
- Physical Oceanography, Particle Tracking, Ocean Modelling

Studies

Research Associate and PhD in Satellite Altimetry and Tide Modelling

At the Technical University of Munich (2019 -)

Masters in Physical Oceanography

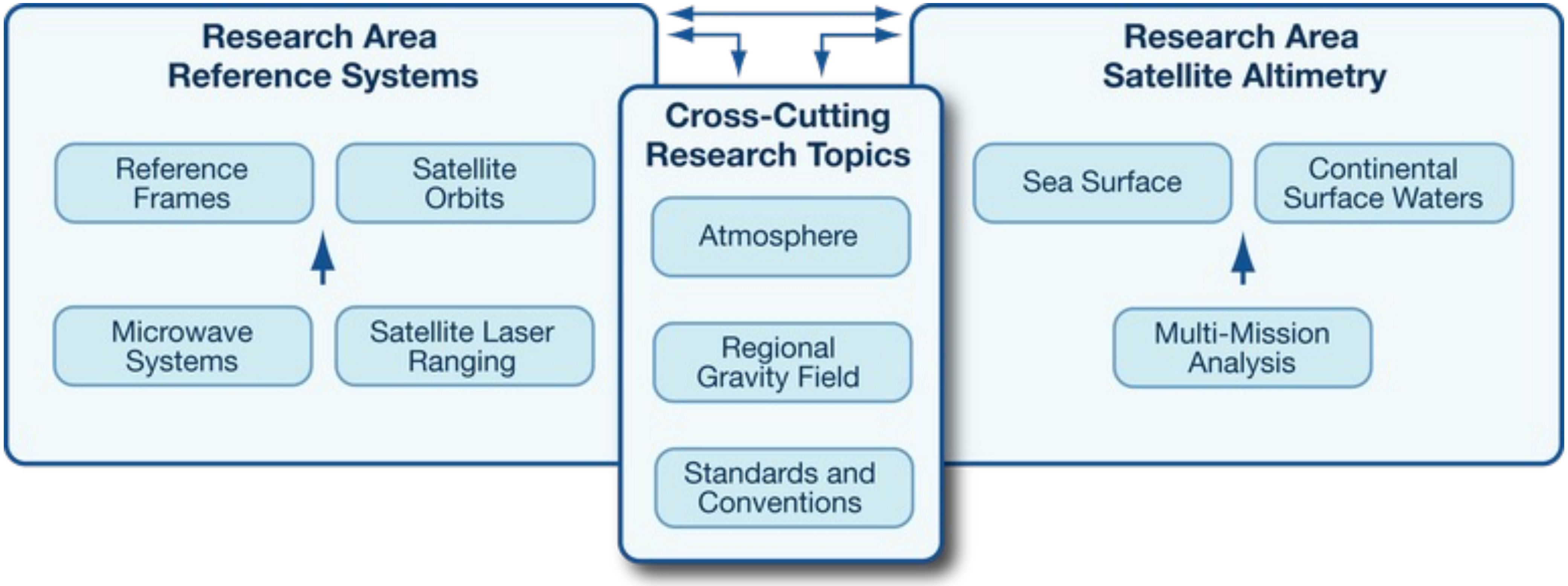
At Nelson Mandela University (2018 – 2019)

Research Exchange (Masters Thesis)

At NERSC and University of Bergen (2018 - 2019)

Deutsches Geodätisches Forschungsinstitut (DGFI-TUM)

- 1952: Founded as a research institute of the German Geodetic Commission (DGK)
- 2015: Integration into TUM, today part of the Department of Aerospace and Geodesy (ASG) of the TUM School of Engineering and Design. Please visit: https://www.dgfi.tum.de/en/



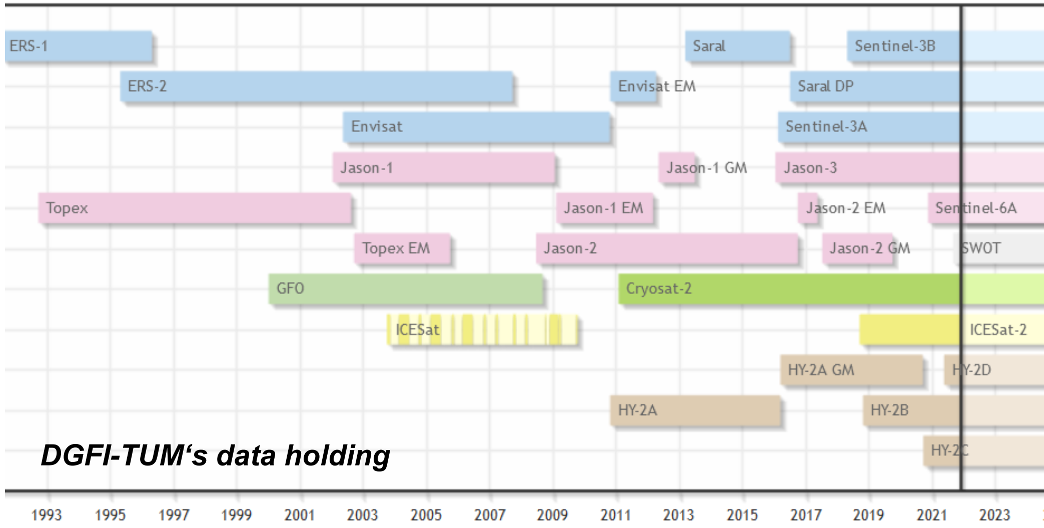
Satellite Altimetry at DGFI-TUM

- DGFI-TUM administrates complete **data holdings** of all altimeter missions since 1992 (radar and laser).

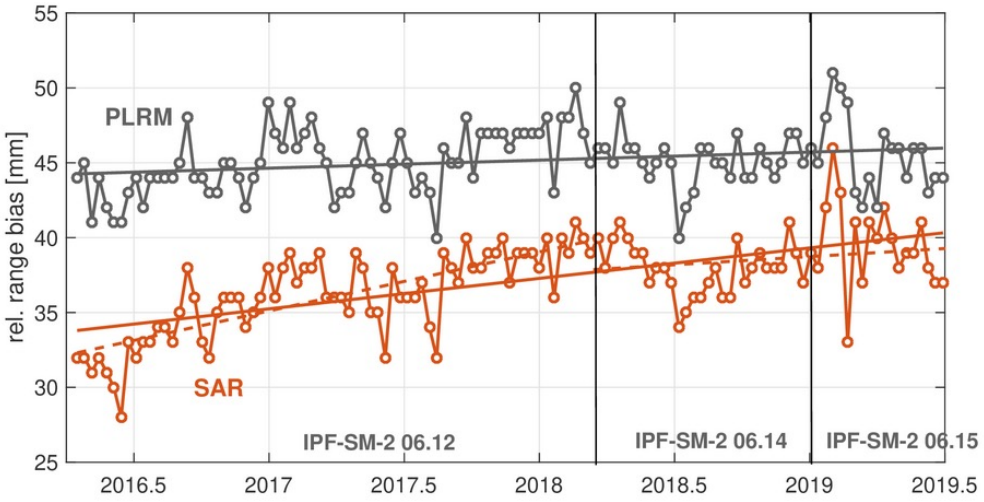
- DGFI-TUM maintains public altimeter data portals for satellite altimeter data and derived high-level products
  - **OpenADB: http://openadb.dgfi.tum.de**
  - DAHITI: http://dahiti.dgfi.tum.de

- DGFI-TUM developed a **global multi-mission crossover analysis** (MMXO) approach in order to ensure a harmonized dataset and an optimal combination of different altimeter missions.
  - ➢ one virtual long-term altimeter mission with optimal temporal and spatial resolution
  - ➢ calibration of single missions
  - ➢ identification and quantification of systematic errors in data and products

- **Scientific investigations** are (mostly) based on cross-calibrated multi-mission altimetry data



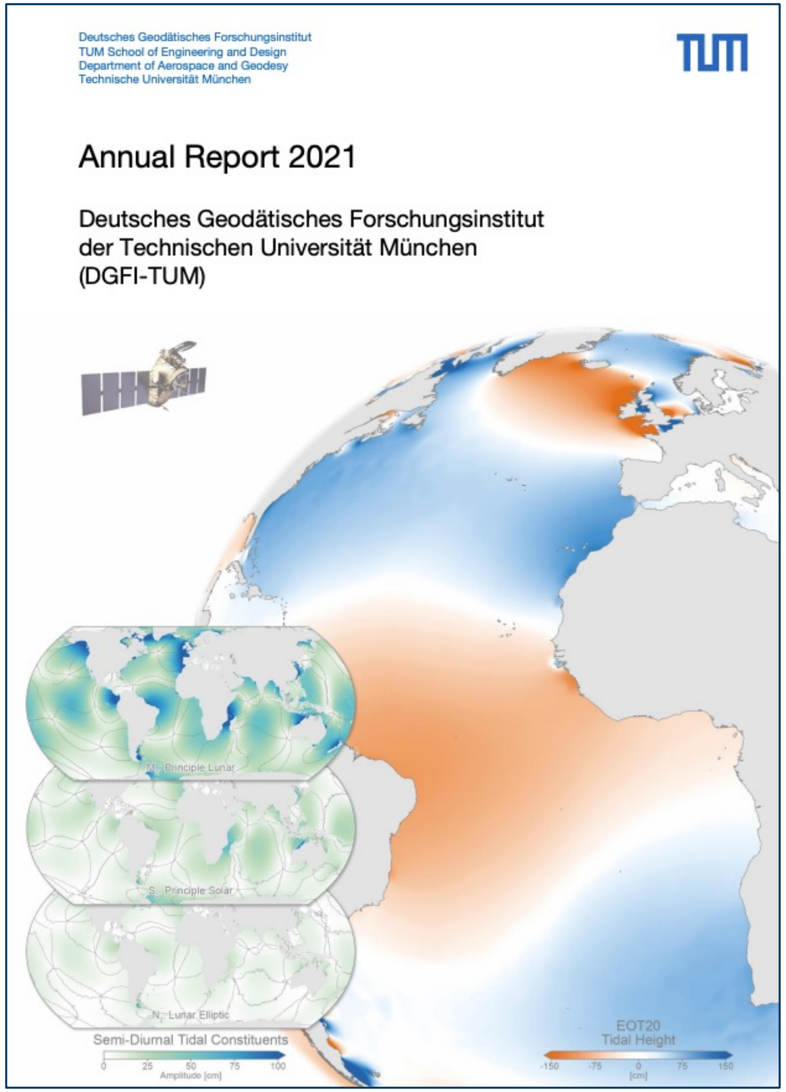
DGFI-TUM's data holding



Relative range bias of Sentinel-3 wrt. Jason-3

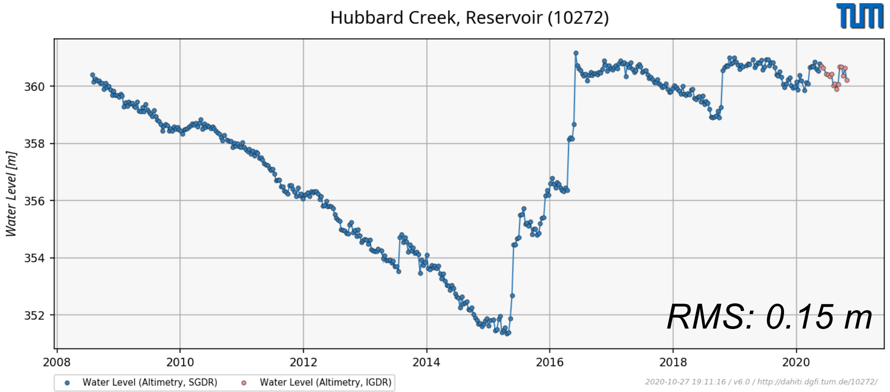
Satellite Altimetry Inland and Oceans

- Sea Level Change
- Sea State
- Empirical Ocean Tide Modeling
- Dynamic Ocean Topography and Geostrophic Surface Currents
- Water Levels of Inland Water Bodies
- Water Storage in Lakes and Reservoirs
- River Discharge
- For more information: Annual Report of 2021:
  https://mediatum.ub.tum.de/doc/1657456/1657456.pdf
  or visit https://www.dgfi.tum.de/



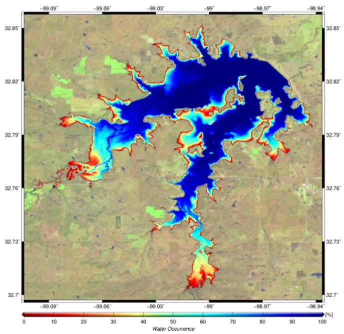
Hydrological Products of Inland Waters

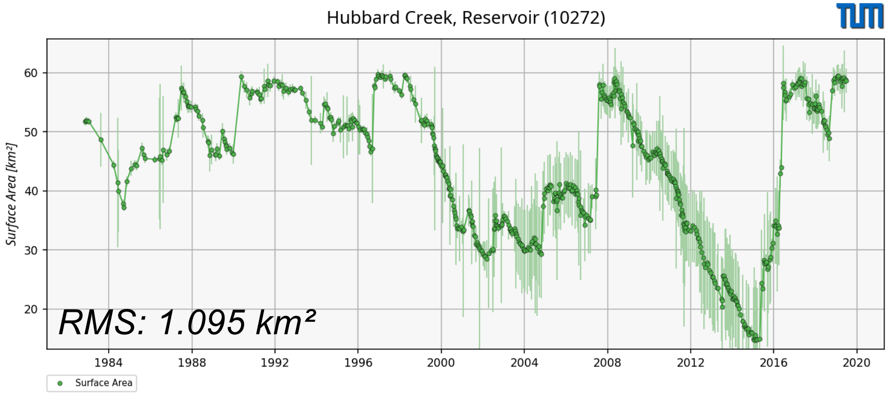
- The **Database for Hydrological Time Series of Inland Waters** (DAHITI, **https://dahiti.dgfi.tum.de**) provides hydrological products derived from remote sensing data



- **Water level time series** for lakes, reservoirs, rivers and wetlands derived from **multi-mission satellite altimetry** using an extended outlier detection and Kalman filter approach (Schwatke et al., 2015)

- **Surface area time series, water occurrence mask** and **land-water masks** for lakes and reservoirs derived from optical imagery (Landsat, Sentinel-2) using a combination of five water indexes and iterative gap filling approach (Schwatke et al., 2019)





Schwatke, C., Dettmering, D., Bosch, W., Seitz, F.: **DAHITI - an innovative approach for estimating water level time series over inland waters using multi-mission satellite altimetry**: Hydrol. Earth Syst. Sci., 19, 4345-4364, doi:10.5194/hess-19-4345-2015, 2015

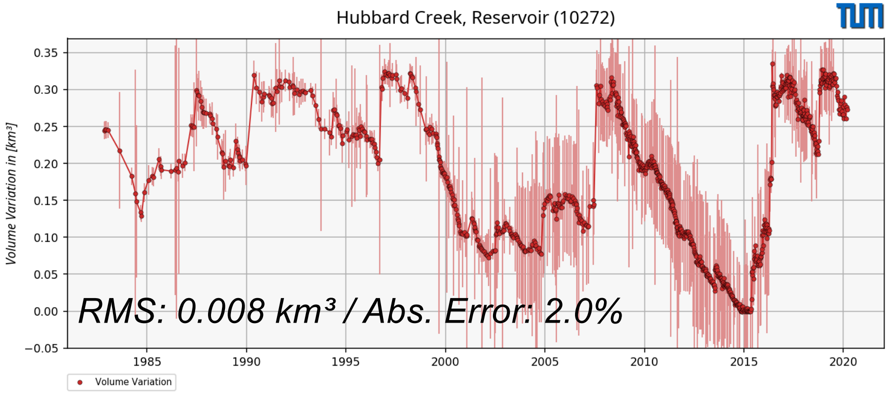
Schwatke C., Scherer D., Dettmering D.: **Automated Extraction of Consistent Time-Variable Water Surfaces of Lakes and Reservoirs Based on Landsat and Sentinel-2**: , Remote Sensing, 11(9), 1010, doi:10.3390/rs11091010, 2019

