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Tides in complex coastal and polar regions

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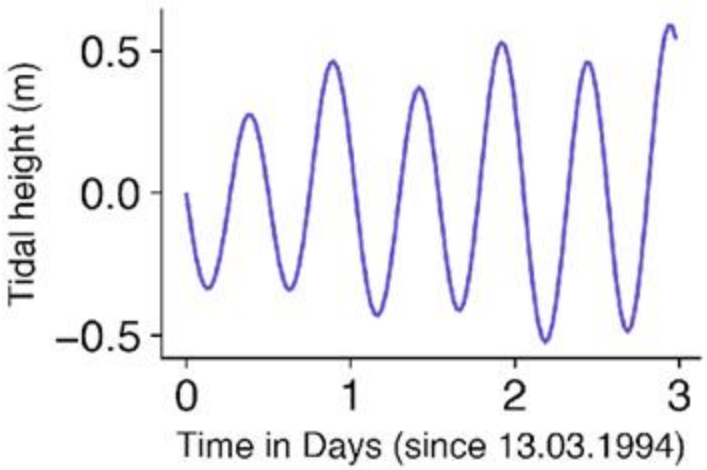
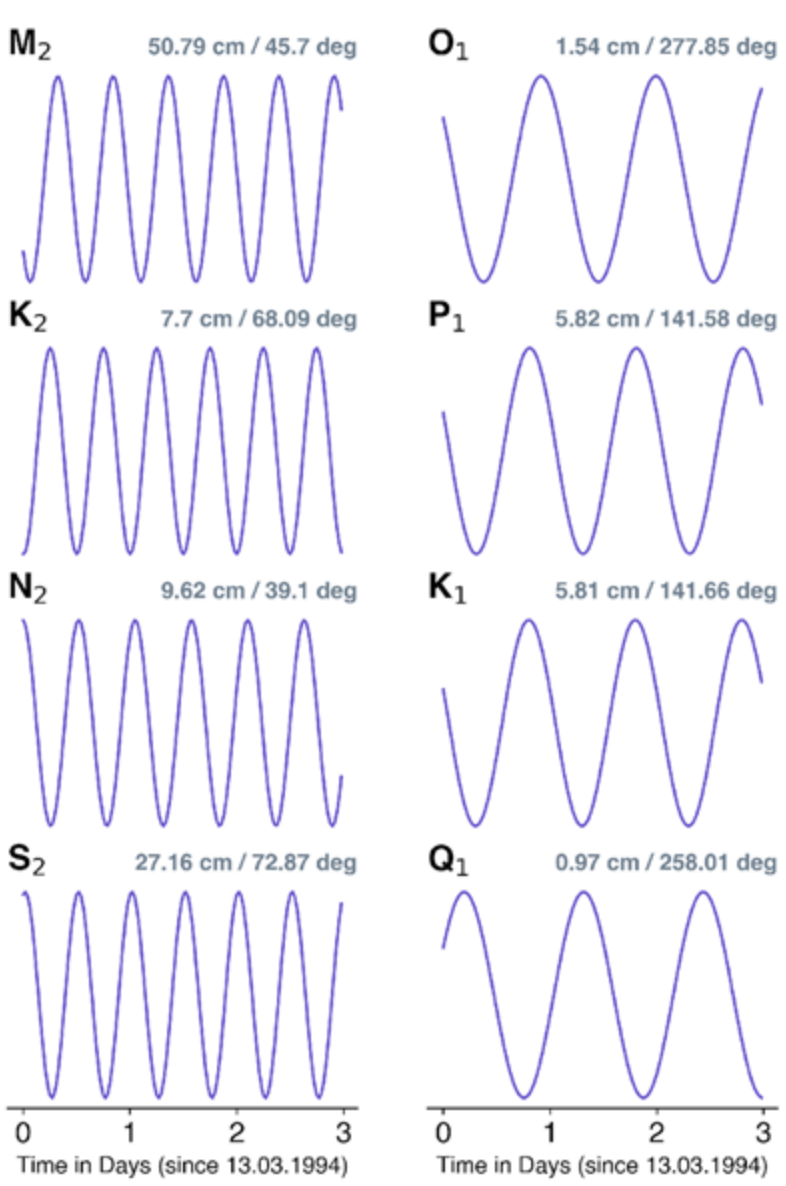
Investigating SWOT for ocean tidal research

- The coastal and polar regions have typically been the most challenging for tidal research, thanks to the complex interactions with tides with several factors such as sea ice, river dynamics and bathymetry.
- The accurate understanding and prediction of tides within these regions can be vital for the use of SWOT in non-tidal applications, which is a current challenge in modern modelling efforts.
- Tides are important across the land-ocean domain, therefore, the different SWOT products are crucial tools for tidal research.
- The door is then open to study tidal dynamics from observations at unprecendented spatial scales but in increasingly complex domains where conventional altimetry has traditionally struggled:
    1. Complex coastal regions [inlets]
    2. Across the land-ocean-aquatic-continuum
    3. Fjords and sea ice regions

Tide theory





Least Squares Harmonic Analysis:

