2021 historical flood and 2024 historical drought of the Amazon River: Seamless modelling of their impacts on the Amazon estuary water level

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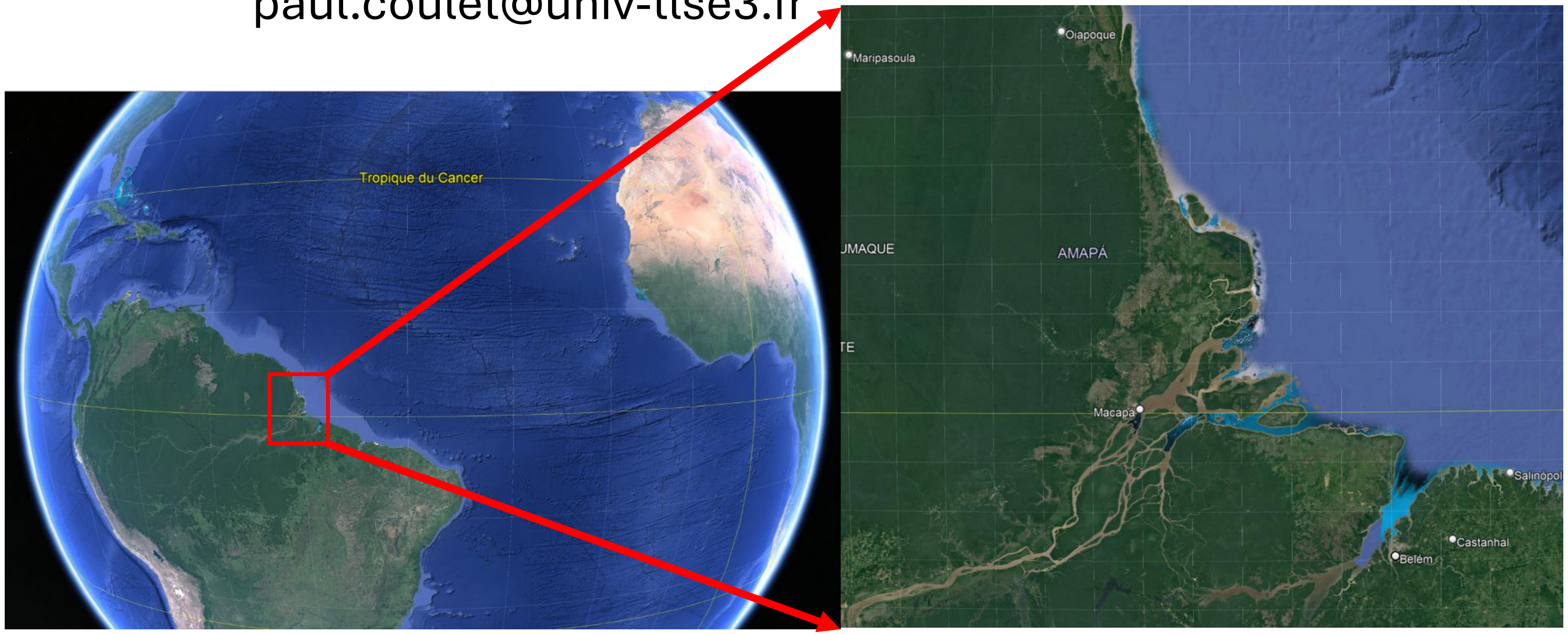


Amazon estuary (Source: Google Earth)

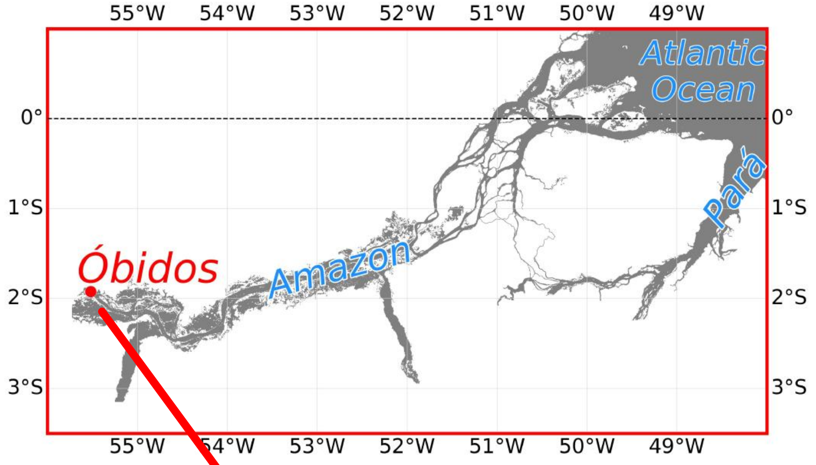
Introduction

- One of the world's largest estuaries:
  - **No. 1 freshwater discharge** in the world
  - **800km** of estuary

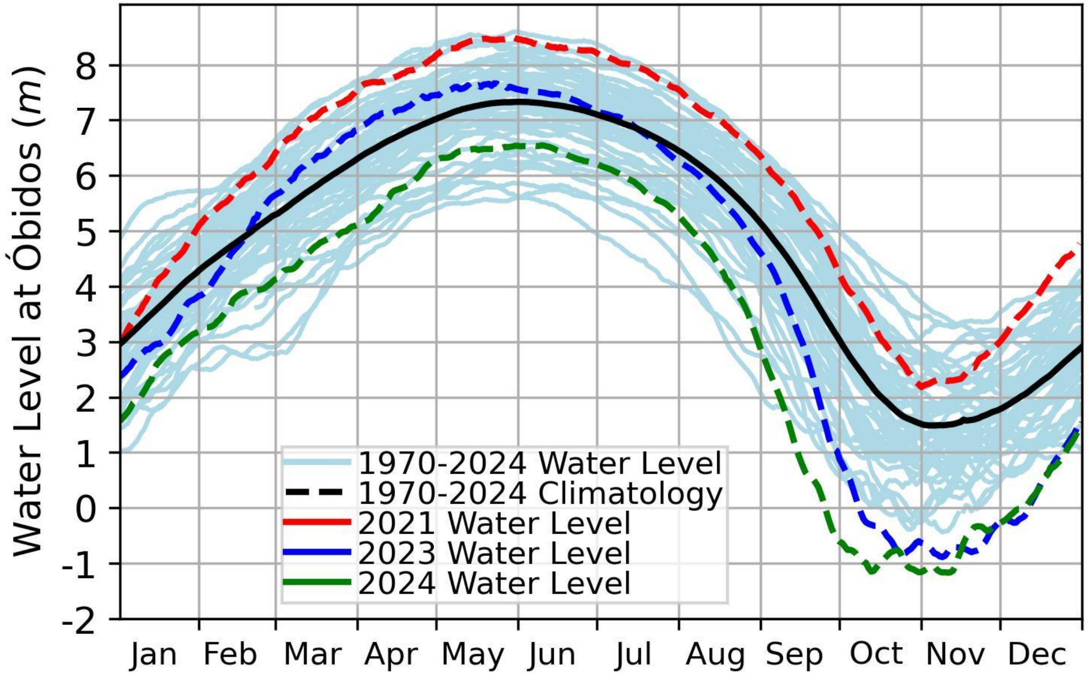
- **Increasing extremes occurrences** (9 of the 10 highest floods have occurred in the last 15 years)
  - 2021 2nd highest flood ever recorded
  - 2023 lowest drought ever recorded
  - 2024 beat 2023 record-breaking drought

- **High socio-economic vulnerability of the riverine population**
  - Highly dependent on Amazon water resources
  - Exposed to water level extremes

- **Poorly observed** system



Amazon estuary



Water level at Obidos from 1970 to 2024

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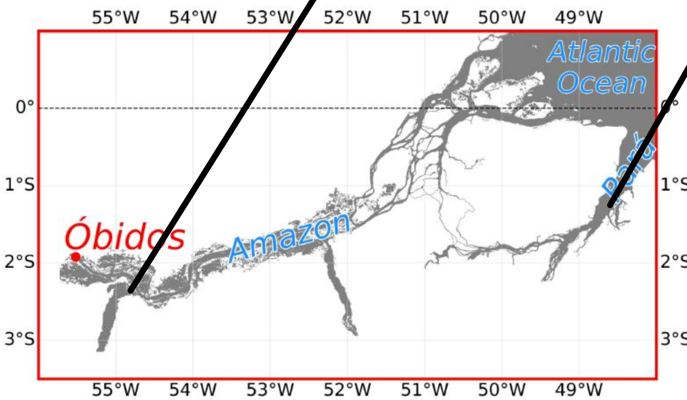

2021 flood at Santarém (source: TV Tapajós)

Unplanned urban area in Belém, 2017 (source: Brasil de Fato)

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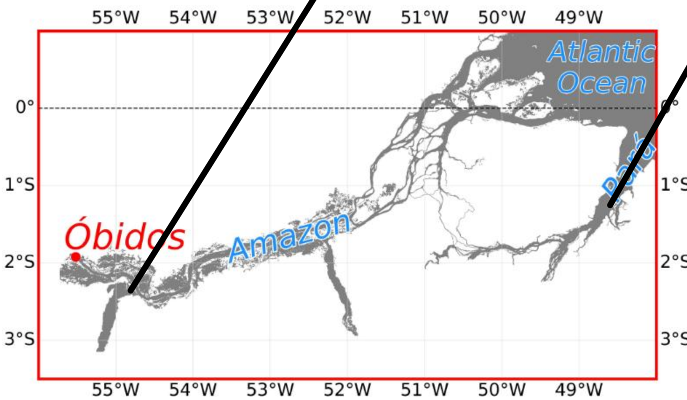
➡ **Urgent need to better understand the hydrodynamics of extreme events**



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Unplanned urban area in Belém, 2017 (source: Brasil de Fato)

Outline

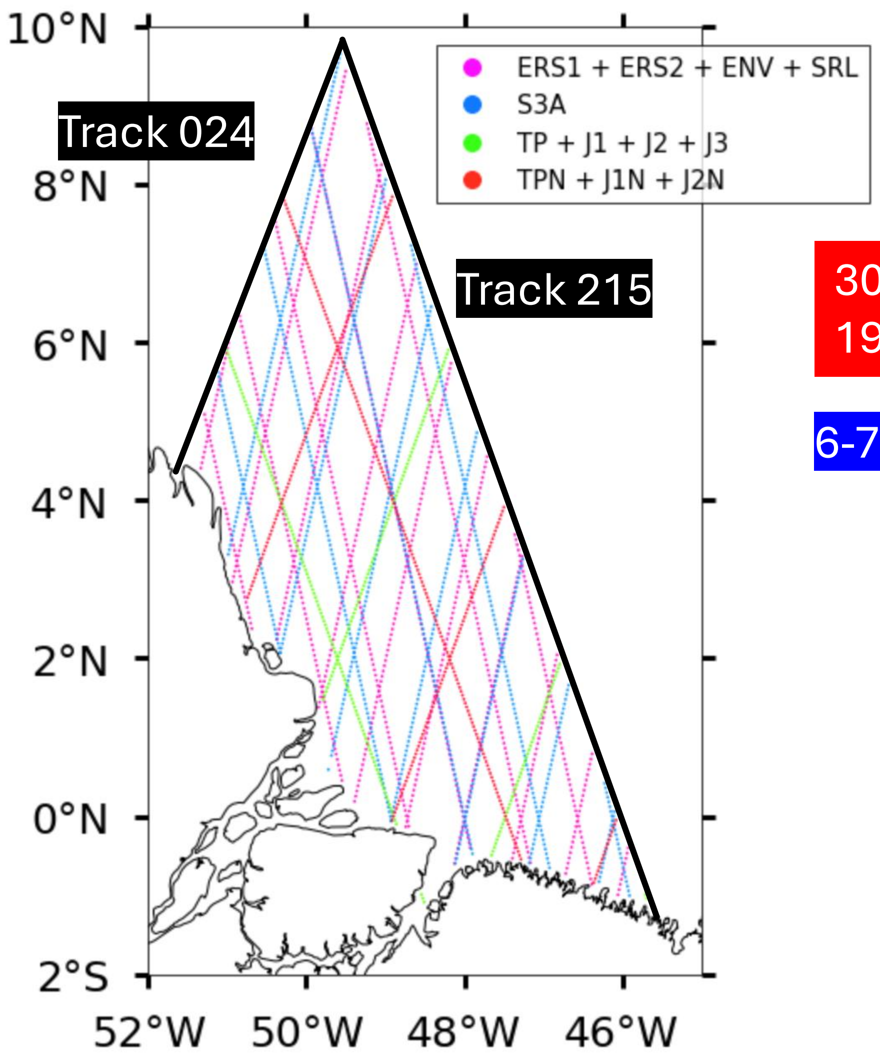
I. A regional multi-mission altimetric tidal atlas: PyAltide

II. Hydrodynamical modeling of the 2021 record-breaking flood and 2024 record-breaking drought of the Amazon estuary

I. A regional multi-mission altimetric tidal atlas: PyAltide

a. Input data

SLA from XTRACK-2022-L2P v2.1 (AVISO+, Birol et al. 2016)

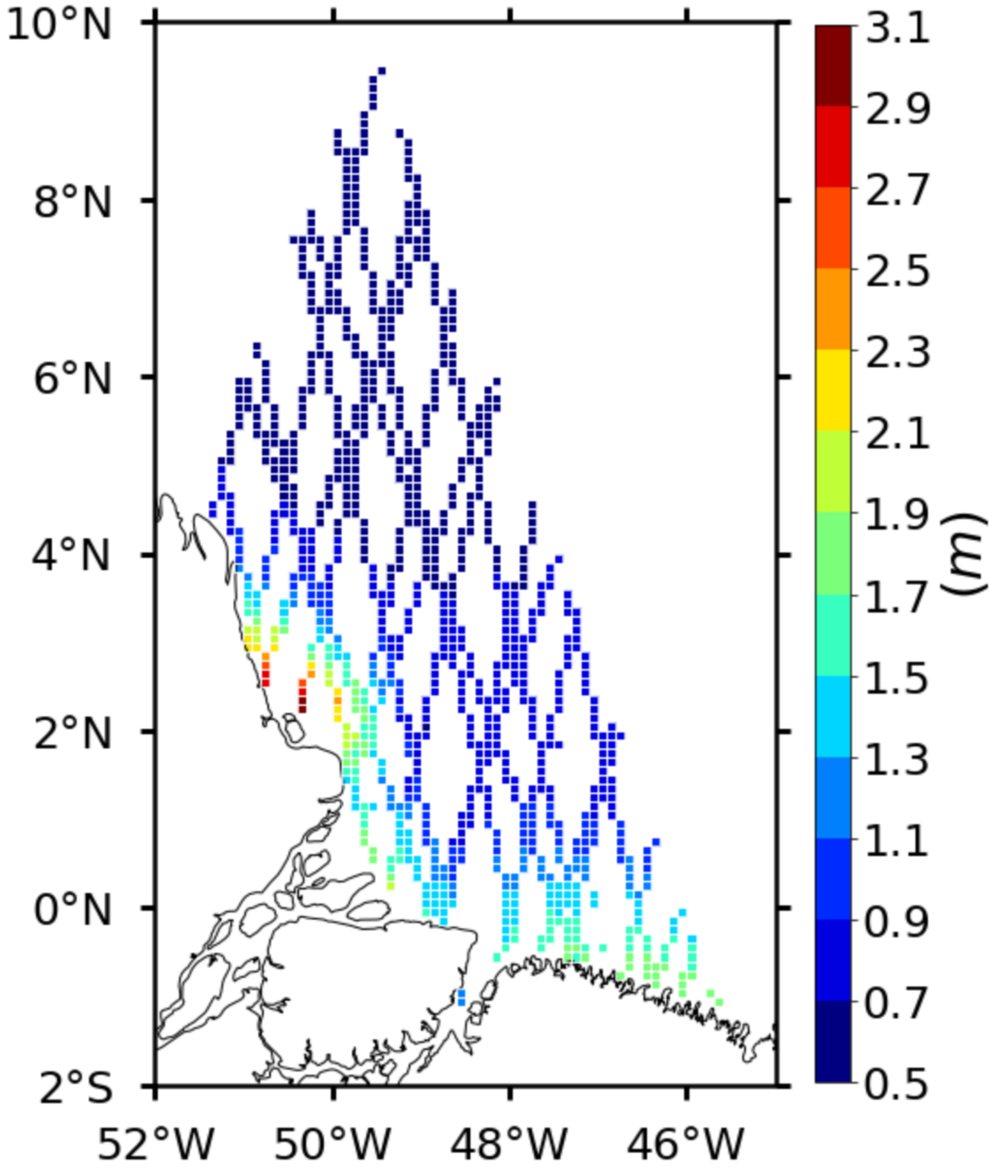


Available altimetric data within our modeling domain over the Amazon shelf

30 years of data
1993 -> 2022

6-7km spatial resolution

b. M2 amplitude over the Amazon shelf



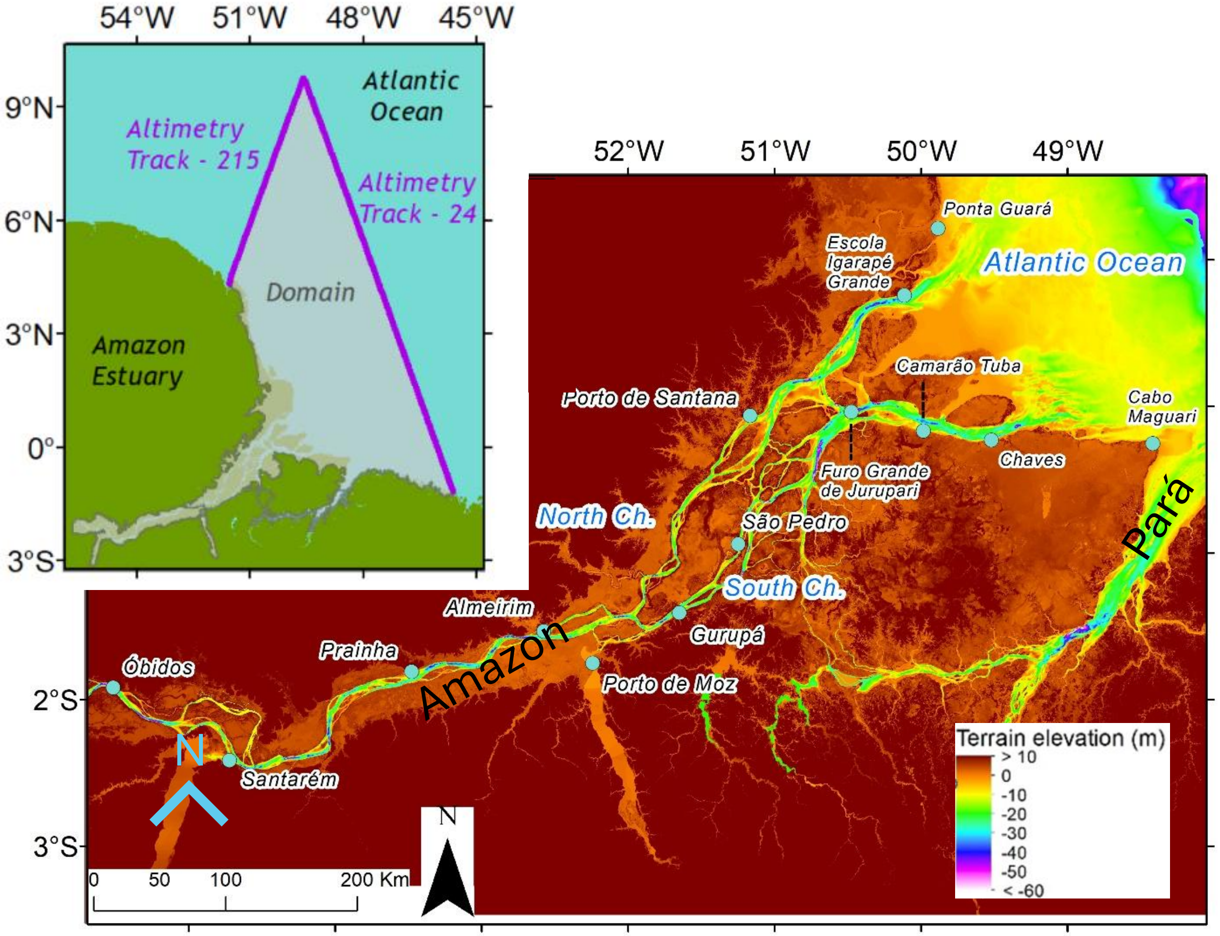
M2 amplitude over the Amazon shelf

- High resolution (1/10°) coastal tidal atlas
- Code available in Python
- Non-stationary (not shown)
- Transferable over any coastal region

➢ A robust validation tool of coastal tide in data-poor regions

II. Hydrodynamic modeling of the 2021 record-breaking flood and 2024 record-breaking drought of the Amazon estuary

a. Seamless hydrodynamic model of the Amazon estuary



Domain of the model and bathymetry

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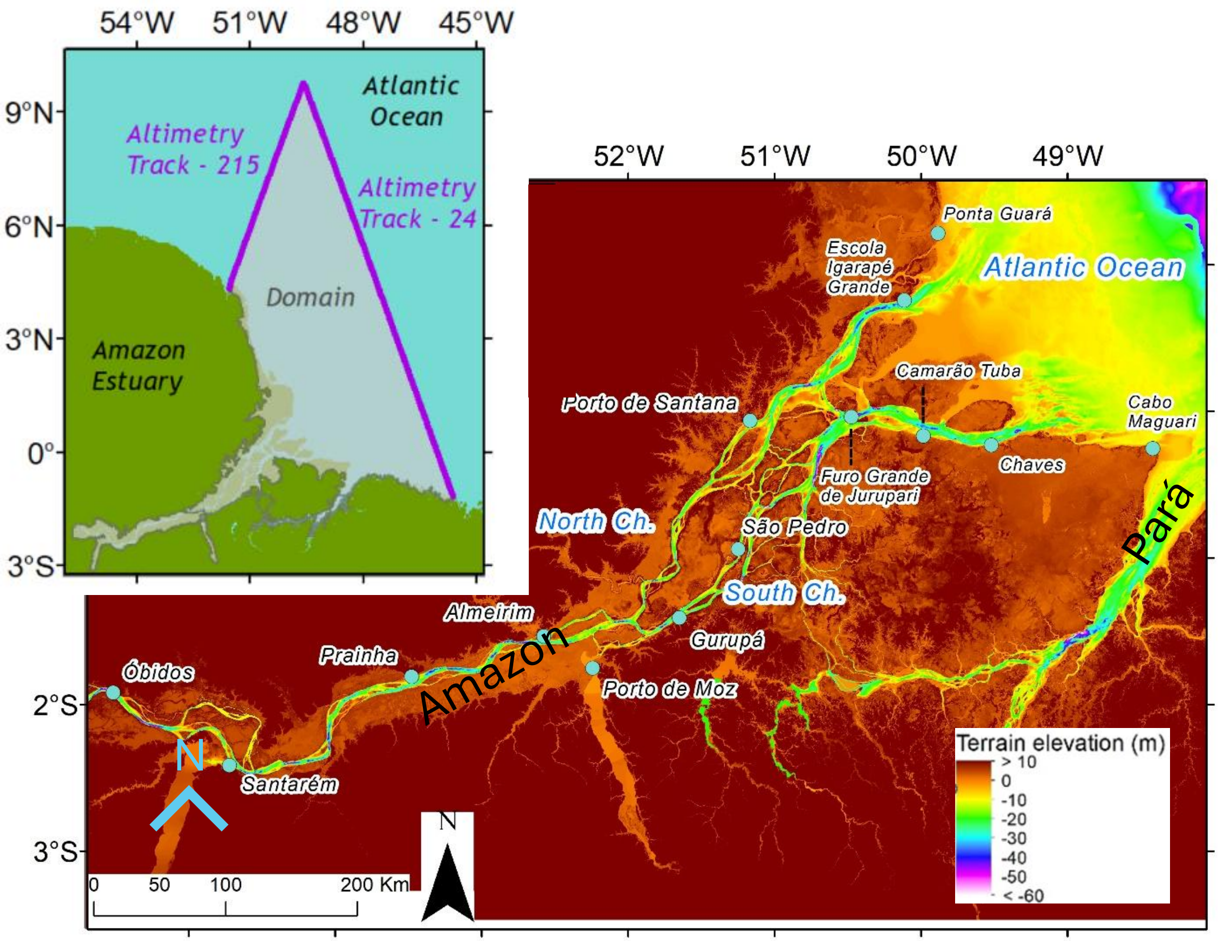

Domain of the model and bathymetry

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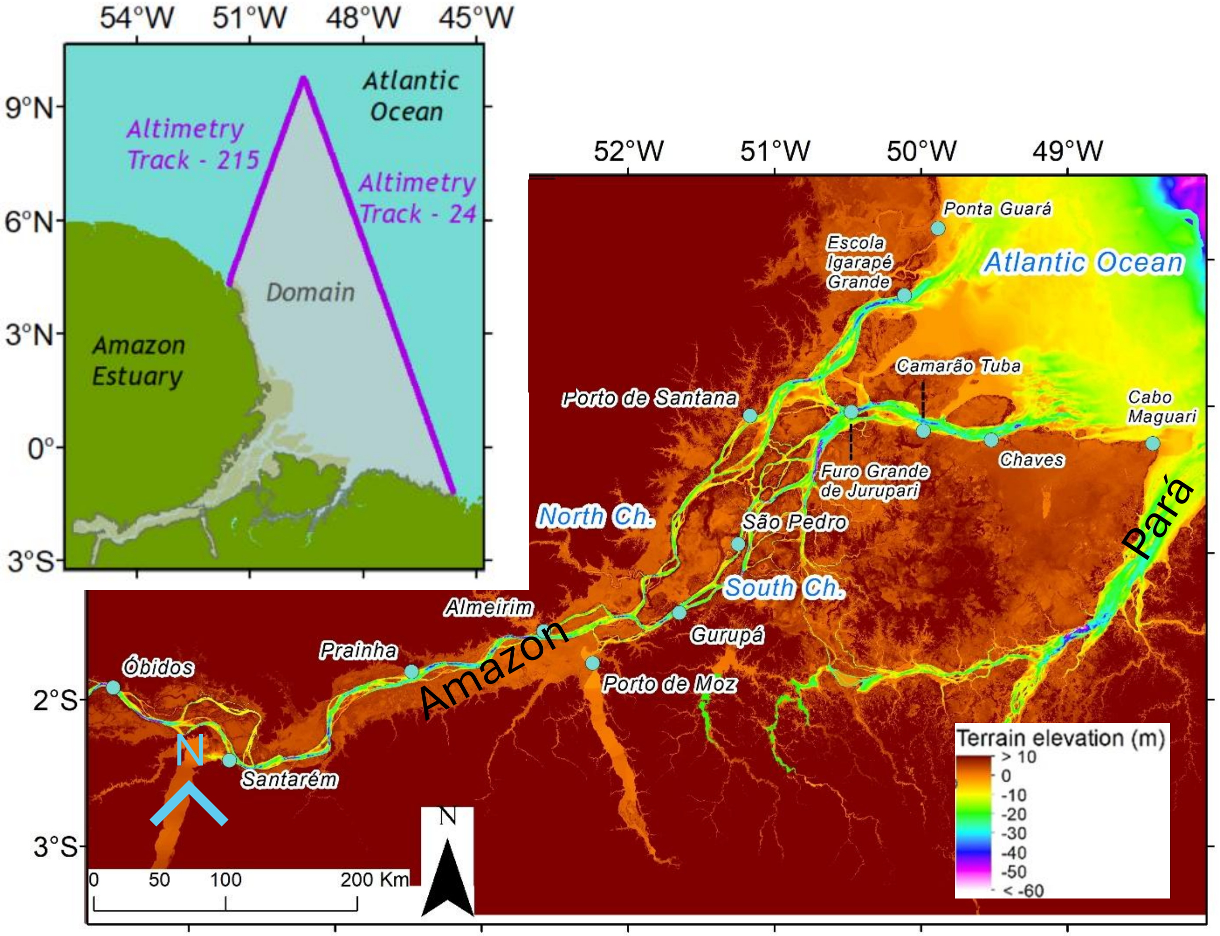