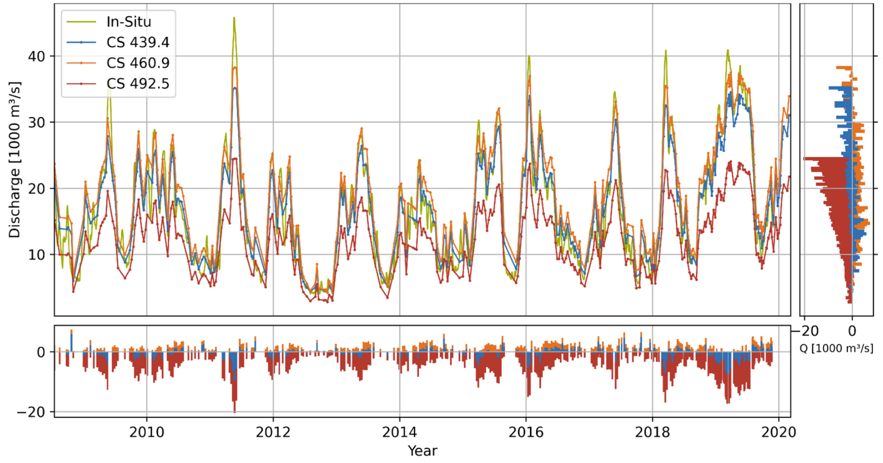
Hydrological Products of Inland Waters

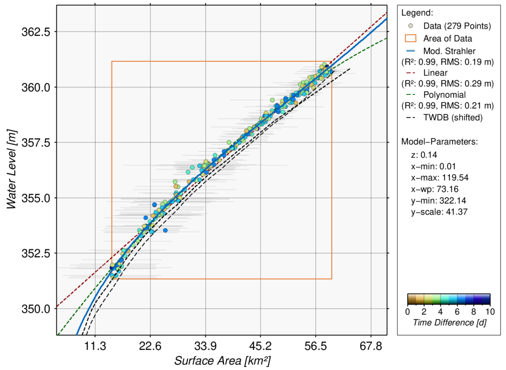
- **Volume variations** and **bathymetry** of lakes and reservoirs are derived by combining water levels from satellite altimetry and surface areas from optical imagery

- The methodology is based on a hypsometry model assigning water levels and surface areas in which a modified Strahler approach is applied (Schwatke et al., 2020)

- **River discharge** derived by combining water levels from satellite altimetry and surface areas from optical imagery using a **hypsometry model** and **physical flow equations** (Scherer et al., 2021)







Schwatke C., Dettmering D., Seitz F.: **Volume Variations of Small Inland Water Bodies from a Combination of Satellite Altimetry and Optical Imagery.** Remote Sensing, 12(10), 1606, doi: 10.3390/rs12101606, 2020
Scherer D., Schwatke C., Dettmering D., Seitz F.: **Long-Term Discharge Estimation for the Lower Mississippi River Using Satellite Altimetry and Remote Sensing Images**. Remote Sensing, 12(17), 2693, doi: 10.3390/rs12172693, 2020

Coastal Sea Level Trends

- DGFI-TUM analyses altimetry observations to determine sea level changes on global scale and within regional studies.
- Coastal zones are highly under-sampled by tide gauges, and altimetry data are largely defective because of land contamination of the radar signals.
- A novel altimetry-based coastal sea level data record has been created.
- It consists of high-resolution (~300 m) monthly sea level data along the satellite tracks, at distances of less than 3-4 km from the coastlines in general, sometimes even closer, within 1-2 km from the coast.

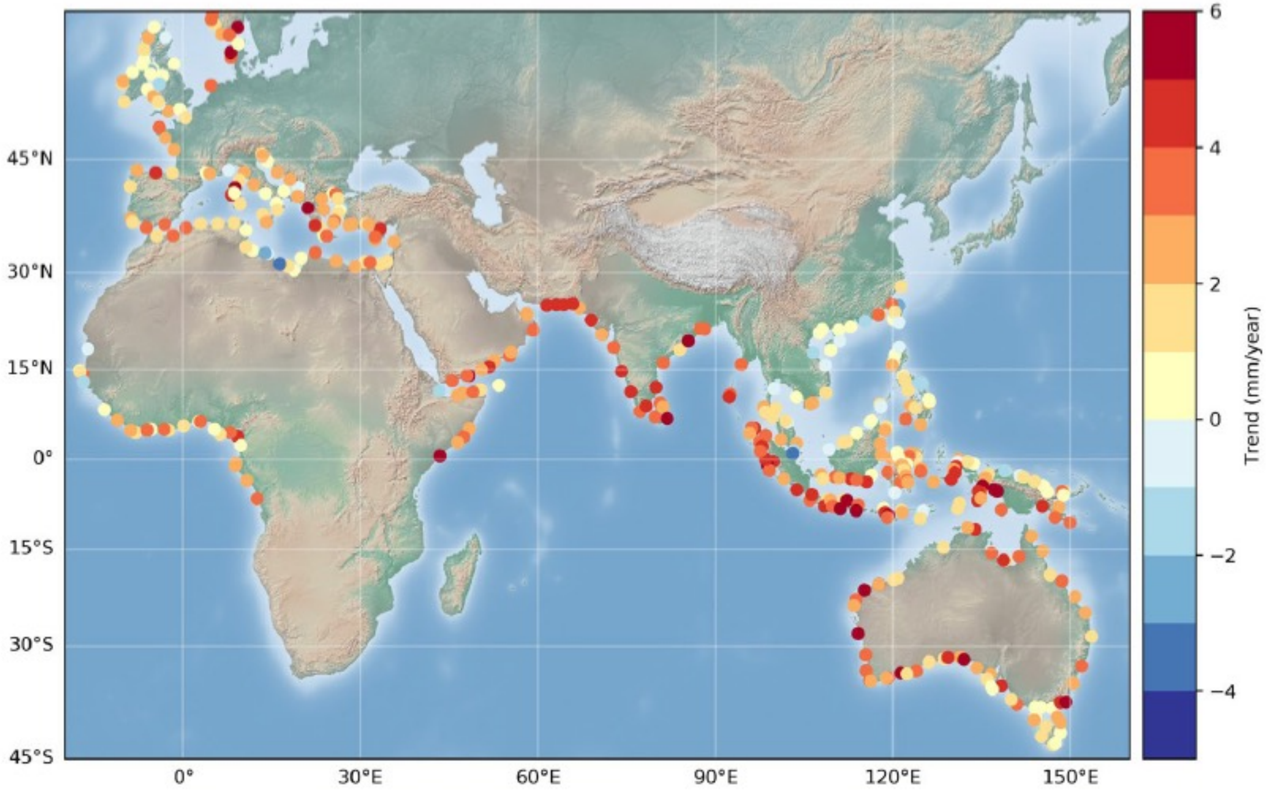
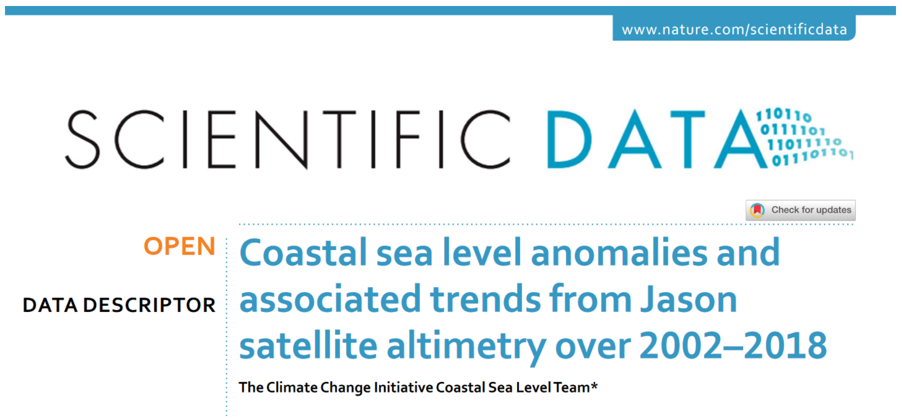


Fig. 9 Coastal sea level trends (mm/yr) at the first valid point from the coast at the 429 selected sites.


www.nature.com/scientificdata

SCIENTIFIC DATA

Check for updates

OPEN

DATA DESCRIPTOR

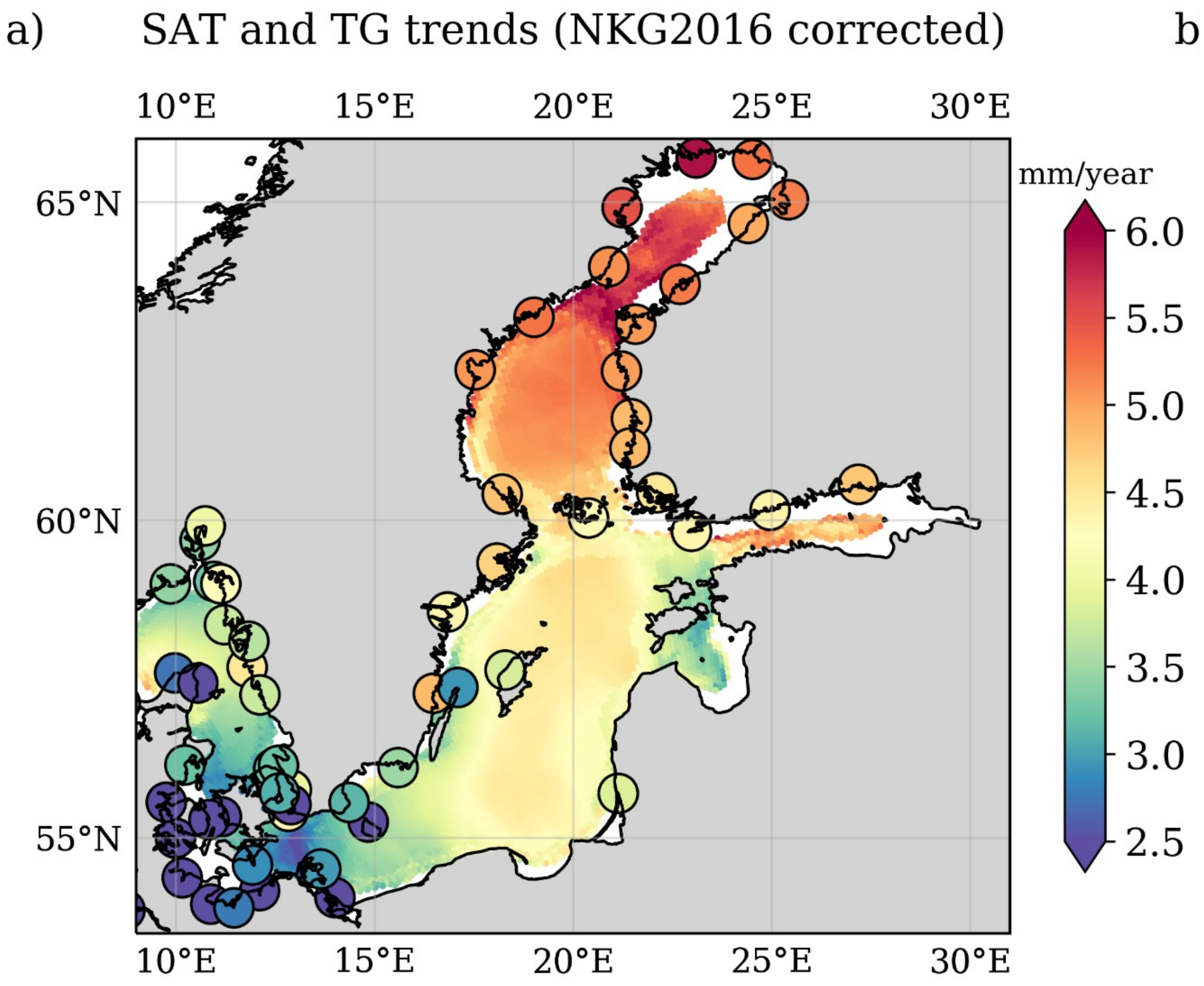
Coastal sea level anomalies and associated trends from Jason satellite altimetry over 2002–2018

The Climate Change Initiative Coastal Sea Level Team*

Updated for global coverage (2022):

Cazenave, A., Gouzenes, Y., Birol, F. *et al.* Sea level along the world's coastlines can be measured by a network of virtual altimetry stations. *Commun Earth Environ* **3,** 117 (2022). https://doi.org/10.1038/s43247-022-00448-z

Gridded Sea-Level Trend Products – Baltic SEAL



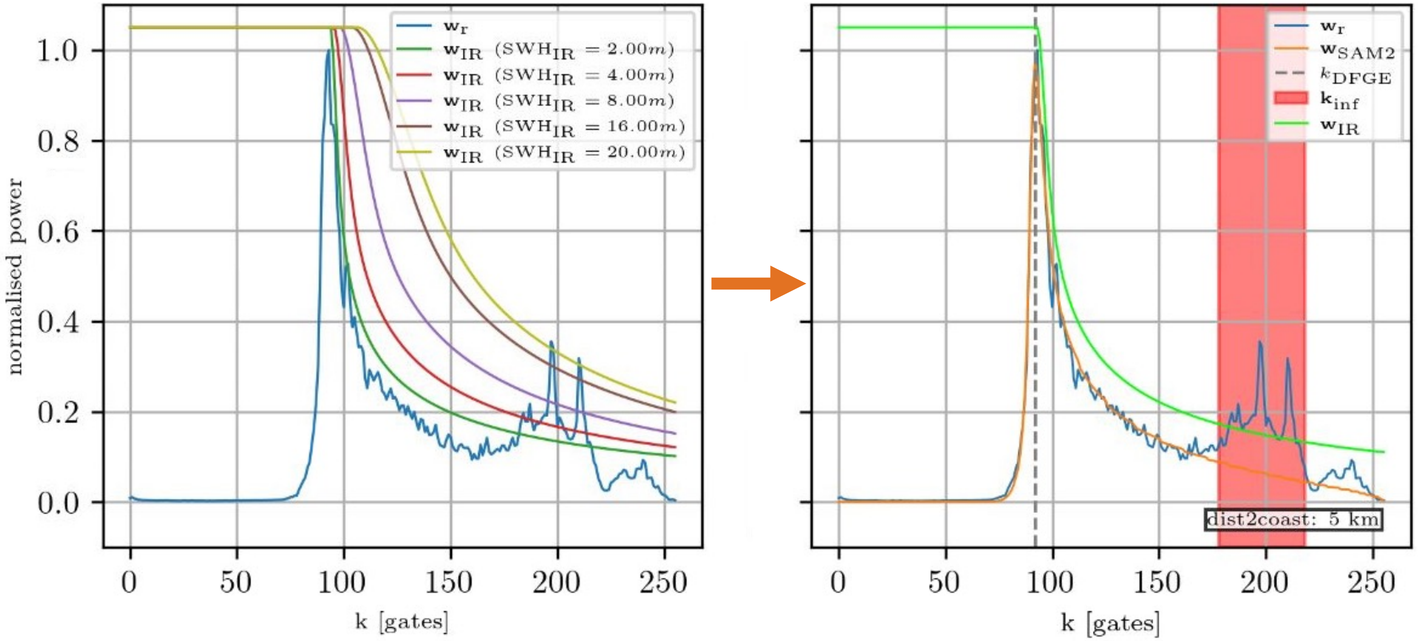
- The absolute sea level trend from May 1995 to May 2019 in the Baltic Sea was studied by means of a regional monthly gridded dataset based on a dedicated processing of satellite altimetry data.
- An overall sea level rise trend of 4.27 ± 3.58 mm/year was found, with the analysis showing that the sea level is increasing across all of the Baltic.
- In this study, the SL trends are compared to in-situ observations to determine the drivers of the changes in the SL trends.
- A gradient of over 3 mm/yr in sea level rise is observed, with the north and east of the basin rising more than the south-west.