$$\zeta(t) = \sum H_n cos(\theta_n t - g_n),$$

$H_n = Amplitude$
$g_n = phase\ lag$
$\zeta_n = sea\ level.$

SWOT for Tidal Research: North Sea

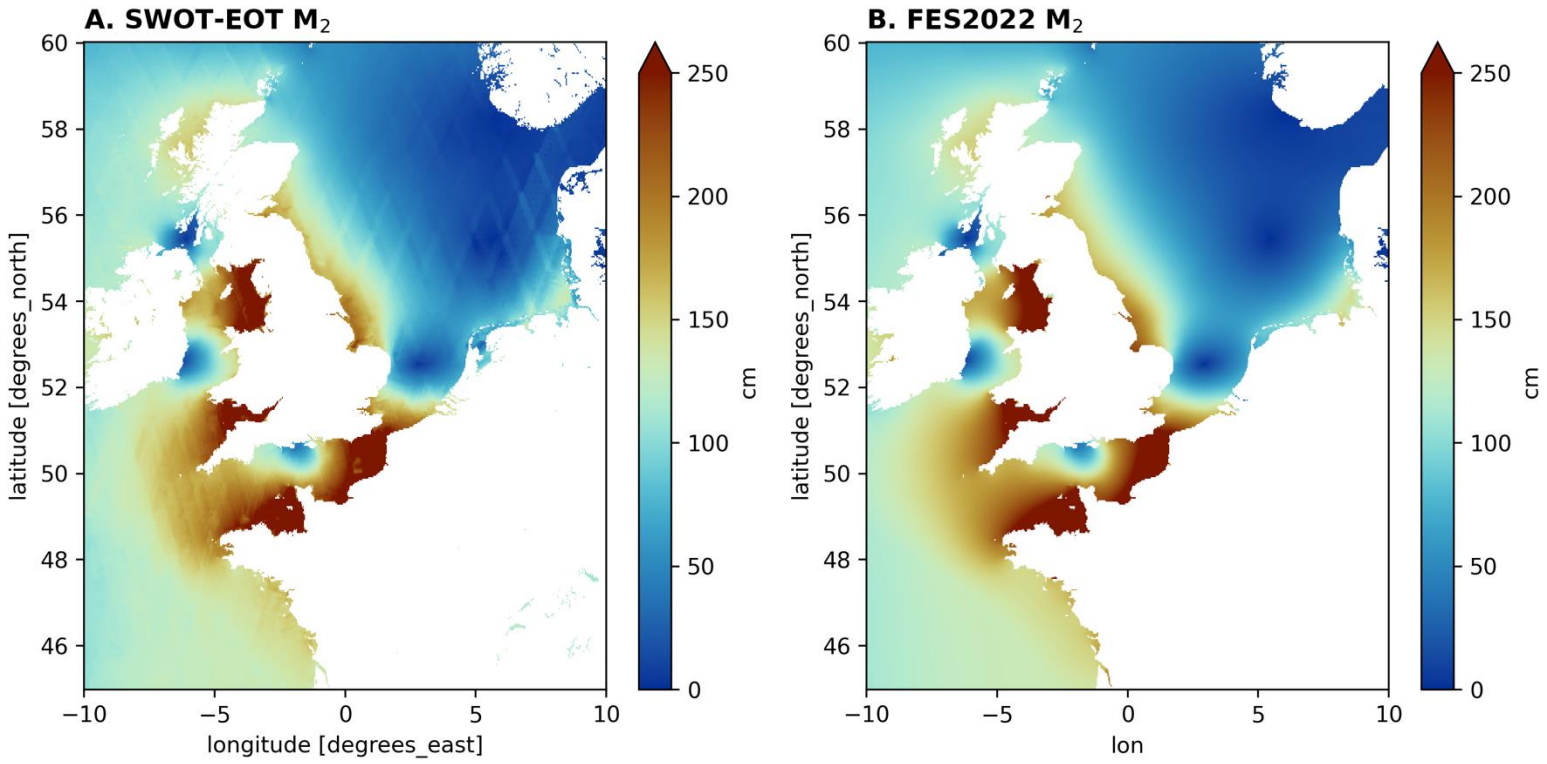
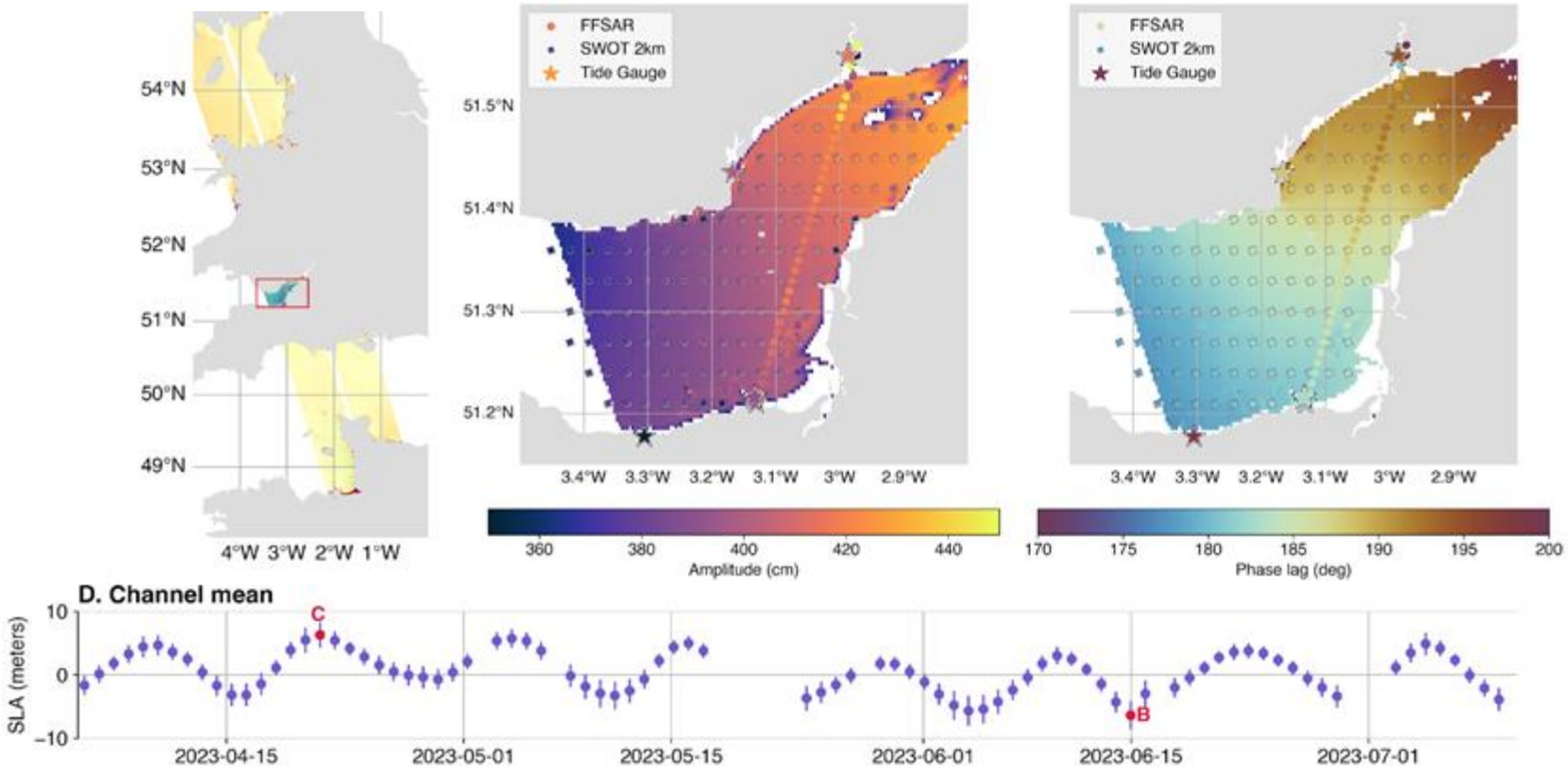


Fig. Full M_2 amplitude estimated from the full SWOT time-series [until September]. For comparisons, the M_2 of FES2022 (Lyard et al 2021; updated) is shown.

- For M_2 and several tidal constituents (not shown), SWOT already performs pretty well, at least visually, in resolving the large scale tidal features.
- We can clearly see some effects of striping on the SWOT estimations, which can be a result of gridding procedures or roll correction error etc etc.
- As an independent dataset, SWOT also confirms that models, such as FES2022, are doing well at representing the observed tidal characteristics.

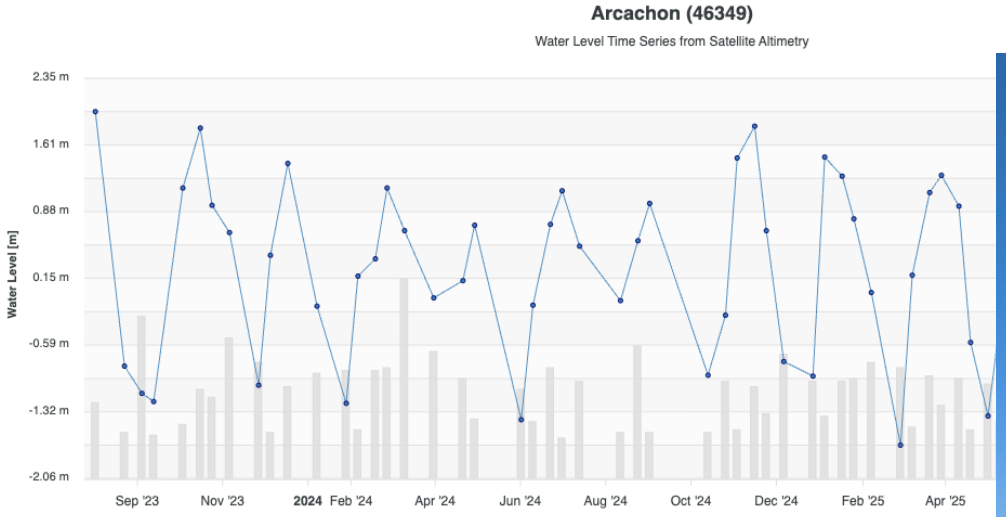
Complex Coastal Regions: Bristol Channel



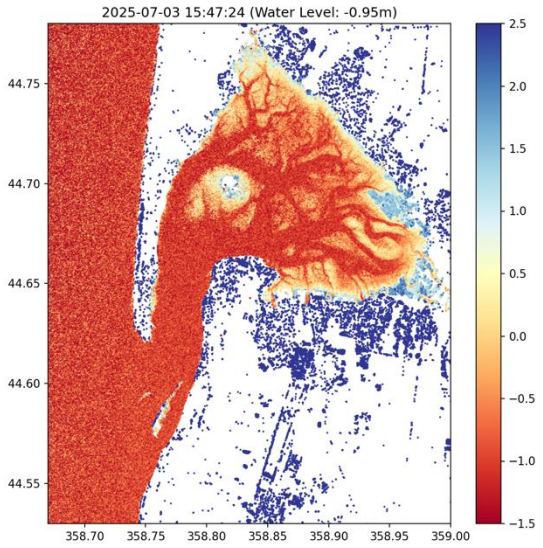
Hart-Davis, M.G., Andersen, O.B., Ray, R.D., Zaron, E.D., Schwatke, C., Arildsen, R.L., Dettmering, D. and Nielsen, K., 2024. Tides in complex coastal regions: Early case studies from wide-swath SWOT measurements. *Geophysical Research Letters*, *51*(20), p.e2024GL109983.