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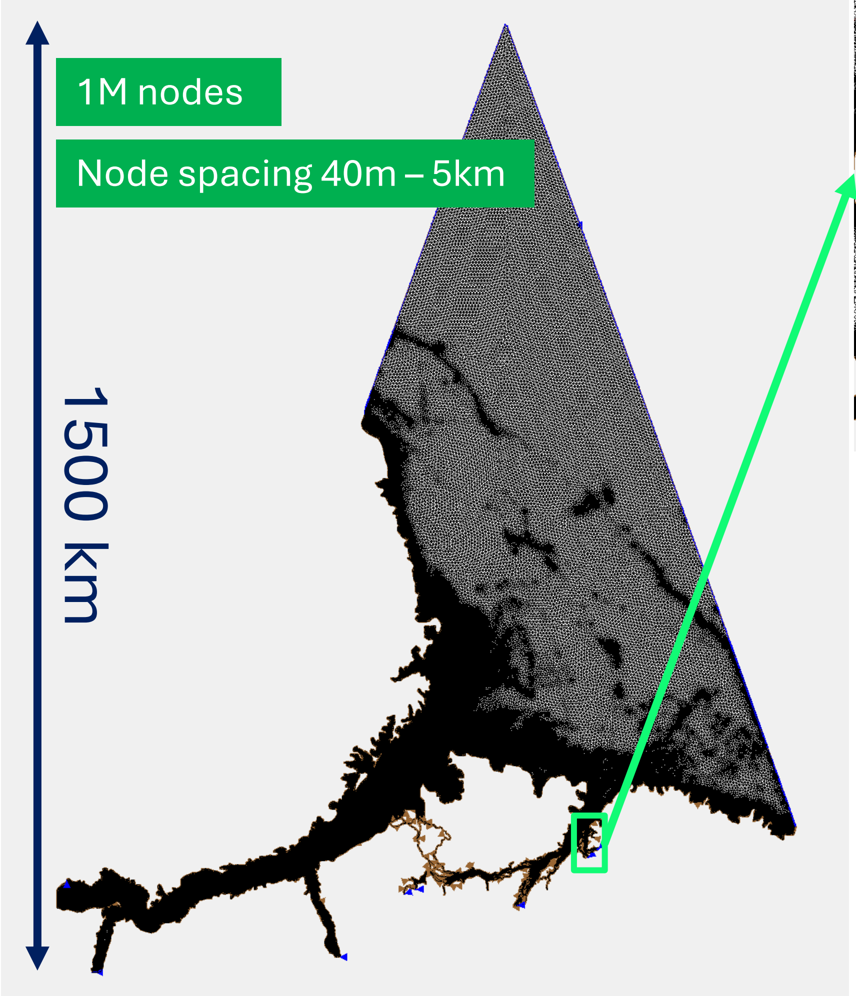
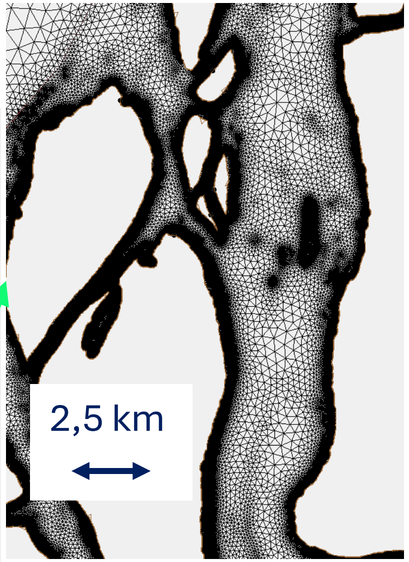


Unstructured grid of the model



Zoom on Belém

SCHISM

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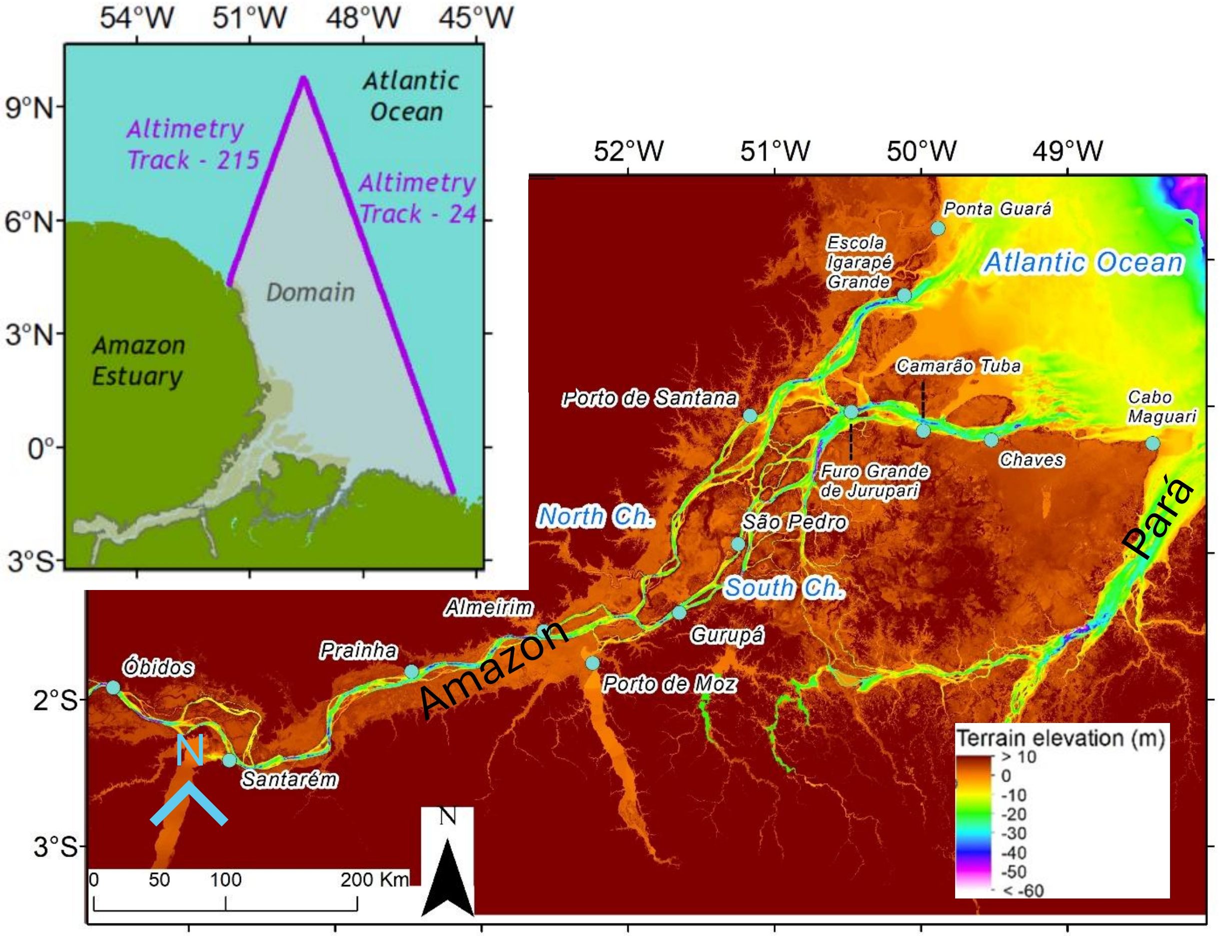

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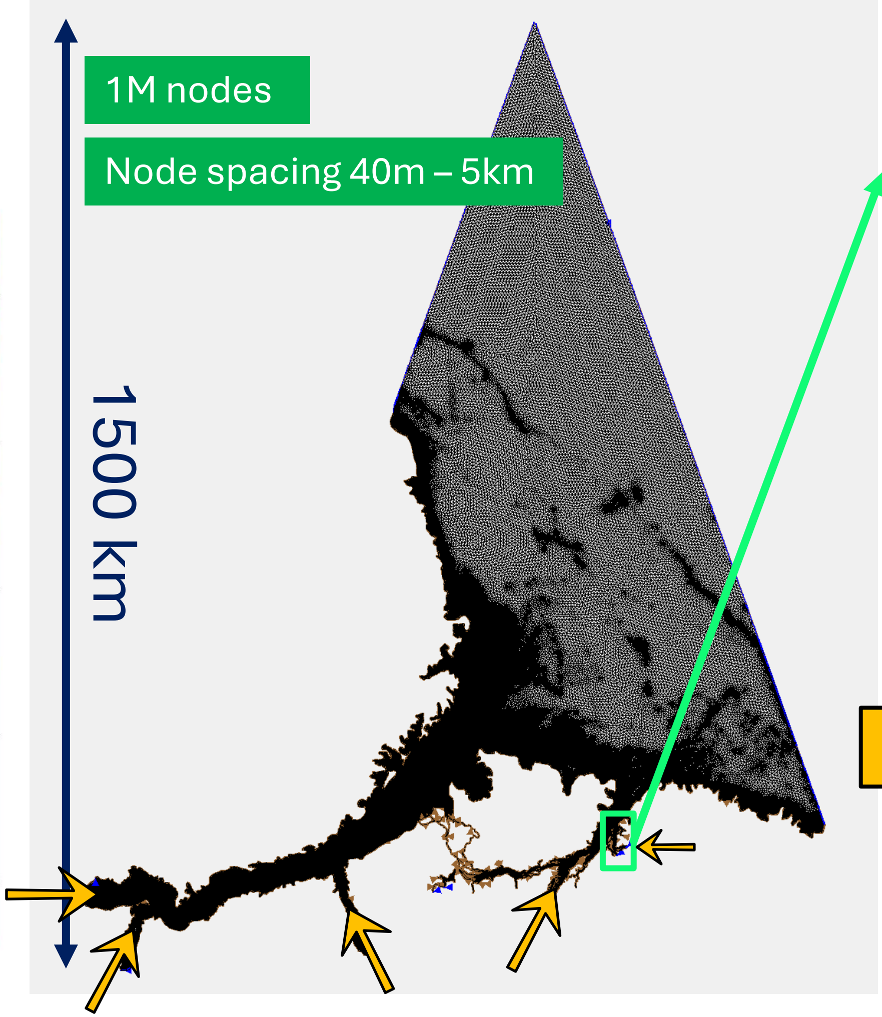

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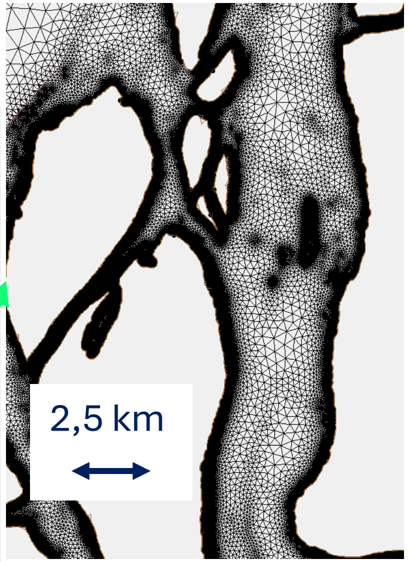

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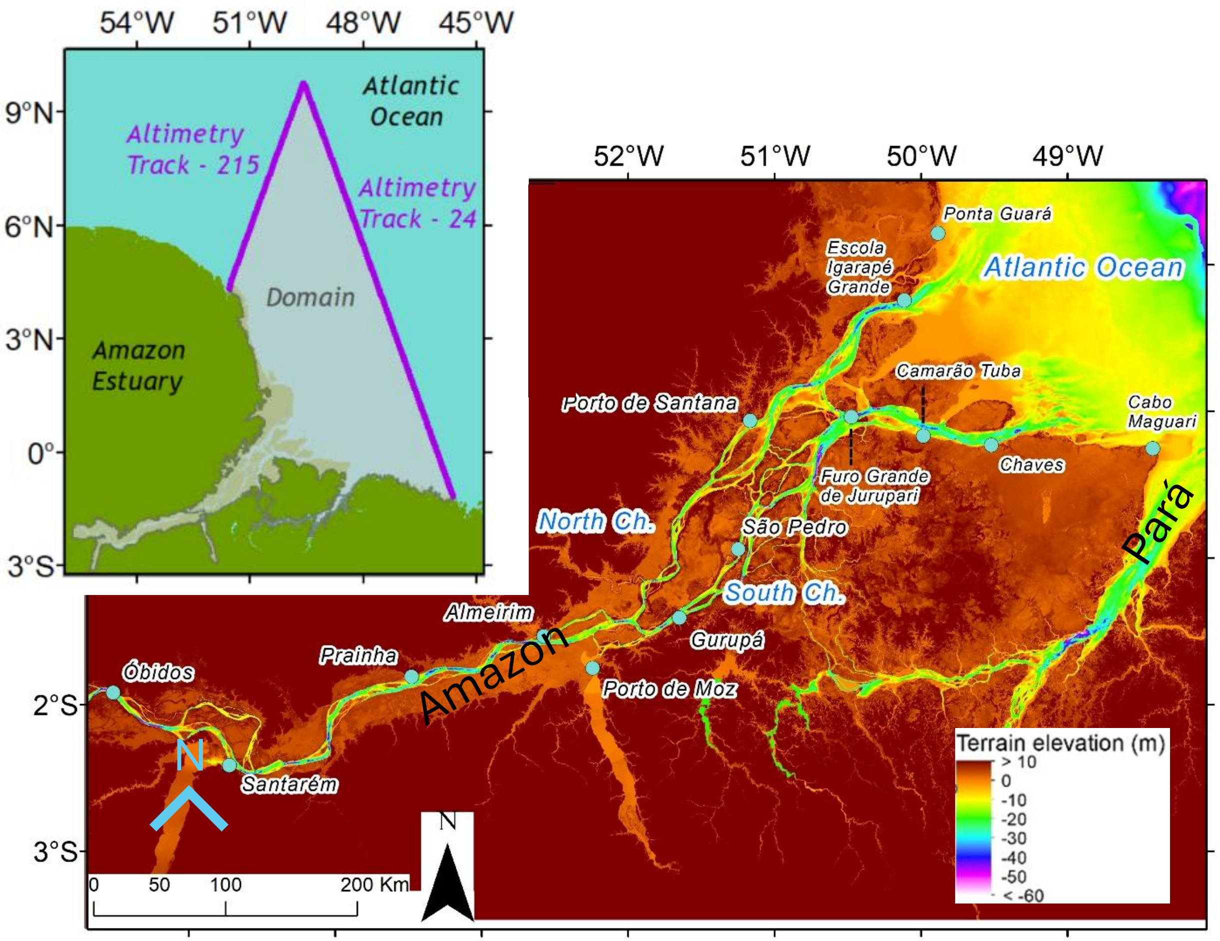

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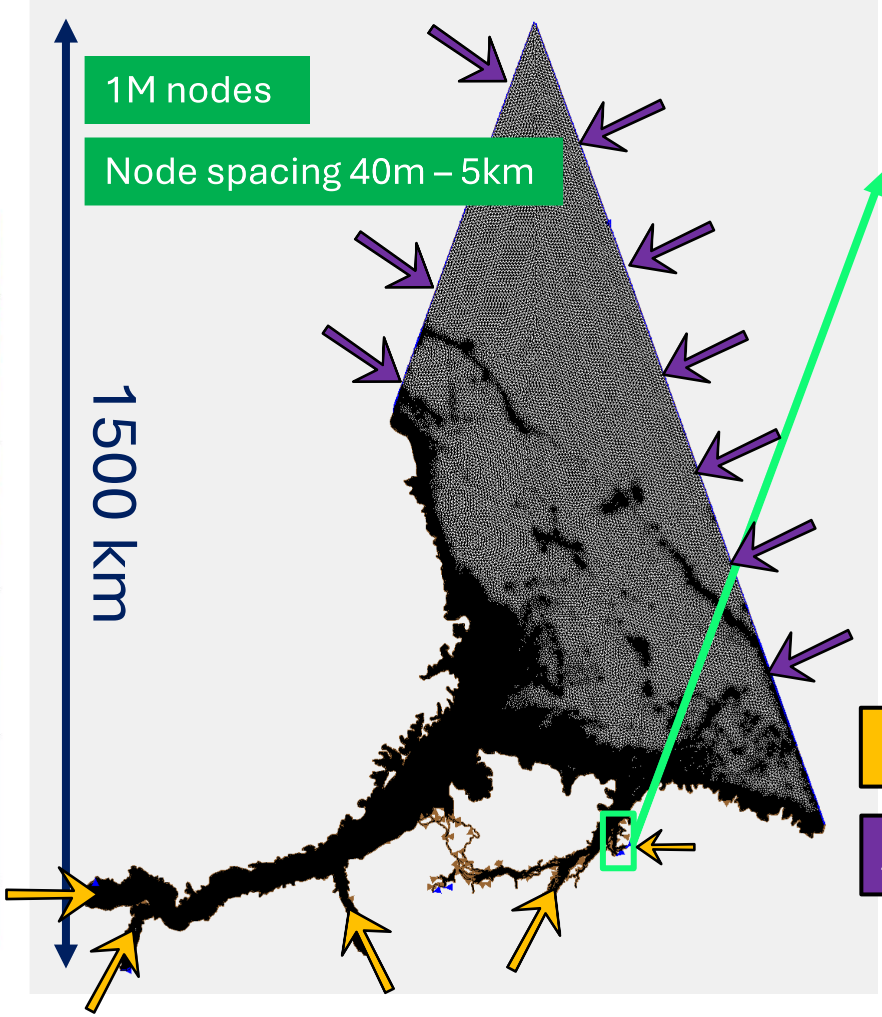

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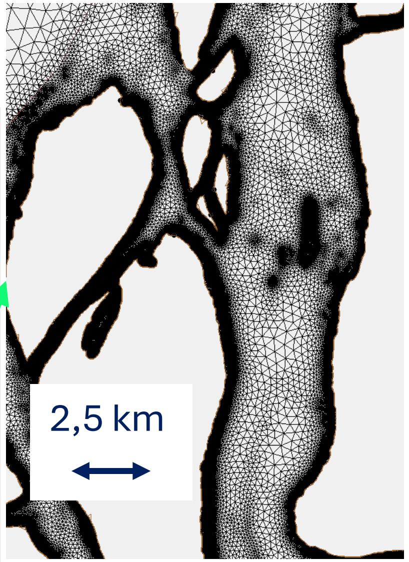

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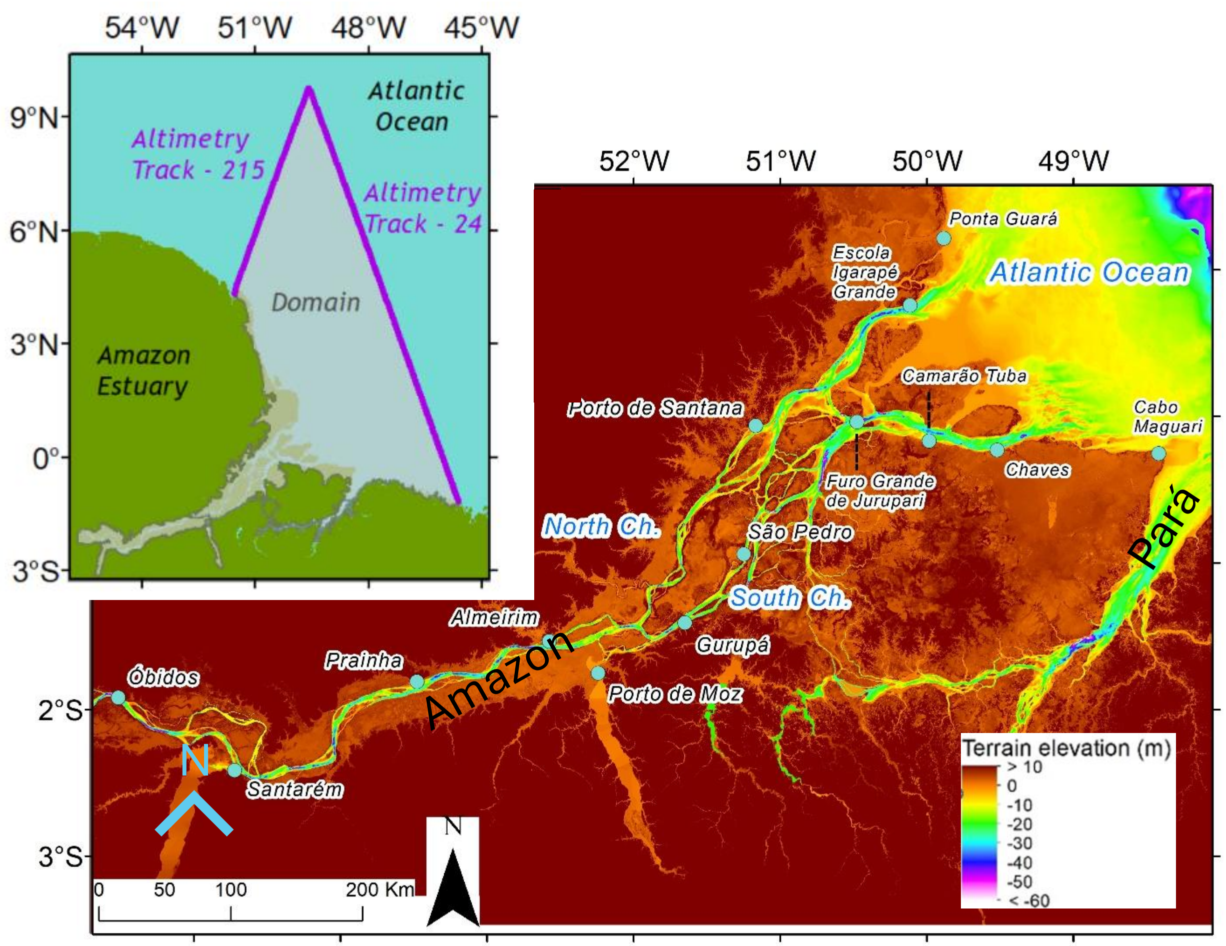

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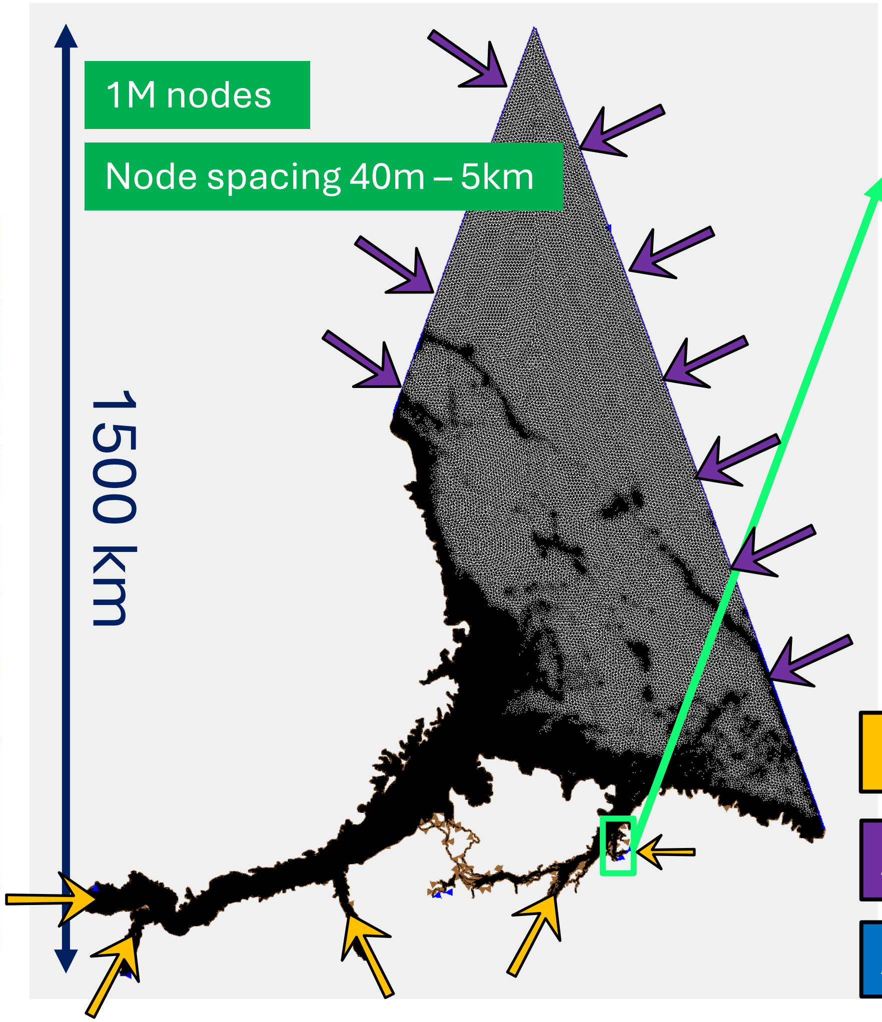