Passaro, M., Müller, F.L., Oelsmann, J., Rautiainen, L., Dettmering, D., **Hart-Davis, M.G.,** Abulaitijiang, A., Andersen, O.B., Høyer, J.L., Madsen, K.S. and Ringgaard, I.M., 2021. Absolute Baltic Sea Level Trends in the Satellite Altimetry Era: A Revisit. *Frontiers in Marine Science*, 8, p.546.

Satellite Altimetry – Coastal CORALv1 Retracker

CORALv1 – a coastal SAR altimetry retracker

→ senses and masks interference within the trailing edge that typically arises from bright targets (mud banks, sheltered bays, shipping platforms etc.) in the coastal zone



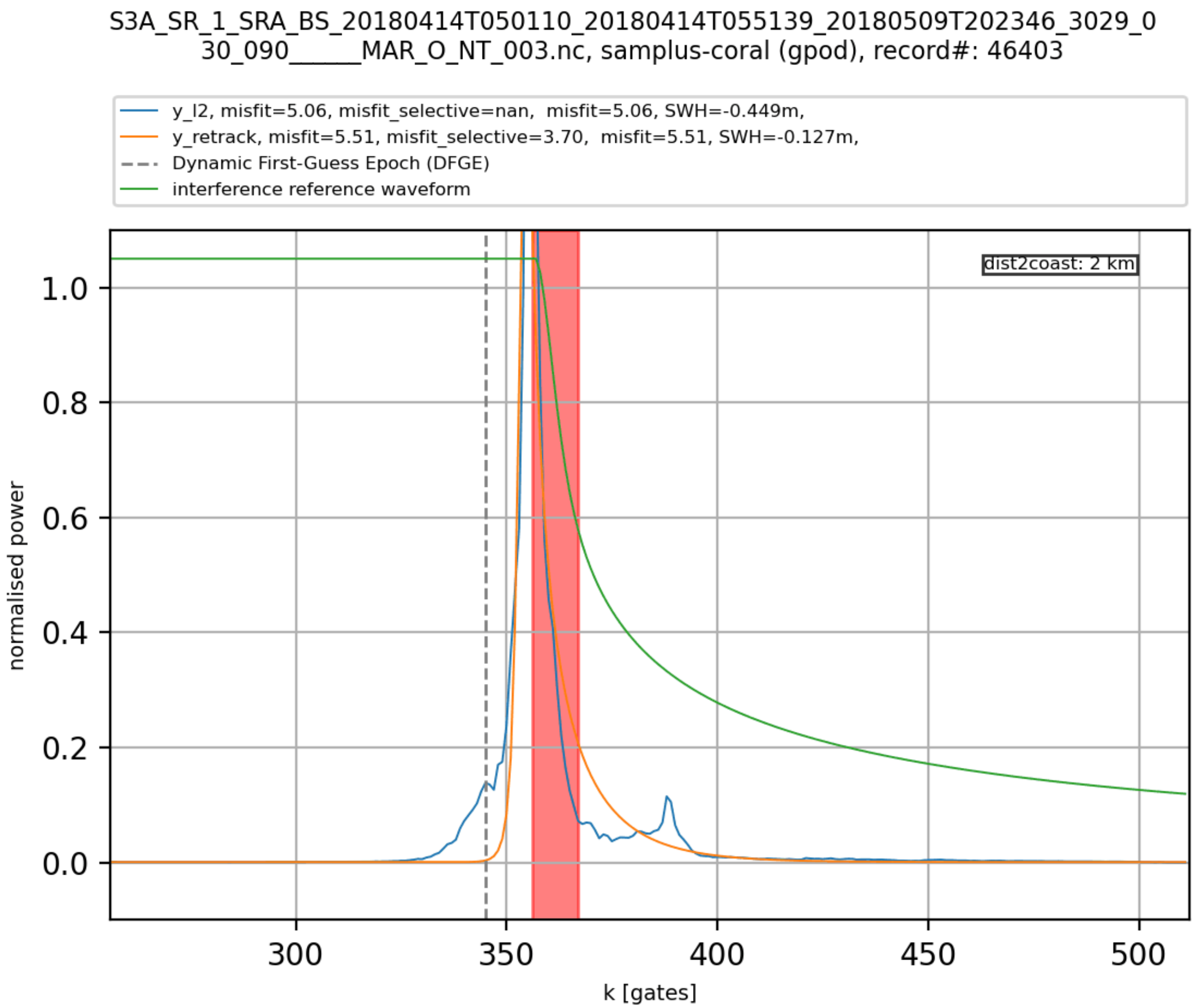
Schlembach et al. „Interference-Sensitive Coastal SAR Altimetry Retracking Strategy for Measuring Significant Wave Height“. *Remote Sensing of Environment*, 274, 112968. https://doi.org/10.1016/j.rse.2022.112968.

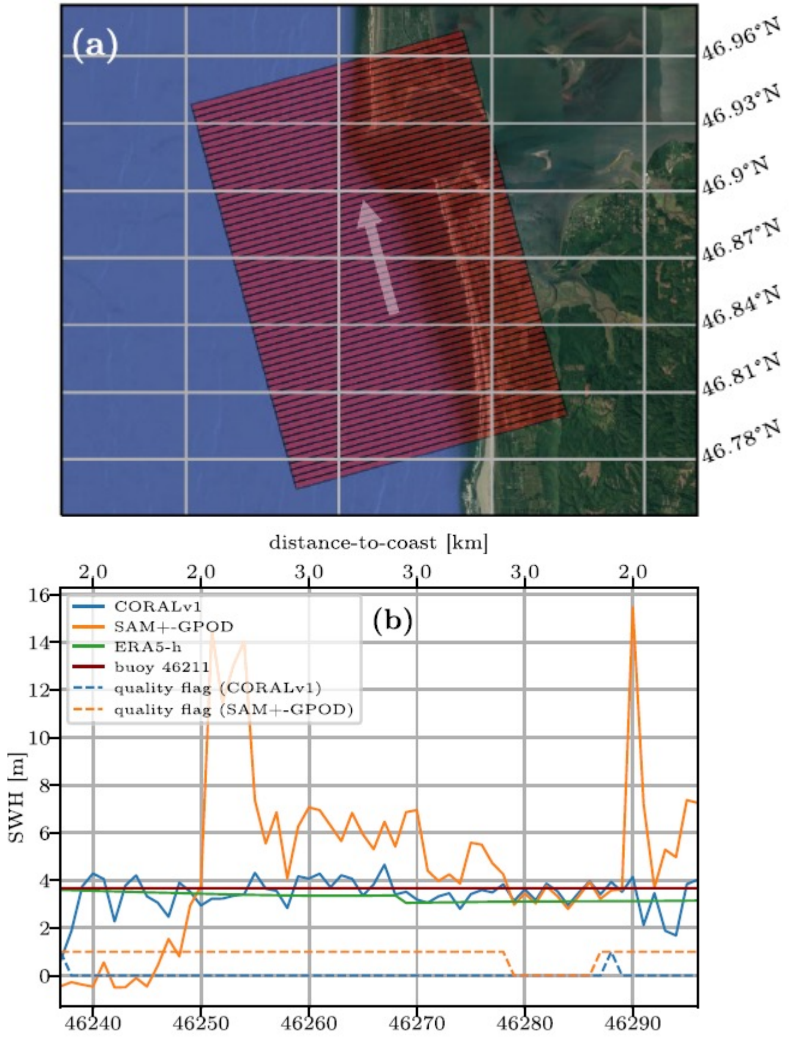
→ CORALv1 detects interference gates and excludes them from fitting procedure → **quality** of the SWH estimates ↗

→ CORALv1 excludes interference gates for the quality flag determination → **quantity** of valid SWH estimates ↗

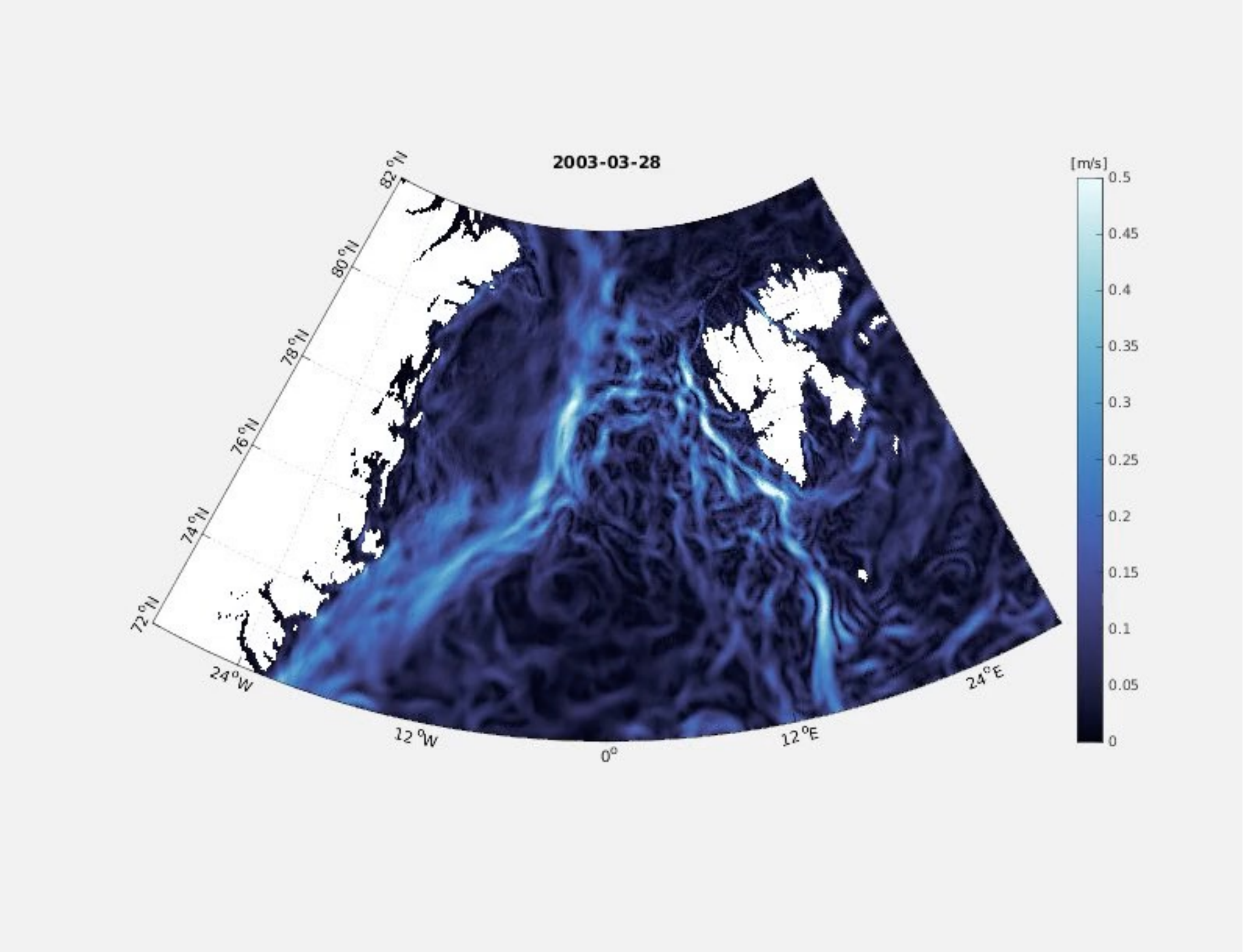
Satellite Altimetry – Coastal CORALv1 Retracker

Retracking waveforms with strong coastal interference by CORALv1 in comparison with SAMOSA+