- Tide gauges from TICON-3 (Hart-Davis et al 2021) and Lichtman pers. comms. were **used for validation**.
- The 2km product showed mean differences of **2.58 cm** and **2.72 degrees** for the amplitude and phase lag, respectively.
- For the 250m product, the differences were **2.72 cm** and **4.03 degrees**, respectively.
- The FFSAR pass was on average 5.89 cm for amplitude and 5.25 degrees for phase lag different at collocated SWOT positions.

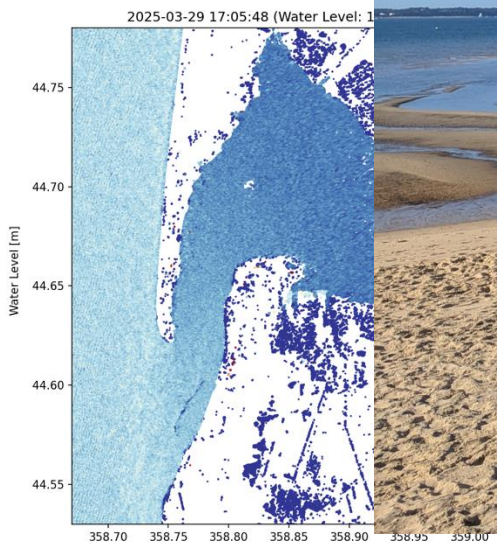
Coastal Coastal Regions: What about Arcachon?