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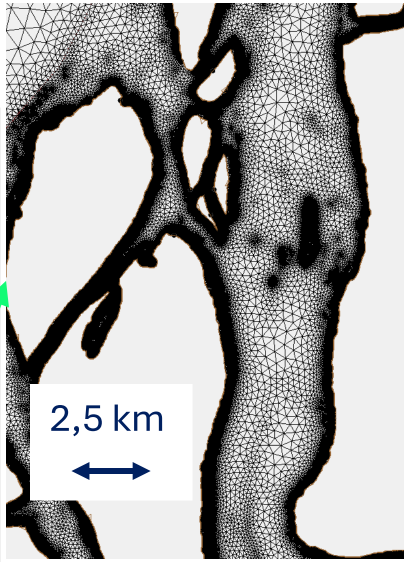

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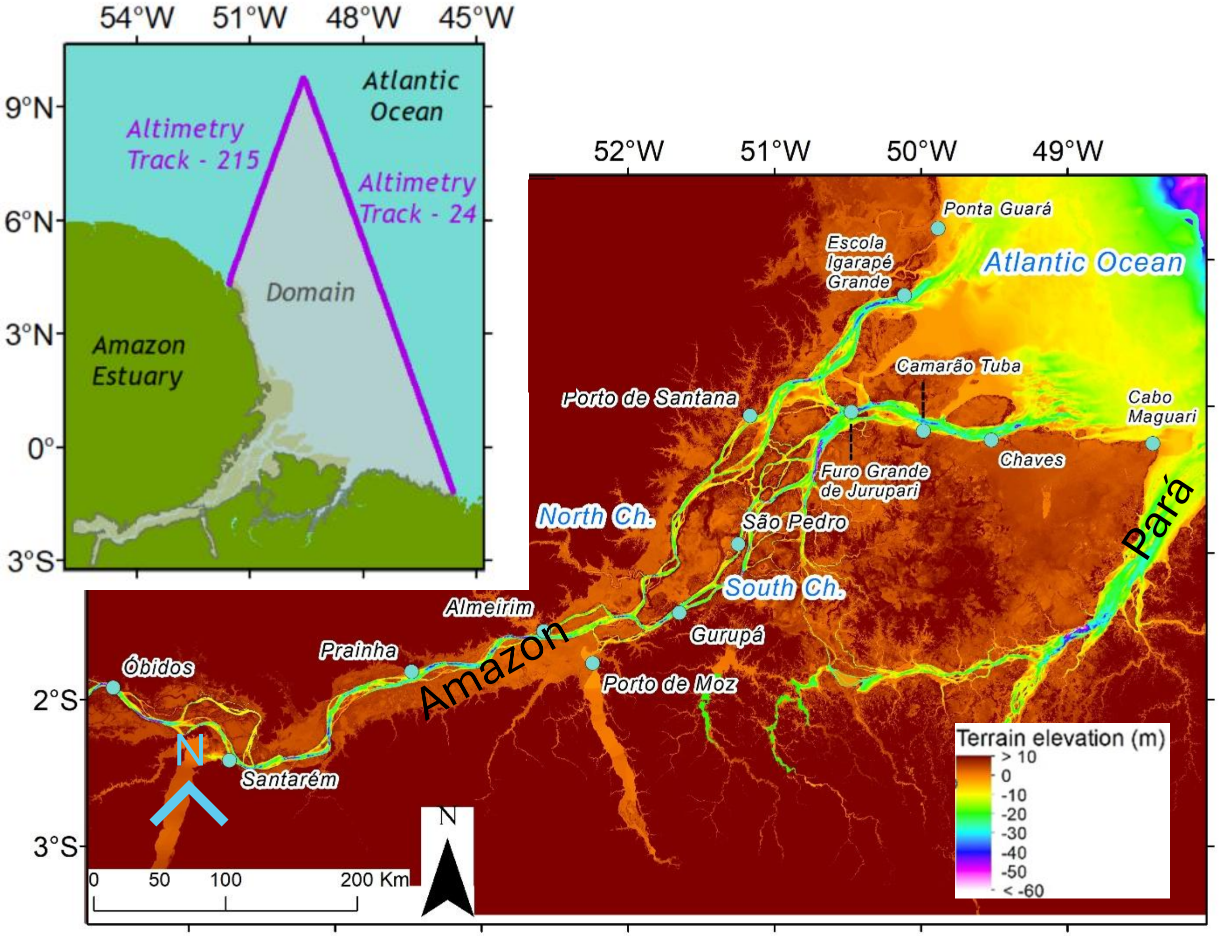

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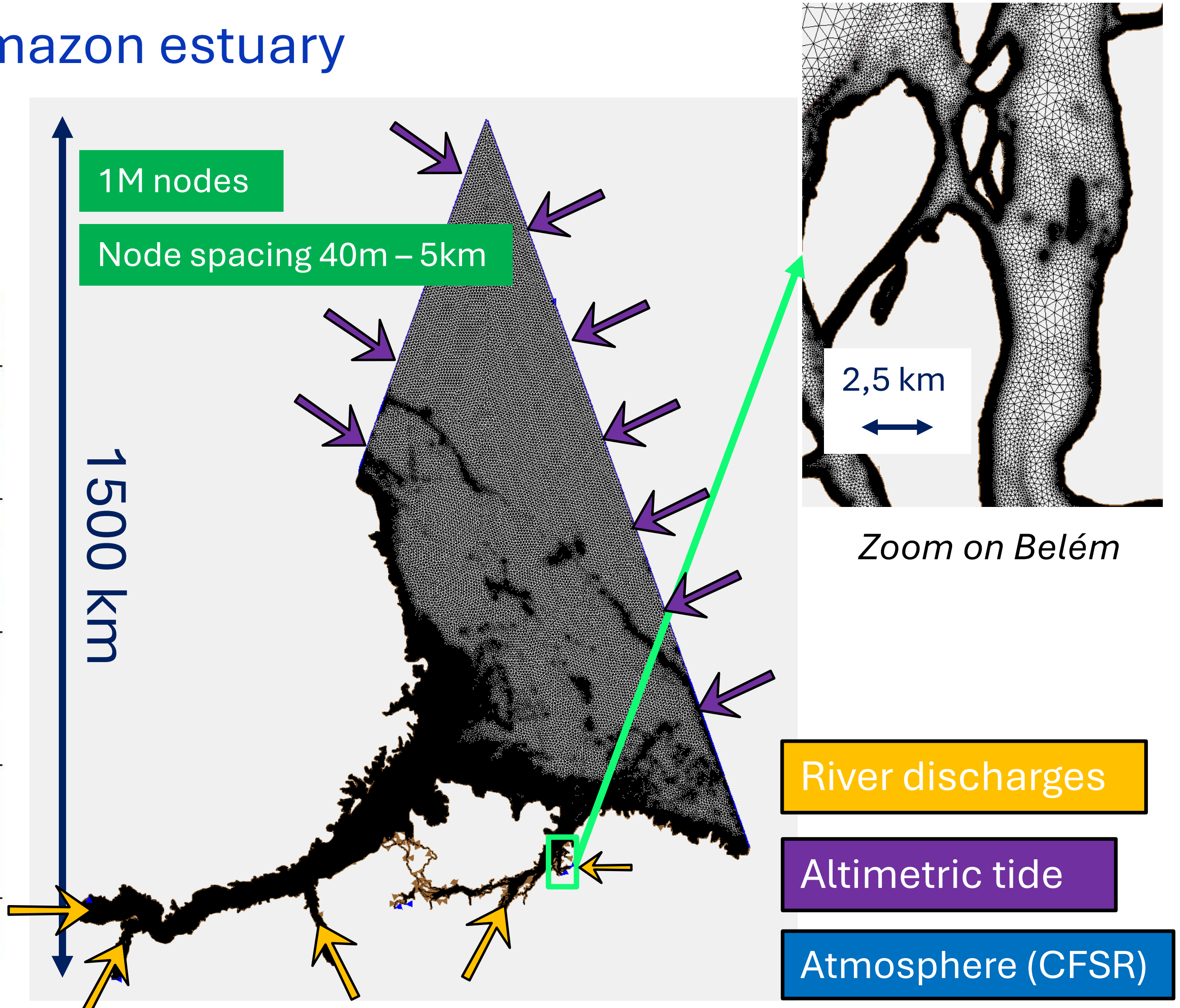
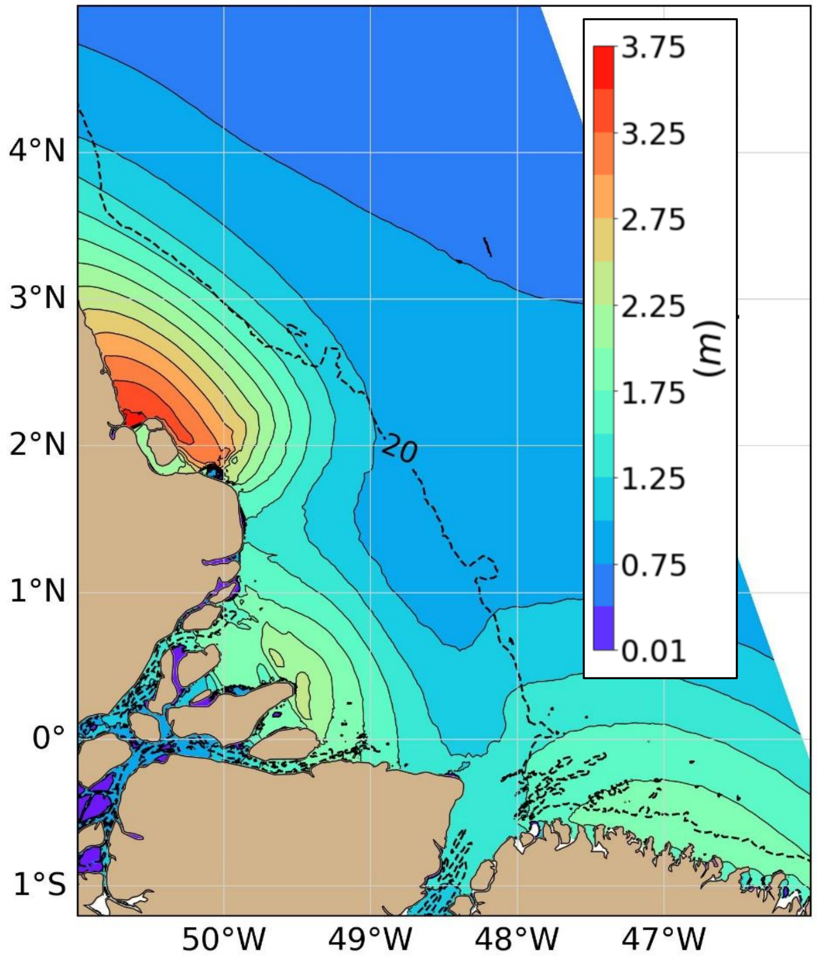


Unstructured grid of the model

- ➢ Seamless high resolution 2DH cross-scale model based on SCHISM
- ➢ Simulation of the last decade 2014-2024

SCHISM

b. Validation of the coastal M2 tide using PyAltide atlas



Modeled M2 amplitude

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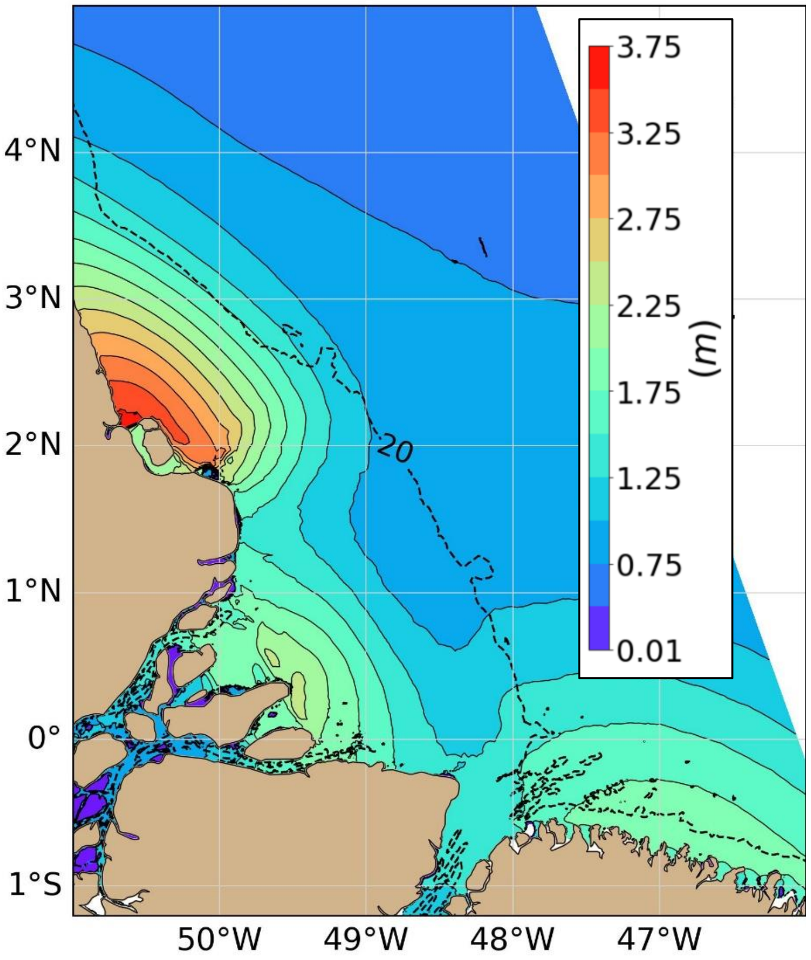

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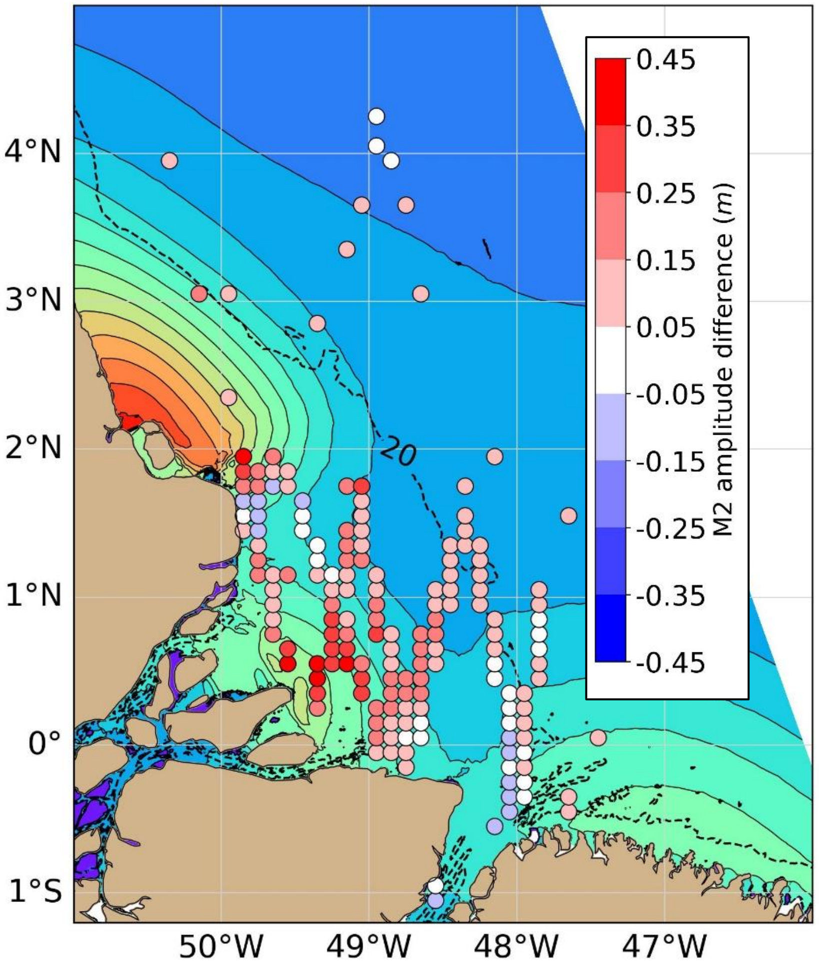
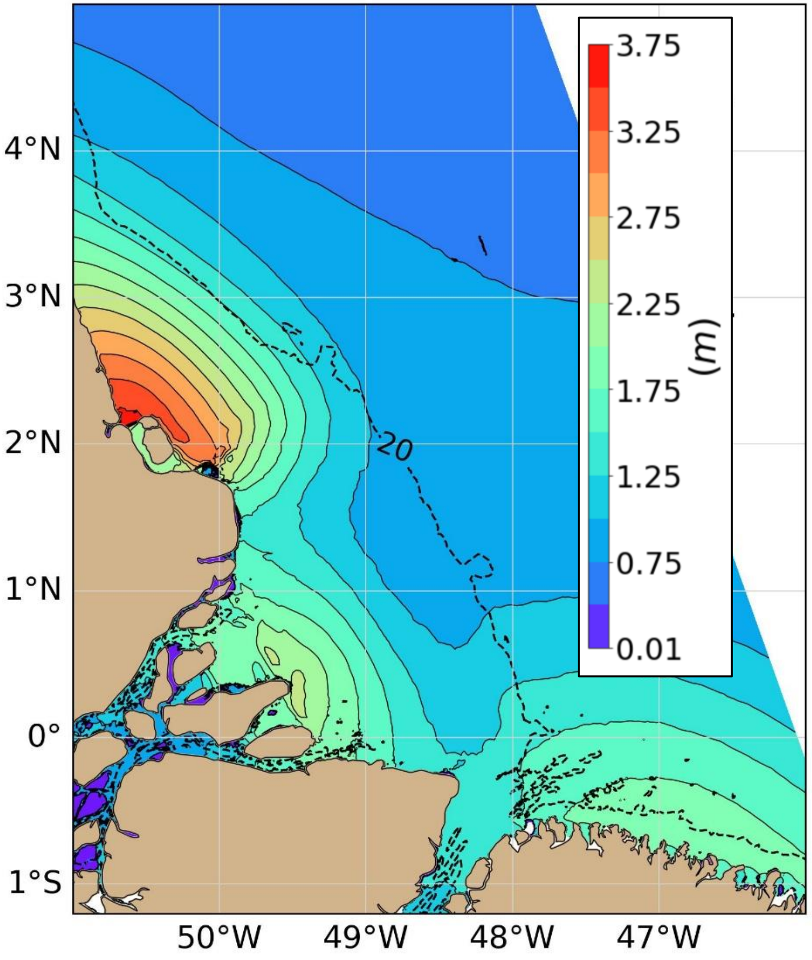


M2 amplitude difference
(modeled – observed)

b. Validation of the coastal M2 tide using PyAltide atlas



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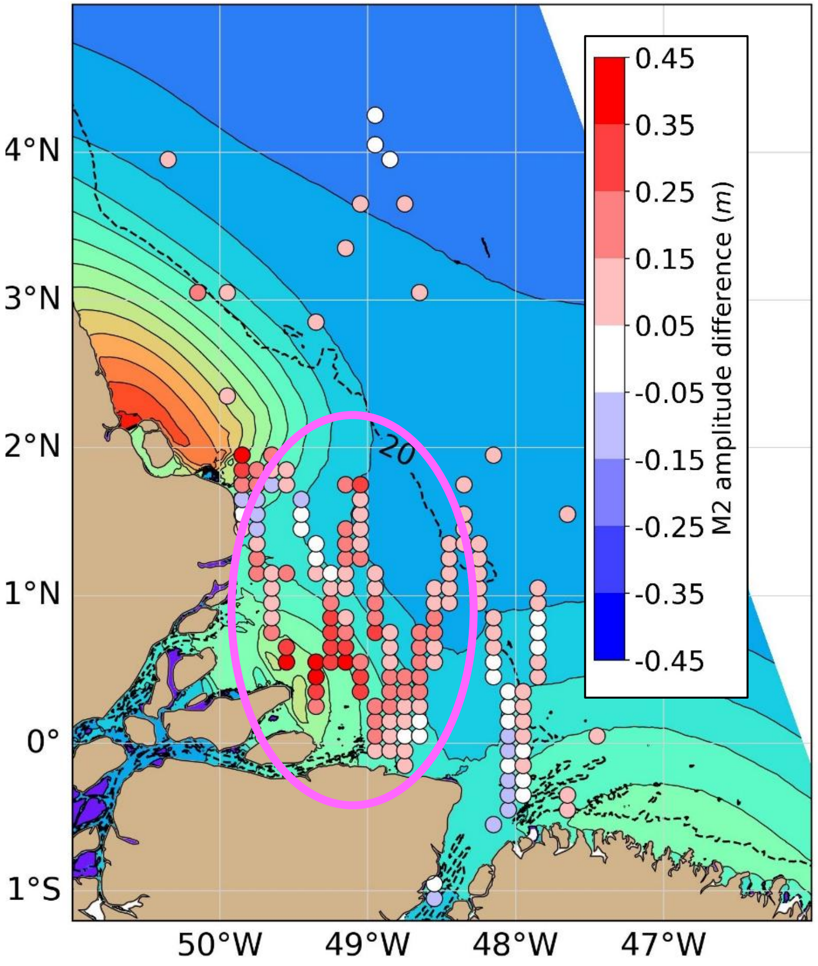

M2 amplitude difference
*(**modeled – observed)***

- Overestimation ~ 18 cm of M2 amplitude
- Regions with high difference (up to + 25 cm) correspond to resonating areas

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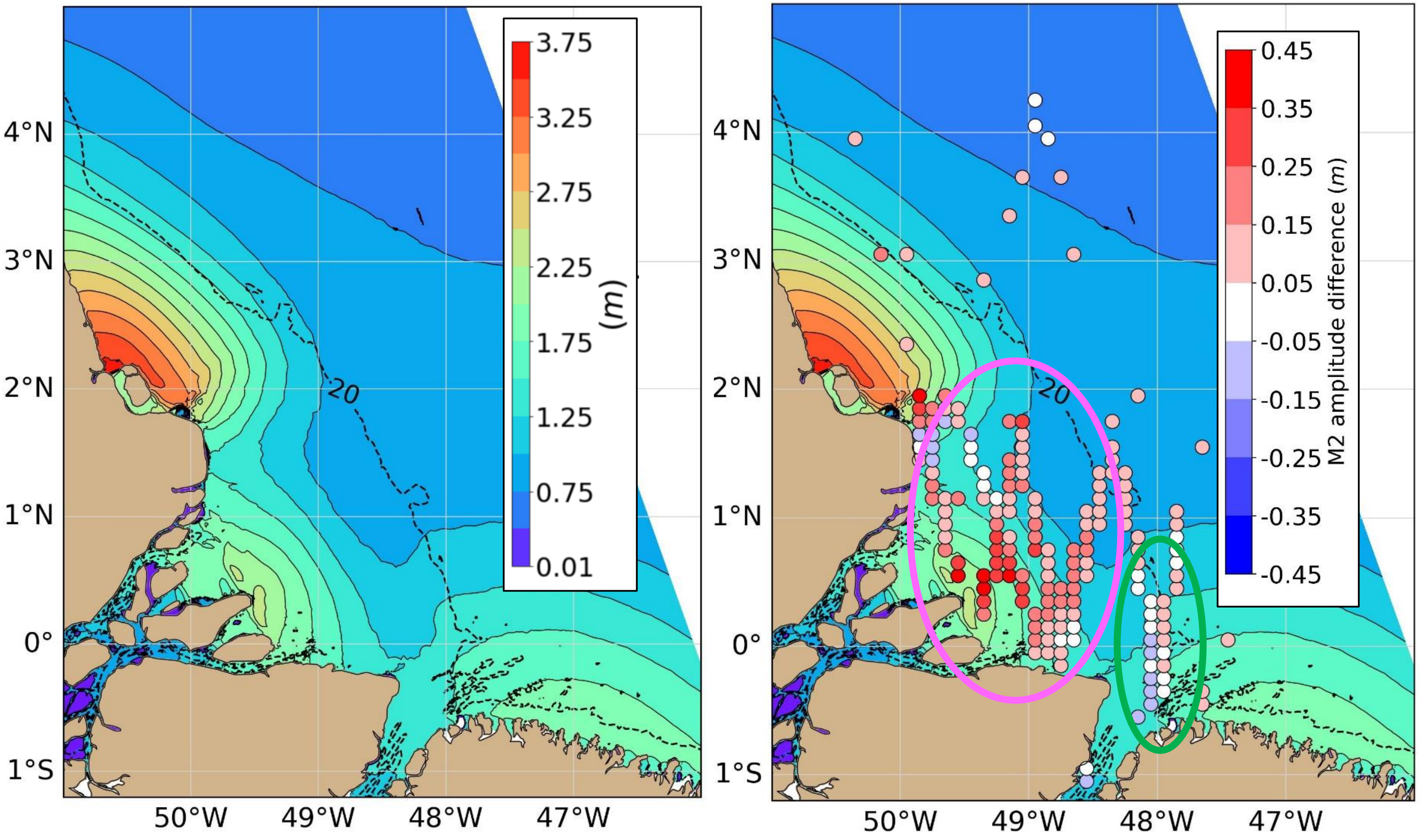

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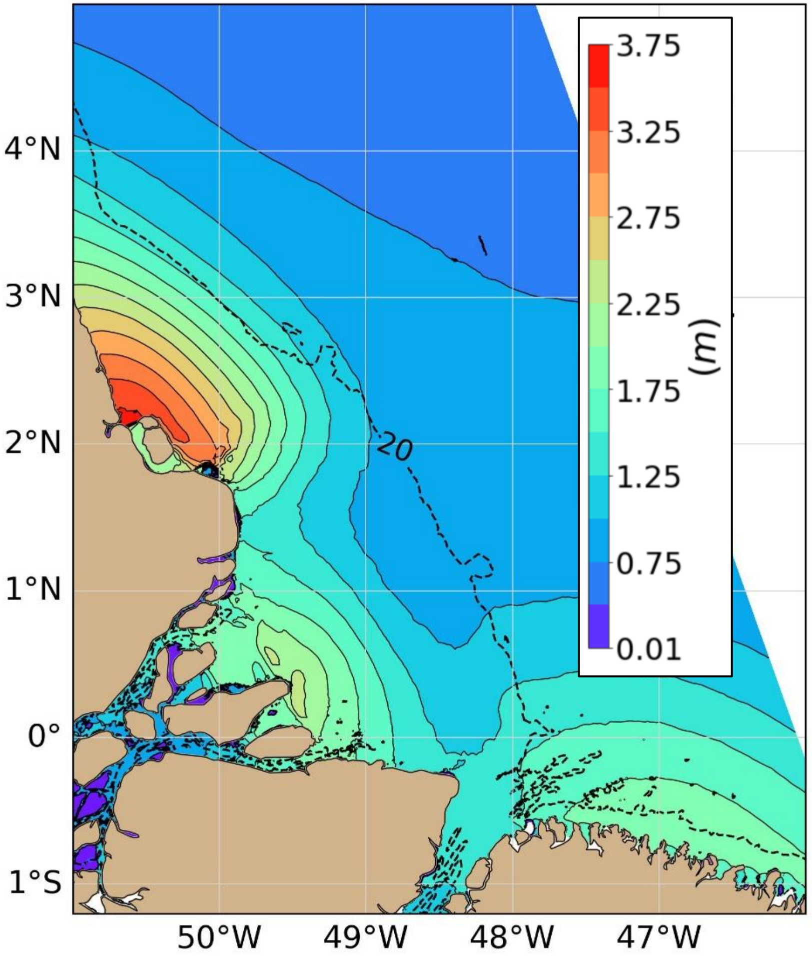