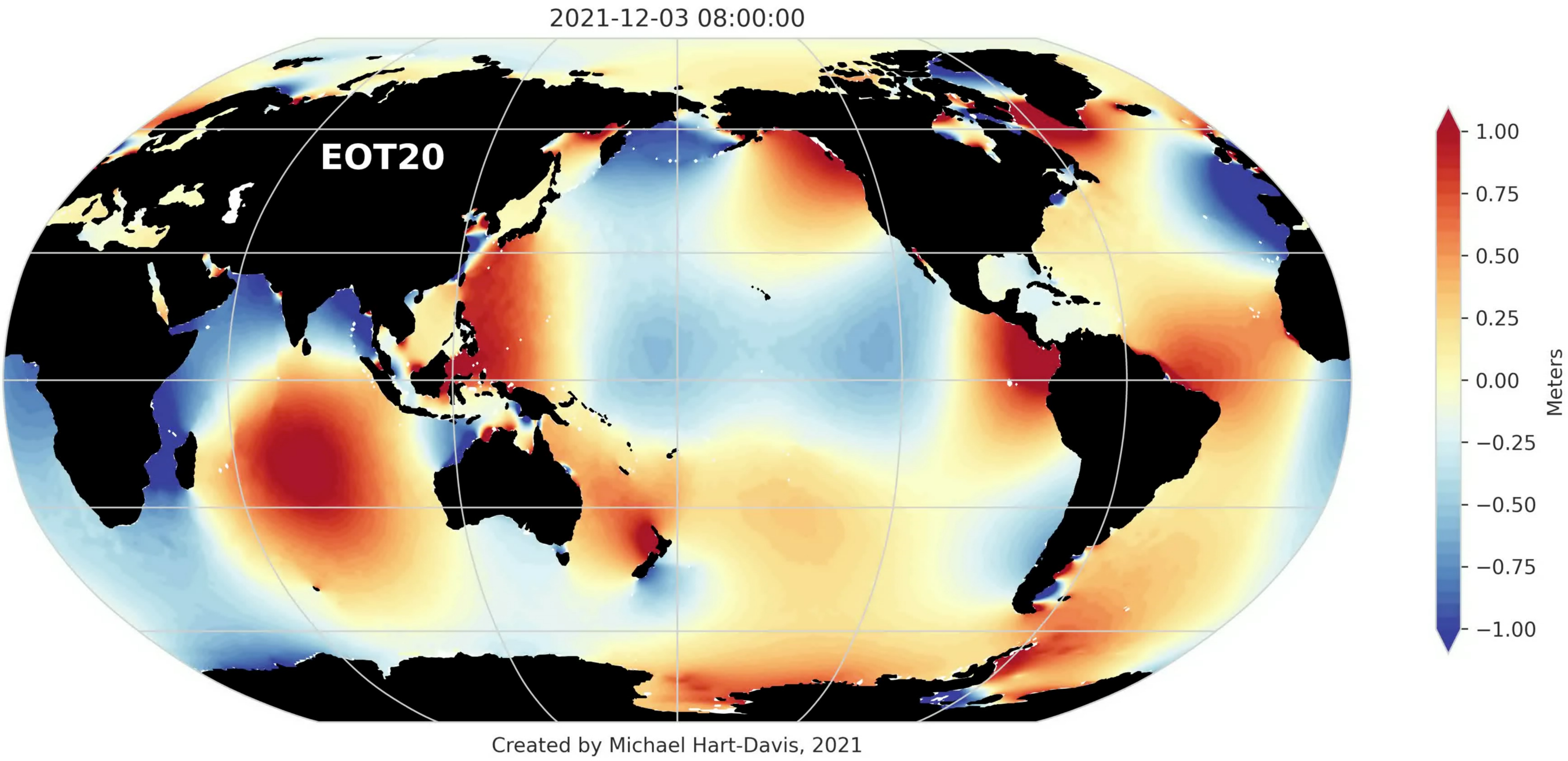
Geostrophic Currents



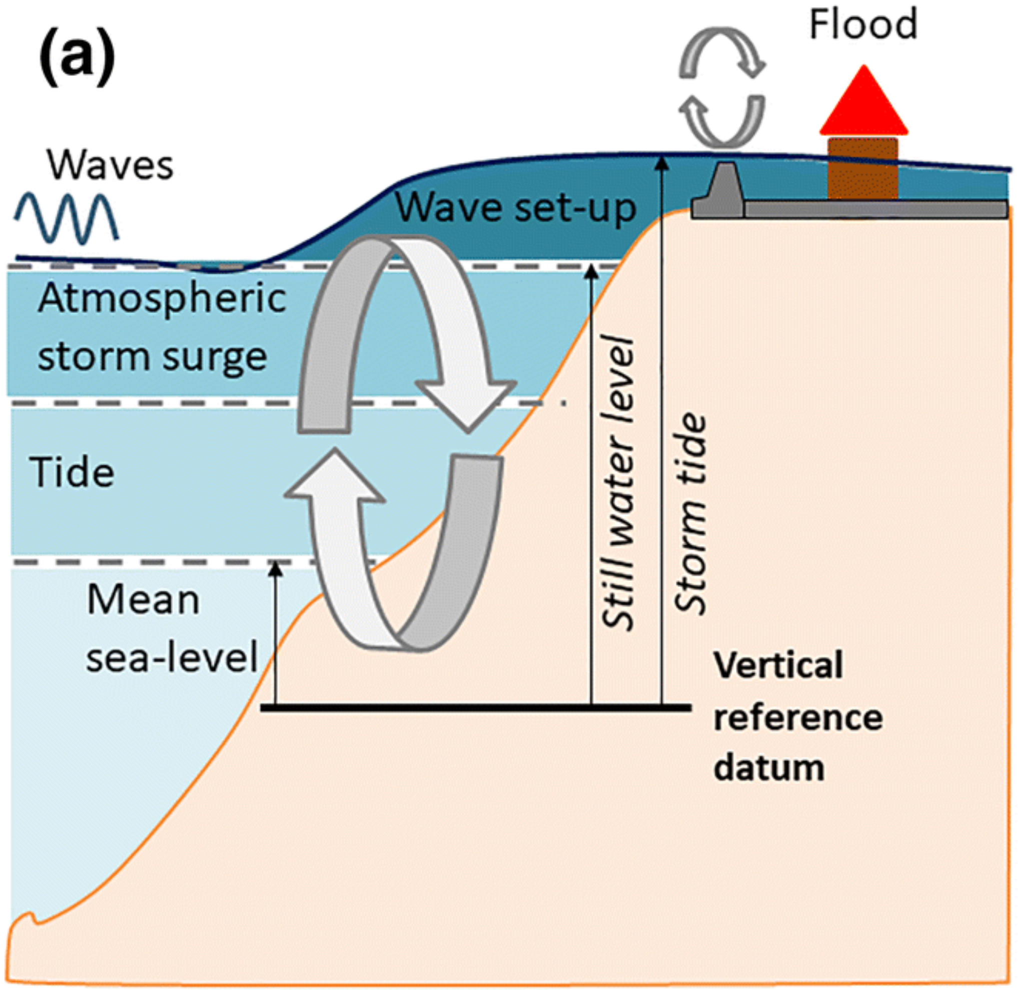
- Geostrophic currents in the northern Nordic Seas from a combination of multi-mission satellite altimetry and ocean modelling
- A novel dataset of geostrophic currents based on a combination of along-track satellite altimetry data and simulated differential water heights from the Finite Element Sea ice Ocean Model (FESOM).
- A direct pointwise comparison between the combined geostrophic velocity components interpolated to drifter locations indicates that about 94% of all residuals are smaller than 0.15 m/s.

Müller F. L., Dettmering D., Wekerle C., Schwatke C., Passaro M., Bosch W., Seitz F.: Geostrophic currents in the northern Nordic Seas from a combination of multi-mission satellite altimetry and ocean modeling. Earth System Science Data, 11(4), 1765-1781, 10.5194/essd-11-1765-2019, 2019

Ocean Tides – A Global Empirical Ocean Tide Model



Tides in the context of studies on sea-level



- Estimates of sea-level from, for example, Satellite Altimetry are influenced by the tides.
- The cycle of the tides can result in over or under-estimated sea-level estimations if tides are not taken into account.
- Therefore, ocean tides need to be removed from the signals of satellite altimetry and tide gauges in order to get more accurate estimates of the sea-level changes.
- This has resulted in the development of the ocean tide models presented in the previous slide to produce ocean tidal corrections for satellite altimetry.

Tide Model Difficulties

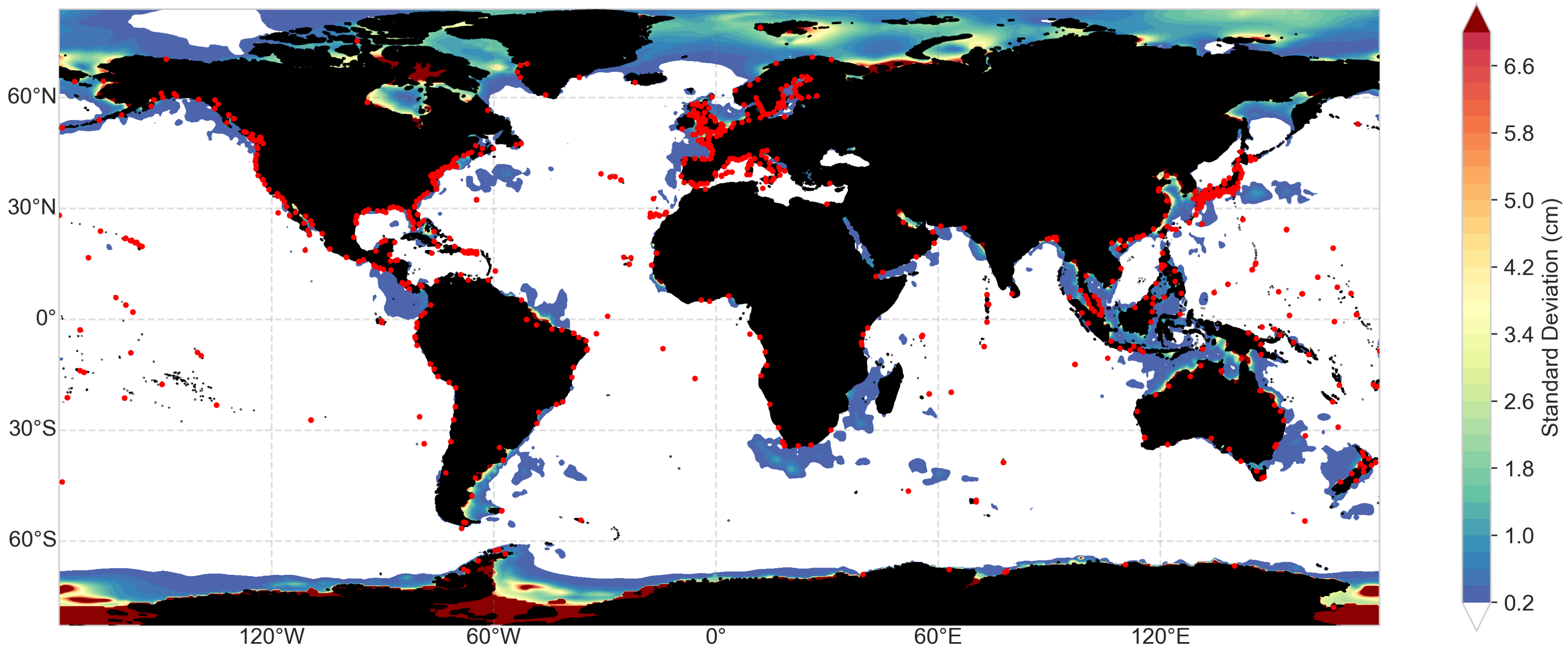


Figure. The standard deviation of the tidal constituents of major global ocean tide models.

- Tide models vary in the coastal and polar regions
- Models also show the highest error compared to tide gauges in the coastal region (> 5 cm)

Difficulty in accurately understanding ocean tides

- Problems in estimating ocean tides frequently occur in the coastal region.

- This is caused by:

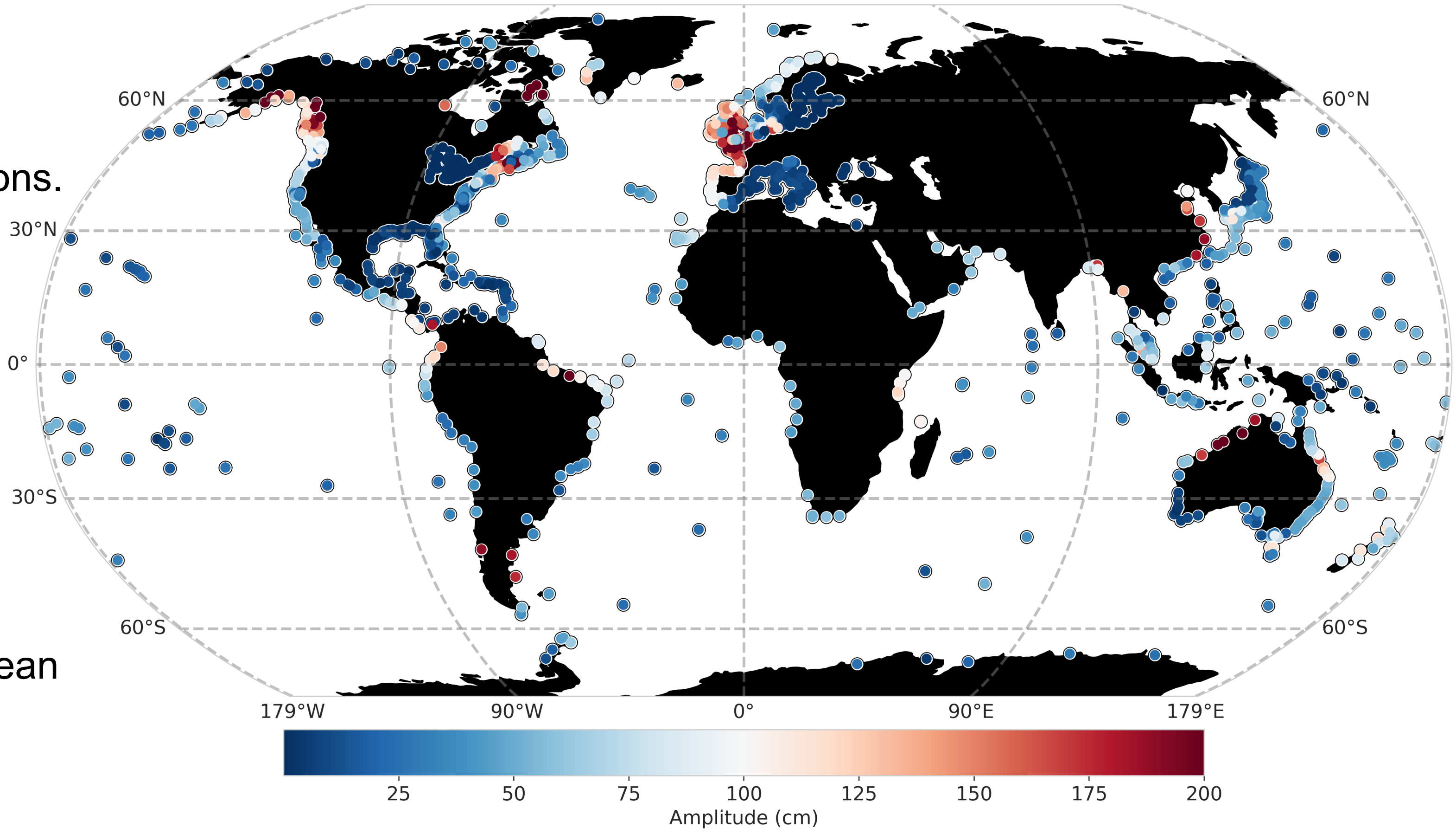
  - The lack of properly distributed observations.

  - Poorly understand bathymetry.

  - Radar returns of satellite altimetry more strongly affected in the coastal region.

  - Requires very high computational load to more accurately estimate all the tidal constituents needed to resolve the full ocean tide.

  - Sea Ice



Introduction to EOT

- EOT20 is the latest in a series of empirical ocean tide (EOT) models derived using residual tidal analysis of multi-mission satellite altimetry at DGFI-TUM.

- The aim of the EOT20 model is to provide a coastal improved estimation of tidal constituents without harming the open ocean performance

- EOT20 takes advantage of the inclusion of more recent satellite altimetry data as well as more missions, the use of the updated FES2014 tidal model as a reference to estimated residual signals, the inclusion of the ALES retracker and improved coastline representation.

- **Hart-Davis, M. G.,** Piccioni, G., Dettmering, D., Schwatke, C., Passaro, M., and Seitz, F. 2021. EOT20: a global ocean tide model from multi-mission satellite altimetry, *Earth Syst. Sci. Data,* 13, 3869–3884, https://doi.org/10.5194/essd-13-3869-2021. Data is available at: https://doi.org/10.17882/79489.