Low Tide

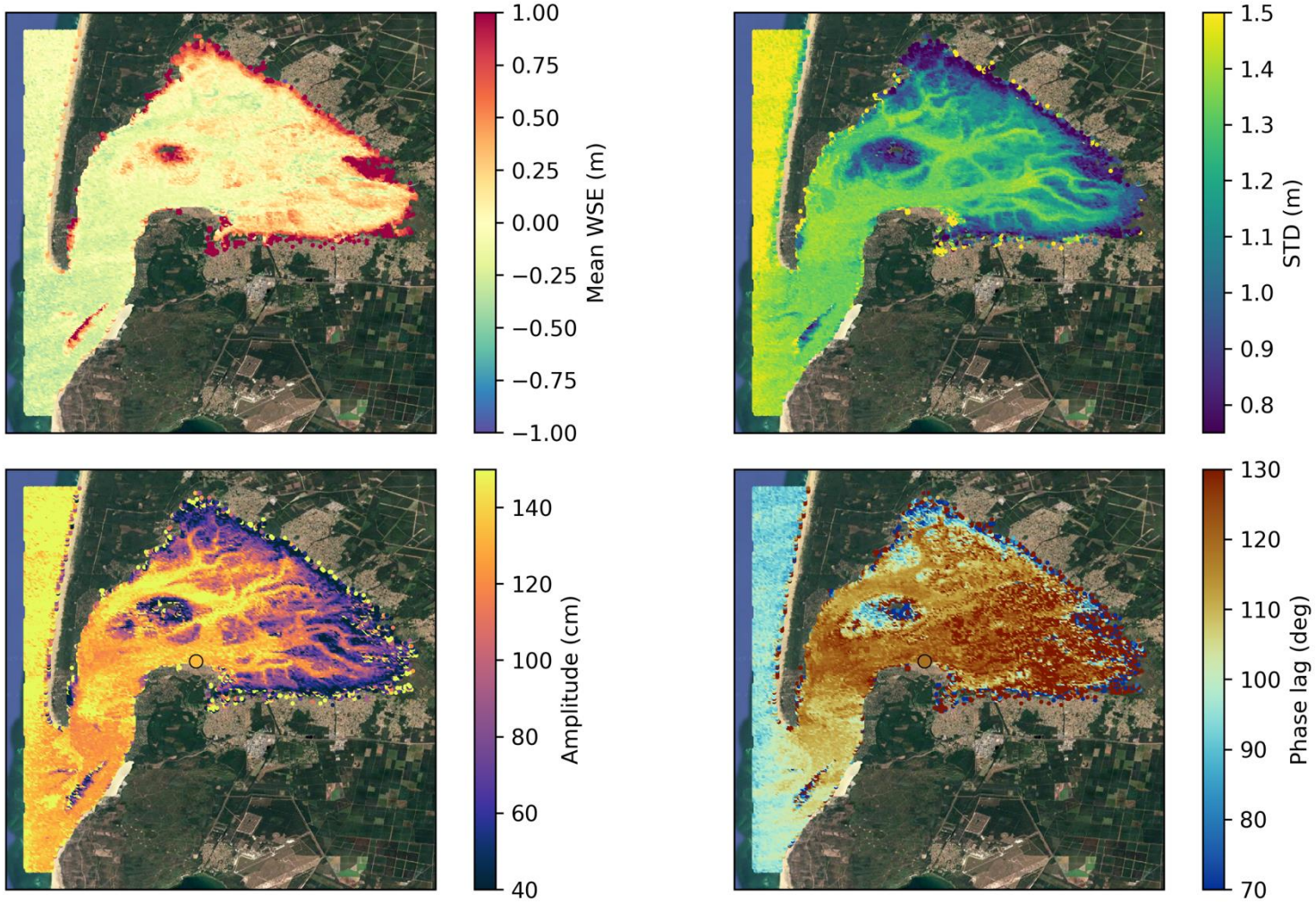


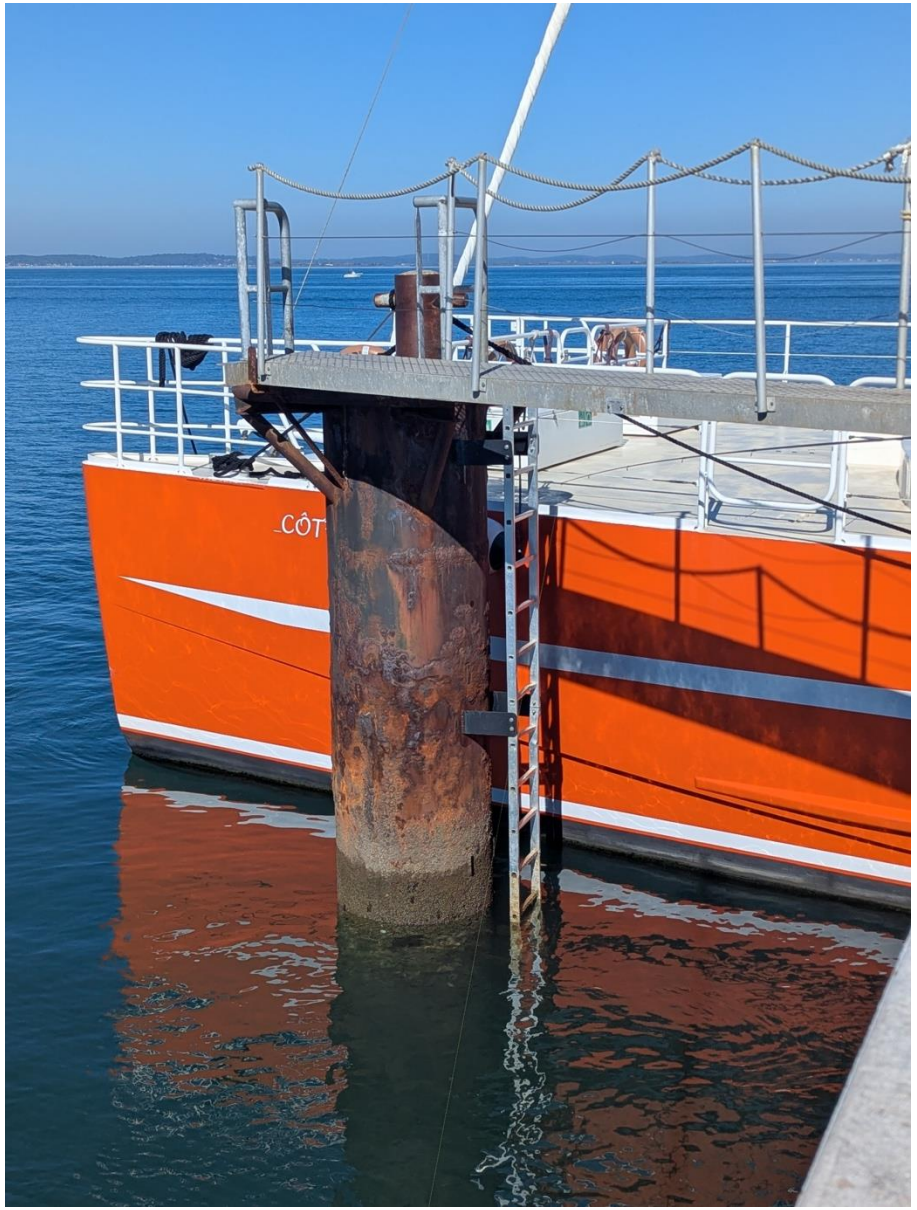
High Tid



Figures from C. Schwatke

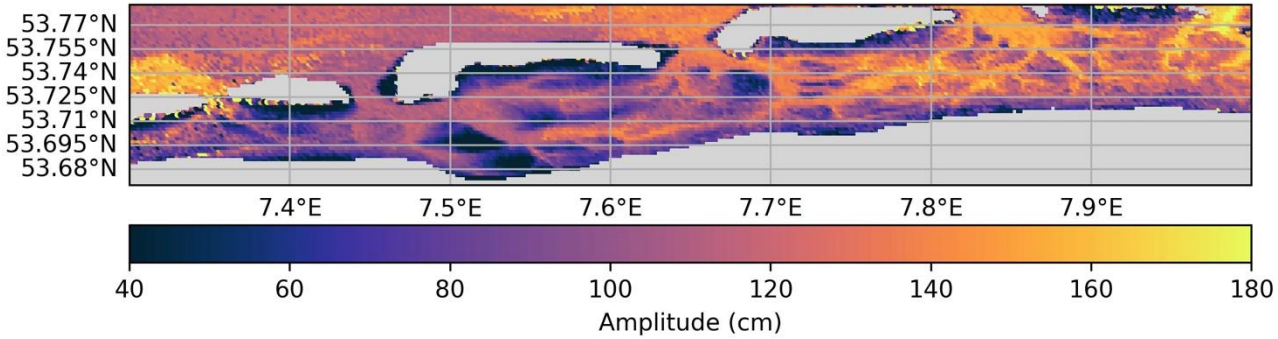
Coastal Coastal Regions: What about Arcachon?

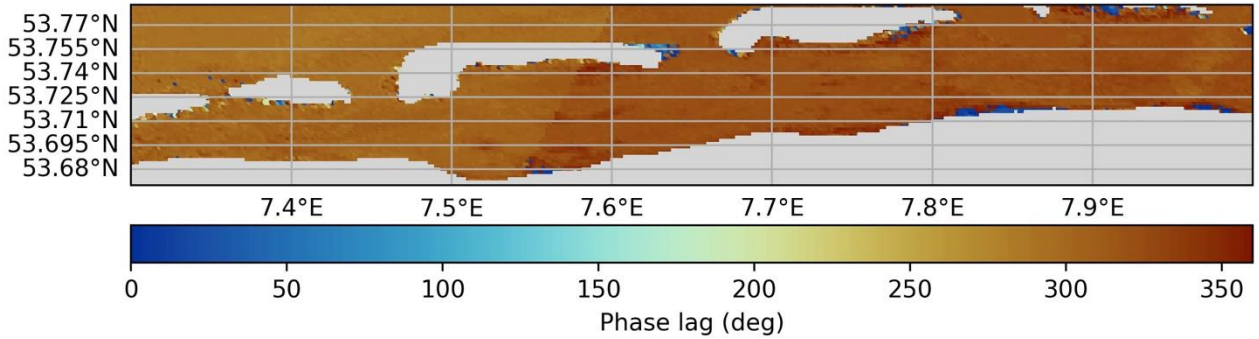




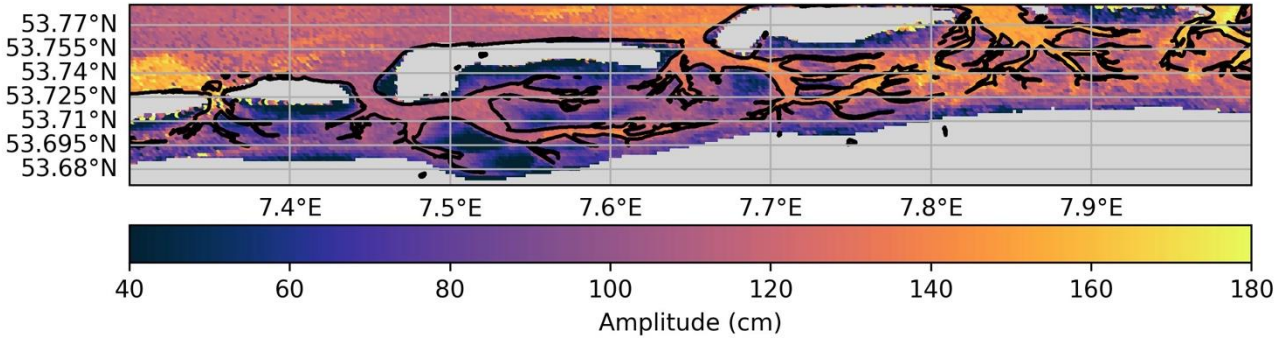
Wadden Sea: An idea?

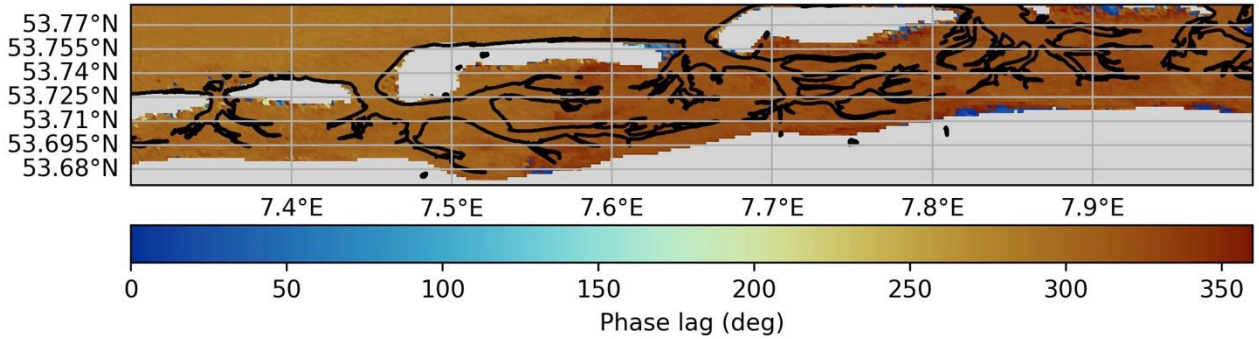
SWOT prediction in the Wadden Sea (M2 Tidal Constituent):