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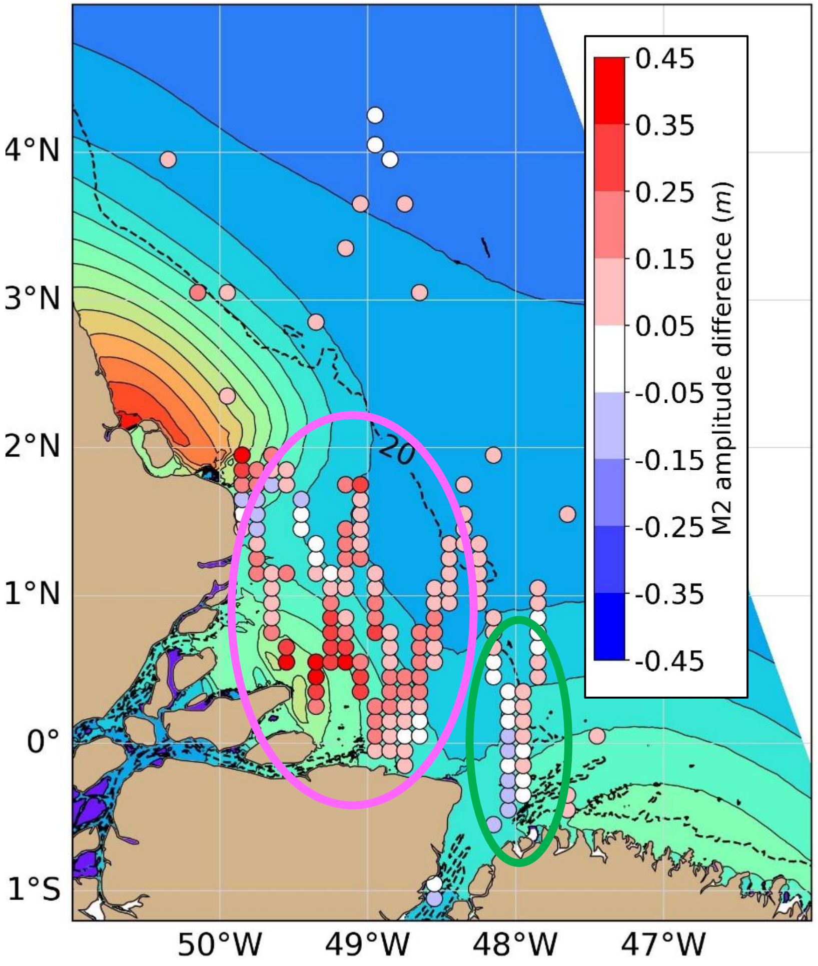

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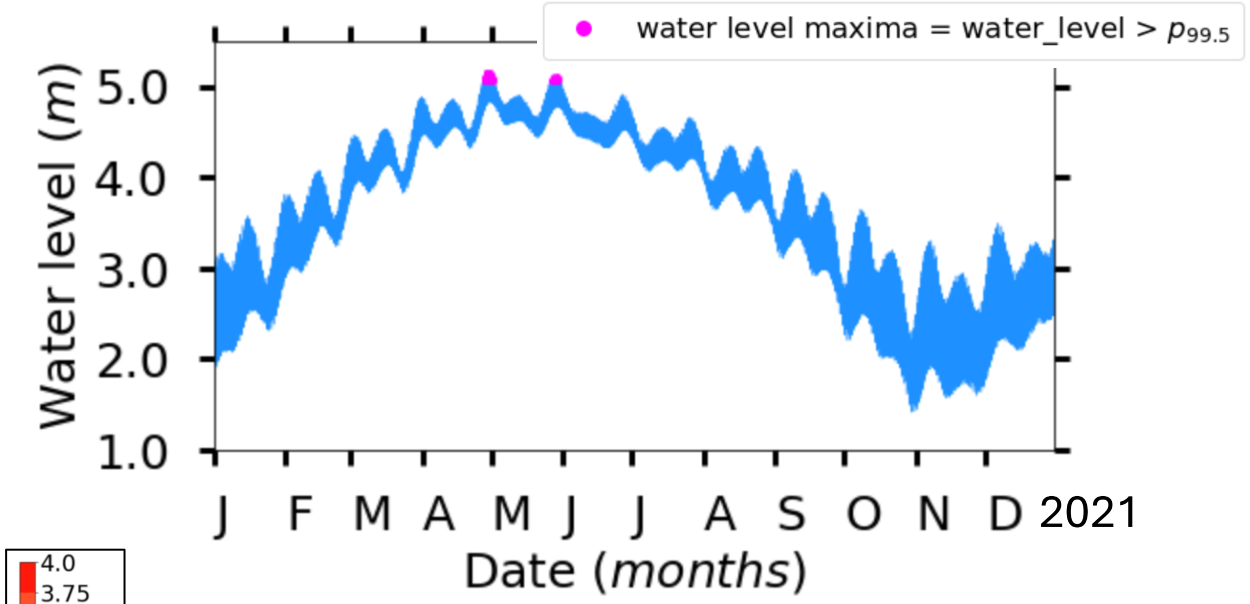
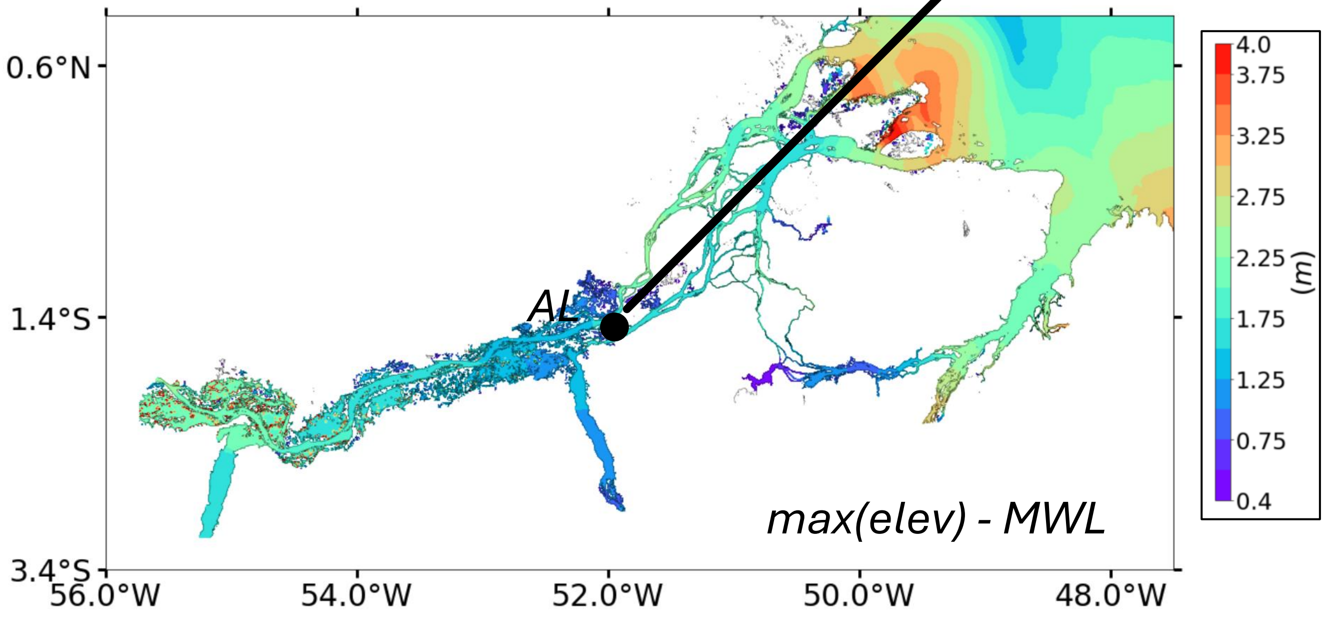
➢ Small residual bias still present after calibration

➢ **13 cm** of mean tidal complex error in the estuary (not shown)

➢ State of the art 2DH model

c. Dynamics of water level maxima in 2021





(Maximum elevation – Mean Water Level) during 2021 flood

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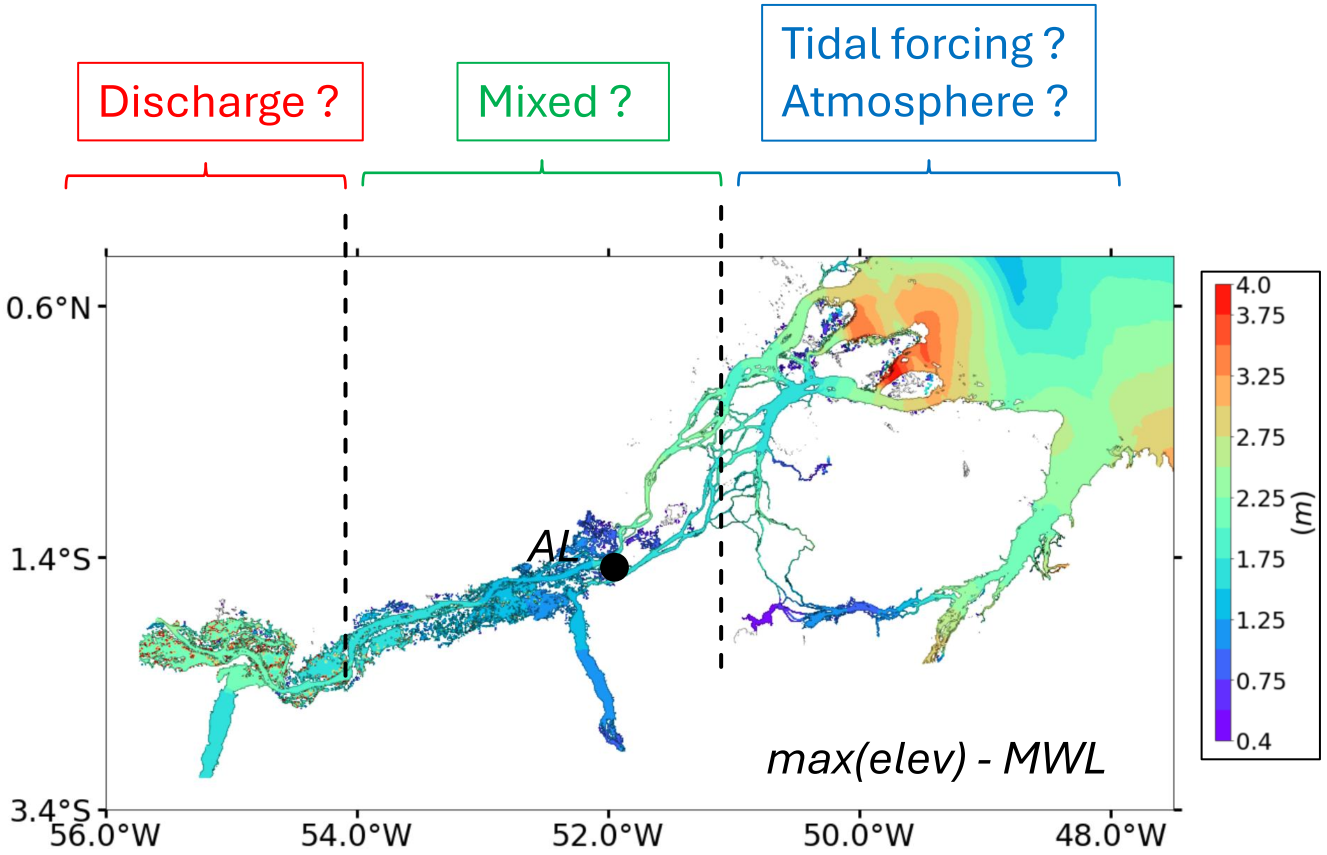

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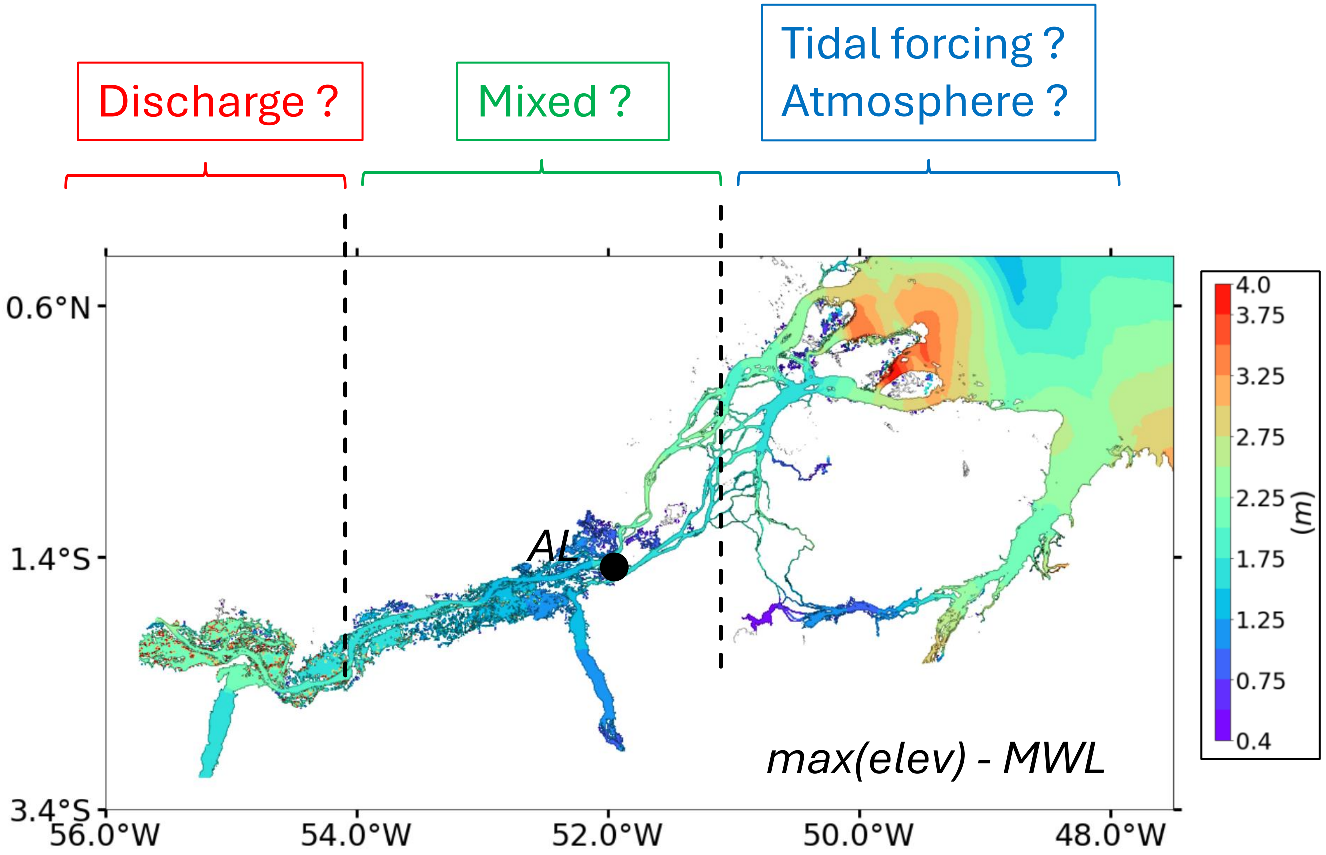
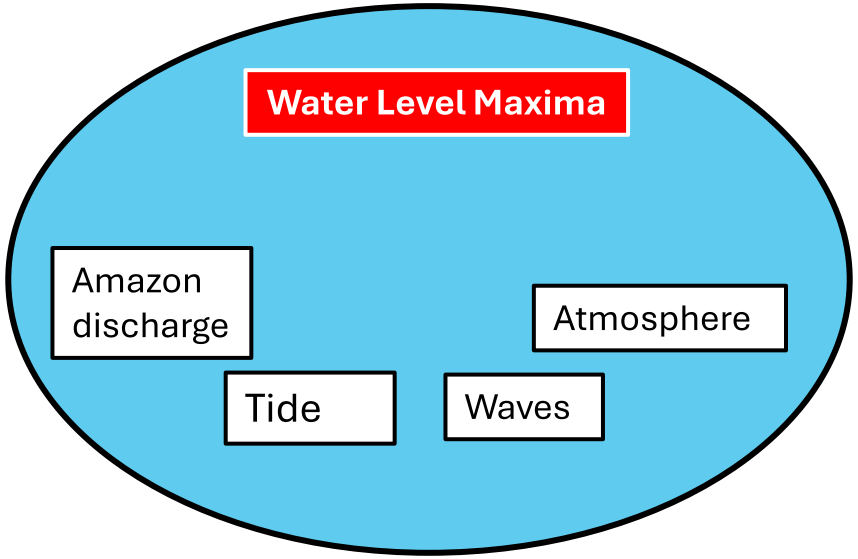


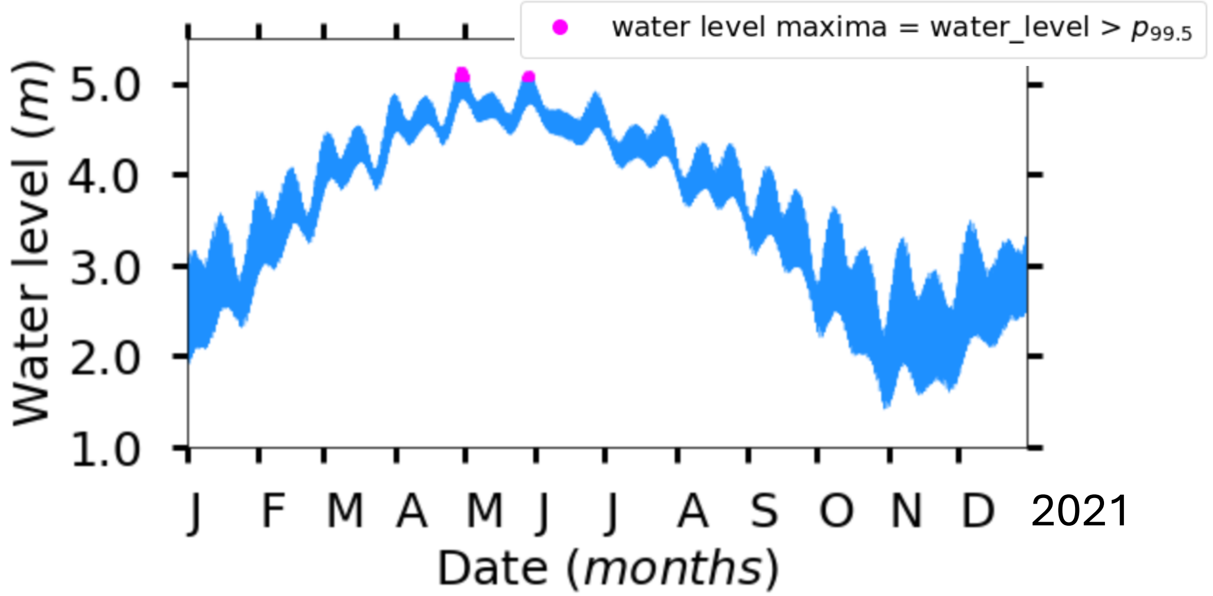
(Maximum elevation – Mean Water Level) during 2021 flood

- A record-breaking year with contrasted patterns of SLA between upstream and downstream.
- **But what drives the extremes ?**

c. Dynamics of water level maxima in 2021



Estuarine Water Level Maxima dynamics



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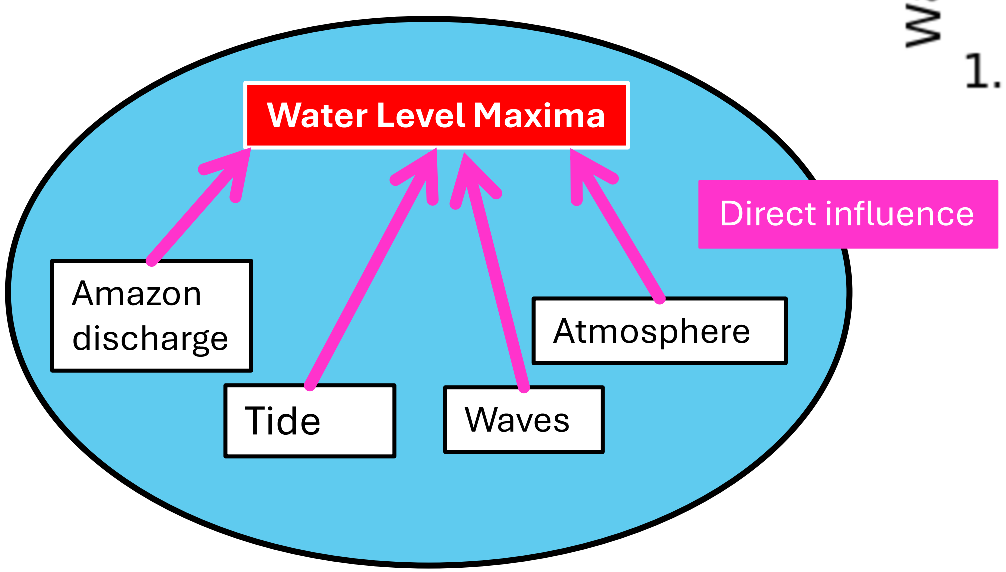

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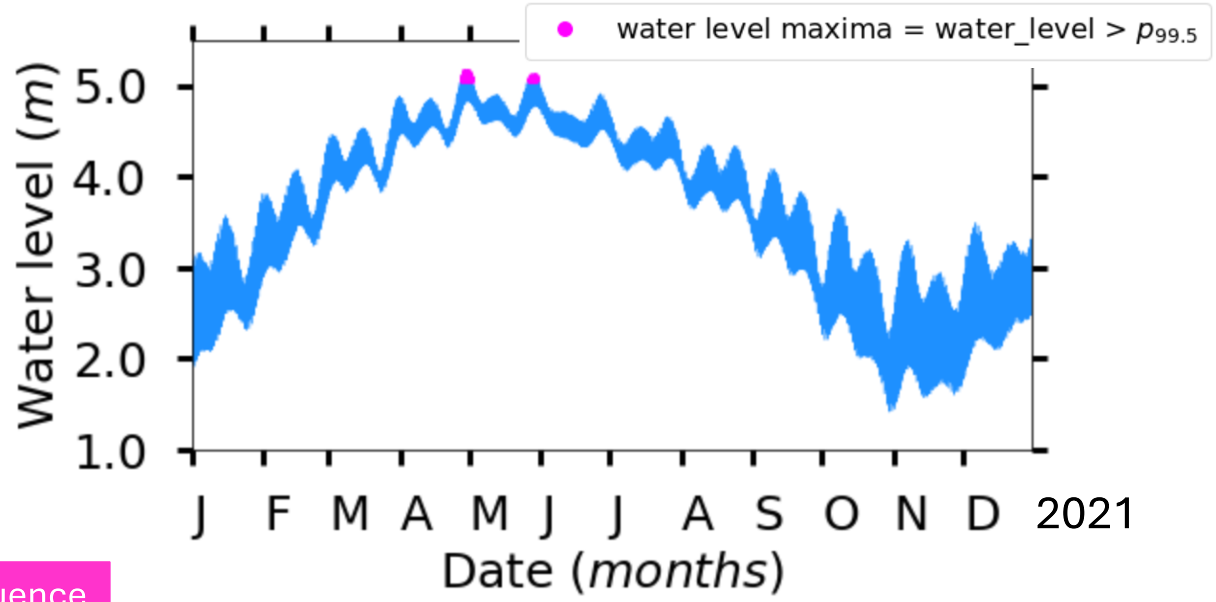

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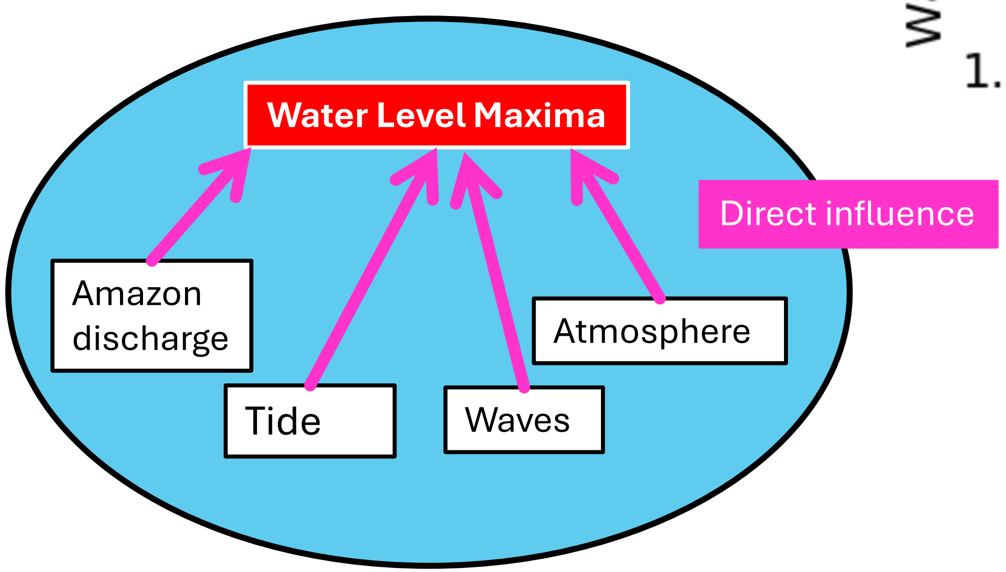