Satellite Altimetry – Sea Level Estimation

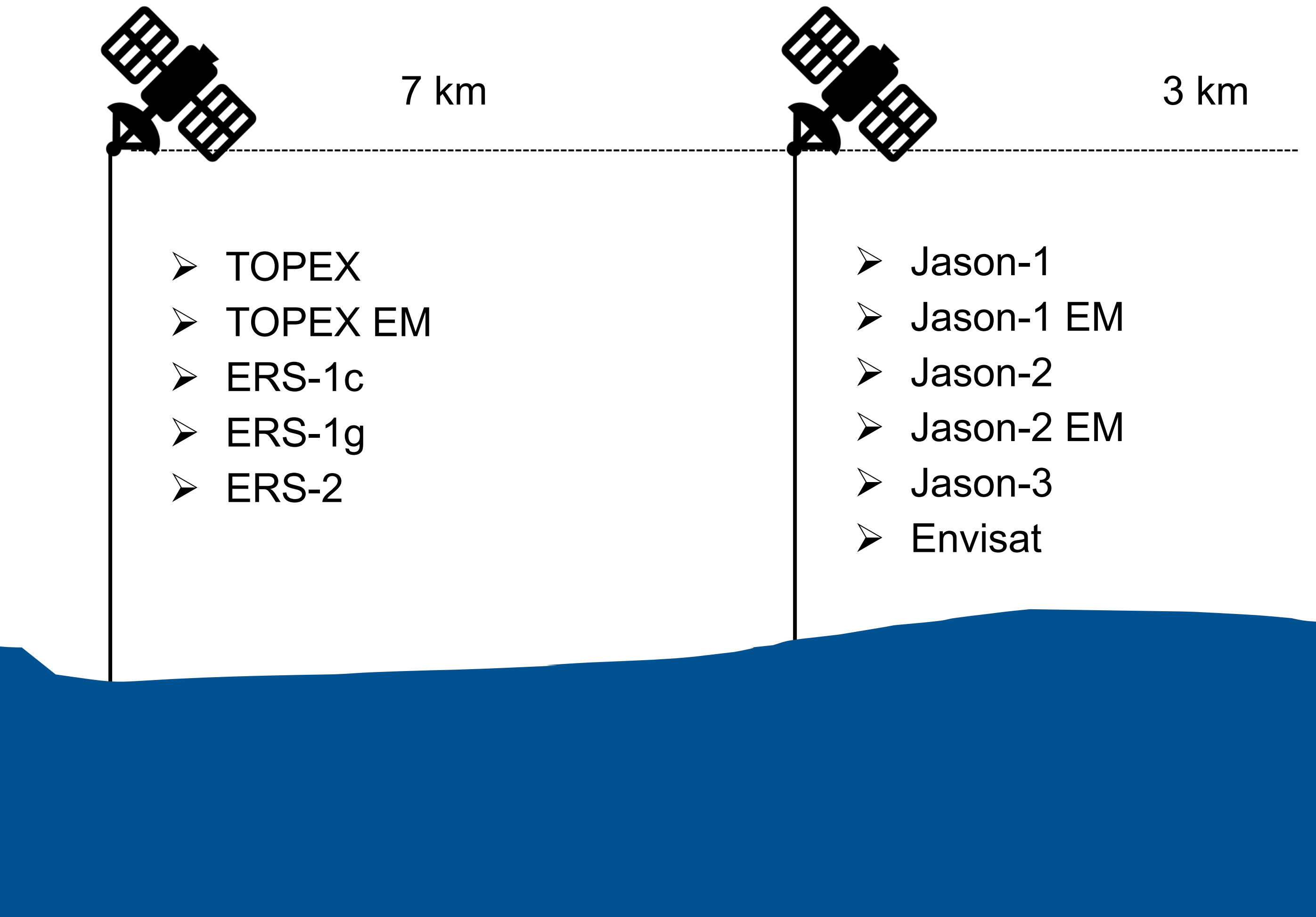
Table 1. The ***multi-mission*** satellite altimeter data used in this study obtained from OpenADB at DGFI-TUM (Schwatke et al., 2014).

Mission	Cycles	Period
TOPEX	001 - 365	1992/09/25 - 2002/08/15
TOPEX Extended Mission	368 - 481	2002/09/16 - 2005/10/08
Jason-1 †	001 - 259	2002/01/15 - 2009/01/26
Jason-1 Extended Mission †	262 - 374	2009/02/10 - 2012/03/03
Jason-2 †	000 - 296	2008/07/04 - 2016/07/25
Jason-2 Extended Mission †	305 - 327	2016/10/13 - 2017/05/17
Jason-3 †	001 - 071	2016/02/12 - 2018/01/21
ERS-1c	082 - 101	1992/03/25 - 1993/12/24
ERS-1g	144 - 156	1995/03/24 - 1996/06/02
ERS-2	000 - 085	1995/05/14 - 2003/07/02
Envisat †	006 - 094	2002/05/14 - 2010/11/26

Table 2 . List of corrections and parameters used to compute SLA for tidal residuals estimation.

Parameter	Model	Reference
ALES sea state bias	ALES	Passaro et al. (2018)
ERS sea state bias	REAPER	Brockley et al. (2017)
TOPEX sea state bias	TOPEX	Chambers et al. (2003)
Inverse barometer before 2017	DAC-ERA	Carrere et al. (2016)
Inverse barometer from 2017	DAC	Carrère et al. (2011)
Wet troposphere	GPD+	Fernandes and Lázaro (2016)
Dry troposphere	VMF3	Landskron and Böhm (2018)
Ionosphere	NIC09	Scharroo and Smith (2010)
Ocean and load tide	FES2014	Lyard et al. (2020)
Solid earth and pole tide	IERS 2010	Petit and Luzum (2010)
Mean sea surface	DTU18MSS	Andersen et al. (2016)
Radial error	MMXO17	Bosch et al. (2014)

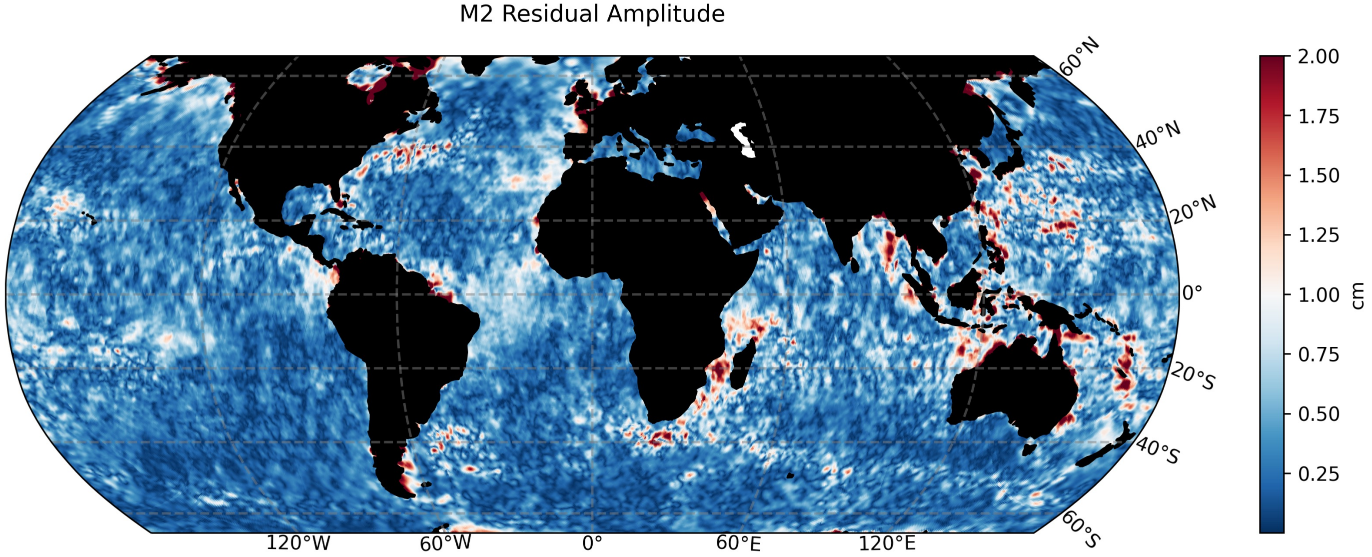
The Inclusion of a Coastal Flag (for ALES)

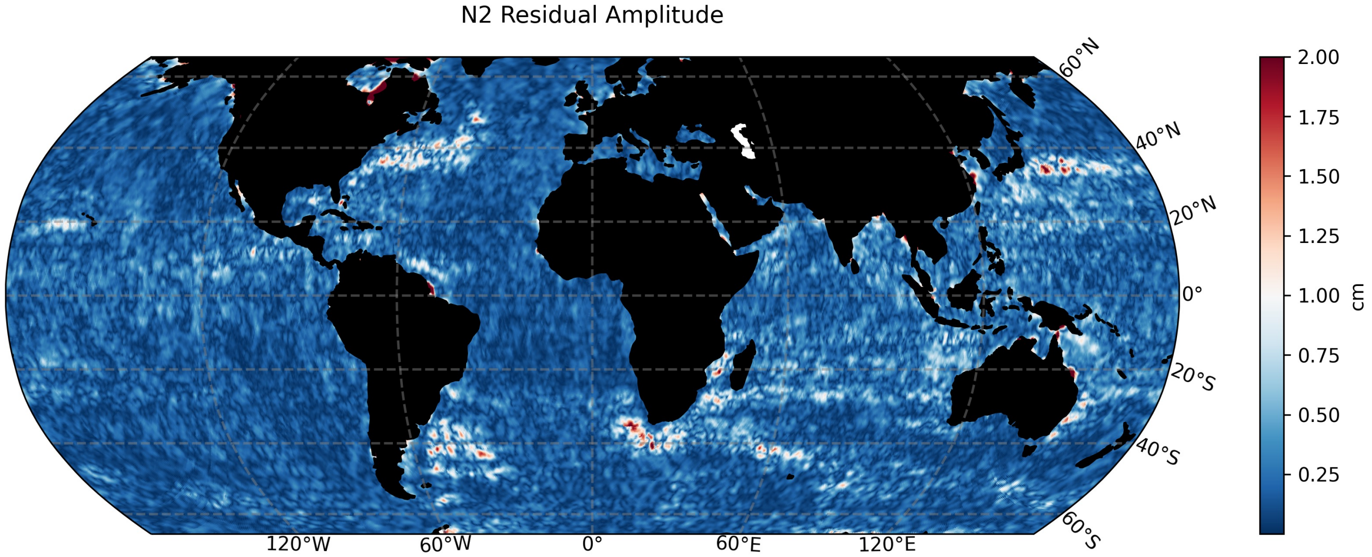


- Implementation of a coastal flag to allow for the full exploitation of ALES (Passaro et al 2014) sea level data.
- Also relies on data that do not contain the ALES sea level data (e.g. TOPEX) for proper tidal estimation.
- Has a positive impact on the estimation of tidal constituents in the coastal region.

Passaro, M., Rose, S.K., Andersen, O.B., Boergens, E., Calafat, F.M., Dettmering, D. and Benveniste, J., 2018. ALES+: Adapting a homogenous ocean retracker for satellite altimetry to sea ice leads, coastal and inland waters. *Remote Sensing of Environment*, *211*, pp.456-471.

Residual Tide Analysis





- Weighted least-squares approach applied to solve the harmonic formula.
- Variance Component Estimation to combine and weight satellite altimetry missions
- Eventually results in amplitudes and phases of 17 tidal constituents, namely:
  - ➢ 2N2, J1, K1, K2, M2, M4, MF, MM, N2, O1, P1, Q1, S1, S2, SA, SSA and T2
- Residuals are the elastic tide which is:
  - ➢ Elastic = ocean + load tide
- **Figure.** The residual amplitude of the M2 and N2 tidal constituents.

The Global EOT20 Model

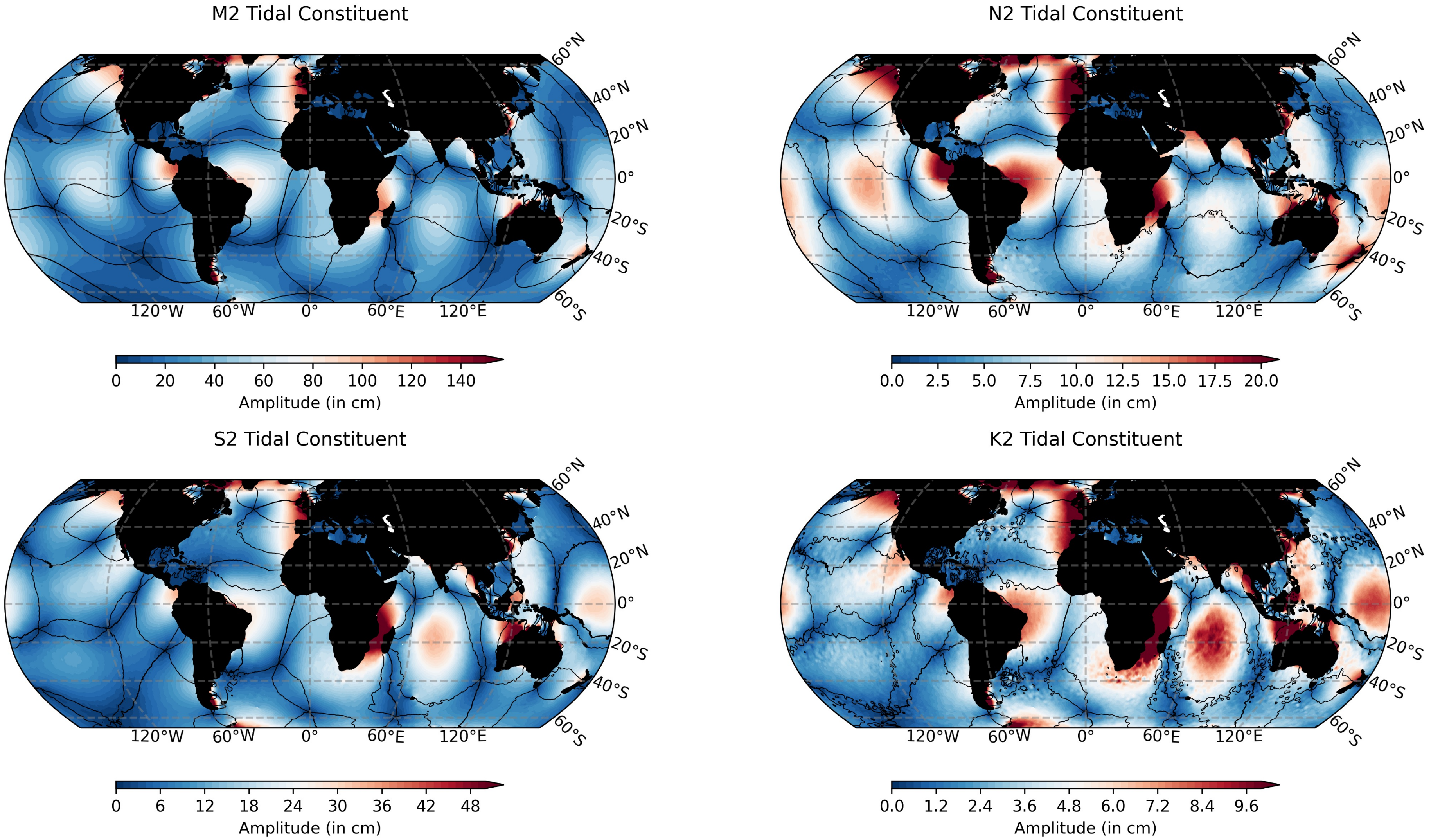
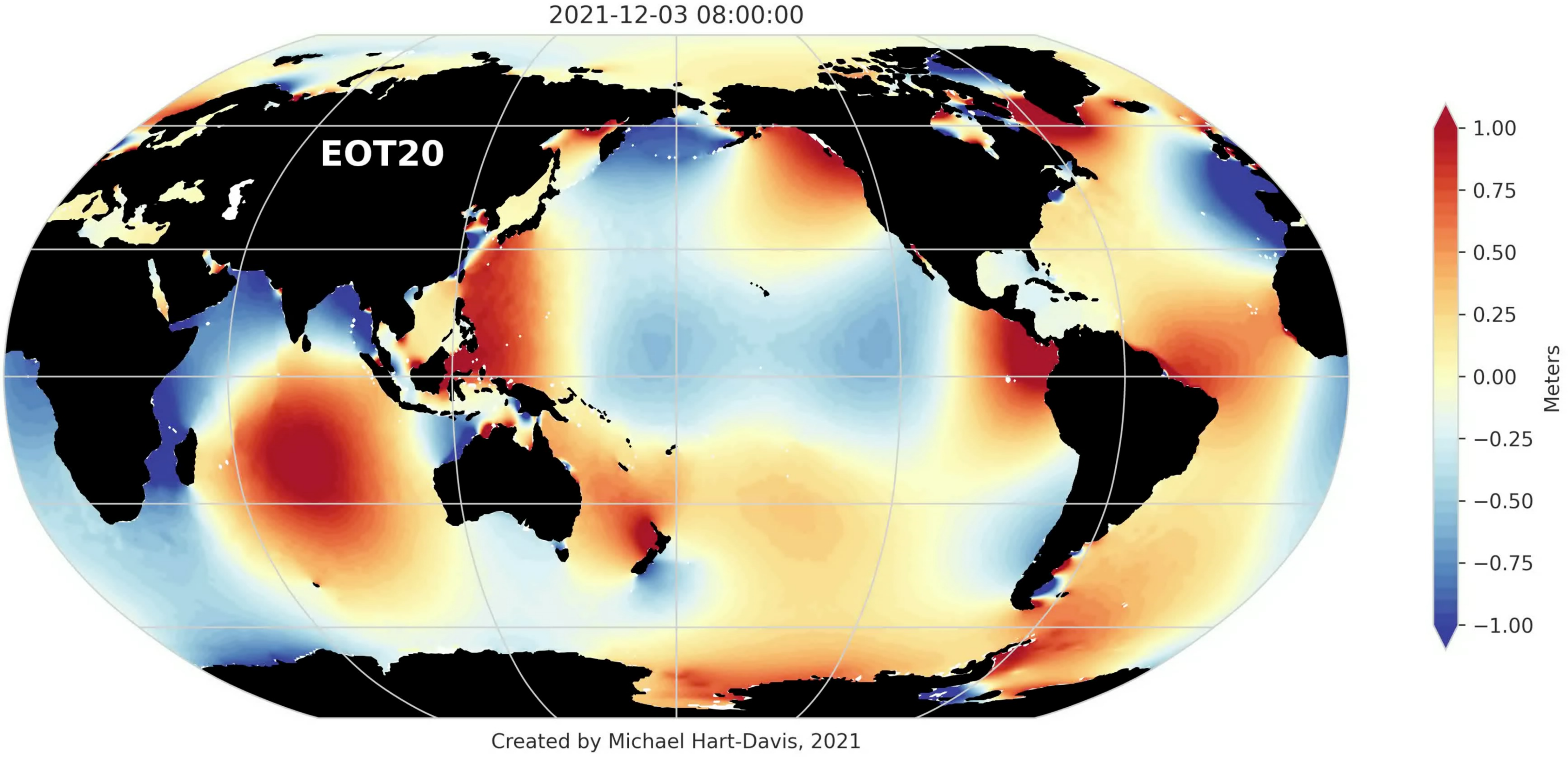