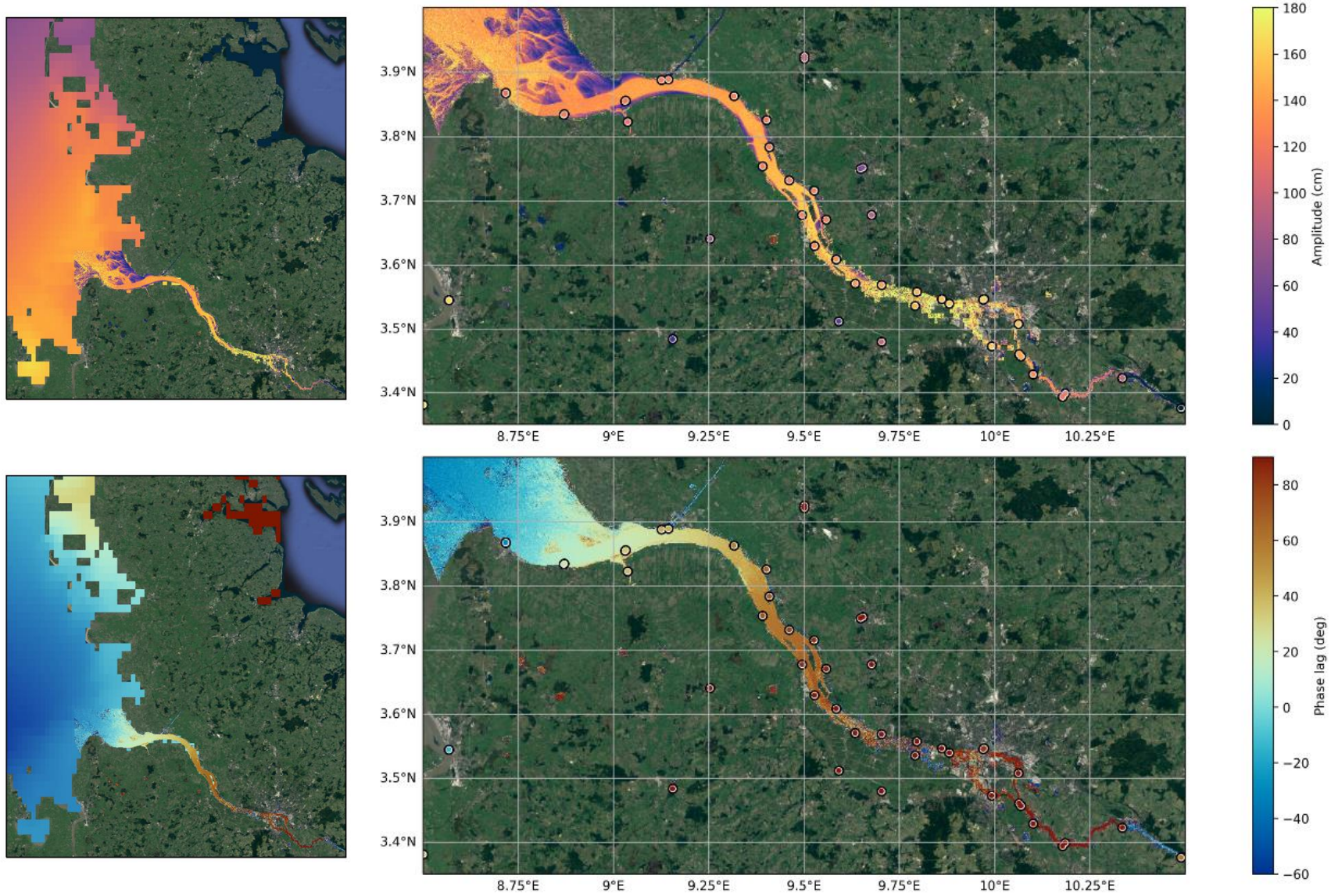


Plotting the ESA EOTideline project (https://eotideline.lab.dive.edito.eu/)





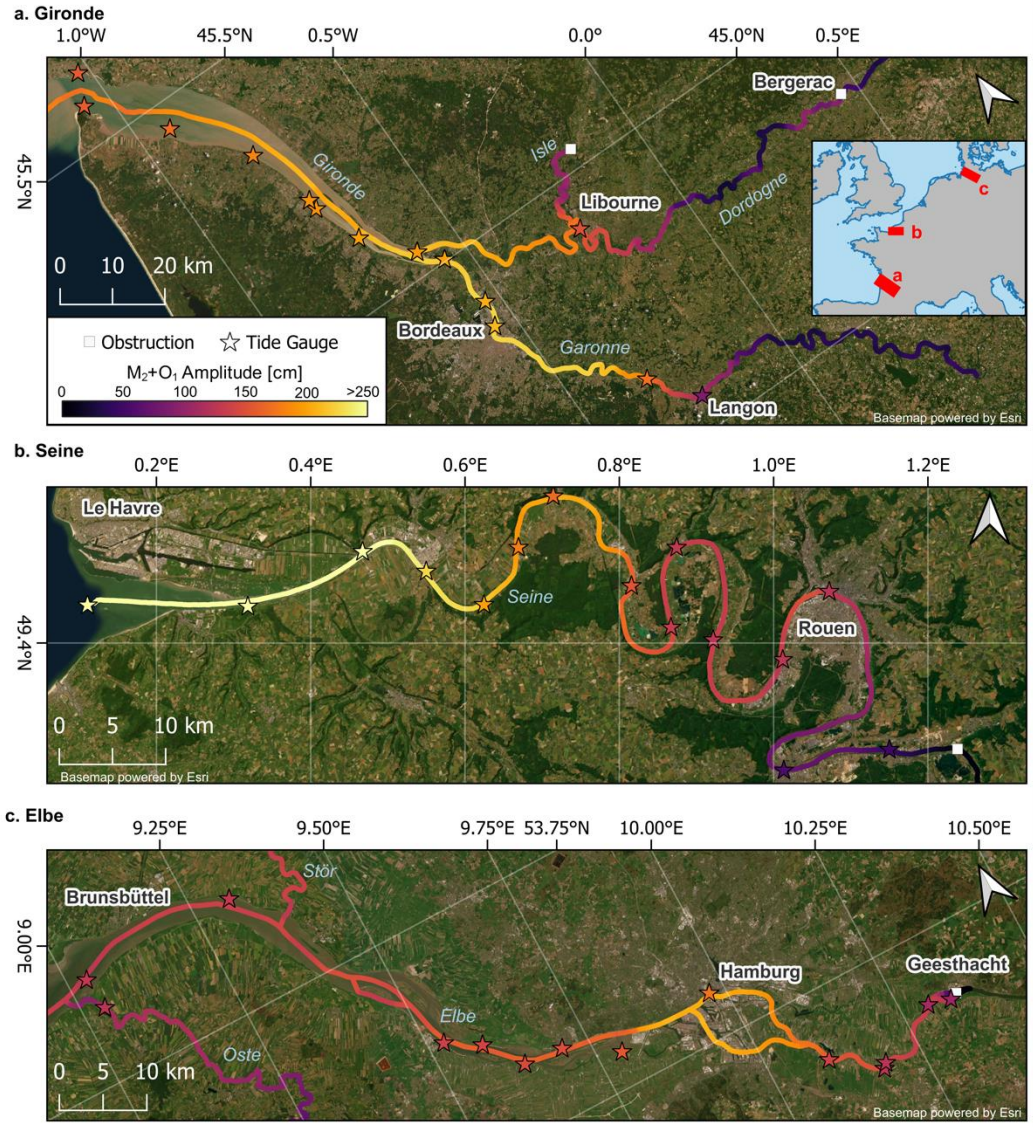
Tides across the land-ocean-continuum – Elbe River



- SWOT from 21-day repeat and 1-day repeat are used here for the Elbe River.
- **The FES2022 model** is used to provide the amplitude and phase lag outside of the river mouth (left subplots).
- Validation with TICON-3 showed a mean difference of:

Amplitude: 2.61 cm
Phase lag: 7.81 degrees

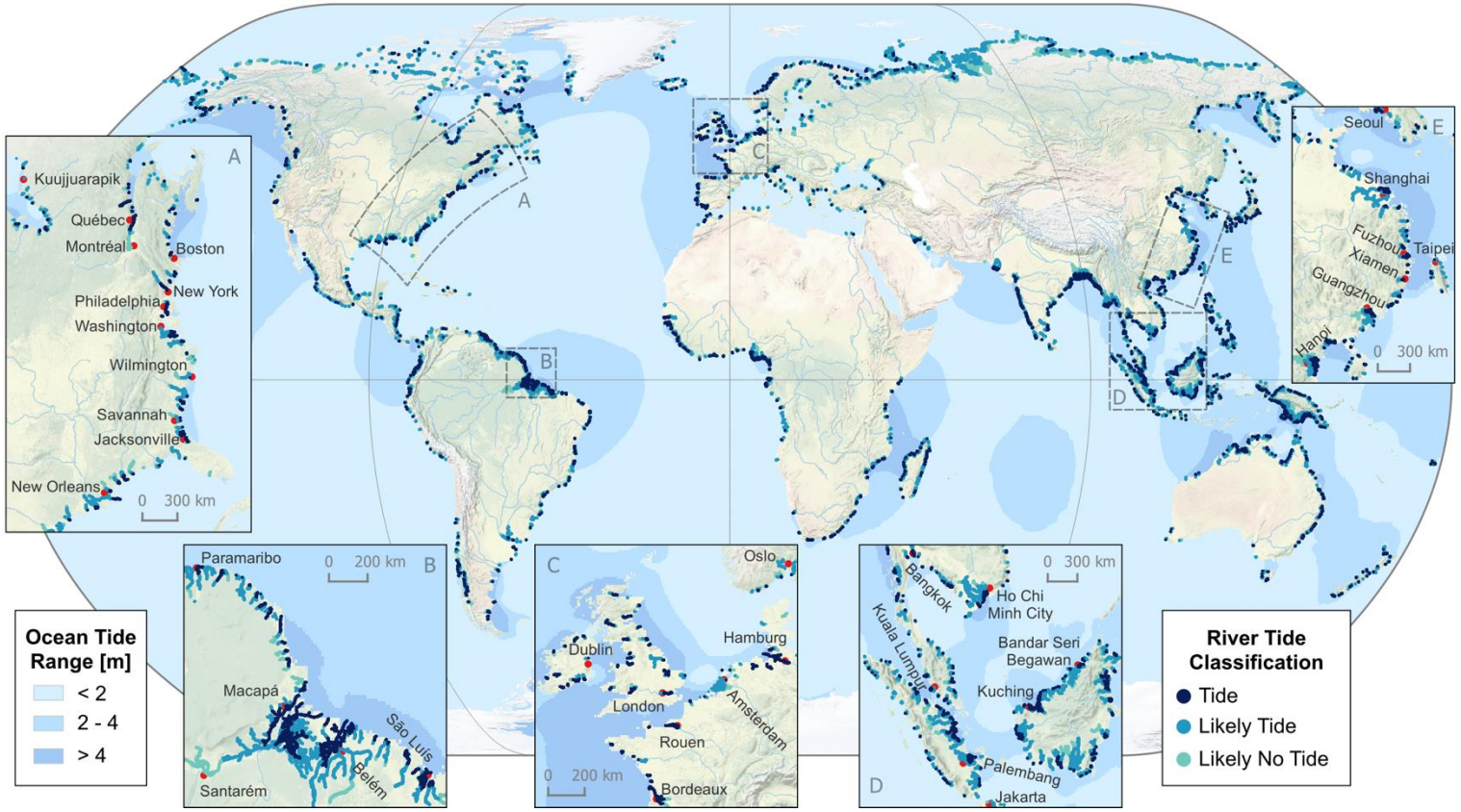
Tides across the land-ocean-continuum



- RiverSP is a SWOT product which provides node scale pre-processed water surface elevation measurements from SWOT.
- The spacing of these nodes are 250 meters, using the SWORD river centrelines.
- Reliable time-series from the period of the Cal/Val and Science orbit are provided.
- Qualitatively, the tidal amplitudes variations derived from SWOT match well with the tide gauges.
- As these data are already pre-processed, the time taken to evaluate the tides in individual rivers is dramatically reduced, allowing for global analysis.
- Expanding this globally, and validated against a global dataset, TICON-4 (Hart-Davis et al., 2025), we obtain errors of ~ 8 cm for M2 and ~ 5 cm for the O_1 tide.

Tides across the land-ocean-continuum

- Over 2-years of the RiverSP SWOT product is used to derive the M_2 and O_1 tidal constituents and produce the first global atlas of tidal extent with observed rivers.
- The results indicate that the tide is stopped by manmade or natural obstacles within approximately 15% of the rivers observed by SWOT.
- It is also calculated that nearly 260 million people live within 1 km of a tidally affected river, with this increasing to above 670 million within 10 km.



Hart-Davis M., Scherer D., Schwatke C., Pavelsky T., Sawyer A., Ray R., Dettmering D, Seitz F.. Observing the pulse of tidal rivers: A first global analysis from the SWOT satellite mission. ***In review.***

- This global dataset opens new possibilities to monitor and model changes in estuarine habitats, salt water intrusion, compound flooding events among a vast number of biogeochemical processes.