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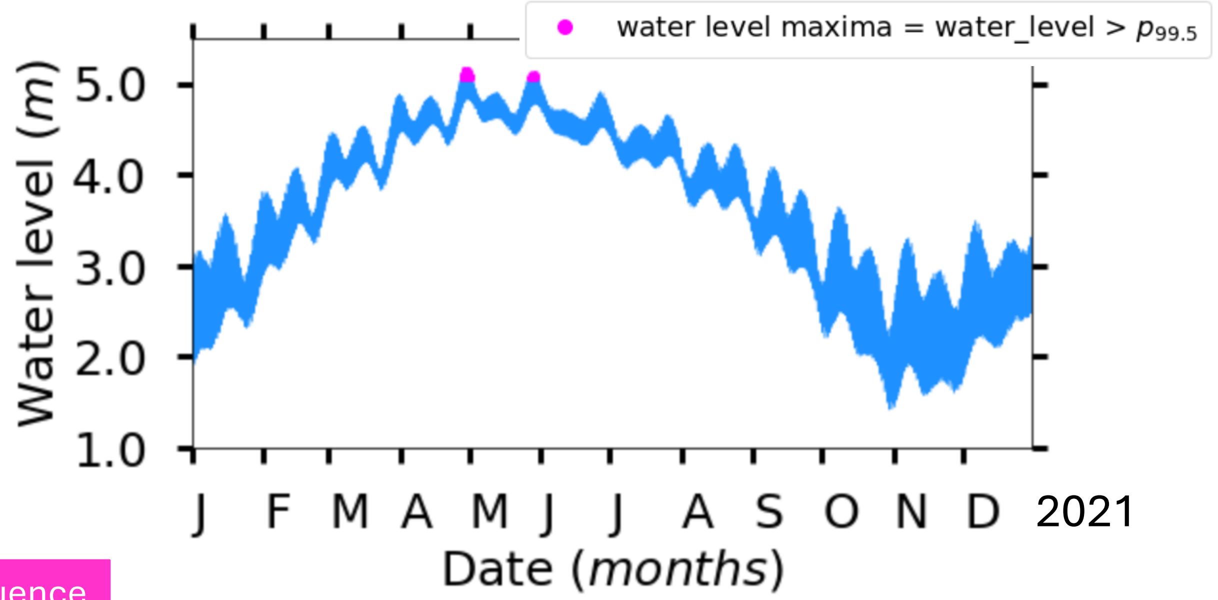
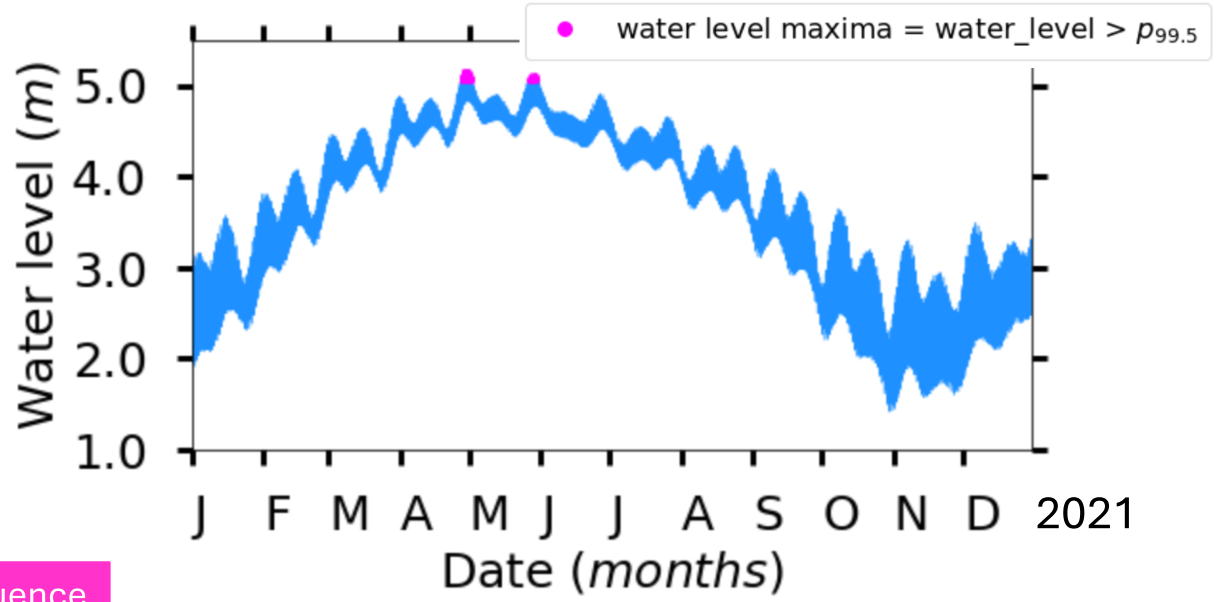
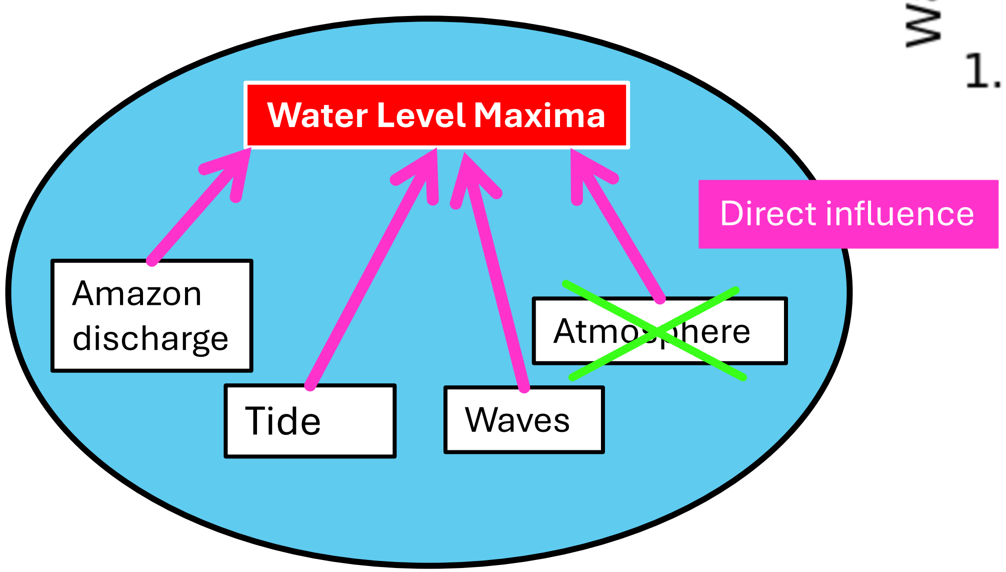


- ➢ What are the contributions of the different forcing factors ?
- ➢ How these contributions vary spatially ?

c. Dynamics of water level maxima in 2021



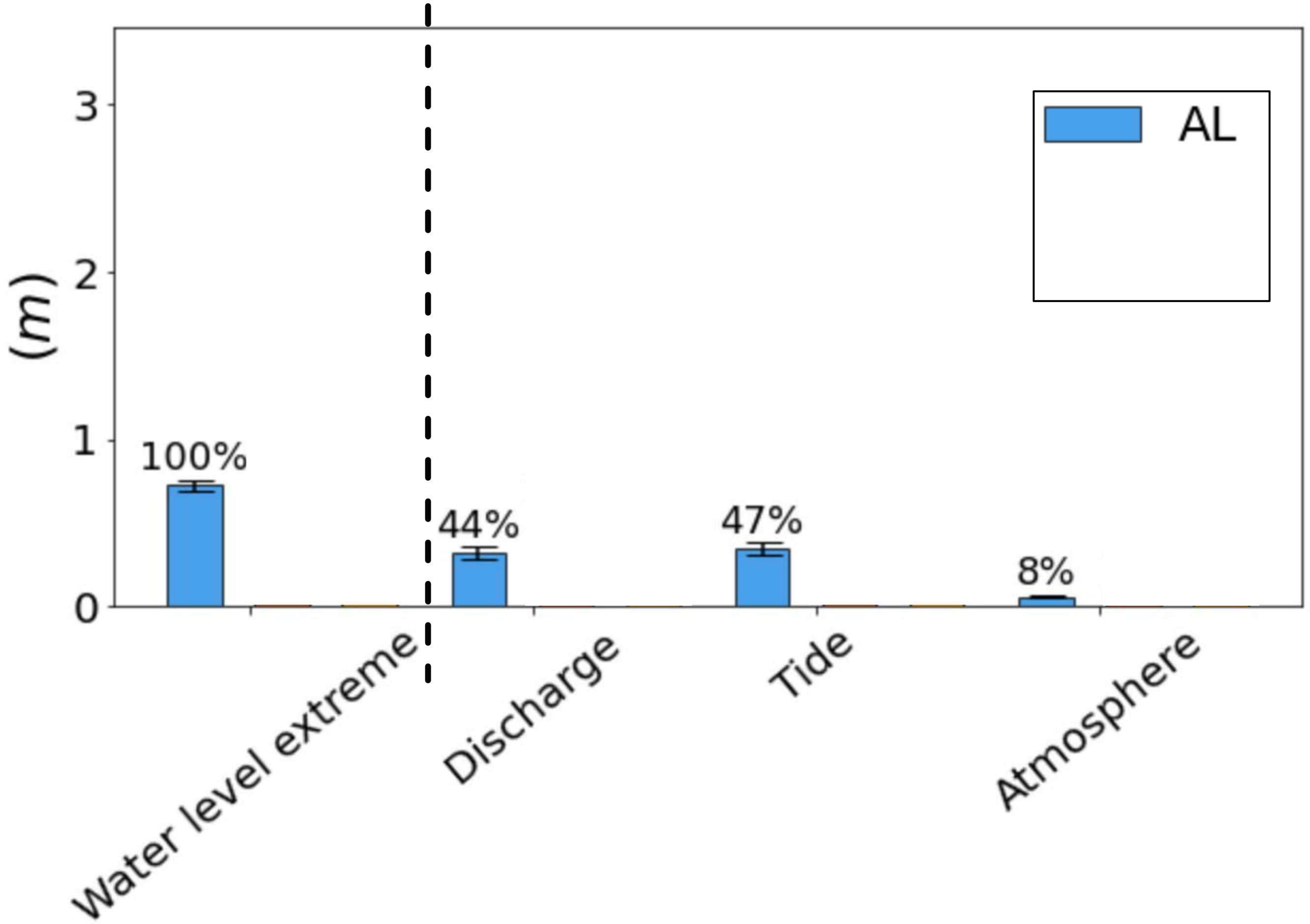


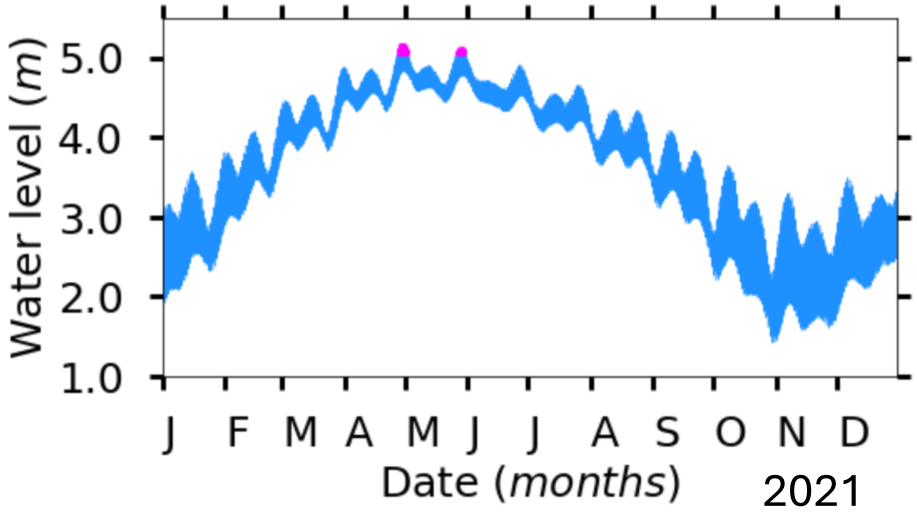
Estuarine Water Level Maxima dynamics

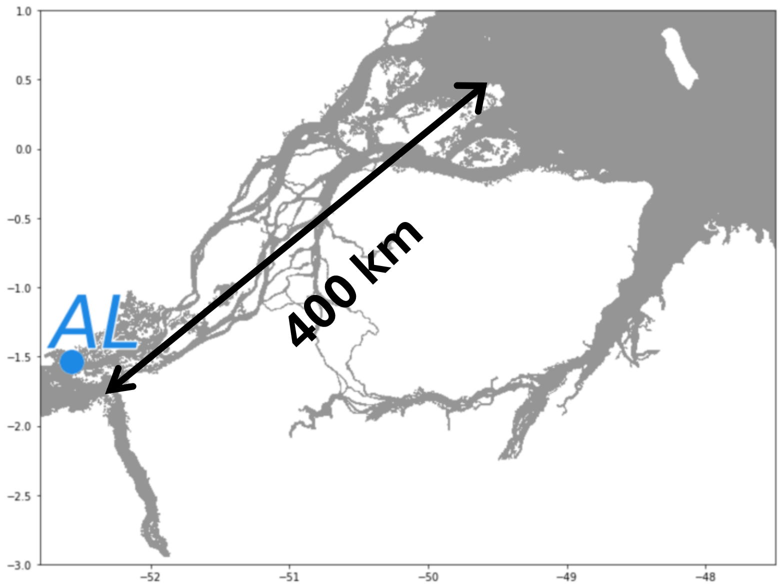
→ Sensitivity tests of the model

- What are the contributions of the different forcing factors ?
- How these contributions vary spatially ?

c. Dynamics of water level maxima in 2021

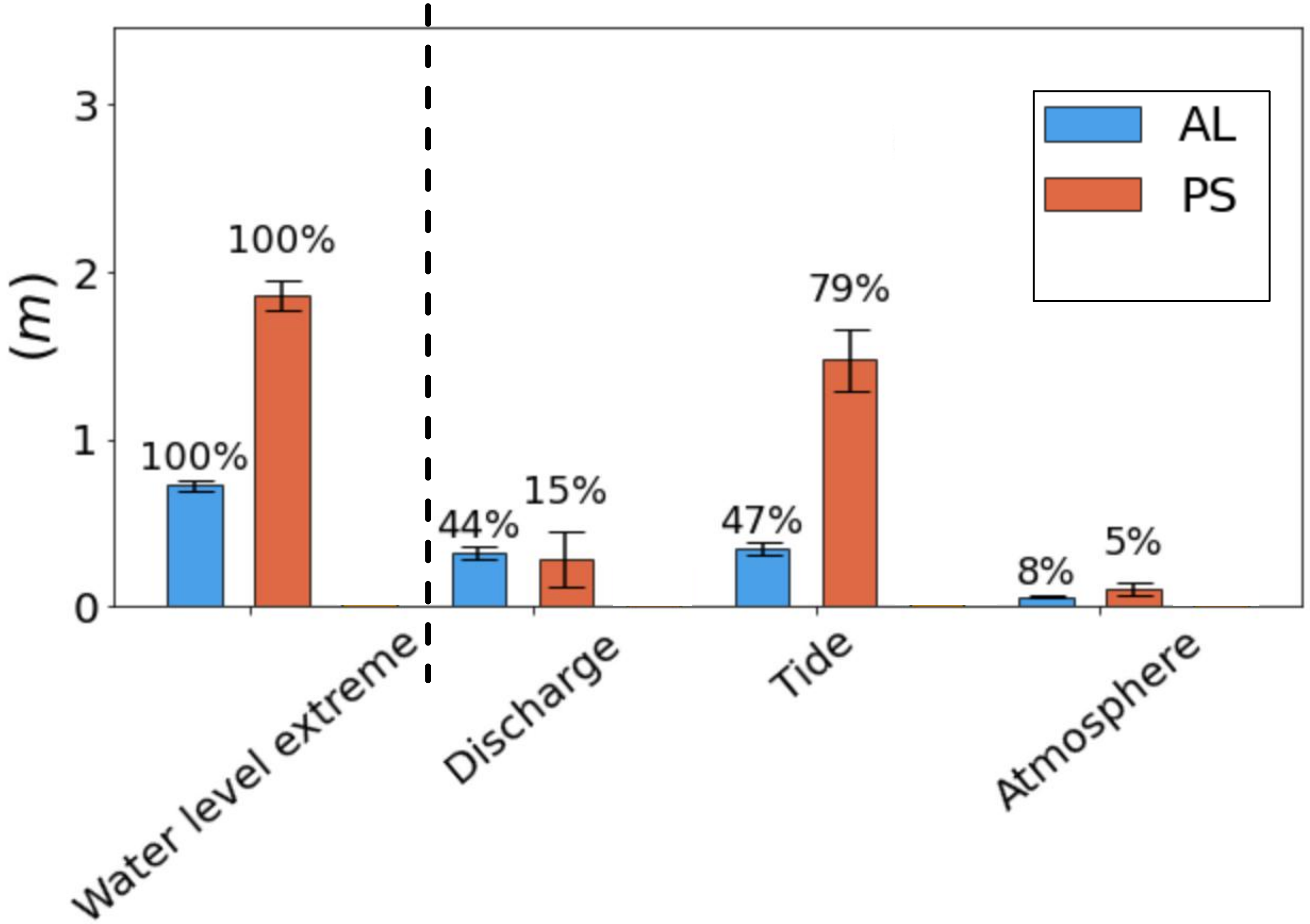


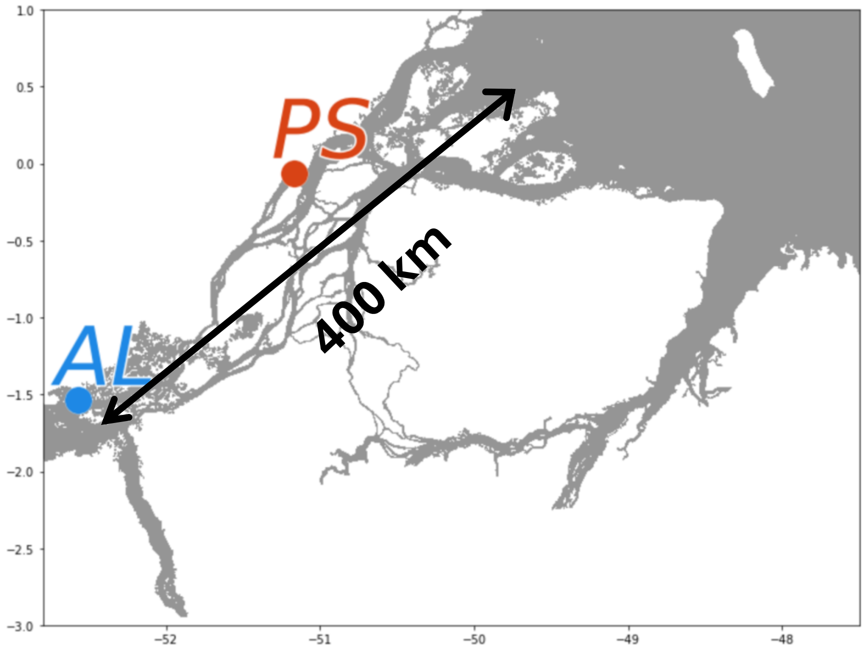




Typology of SLA during maxima for 2021 in the Northern Channel of the Amazon estuary

c. Dynamics of water level maxima in 2021





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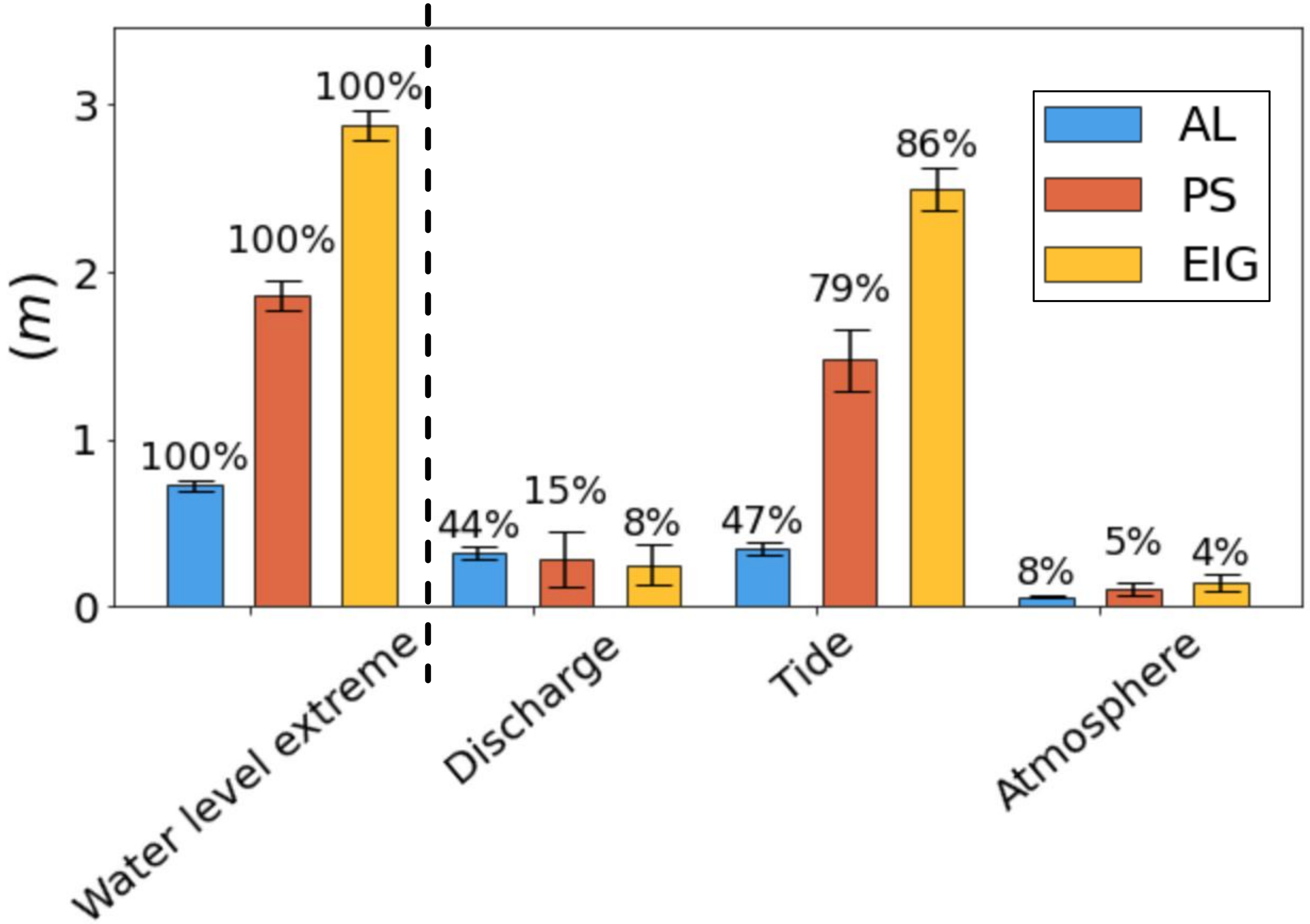

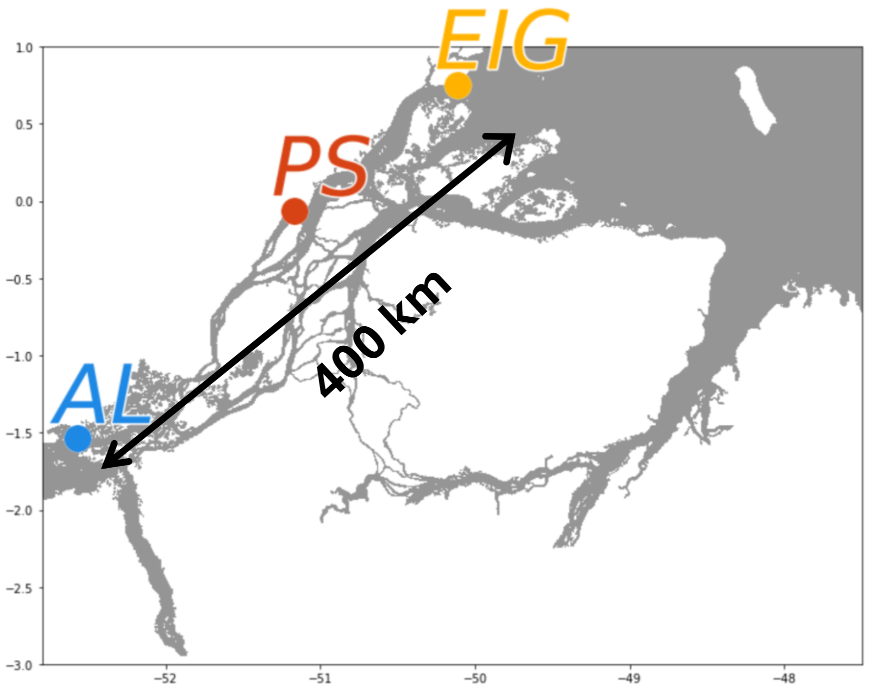

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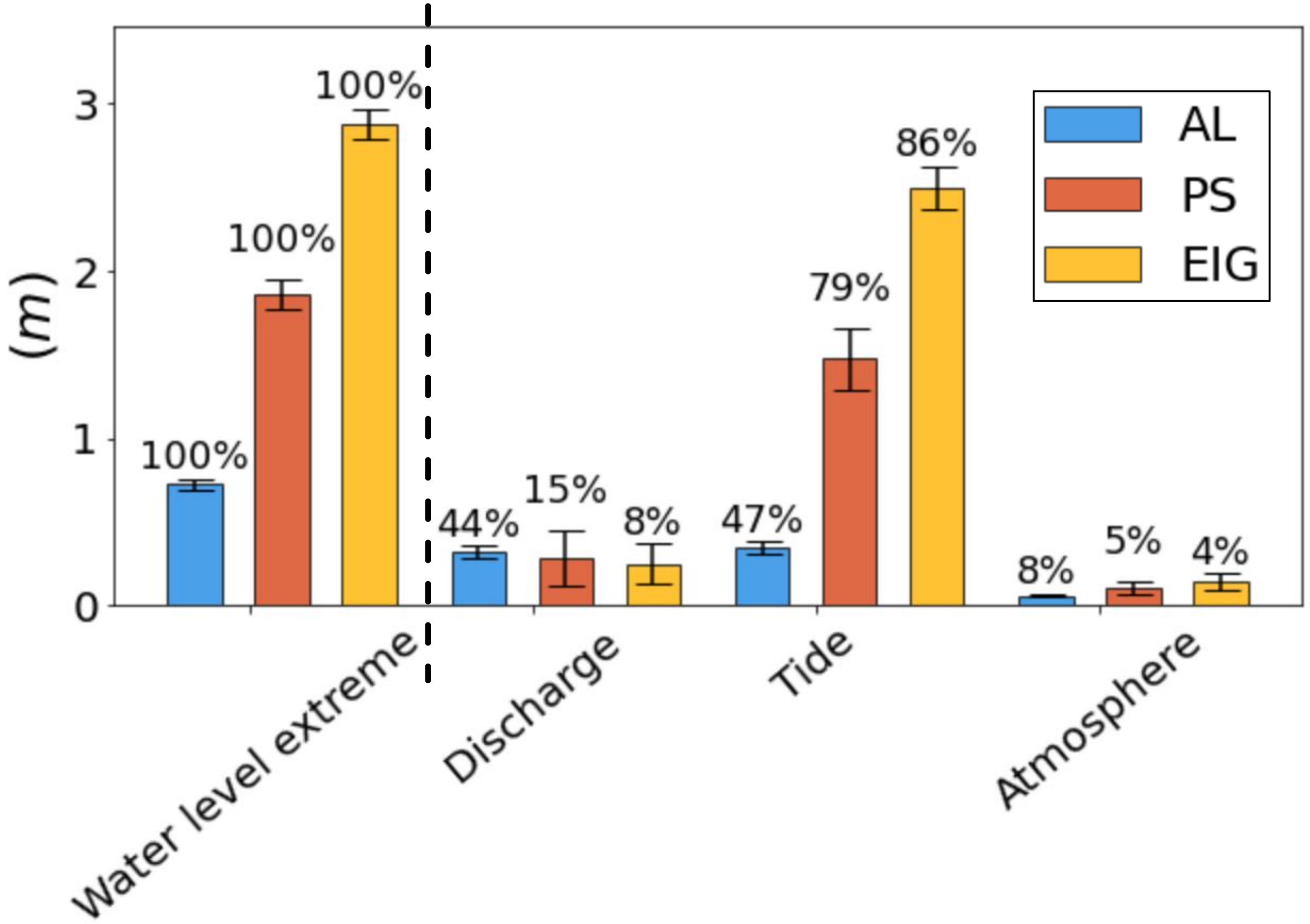