Figure. The amplitude and phase (contour lines in 60 degree increments) of the M2, N2, S2 and K2 tidal constituents

Ocean Tides – A Global Empirical Ocean Tide Model



https://www.youtube.com/watch?v=L7vtDhPzq6w

Global Tide Gauge Analysis

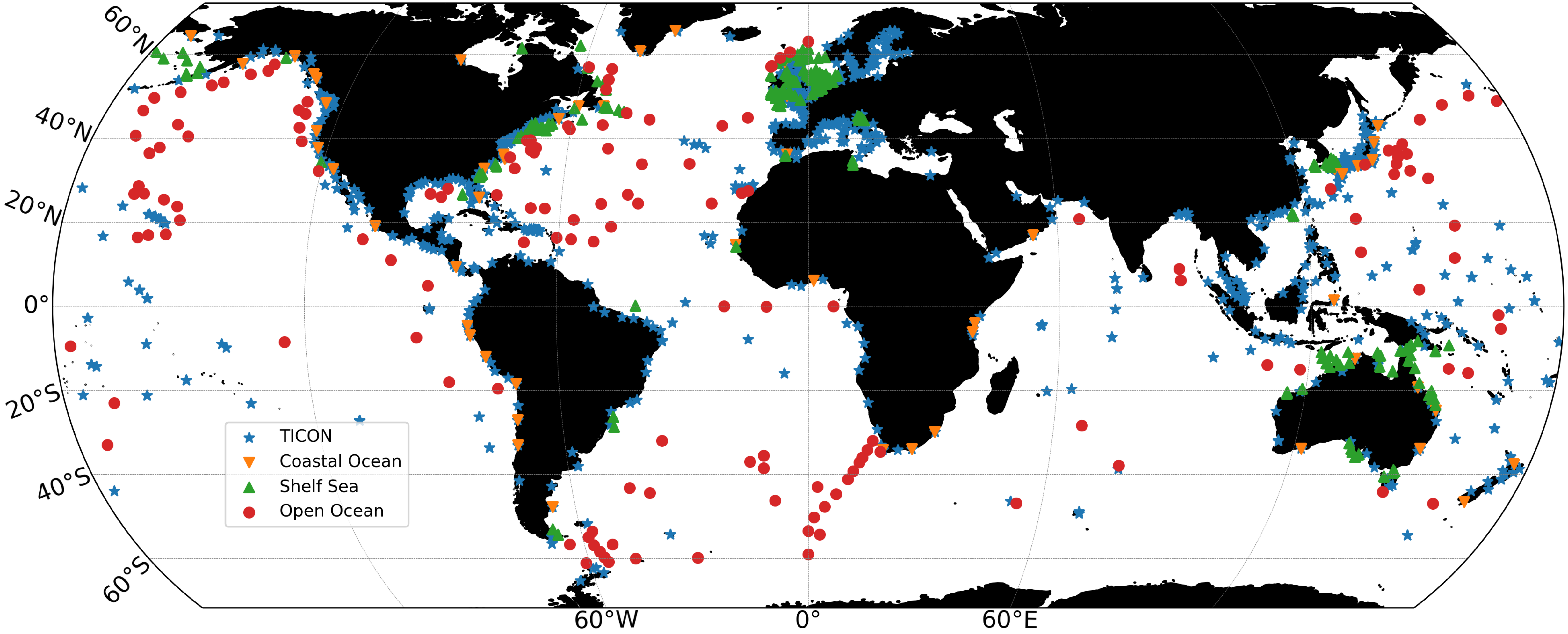
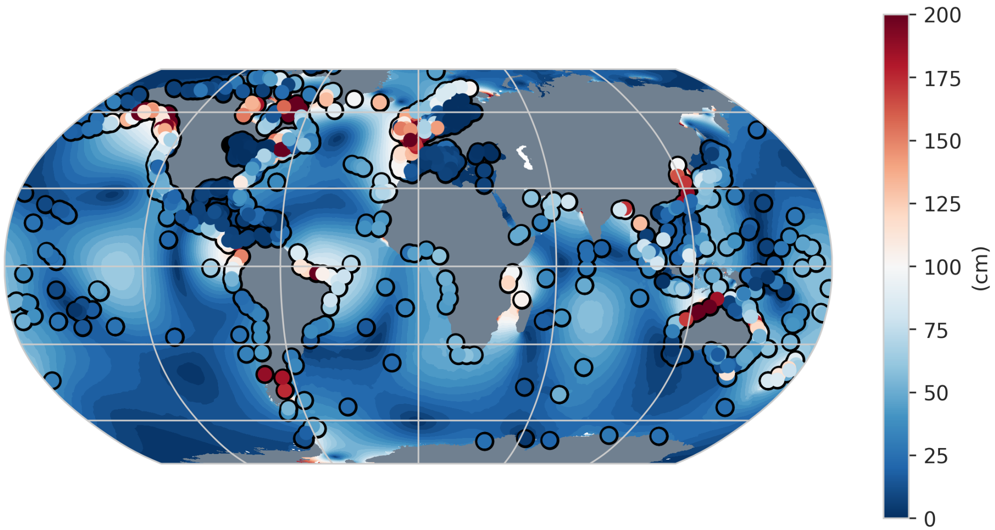
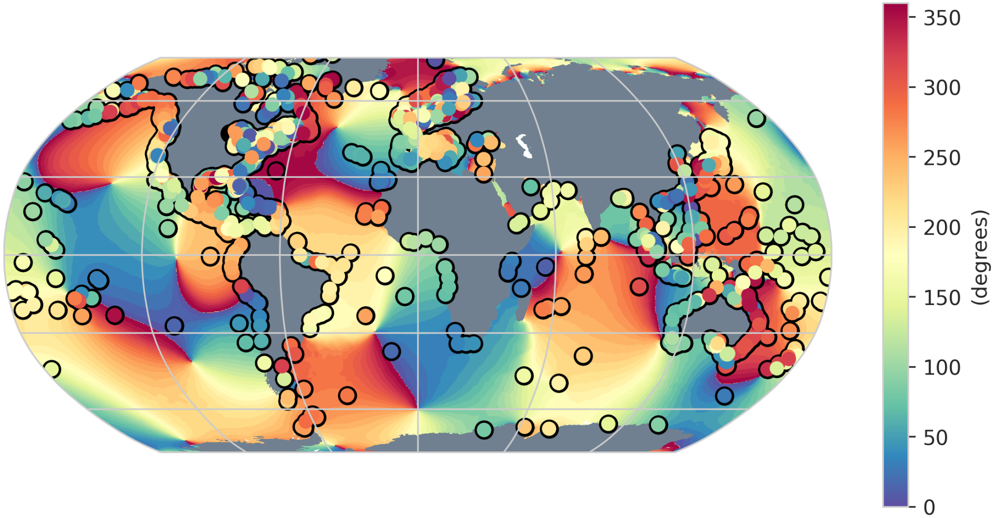


Figure. The tide gauge distribution used in the validation of the models

Side Note: TICON-3





TICON-3:

The TIdal CONstants (TICON) dataset was first published in Piccioni et al (2019). The dataset has served the community well as it was used for the validation of global ocean tide models in several studies (e.g. Hart-Davis et al 2021; Sulzbach et al 2021).

- An update is in process of being made public, based on the updated GESLA-3.
- 3679 Tide Gauges
- 1.1 billion observations
- Above 66N/S – 70 tide gauges
- TICON-3, M. Hart-Davis, D. Dettmering, F.Seitz (2022) Pangaea.

Global Tide Gauge Analysis

Table. The Root Mean Square (RMS) and RSS (Root Square Sum) in cm of the eight major tidal constituents for five global tide models

Constituent	GOT4.8	DTU16	EOT11a	FES2014	EOT20
M2	5.313	4.020	4.839	3.587	**3.352**
N2	1.326	0.908	1.311	0.805	**0.802**
S2	2.484	1.480	2.330	1.434	**1.411**
K2	1.159	0.848	1.093	**0.744**	0.783
K1	1.214	1.051	1.209	**0.866**	0.906
O1	0.981	0.837	0.843	0.673	**0.653**
P1	0.785	0.807	0.772	**0.664**	0.687
Q1	0.384	0.359	0.383	**0.276**	0.360
RSS	6.380	4.741	5.888	4.224	**4.042**

Global Tide Gauge Analysis

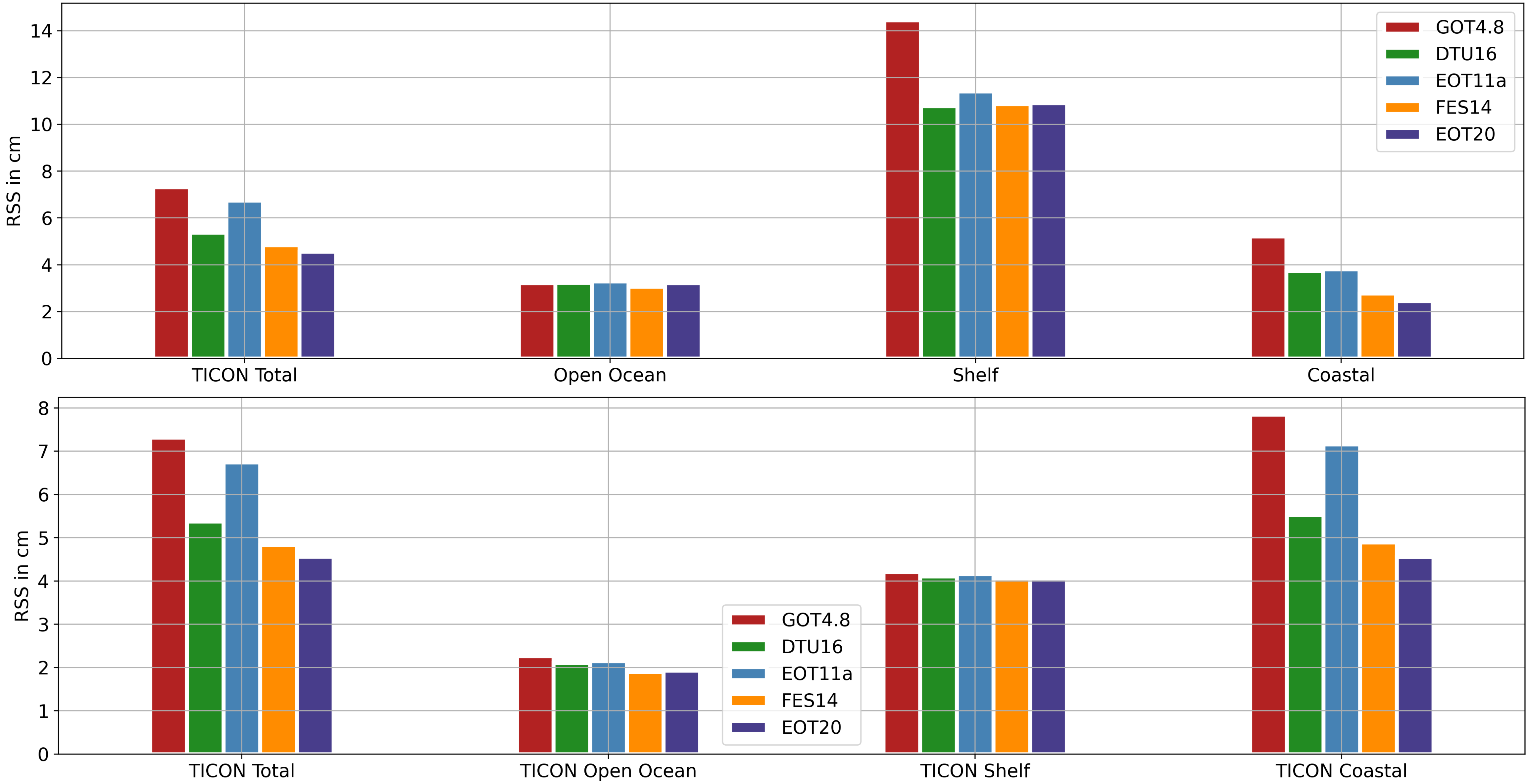
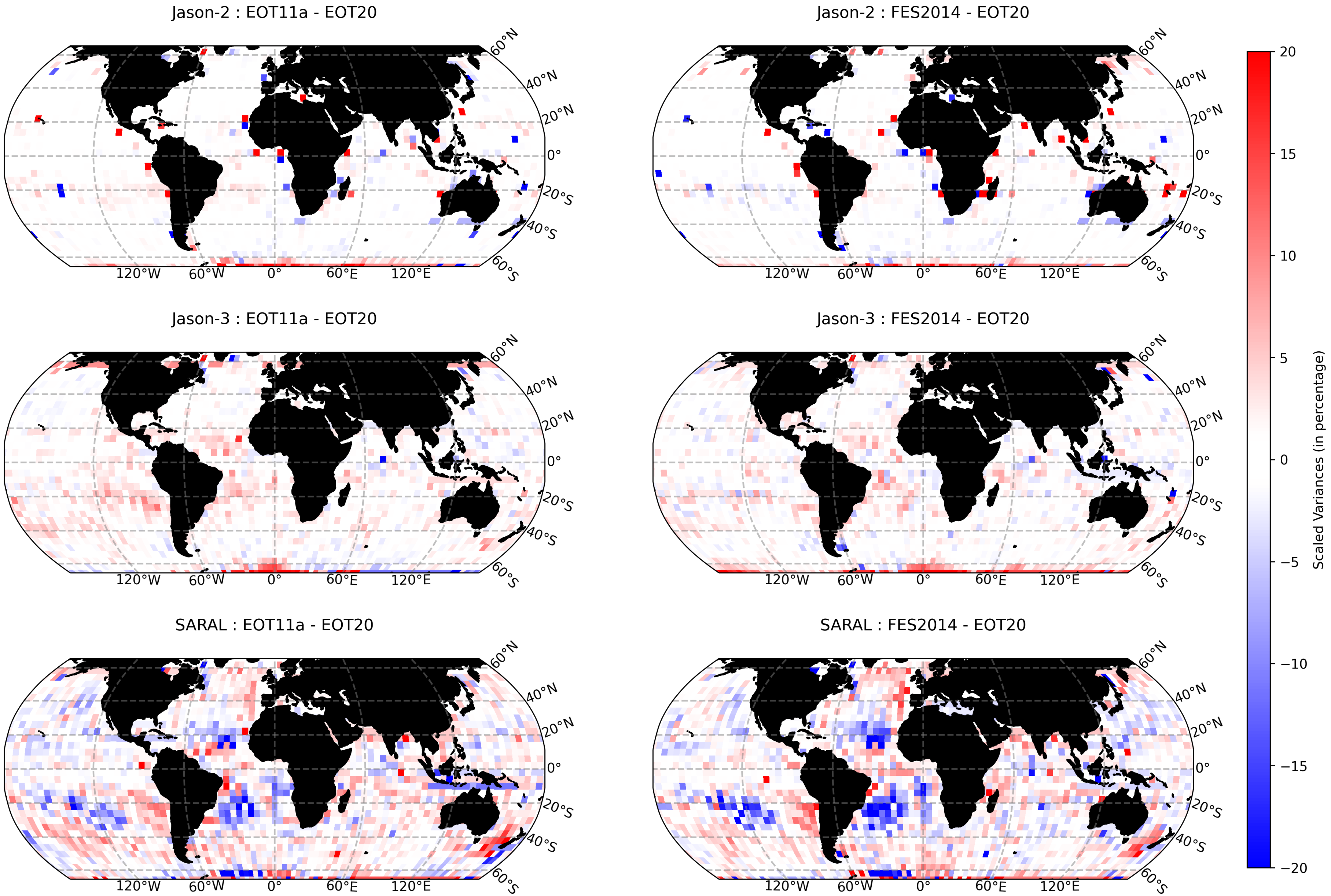


Figure. The Root Square Sum (RSS) for the eight major tidal constituents from the five tide models in the different regions.