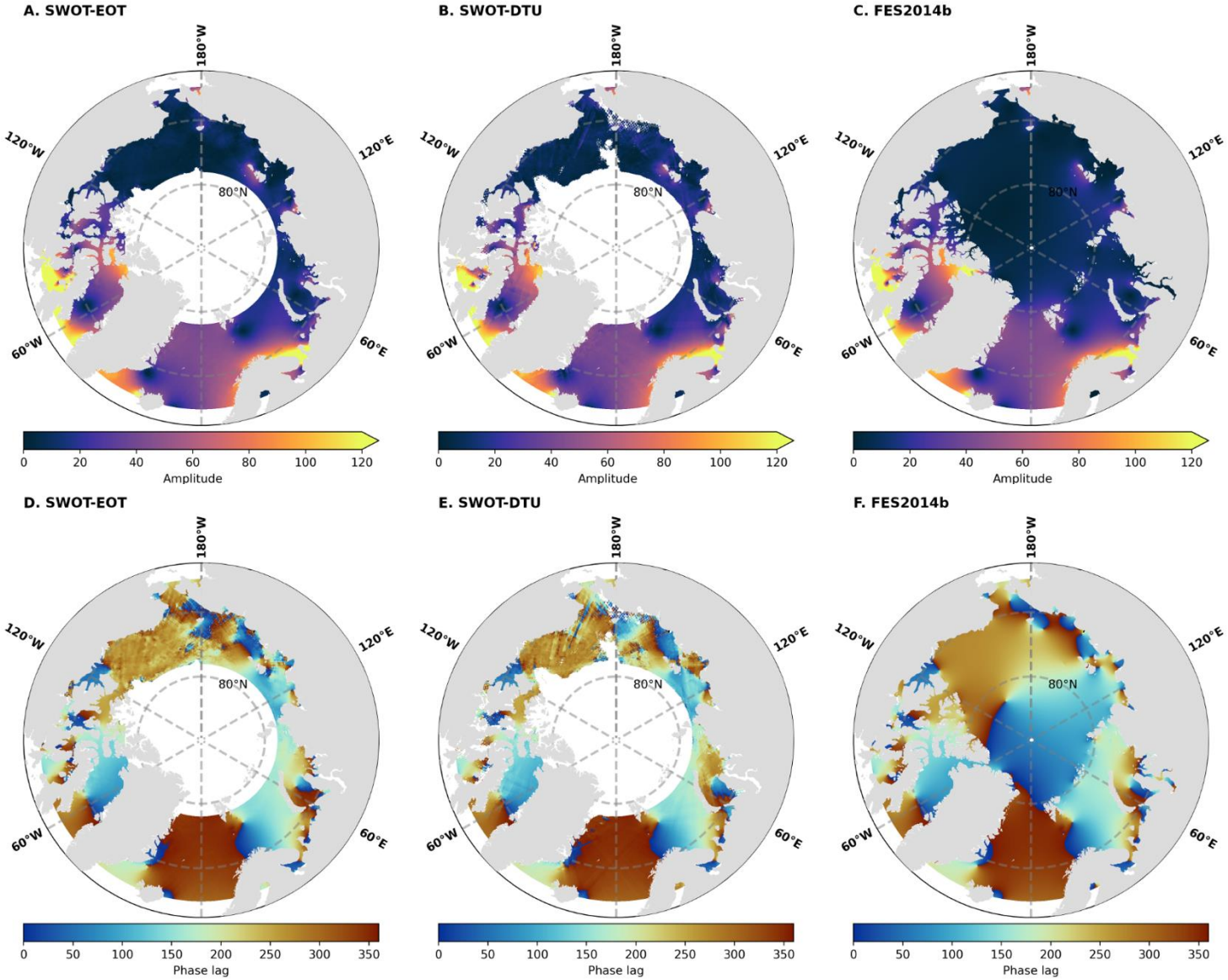
Interactive

https://dahiti.dgfi.tum.de/en/products/river-tides/map/

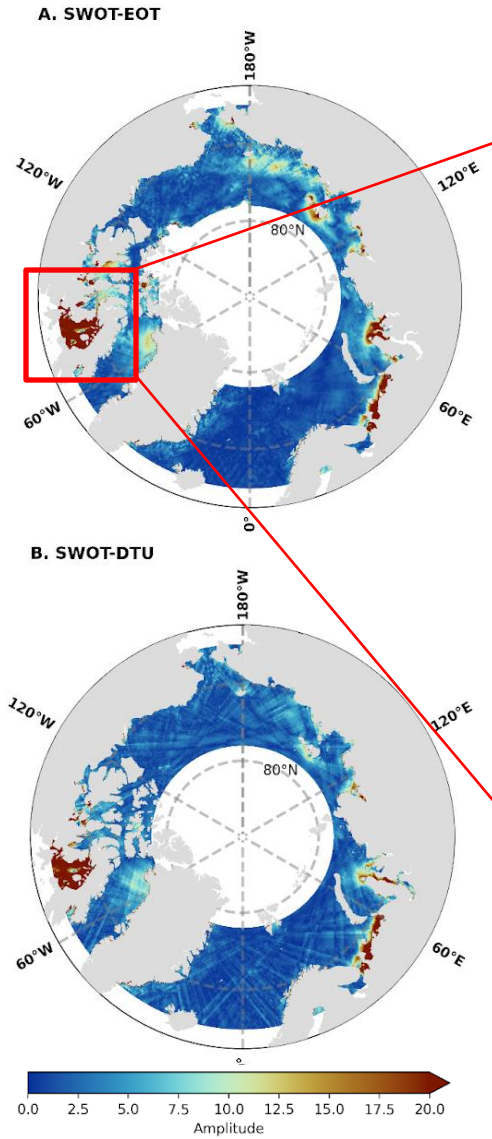
Summary and Perspectives

- We have assessed “most” SWOT products across the land-ocean-continuum and can see that all of them are useful for tidal research.
- In the coastal zone, we have the opportunity to exploit SWOT to fill the gaps in our knowledge on coastal tidal dynamics at finer spatial scales.
- As we move into inland waters, the RiverSP products present a useful dataset for tides to be determined both accurately and efficiently, making it foreseeable that they can be incorporated into our models.
- Much like the coastal zone, parts of the higher latitudes can benefit from SWOT, particularly in regions where complexities exist both in spatial variability and in the presence of sea ice.
- Dealing with sand banks and exposure of bottom topography at low tide is a limitation that needs to addressed when trying to automize and expand the use of SWOT throughout the global coasts.

Polar Regions: The Arctic Ocean



Polar Regions: The Foxe Basin



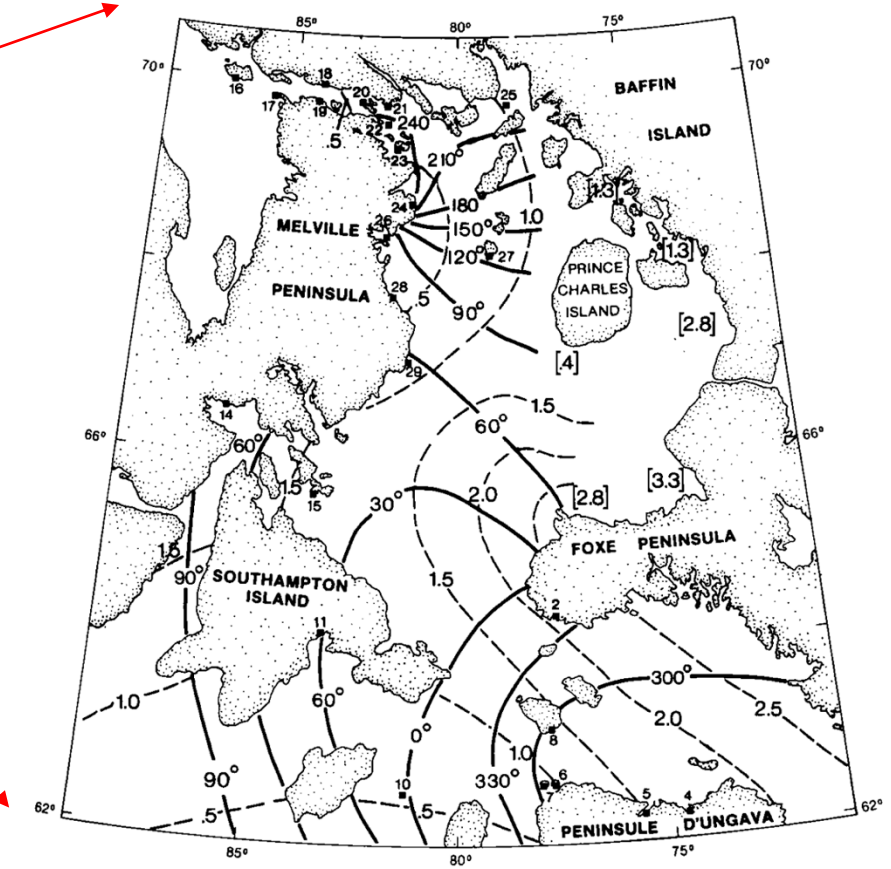
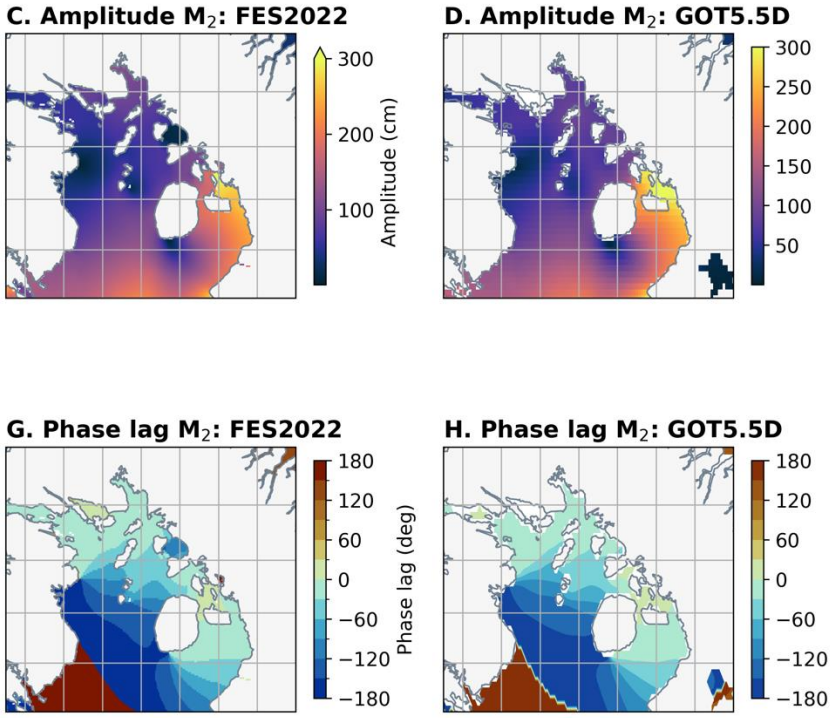