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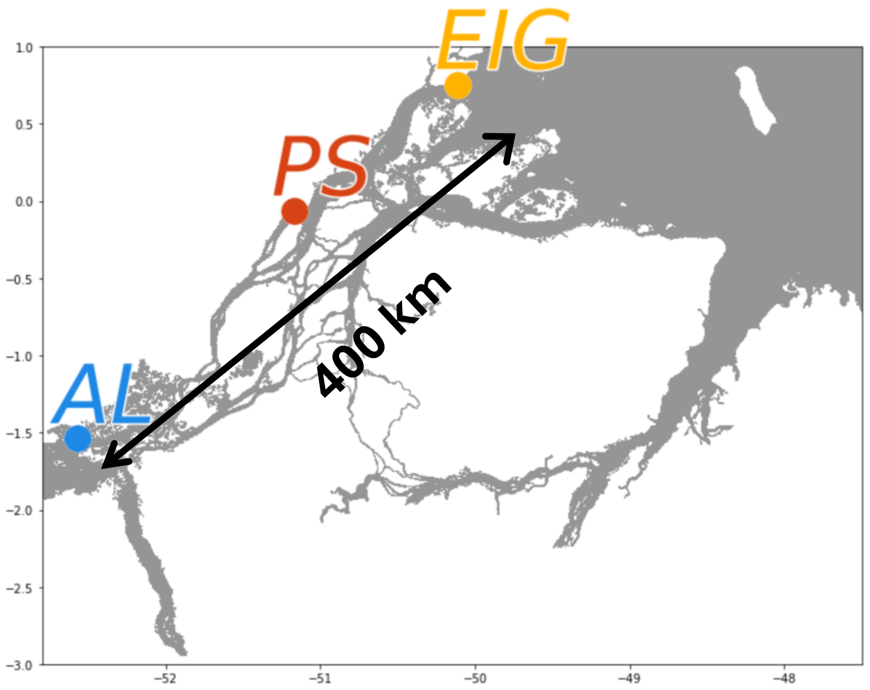
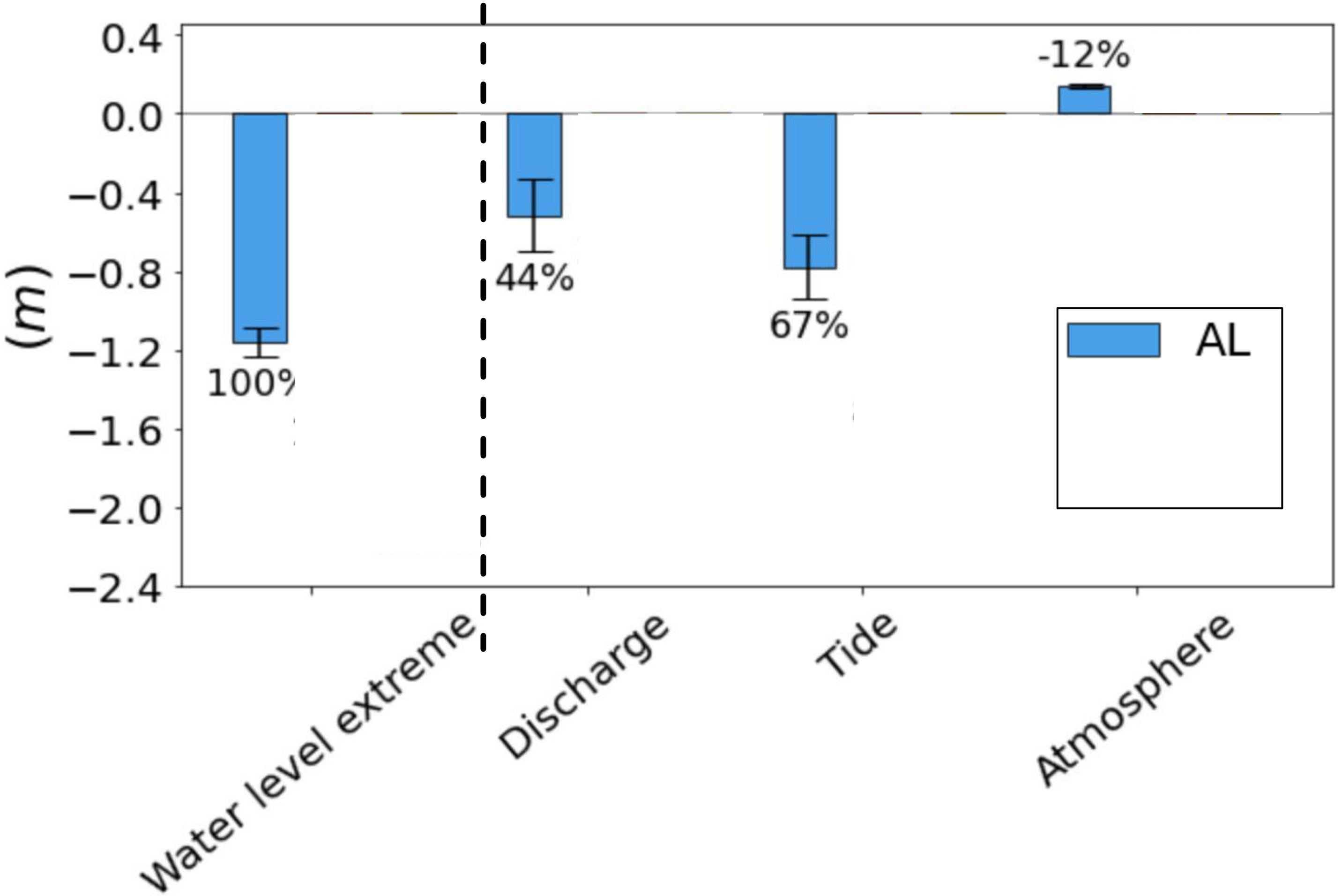
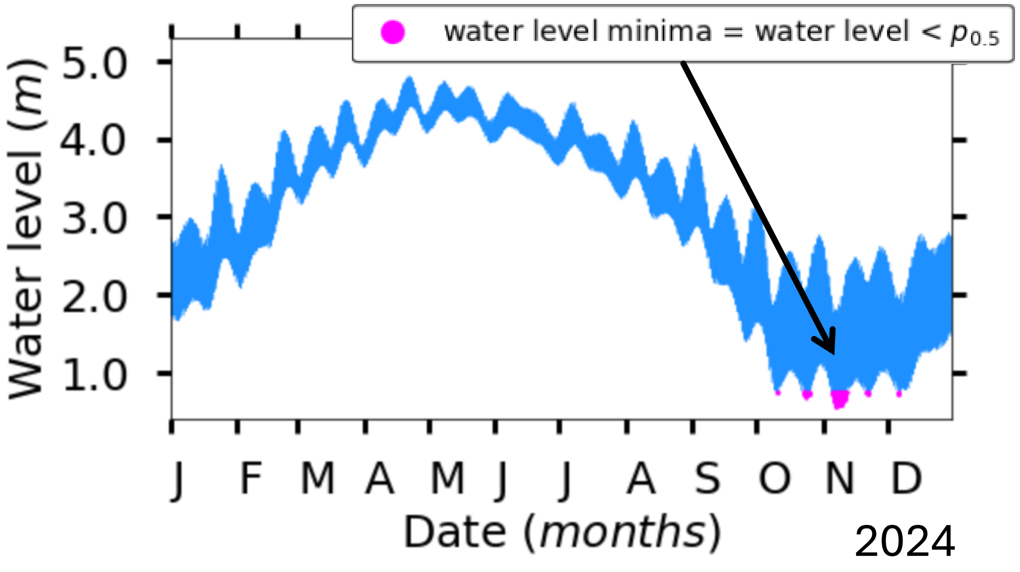


- ➢ Joint influence of river discharge, tide and atmosphere (trade wind bursts) in generating water level maxima
- ➢ Influence of the river discharge diminishes drastically downstream

d. Dynamics of water level minima in 2024





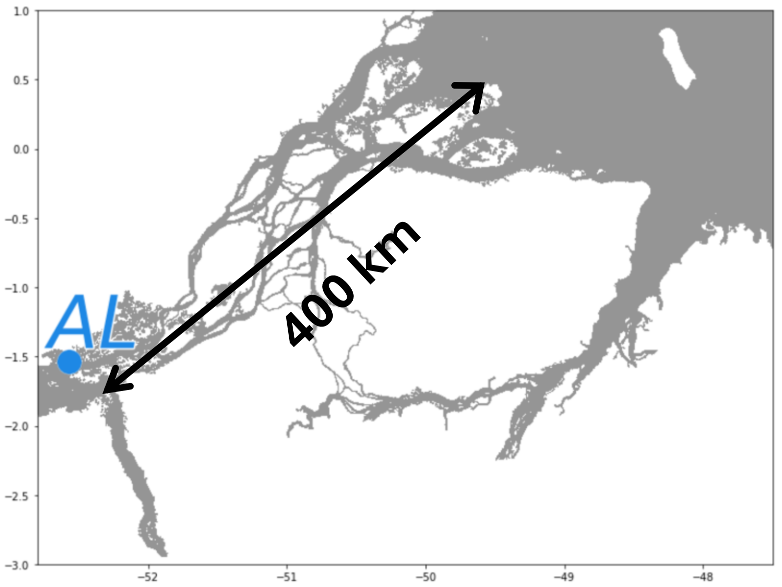


Fig12. Typology of water level minima for 2024 in the Northern Channel of the Amazon estuary

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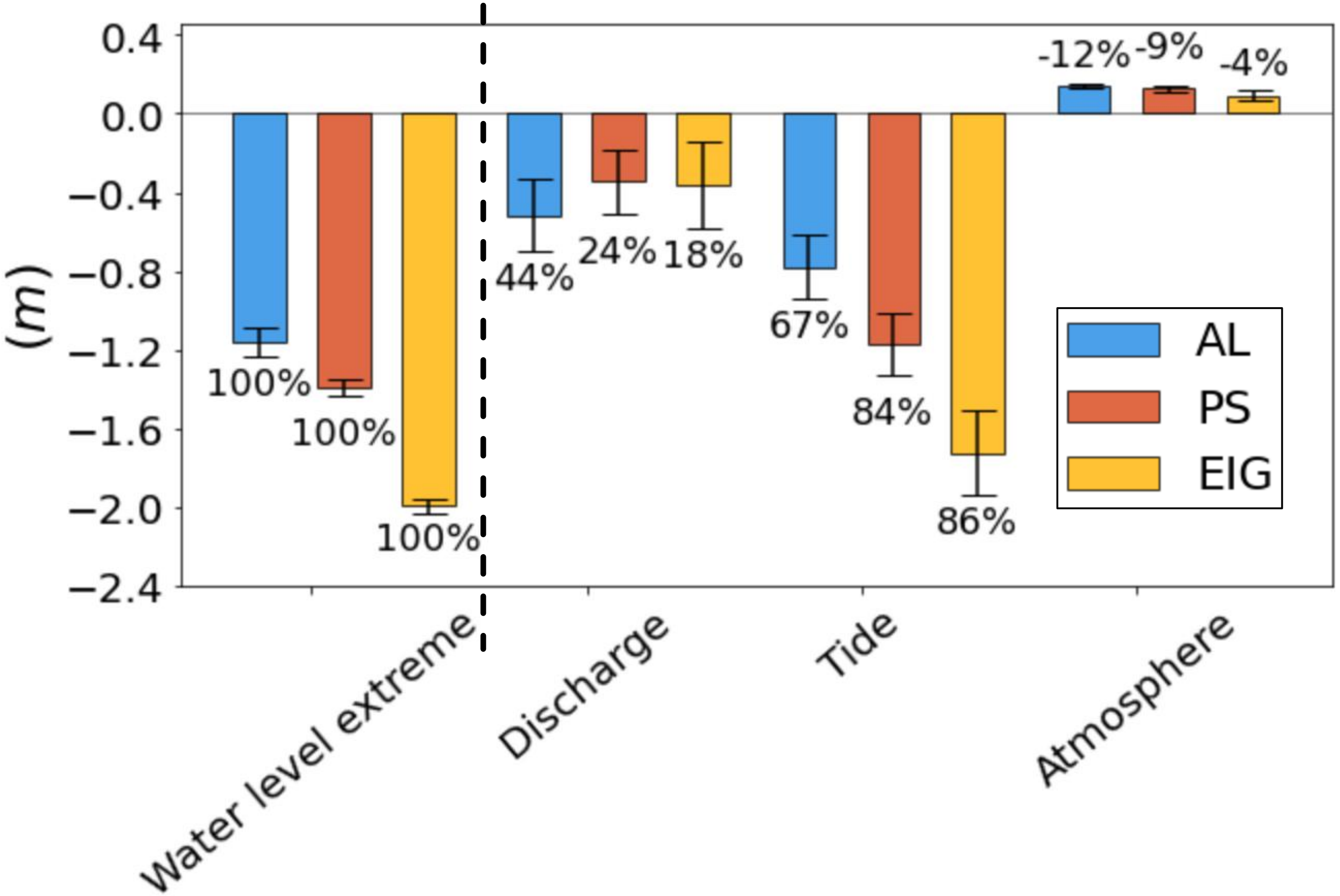

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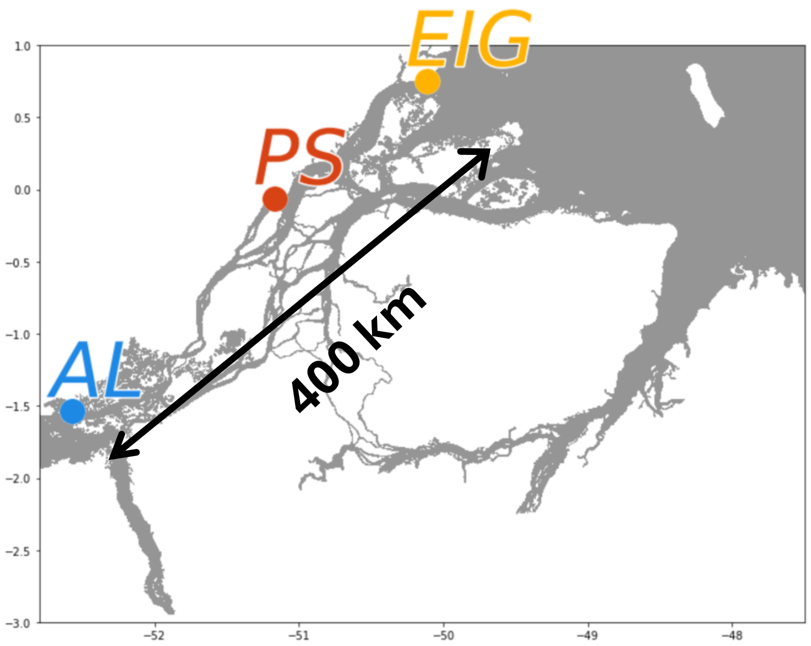
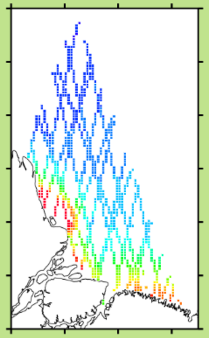


- Lack of river discharge and low tide are the main drivers of minima during drought
- Atmosphere has a negative contribution on minima generation
- Higher contribution of the tide upstream compared to its contribution to maxima

Conclusions

- **PyAltide, a multi-mission altimetric tidal atlas**
  - High resolution
  - Transferable to any coastal region (already available over Amazon Shelf and Madagascar)
  - Easy to use Python code
  - Accessible (contact: paul.coulet@univ-tlse3.fr)



- **Seamless high-resolution cross-scale hydrodynamic model of the Amazon delta**
  - Comprehensive domain from deep ocean to inner braided estuary
  - Quantitative tide validation using PyAltide atlas

➢ Tide, discharge and atmosphere (wind) all contribute to extreme events with strong spatial differences

➢ As far as 400km inland, ~50% of SLA maxima and ~ 70% of minima is driven by tide

➢ Wind increases maxima intensity while reducing minima intensity

➢ For extreme events analysis, it is necessary to have a cross-scale non-linear model, even far inland.

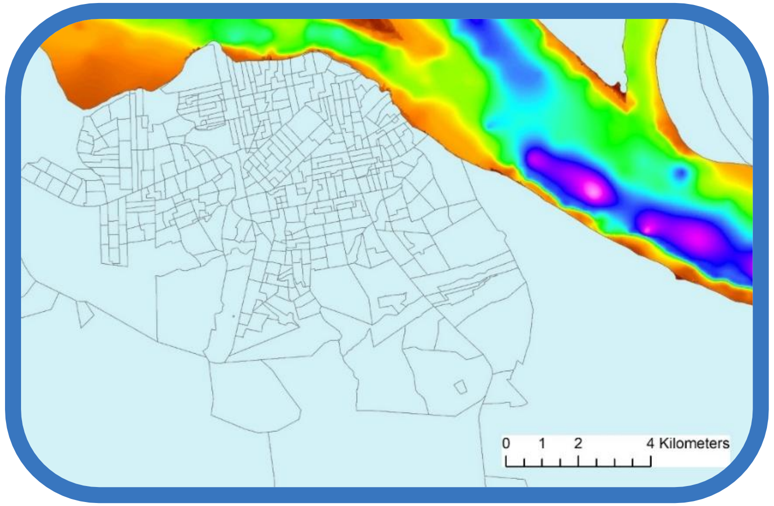
➢ How does the extreme events hazard impacts the riverine society ?

Perspectives : Socio-economic impacts (in collaboration with Anouch Missirian)

Toulouse School of Economics

Socio-economical variables
from census data from
1990 to 2010

1990 | 2000 | 2010



Housing quality / Education
/ Characteristics of the household
/ Mobility / Surroundings

Perspectives : Socio-economic impacts (in collaboration with Anouch Missirian)

Toulouse School of Economics

Hindcast hazard from 1980 to 2010 using our hydrodynamical model

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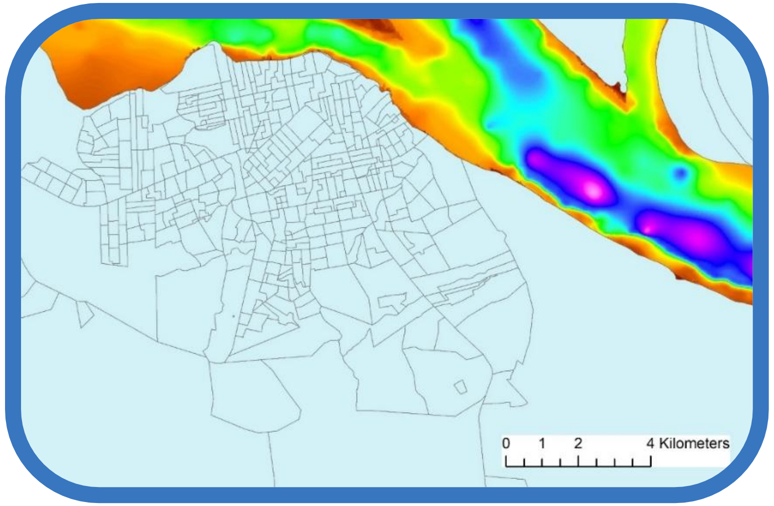
Socio-economical variables from census data from 1990 to 2010

1990 2000 2010



Housing quality / Education / Characteristics of the household / Mobility / Surroundings

Perspectives : Socio-economic impacts (in collaboration with Anouch Missirian)

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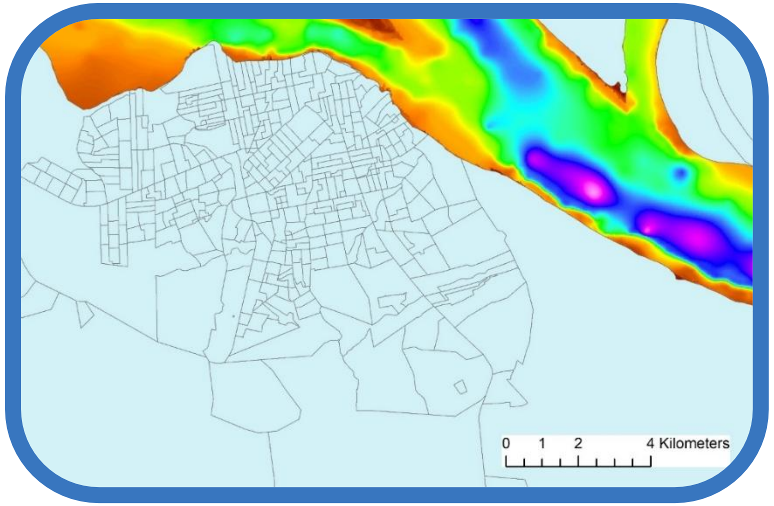
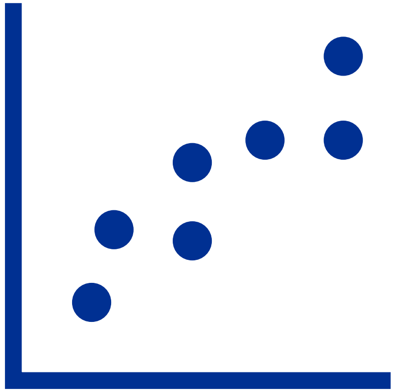


Housing quality / Education / Characteristics of the household / Mobility / Surroundings

=

Estimate the causal effect of hazard experience on riverine society



Thanks for your attention !

Available here !