Gridded Sea Level Variance Analysis



- SLA estimated for three mission for each cycle
- Ocean tide correction varied between EOT20, EOT11a and FES2014
- Each cycle is gridded onto a 4-degree grid
- Scaled variance between each cycle estimated for the full altimetry mission
- Overall, EOT20 showed a mean reduction in variance compared to both EOT11 and FES2014 for all altimetry missions
- **Figure.** The scaled sea-level variance differences between the tide models

Gridded Scaled Variance Analysis

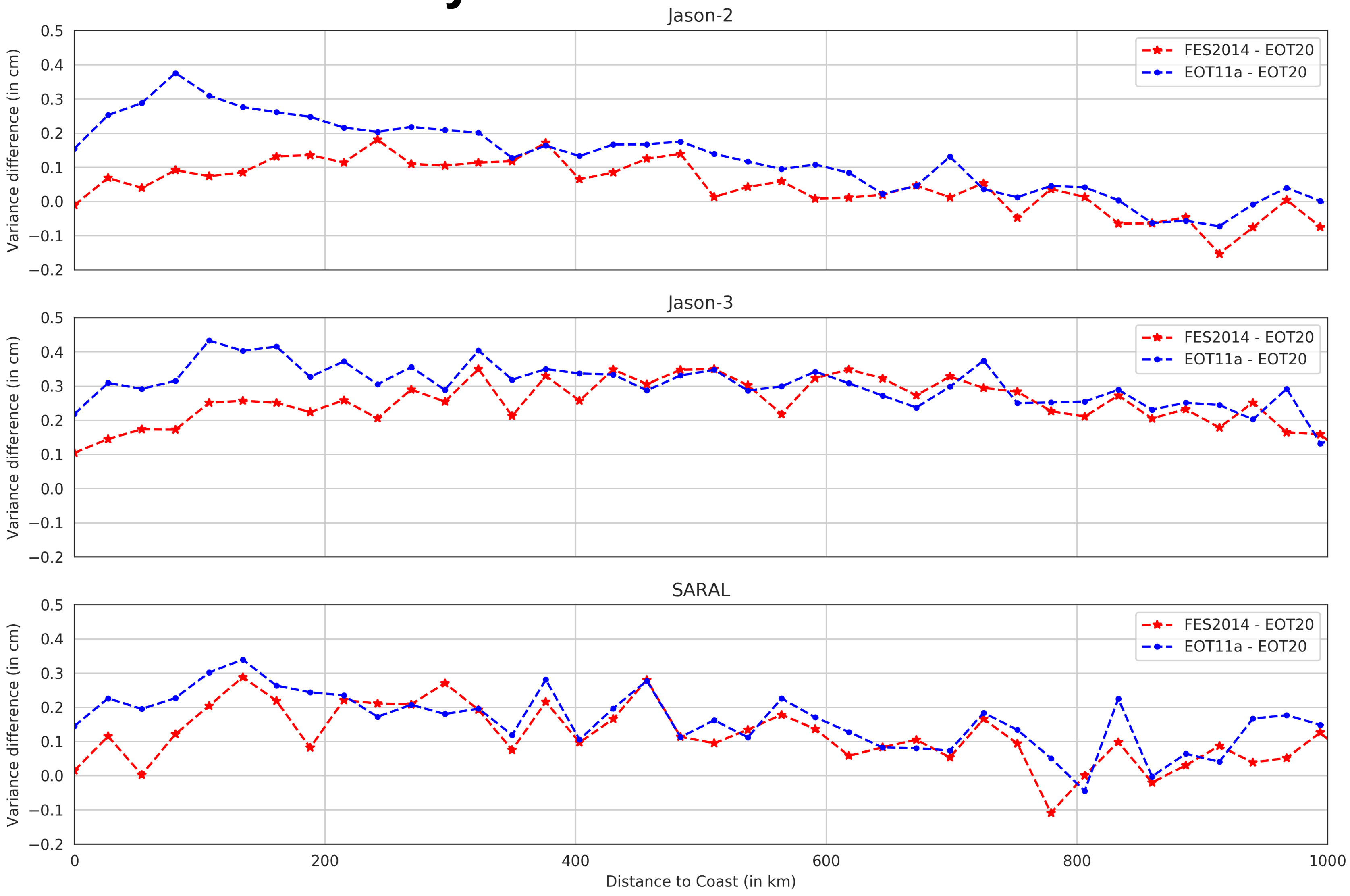


Figure. The scaled variance differences between the tide models as a function of distance to coast.

Minor tidal signals

The importance of minor tides

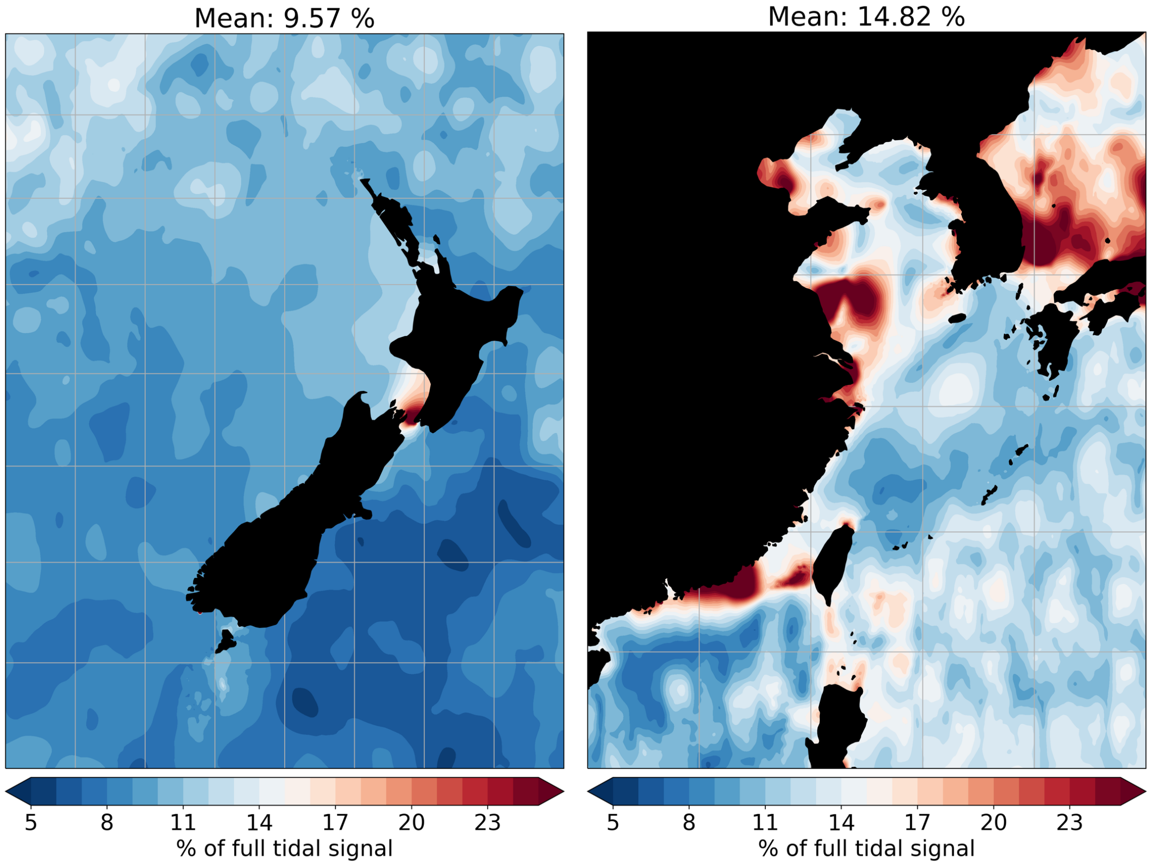


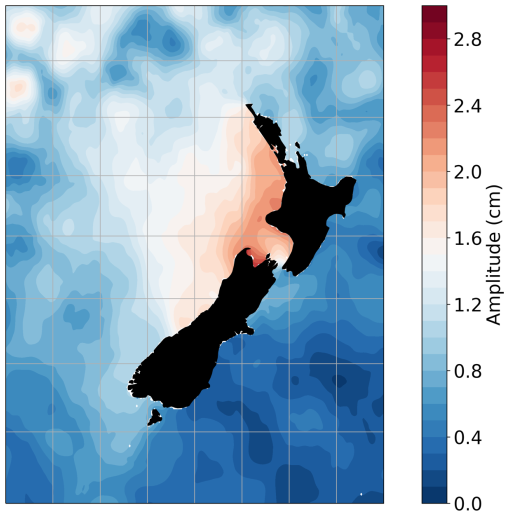
Figure. The percentage contribution of seventeen 'minor' tides from a regional EOT model relative to the full tidal signal comprising of 34 tidal constituents (including long-period and the major constituents) in (left) New Zealand and (right) the Yellow Sea + East China Sea.

- Minor tides have long been included in the estimation of tidal corrections and play an important role in the prediction of sea level from satellite altimetry.
- In the two regions shown here, the 17 minor tides* make up 9.6% and 14.8% of the tidal signal obtained from a total of 34 constituents, respectively.
- Most empirical ocean tide models infer the minor tidal constituents using Admittance theory (Ray 2017), due to the difficulty of estimating these tidal signals and computational load.
- In this presentation, we discuss the accuracy of inferred tidal constituents compared to direct estimations from empirical and numerical model simulations.

* Minor tides used: R2, NI2, MS4, M4, LA2, MSF, EPS2, N4, MSQM, M3, MKS, MN4, MI2, J1, T2, L2 and MKS2

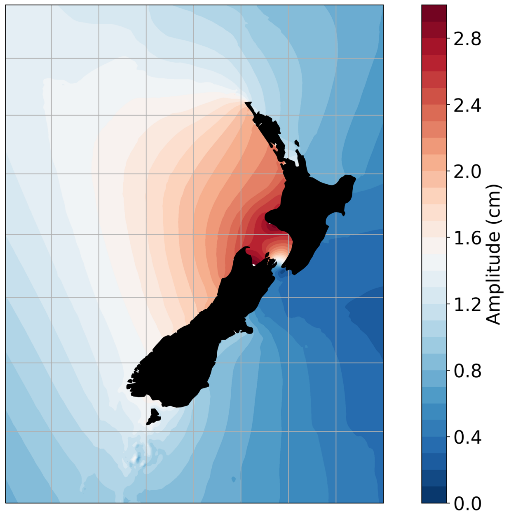
The approaches of minor tide estimation (showing J1 below)

- Empirical Model Estimation (EOT20, *Hart-Davis et al 2021a*)



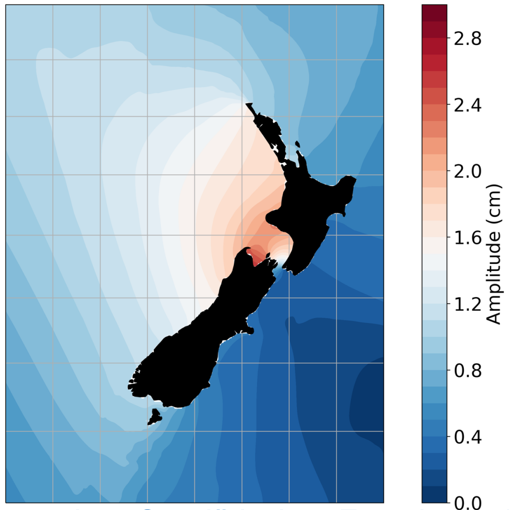
- EOT20 is the latest in a series of empirical ocean tide (EOT) models derived using residual tidal analysis of multi-mission satellite altimetry at DGFI-TUM.
- In this study, a regional version of EOT20 (henceforth known as EOT-R) is presented that contains an extended number of tidal constituents.

- TiME hydrodynamic model (TiME, *Sulzbach et al 2021*)



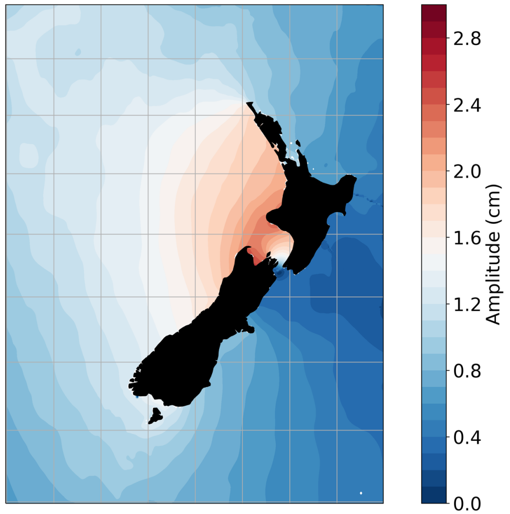
- TiME is a numerical tide model that provides a vast number of minor tidal constituents that.
- TiME solves the shallow water equations on a global 1/12-degree grid under consideration of dynamic effects, that are known to exert a critical influence on tidal oscillation systems.

- Data-assimilative hydrodynamic model (FES2014, *Lyard et al 2021*)



- The FES2014 model is an ocean tide model that produces global atlases of 34 tidal constituents.
- FES2014 is considered a valuable model for satellite altimetry corrections and, therefore, provides suitable reference for the results presented below.

- Linear admittance approach (from EOT20 tide model)



- Using linear admittance, eight additional tidal constituents were inferred from the EOT20, henceforth referred to as EOT-I.
- These constituents are:

  2N2, ϵ2, MSF, T2,
  J1, L2, μ2 and ν2.