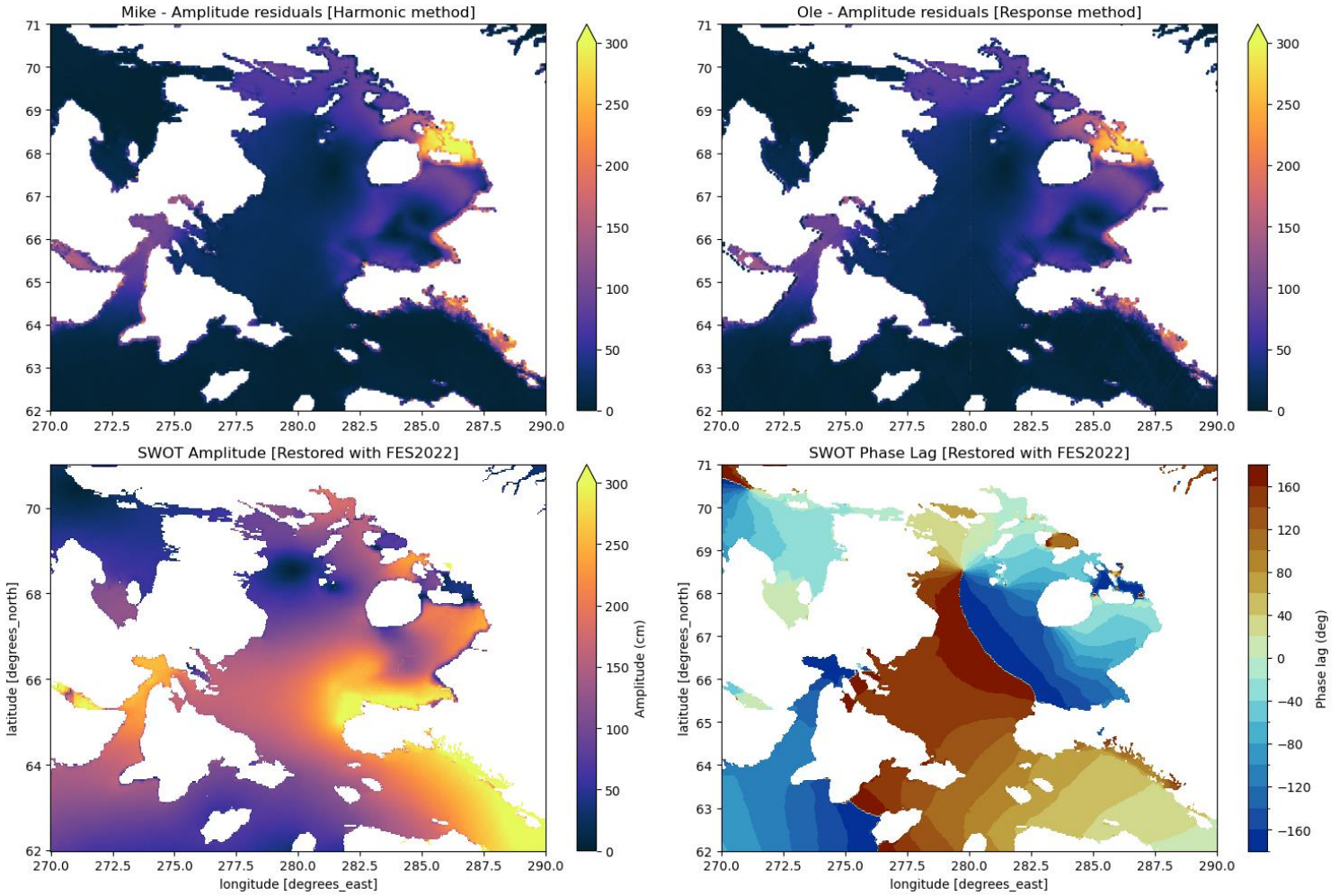
Figure 12.7. M_2 co-tidal chart for GMT + 4 hr time zone. Co-phase (deg.) represented by solid lines and co-amplitude (m) by dashed lines. Smaller numbers indicate station numbers whose data (Table 12.1) is used to plot chart. Large numbers in square brackets are reported tidal amplitudes (no phases).



- The Foxe Basin has historically been a challenging region due to **sea ice coverage, very shallow depths** [> 20 meters] and limited in-situ coverage [no tide gauges except the temporary ones presented in the left]

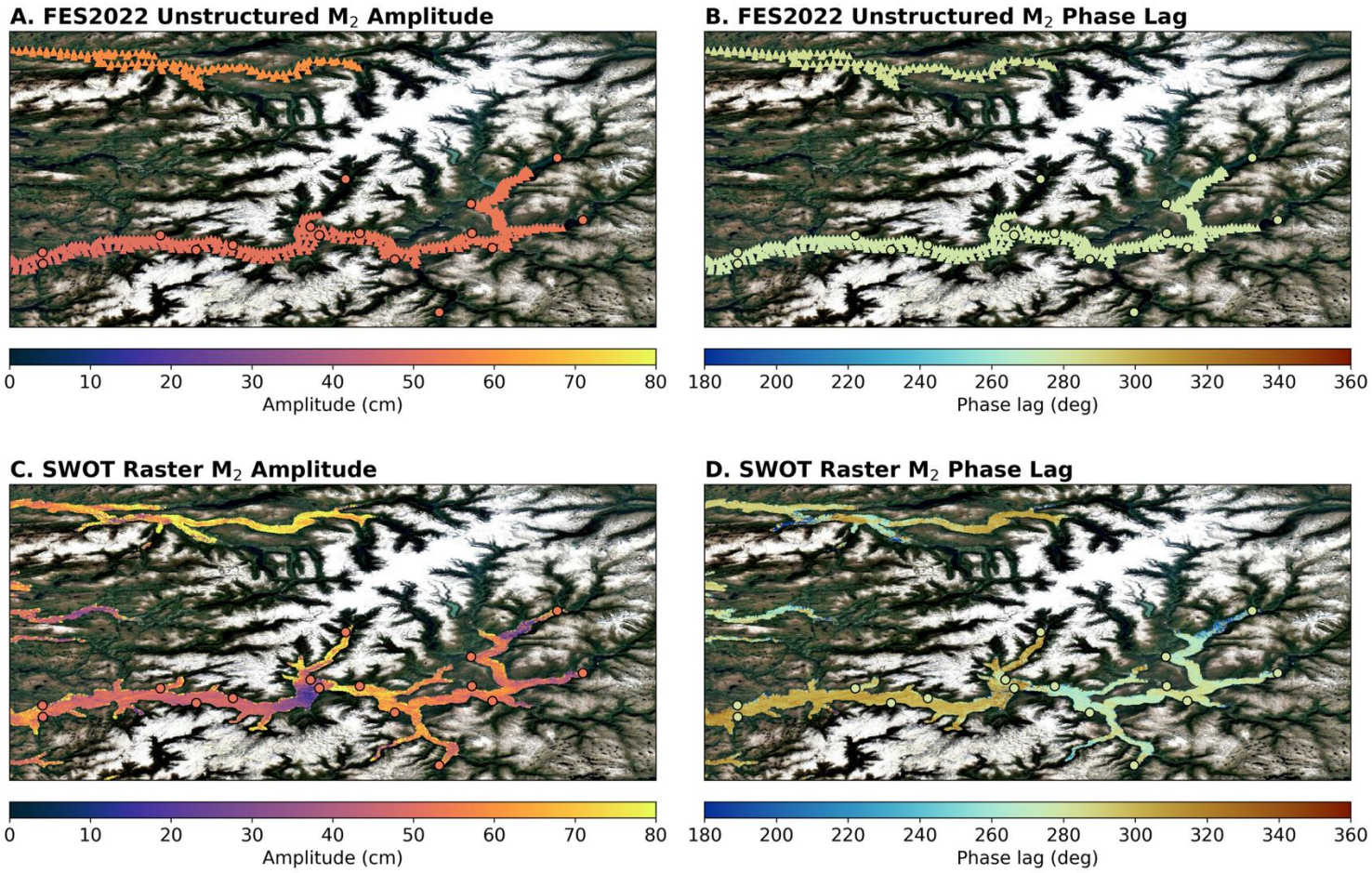
Middle Figure Taken from Prinsenberg, S. J. (1986)

Polar Regions: The Foxe Basin



- A very first look at this region revealed nearly **3 meter residuals** in a small part of the Foxe Basin but also large regions where the residuals **exceed 1 meter**.
- What we found when restoring residuals to the full signal, was that there was an **overestimation of the tide** [likely resulting from the sea ice and extreme shallow waters within narrow channels].
- Additionally, the findings of the amplitude and phase lag of M_2 match better the temporary gauges presented in the previous slide.
- Numerical simulations that add and remove sea ice, showed the tidal **amplitude is influenced by 1 meter** with the inclusion of sea ice.

Polar Regions: Fjords [Sognefjord]



- For data constrained modelling, fjords have historically not really been observable with nadir altimetry.
- We tested the estimation of tidal constituents from SWOT within the large Sognefjord in Norway, using data from August 2023 to March 2025.
- We noted the following:

M_2: 2.2 cm RMS of mean signal 52 cm
S_2: 2.8 cm RMS of mean signal 22 cm
O_1: 2.3 cm RMS of mean signal 5.7 cm

- Positive results from SWOTbut a bit more strategy refinements are needed, to avoid the influence of land and bottom topography especially at the edges of the fjord.