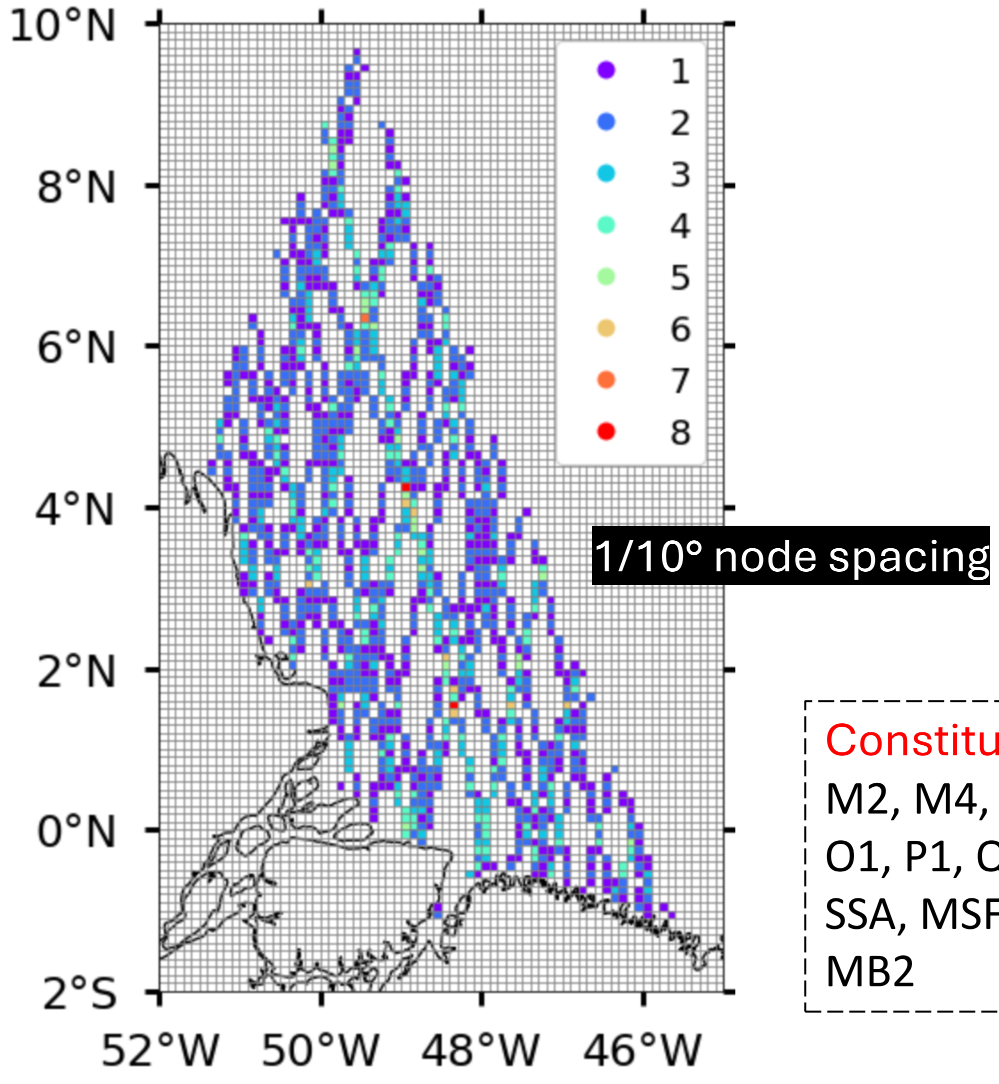
Recent Open Access publications:

Coulet, P., Durand, F., Fassoni-Andrade, A., Khan, J., Testut, L., Toublanc, F., Santos, L.G., Moreira, D.M., 2025b. ***Assessment of the hydrodynamical signature of the record-breaking 2021 flood along the Amazon estuary****. Ocean Modelling 196, 102536.*

Coulet, P., Durand, F., Fassoni-Andrade, A., Khan, M.J.U., Testut, L., Toublanc, F., Santos, L.G., Moreira, D.M., Azevedo, A., 2025a. ***Dynamics of Yearly Maximum Water Levels in the Amazon Estuary.*** *Estuaries and Coasts 48, 54.*

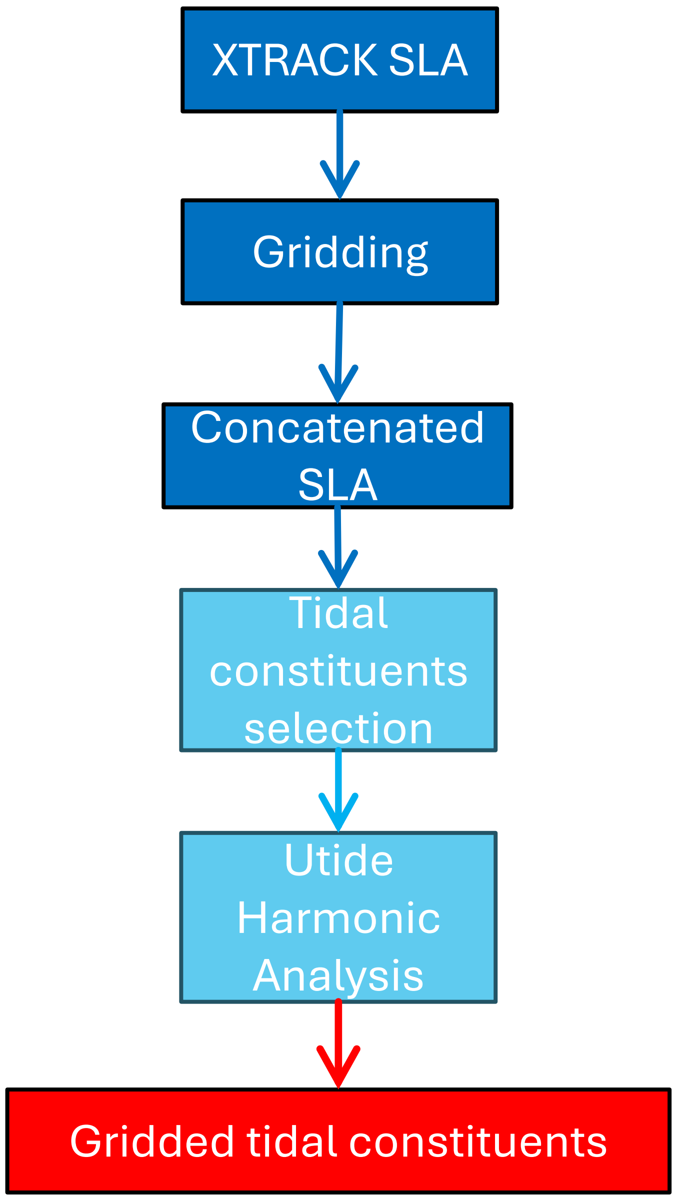
Available here !

Supplementary materials



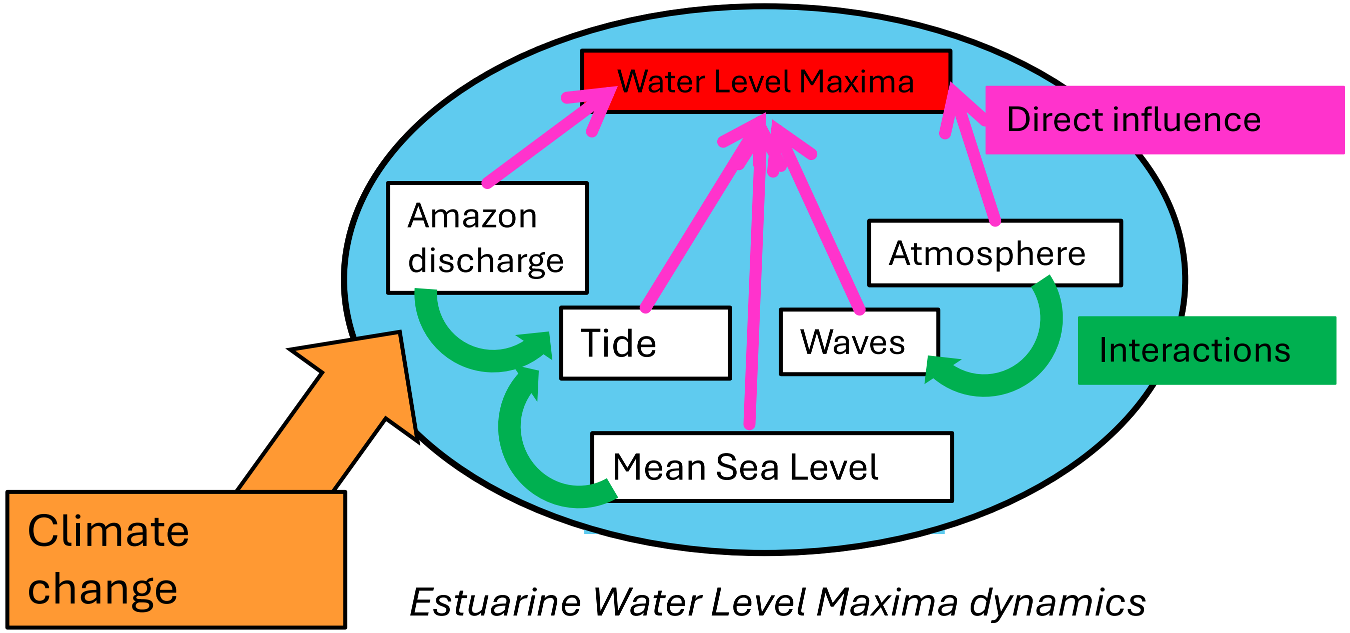
Number of altimetric points within each grid cell

Constituents analyzed
M2, M4, MF, MM, N2, O1, P1, Q1, S1, S2, SA, SSA, MSF, K1, K2, MA2, MB2



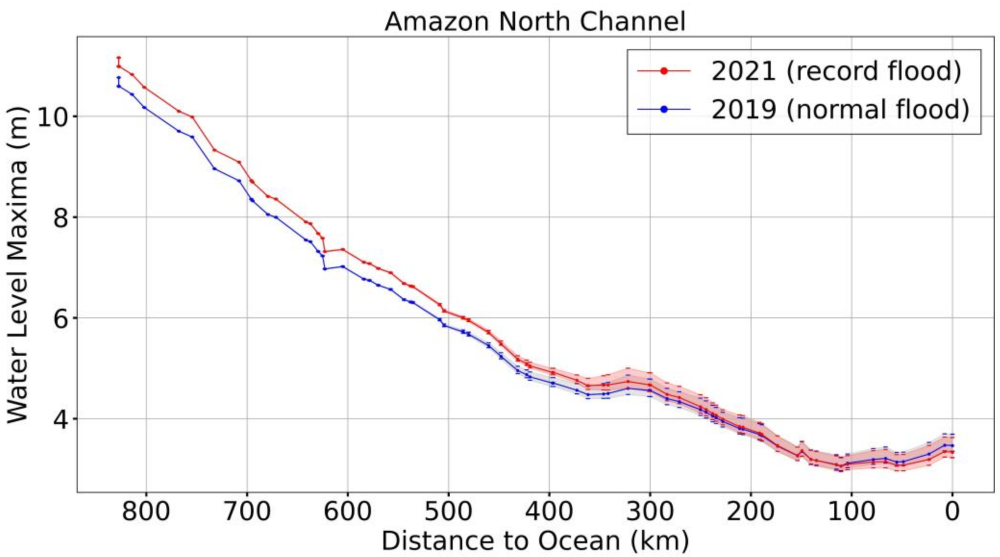
Methodology to compute tidal constituents

Supplementary materials

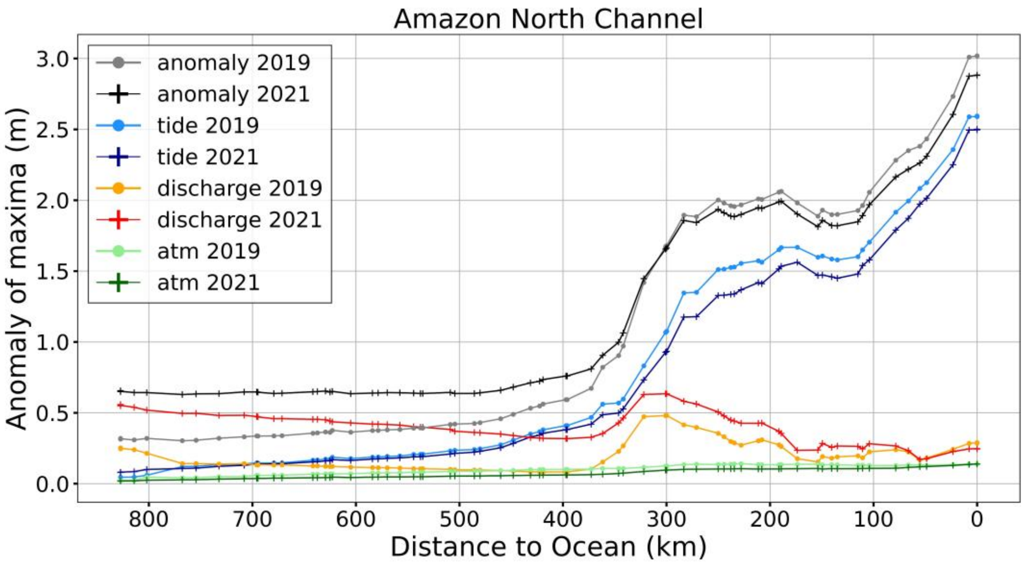


Estuarine Water Level Maxima dynamics

Supplementary materials

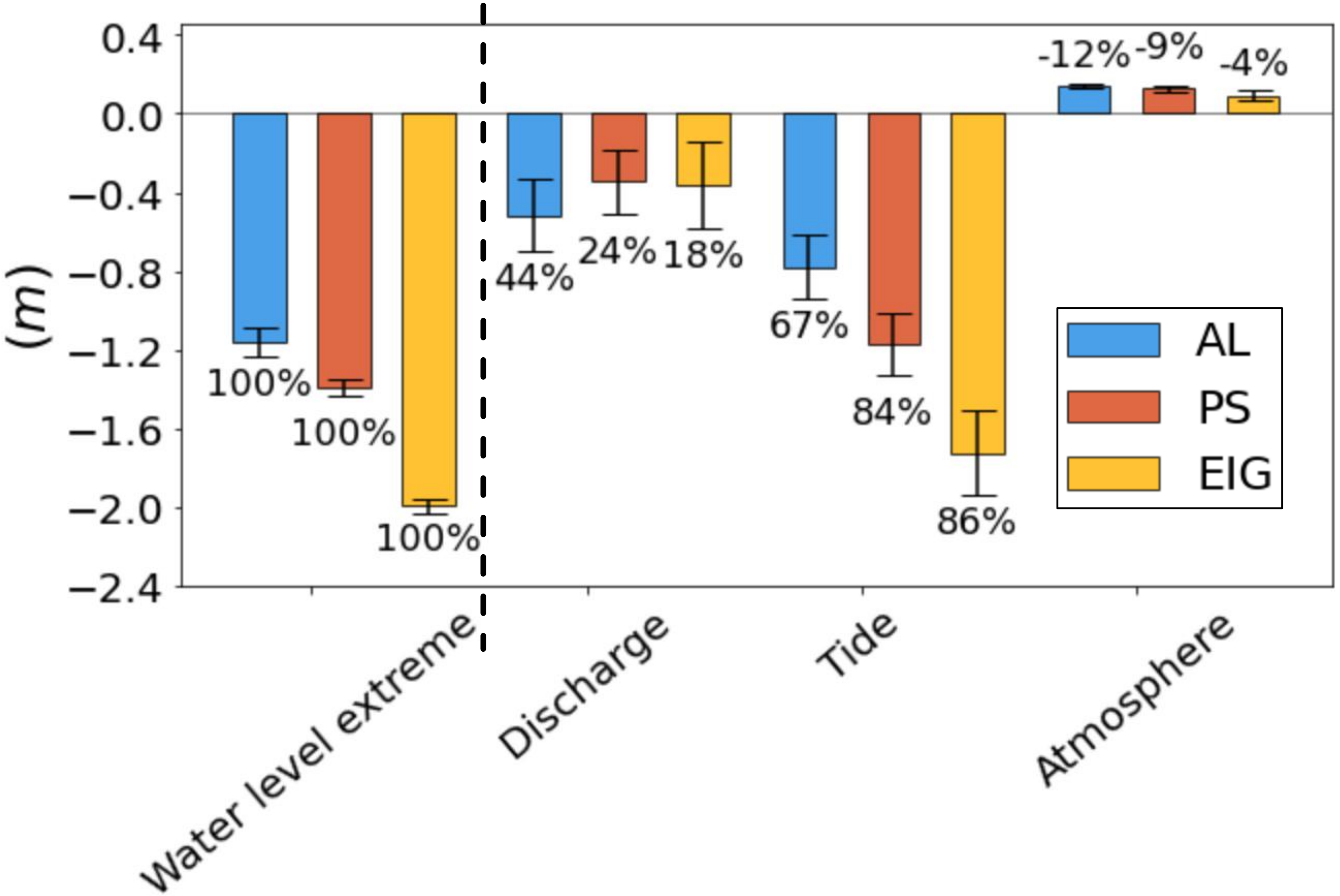


Along-estuary distribution of water level maxima in Amazon North Channel for 2021 (record flood) vs 2019 (normal flood). Min-max deviation is also displayed



Along-estuary distribution of the water level anomaly during the maxima events of 2021 (record flood) and 2019 (normal flood), along with its various contributors (river discharge, tide, atmospheric forcing).

Supplementary materials



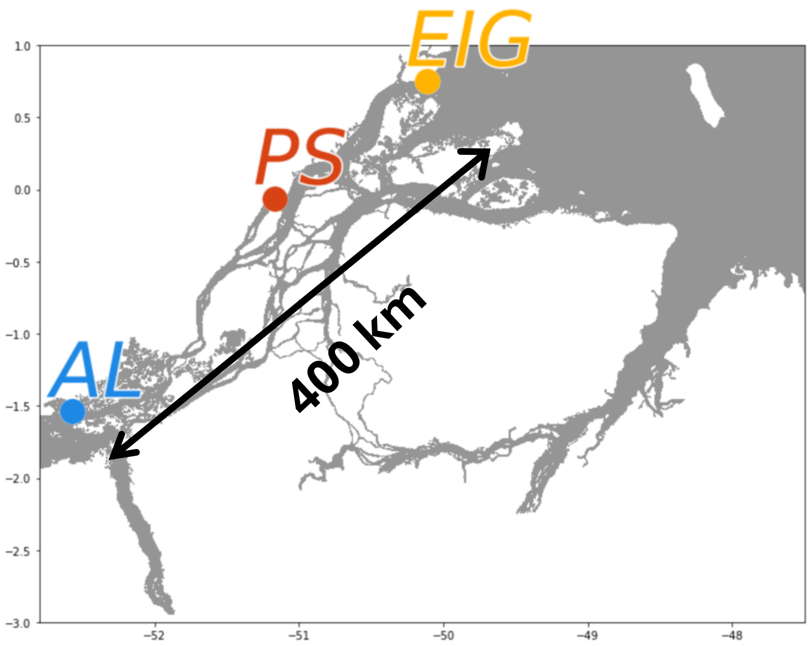


Fig12. Typology of SLA during minima for 2023 in the Northern Channel of the Amazon estuary

- River discharge and tide are the main drivers of minima during drought
- High contribution of the tide, either upstream or downstream

Supplementary materials

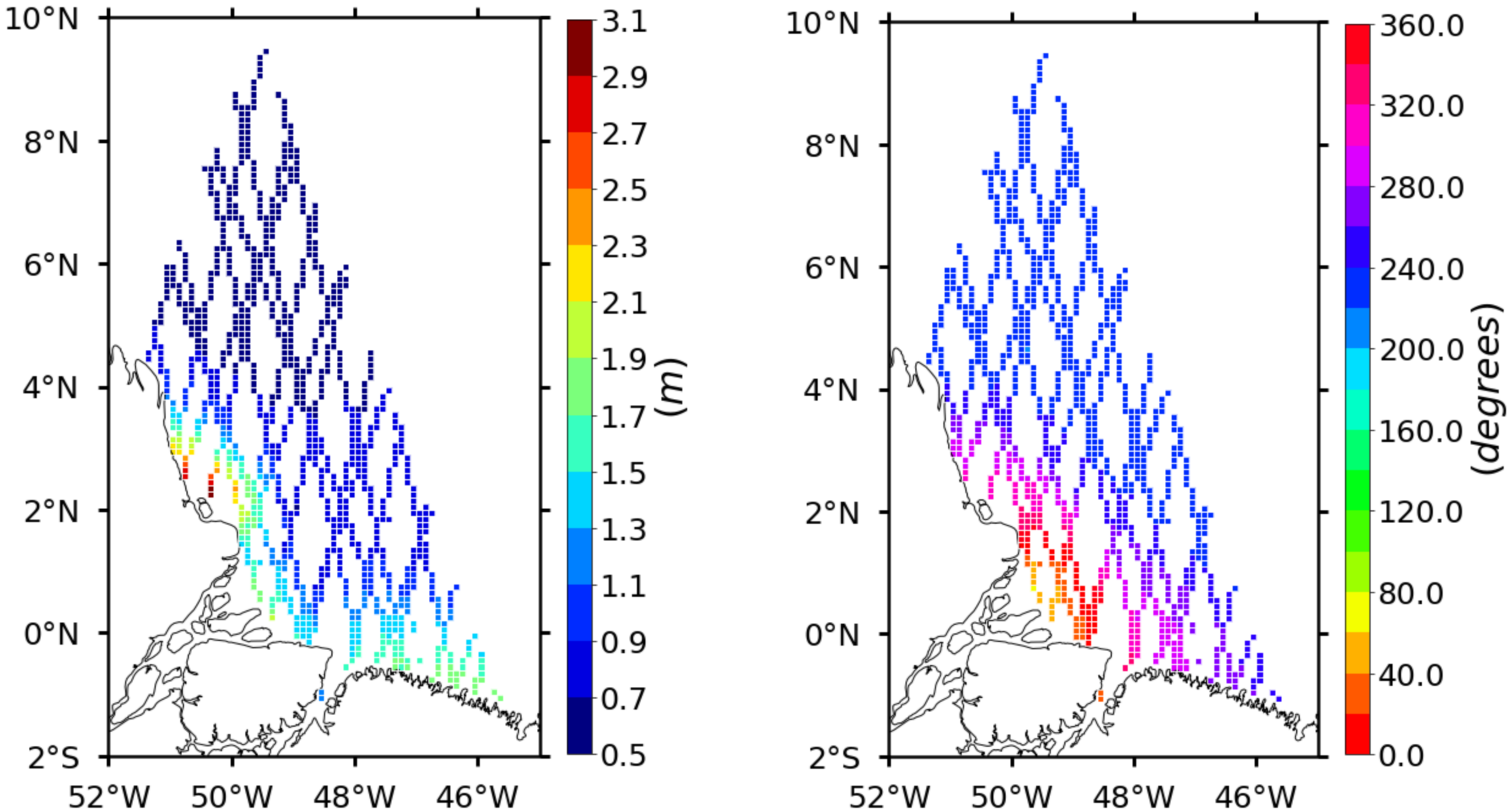


Fig. M2 Amplitude and phase from PyAltide

Supplementary materials

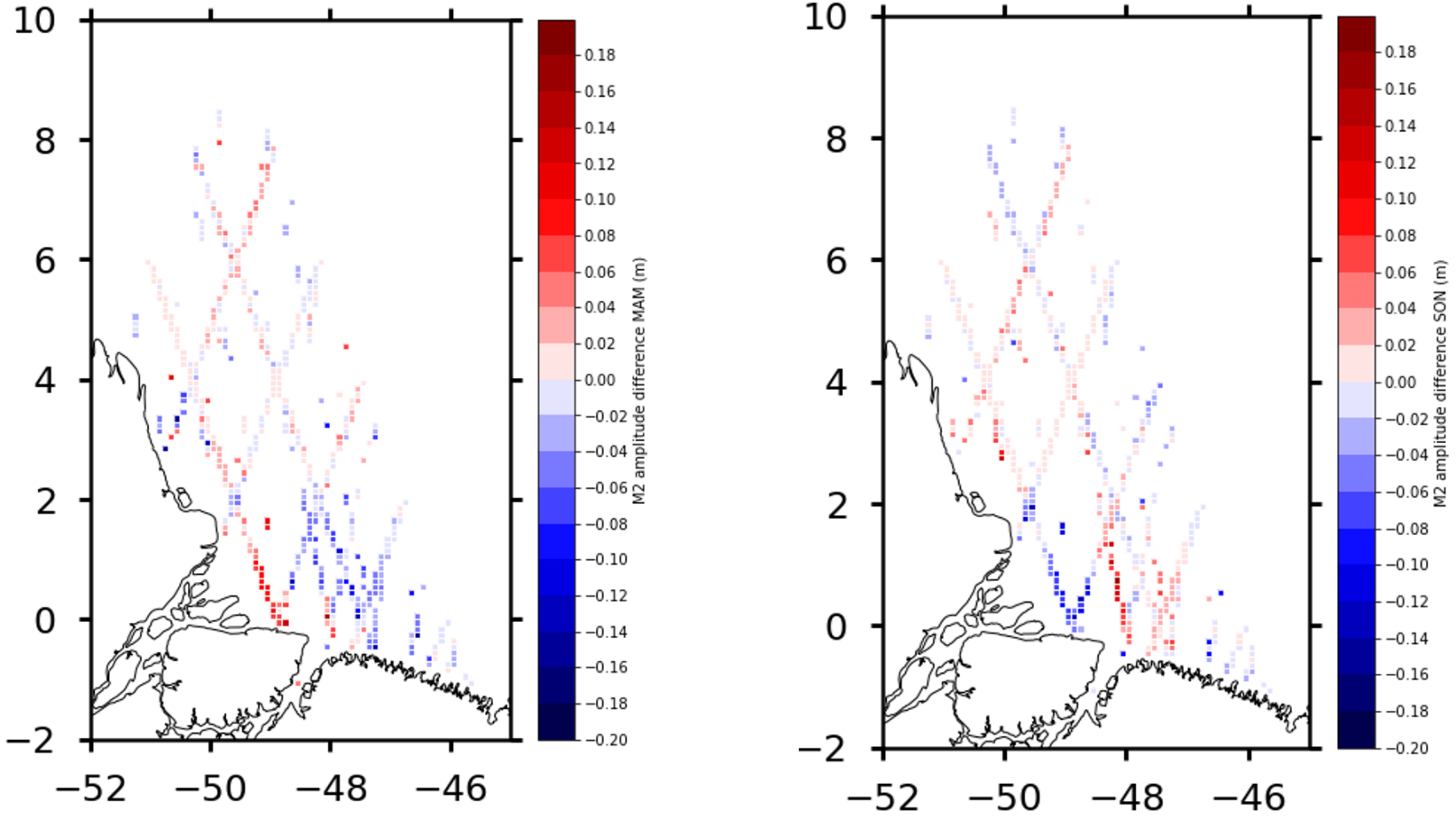


Fig. M2 seasonal anomaly “DJF” (left) M2 seasonal anomaly “SON” (right)