Regional improvements based on constituent estimation

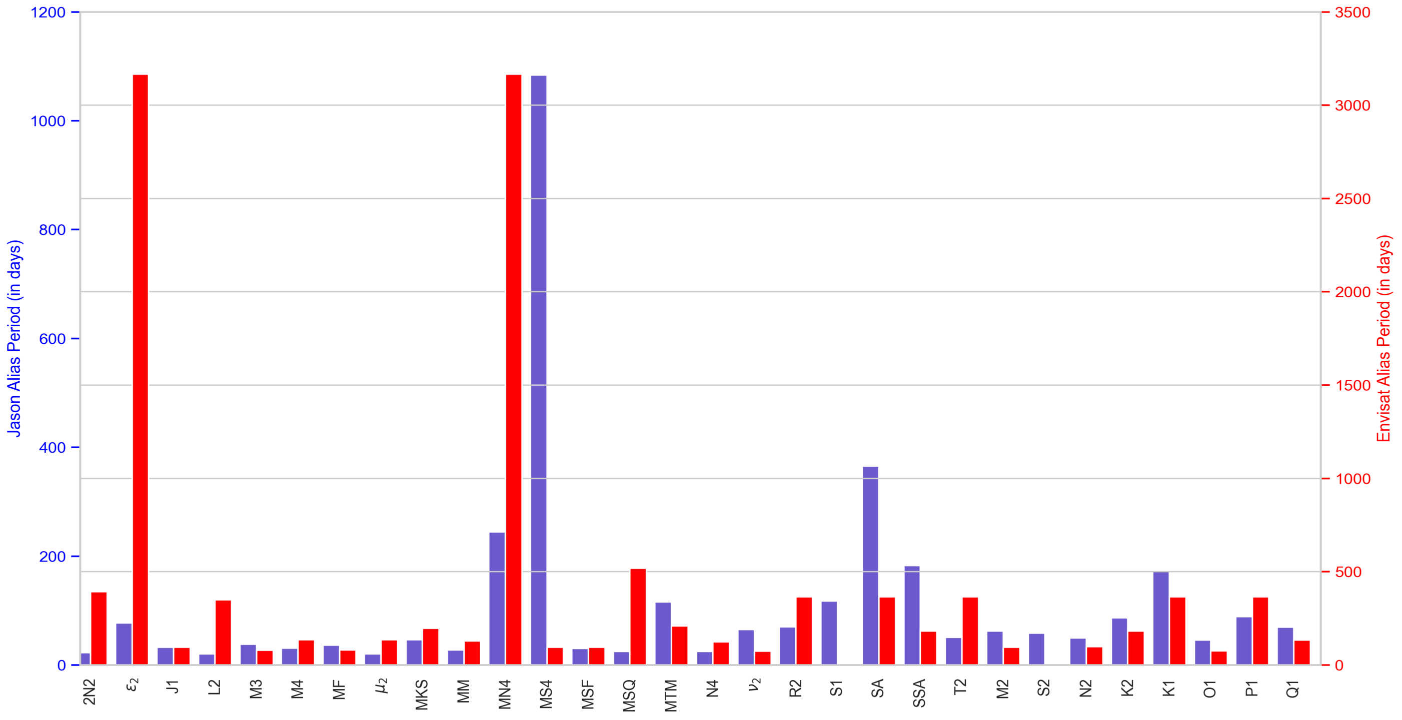


Figure. Aliasing periods of tides base on the orbits of the Jason and Envisat missions for the major and minor tides.

- The tidal aliasing periods of certain tidal constituents allow for the determination of certain tides from along-track satellite altimetry.
- Based on this, in order to get an accurate determination of the tidal heights based on using the full spectrum of tidal constituents.
- A common theory to determine tides, is linear admittance theory which is the relation of the tidal height with respect to the amplitude of the corresponding tide generating potential for a specific tidal wave.
- We evaluated the accuracies of these estimations vs other models and tide gauges

Hart-Davis, M.G., Dettmering, D., Sulzbach, R., Thomas, M., Schwatke, C. and Seitz, F. 2021. Regional Evaluation of Minor Tidal Constituents for Improved Estimation of Ocean Tides. Remote Sens., 13, 3310. https://doi.org/10.3390/rs13163310

Regional improvements based on constituent estimation

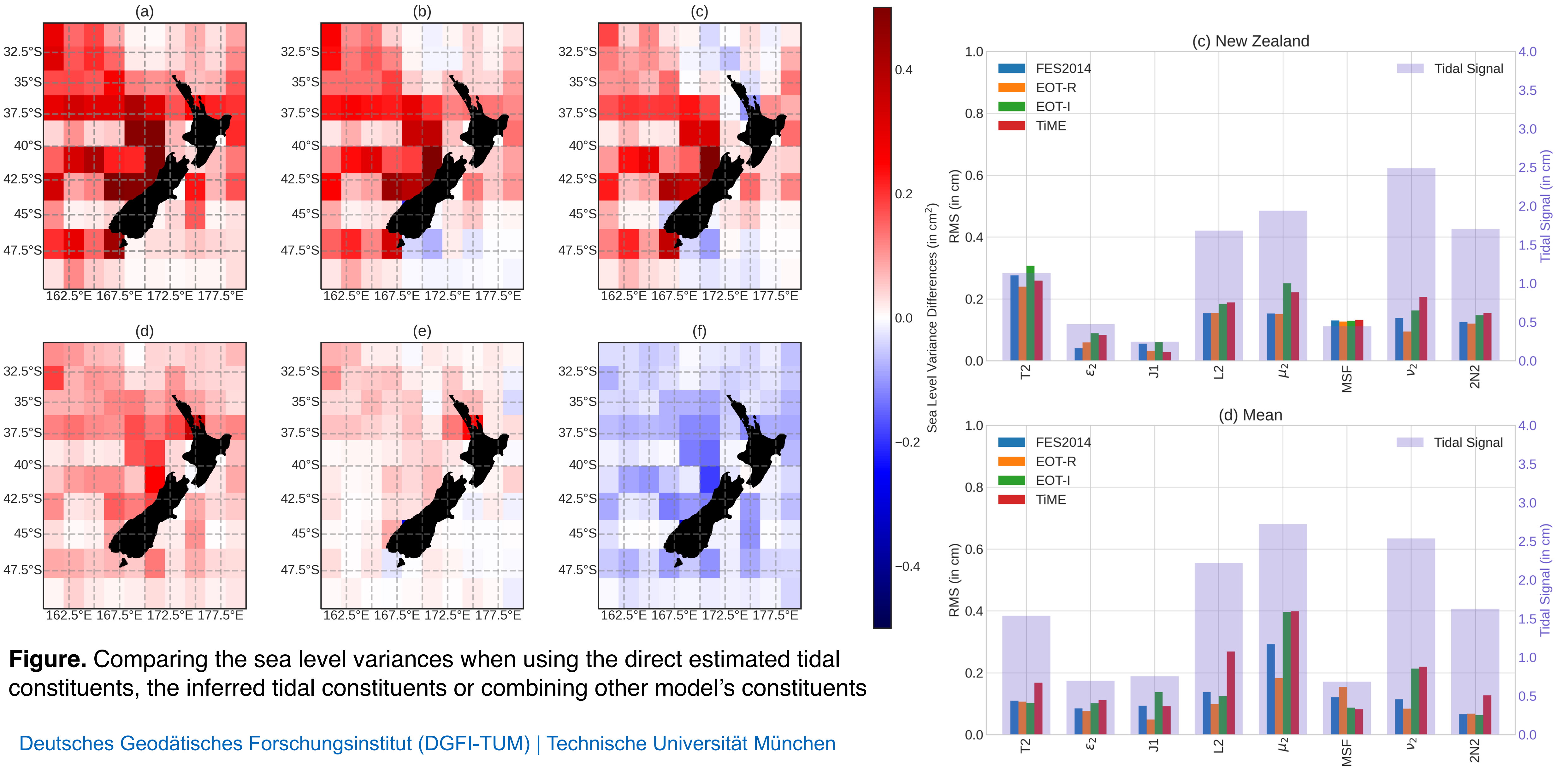


Figure. Comparing the sea level variances when using the direct estimated tidal constituents, the inferred tidal constituents or combining other model's constituents

Third Degree Tides

Modeling gravimetric signatures of third-degree ocean tides and their detection in superconducting gravimeter records

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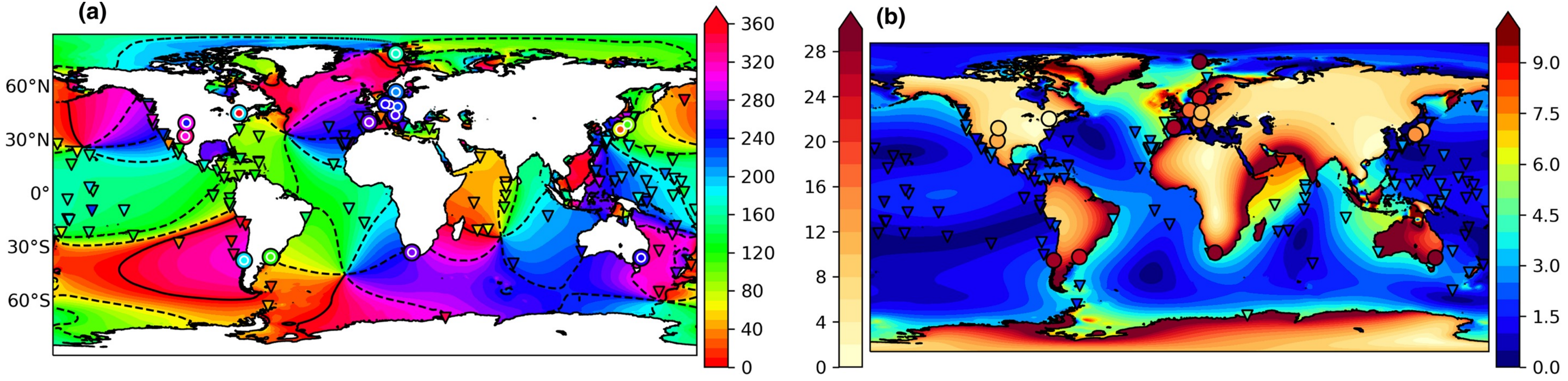
Received: 1 November 2021 / Accepted: 18 February 2022

Associated Dataset:

Hart-Davis, M. G., Sulzbach, R., Dettmering, D., Thomas, M., & Seitz, F. (2022). TICON-td: Third-degree tidal constants based on GESLA sea-level records from globally distributed tide gauges (data). *Deutsches Geodätisches Forschungsinstitut, München. Pangaea*.



Tides in Polar Regions

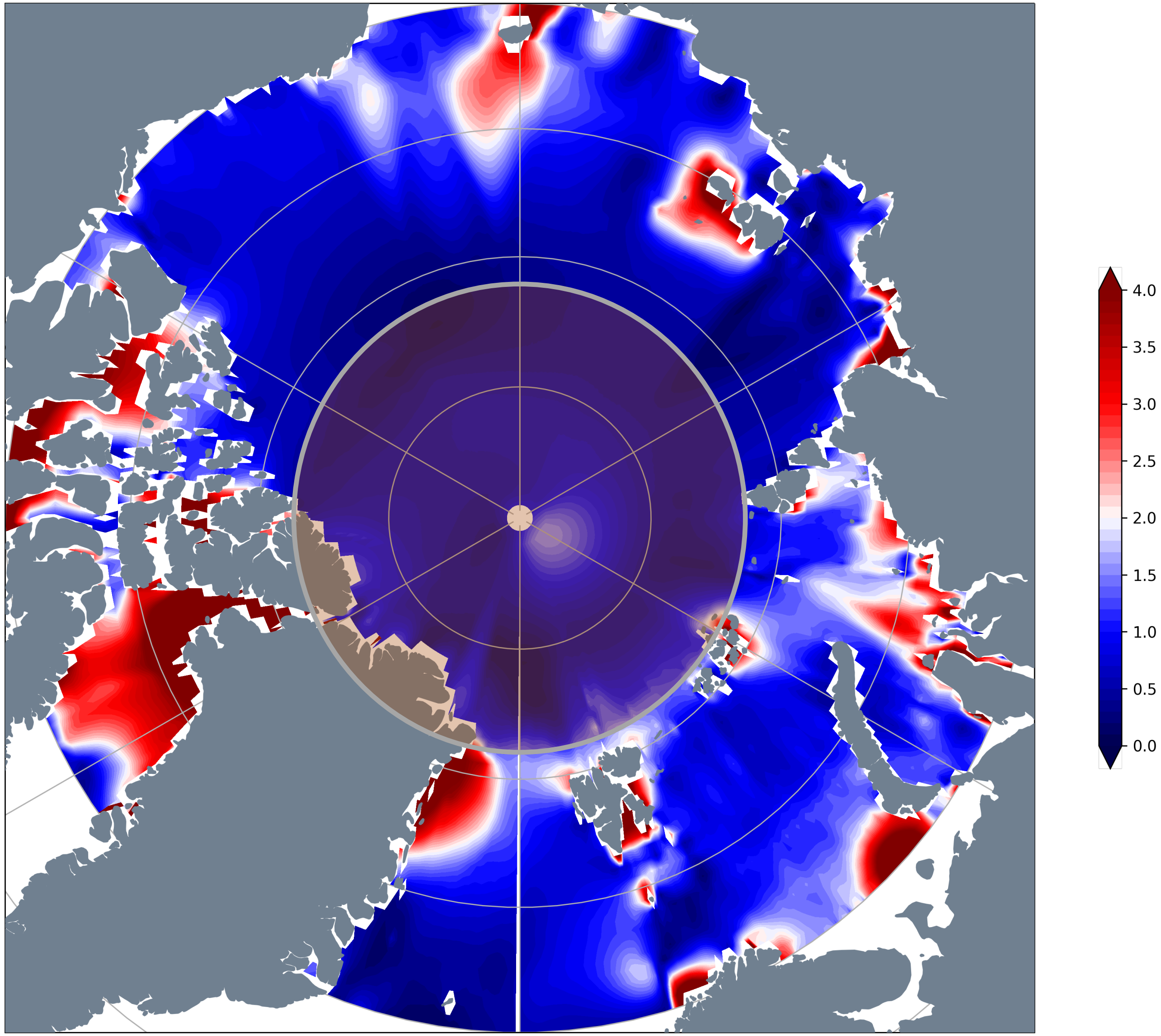
- **Figure.** The standard deviation (cm) of only the amplitude of the M2 tide for 5 major tide models.

- Sea ice and poor bathymetry mean that the polar region is an extremely difficult region for both empirical and numerical models.

- Most tide models differ significantly in large parts of the Arctic and a high standard deviation can be see (here we see a standard deviation in the order of centimeters for the most understood tidal constituent).

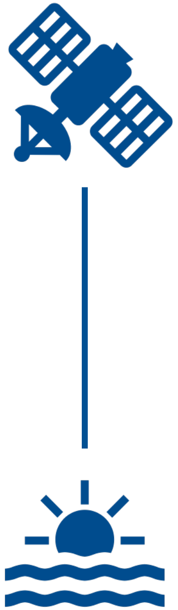
- Difficulties also arise from the lack of observations and limited altimetry coverage.

- The major focus of research done on ocean tides at DGFI-TUM in the near future.



Take home messages

Development	Validation	Results	Future Work
EOT20 builds on the previous EOT global models by incorporating ALES retracked data, the FES2014 tide model as a reference model and an improved coastal representation	The model was validated using tide gauges and sea level variance analysis with the results being compared to other global tide atlases.	EOT20 demonstrates a clear improvement in the coastal region compared to other global ocean tide models.	The inclusion of additional altimetry missions to allow for the expansion into the polar regions and the improvement of altimetry data to optimise tide estimations.



Thank you! Questions?

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