Supplementary materials

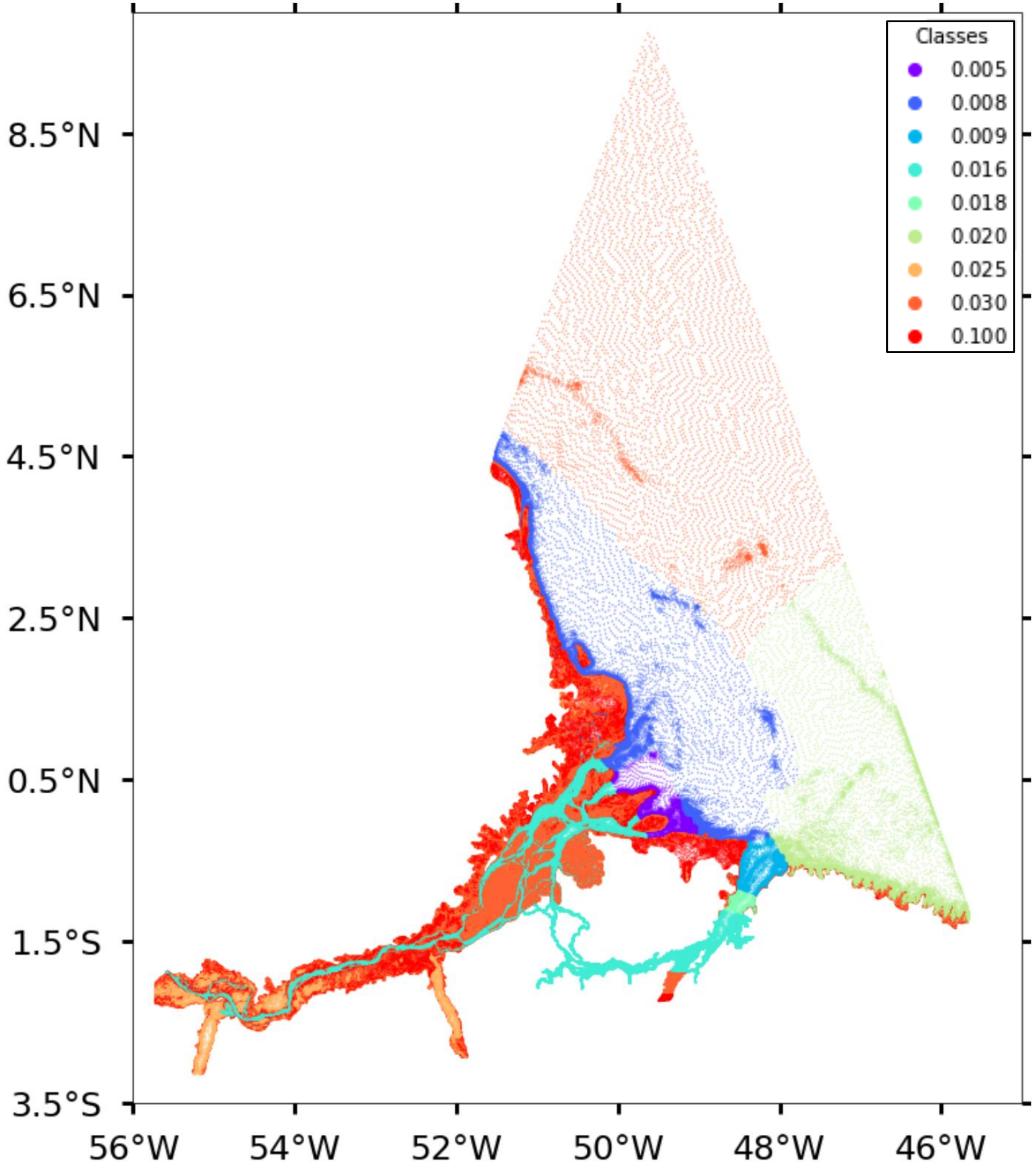
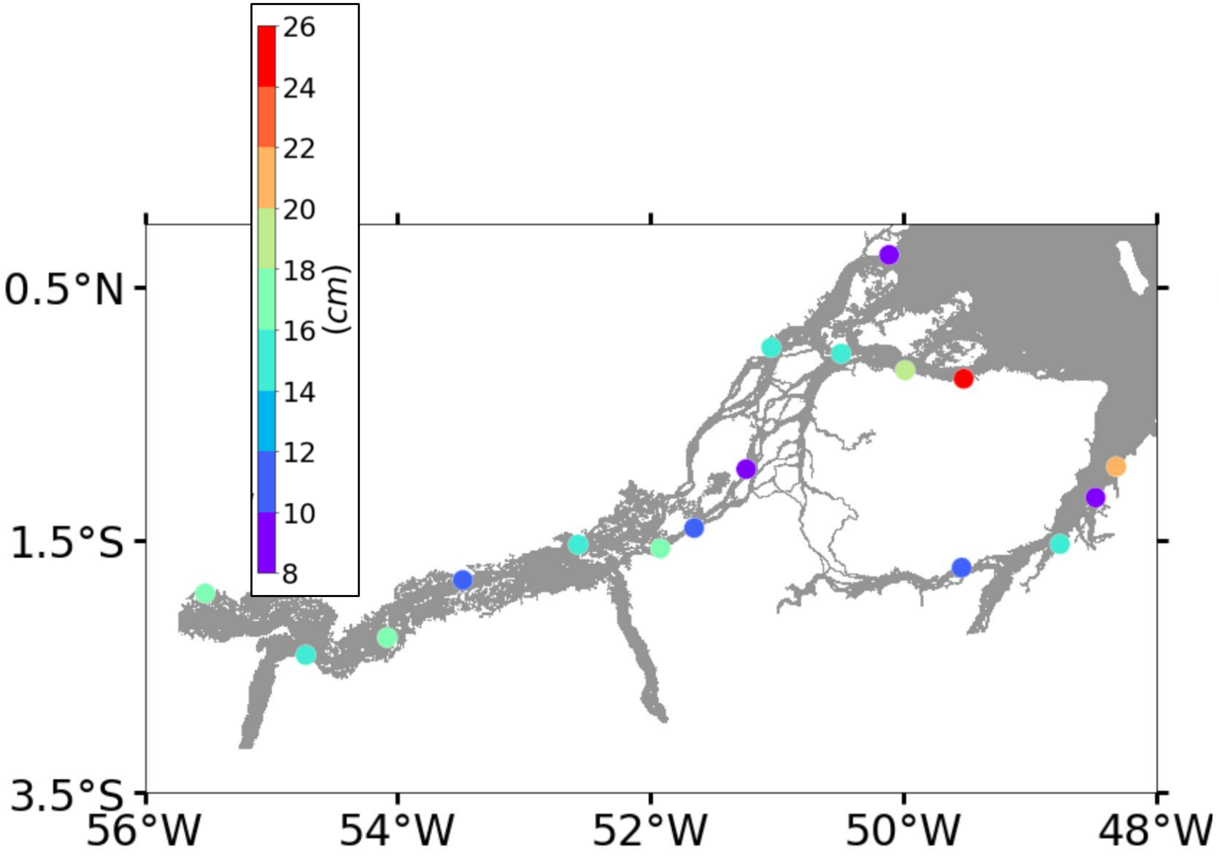
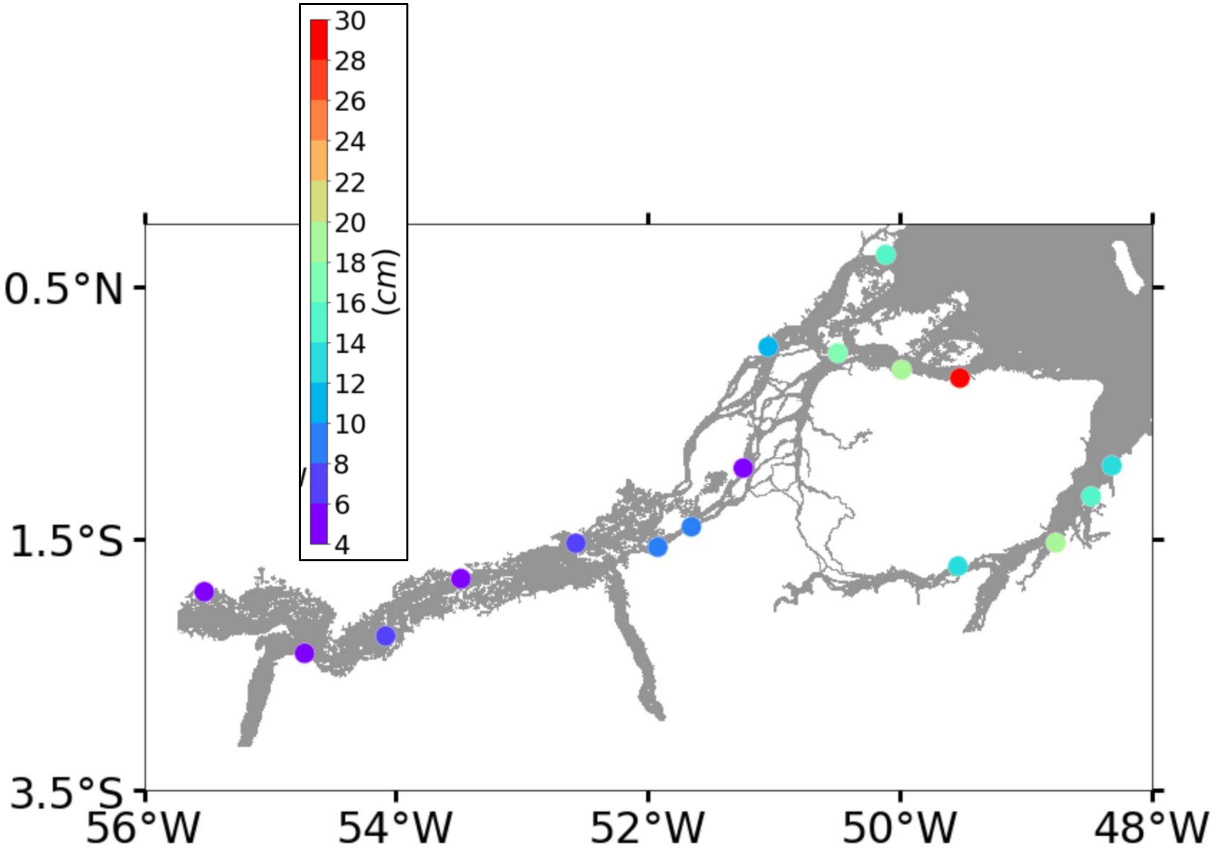


Fig. Distributed Manning's coefficient of the model

Supplementary materials

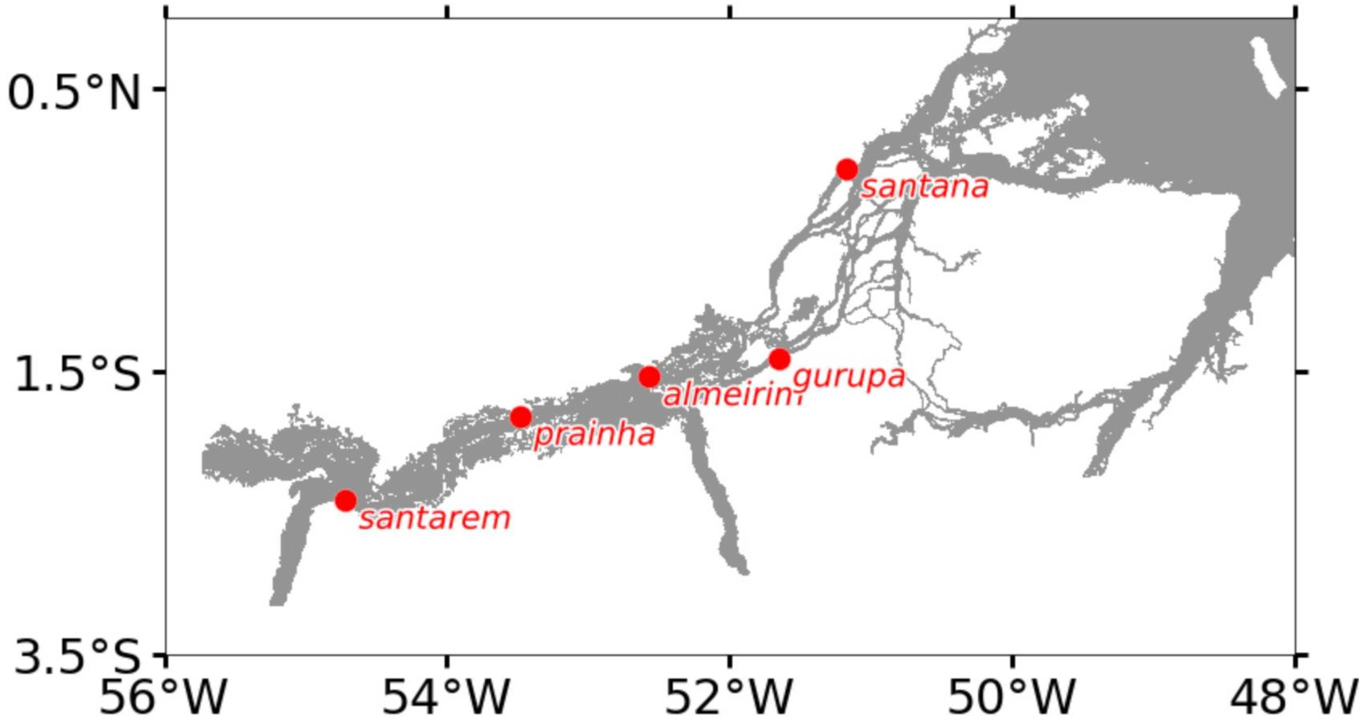


Total complex error for M2, S2, M4, MM, MSf in 2020 drought period



Total complex error for M2, S2, M4, MM, MSf in 2020 flood period

Supplementary materials



Stations	Model	Observed
santarem	6.85	6.62
almeirim	3.63	3.66
prainha	4.85	4.8
gurupa	2.74	2.36
santana	1.45	1.86

Fig. Mean water level comparison between model and observations (Callède et al. 2013)

Supplementary materials

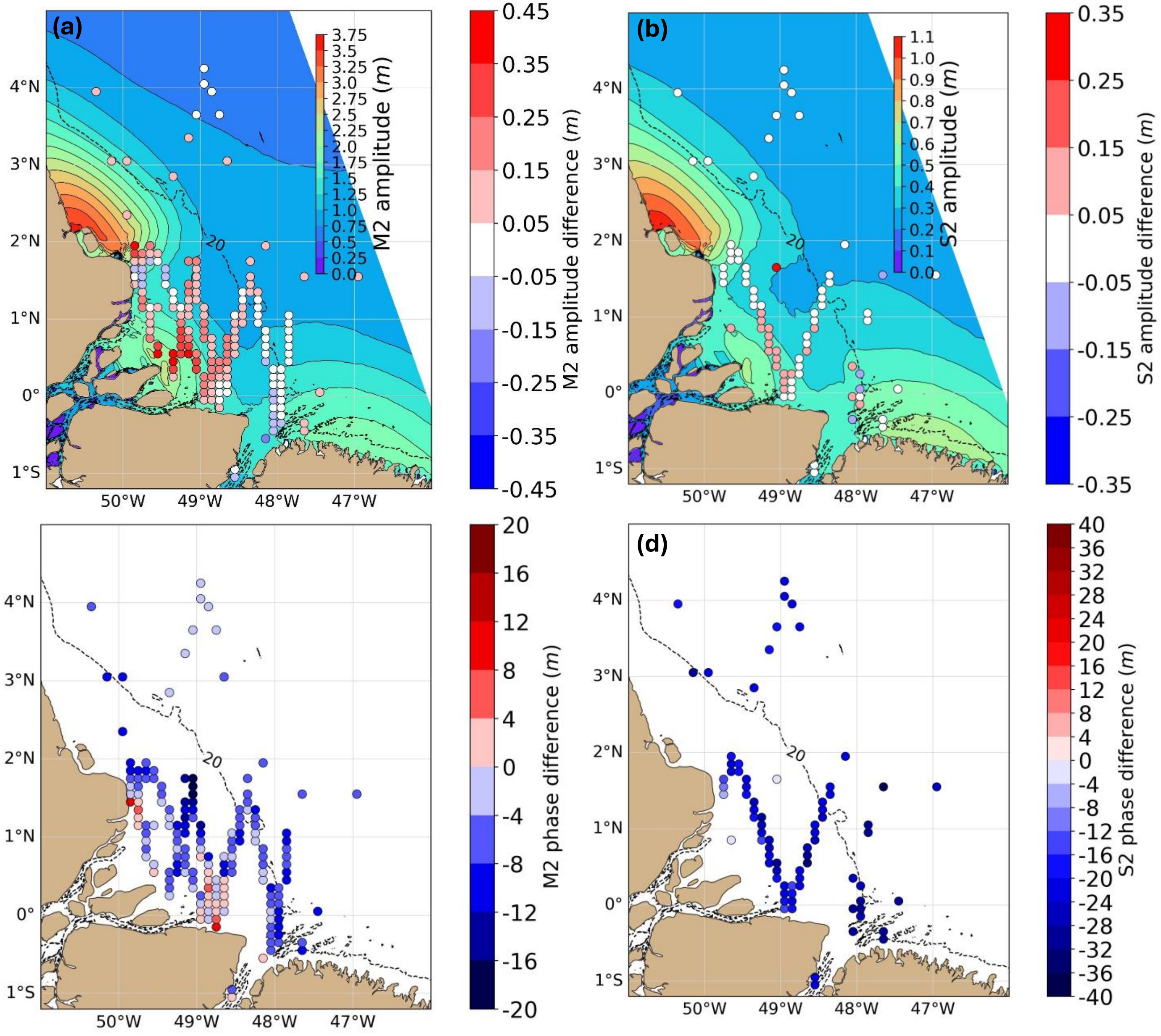
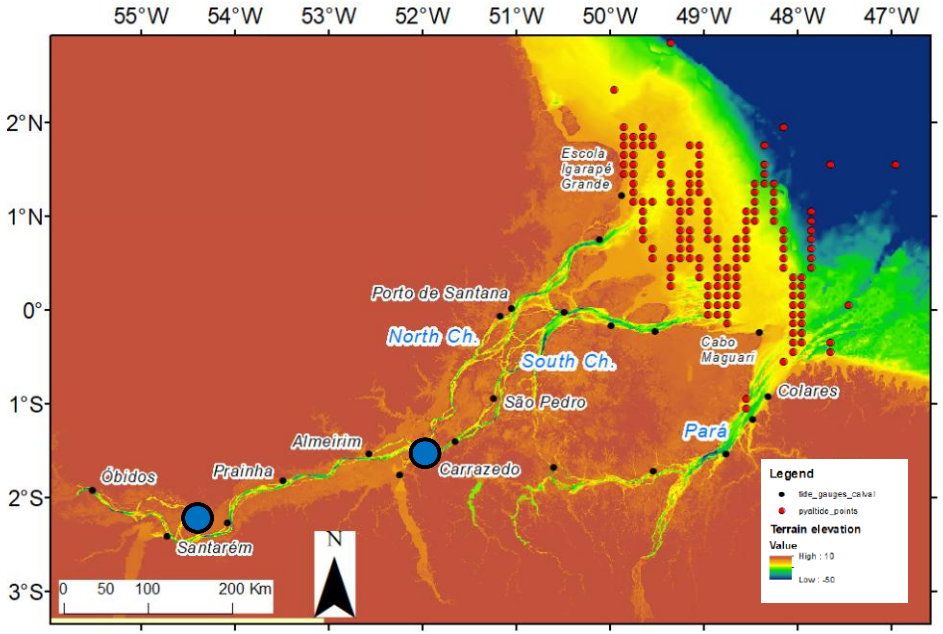


Fig. Amplitude difference (modeled – observed) of the main oceanic tidal constituents M2 (a) and S2 (b). Phase difference (modeled –observed) of M2 (c) and S2 (d) tidal constituents.

3. Socio economical impacts
3.1 Results of small survey in the upstream estuary



Impacts of the river drought on riparian population

Fishery

Education access (drying of navigation channels)

Goods transportation

High prices for consumables

Disruption of shipping channels for trade

Impacts of the river flood on riparian population

Livestock management

Furniture loss/ house damaging

Education access (flooded school)

Crop field damages (mud deposits)

+ Risk perception
+ Adaptation mechanisms

3. Socio-economical impacts

3.5 Bits of methodology

Main Objective: Measure the effect of the water level maxima hazard Di (the treatment) on the socio-economic variables Yi (the outcomes)

Two main issues:

- The Fundamental Problem of Causal Inference
- The Fundamental Problem of Statistic Inference

Rubin Causal Model

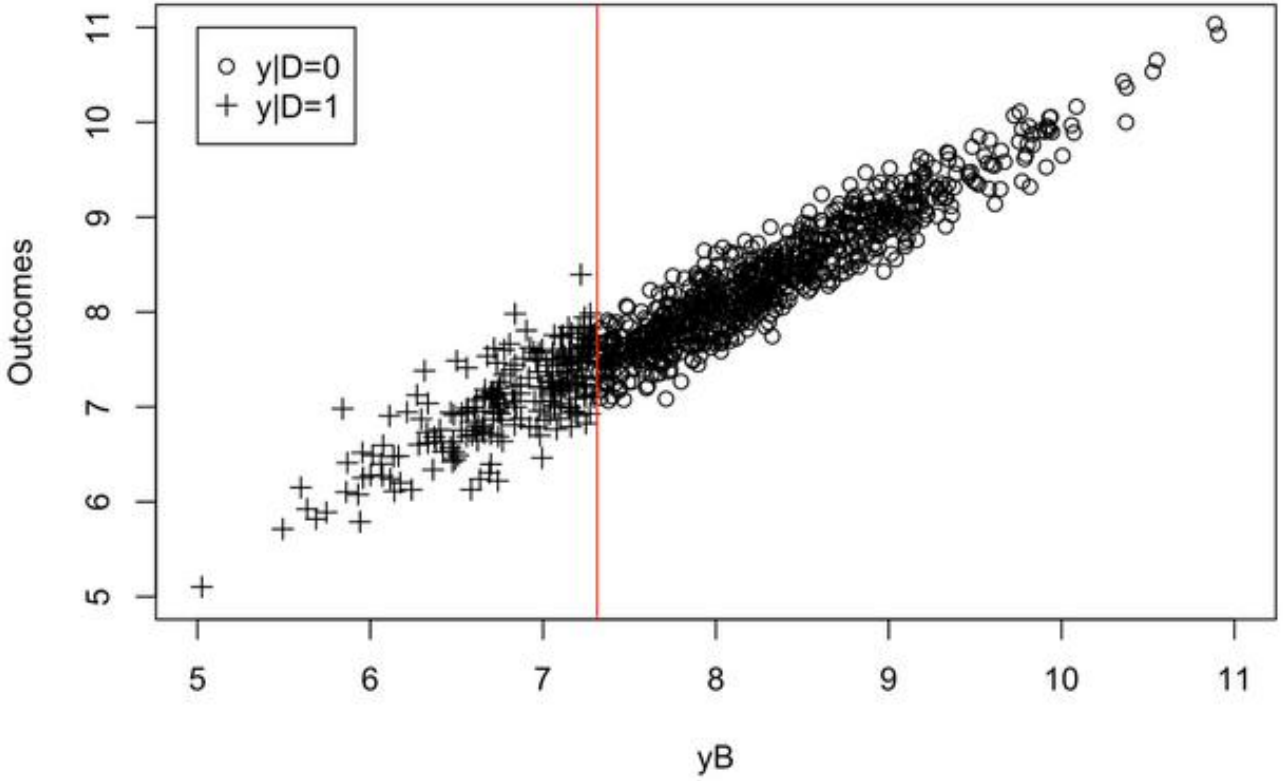
$D_i = 1$ *the unit i receives the treatment*
$D_i = 0$ *the unit i doesn't receives the treatment*

$$Y_i = \begin{cases} Y_i^1 & \text{if } D_i = 1 \\ Y_i^0 & \text{if } D_i = 0 \end{cases}$$
$$= Y_i^1 D_i + Y_i^0 (1 - D_i)$$

Definition 1.1 (Potential outcomes) For each unit i, we define two potential outcomes:

- Y_i^1: the outcome that unit i is going to have if it receives the treatment,
- Y_i^0: the outcome that unit i is going to have if it **does not** receive the treatment.

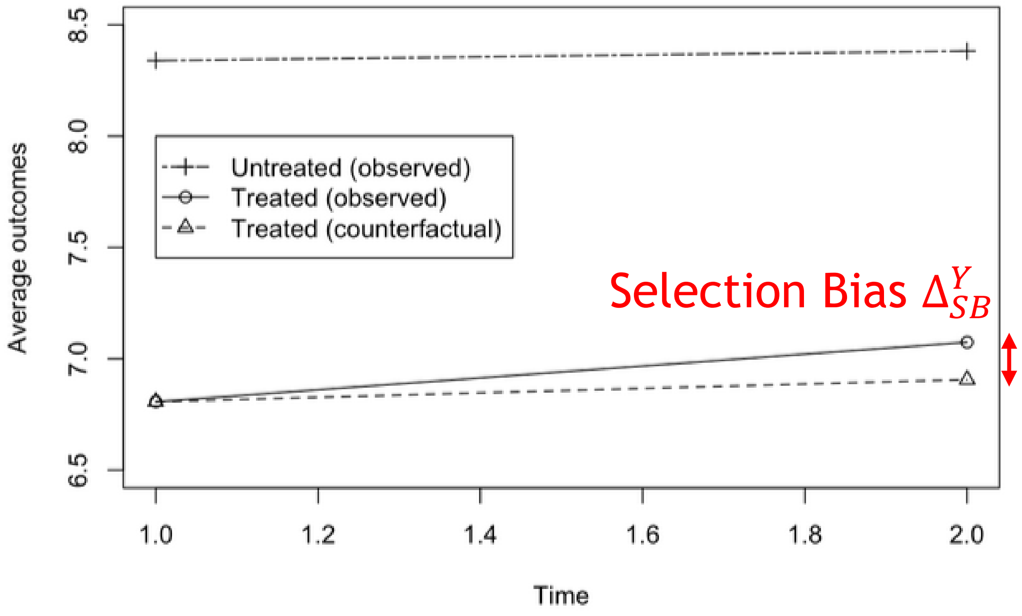
The Fundamental Problem of Casual Inference



$$\Delta^Y_{TT} = \mathbf{E}[Y_i^1 - Y_i^0 | D_i = 1]$$
$$= \mathbf{E}[Y_i^1 | D_i = 1] - \mathbf{E}[Y_i^0 | D_i = 1]$$

Unobserved quantity (The counterfactual

$$\Delta^Y_{WW} = \mathbf{E}[Y_i | D_i = 1] - \mathbf{E}[Y_i | D_i = 0]$$



$$\Delta^Y_{TT} = \Delta^Y_{WW} + \Delta^Y_{SB}$$

3. Socio-economical impacts

3.5 Bits of methodology

How to estimate the Δ_{TT}^{Y} in our case ?

- **Instrumental Variables approach (IV)**, it relies on finding a plausibly exogeneous source (i.e. not the flooding hazard) of variation of the outcomes both on the flooded and not flooded

- **Difference In Differences (DID)**, the difference between flooded and not flooded before the flooding hazard occurence is used to approximate selection bias.

- **Nearest neighbor matching (NNM)**, the M closest non flooded sectors for each flooded sector, we compute the average outcome of the M twins to be the imputed counterfactual mean for the flooded sector

3. Socio-economical impacts

3.6 What do we need ? The key ingredients (non-exhaustive list)

- **A wide variety of censed socio-economic variables** (income, household composition, mobility, etc.) on the riverine population but also more inland, **with temporal depth**.

- **A good bathymetry and a good hydrodynamic model of the region**.

- **A comprehensive description of your hazard**. The resolution of the hazard must at least equal the spatial scale of the censed sectors. As for the temporal description, one must have information on the hazard description before the first timestamp of the censed data.

- If you want to make in-depth study on **causality**, it is better to dimension surveys such that they **cover a wide panel of hazard intensity and socio-economic situations of the censed cities or communities**. This should be done at **multiple timestamps**, within which hazard occurs. This will allow the use of econometric methods to reduce the uncertainty on your sample-based counterfactual.