TÉCNICO LISBOA

blueOASIS
ocean sustainable solutions

A verification and validation exercise with MOHID Water

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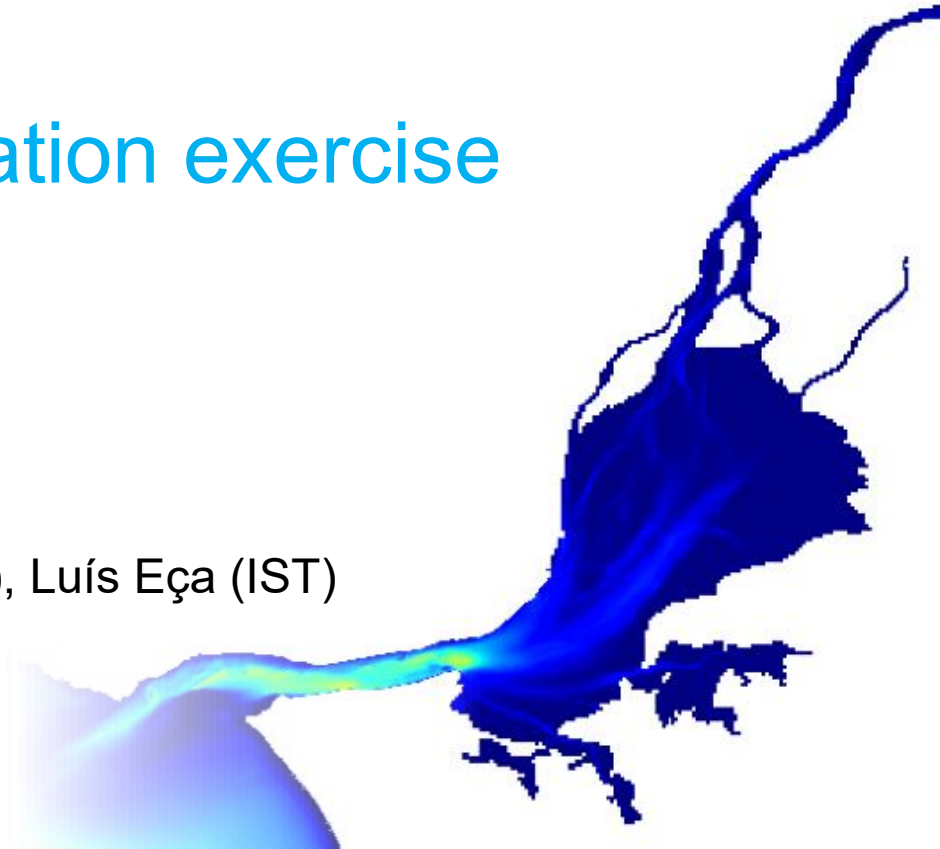


blue oasis
ocean sustainable solutions

MARKETS

Creating Positive Impact in...

Renewable Energy

Ocean Conservation

Maritime Design

Naval Innovation

CAPABILITIES

With integrated technical expertise on...

Maritime & Renewables

Digital Twins

Underwater Acoustics

LOCATIONS

And operations in...

Ericeira
Portugal

Leiria
Portugal

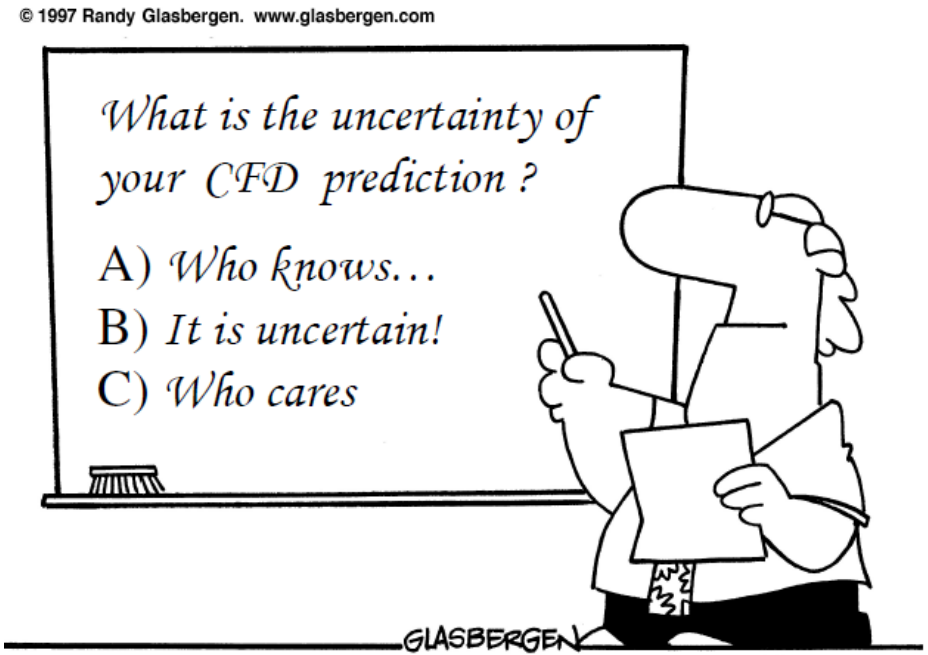
Azores
Portugal

Utrecht
Nederlands

Making the World Green and the Oceans Blue.

Verification & Validation

- How good are my simulation results?



Verification & Validation

- How good are my simulation results?
  - How well is my numerical model representing reality? → Validation
    → e.g. Comparison with experiments
  - How reliable are the numerical results? → Verification
    - Code verification: Check if code is bug-free and working as intended
    - Solution verification: Estimate numerical uncertainty

Verification & Validation

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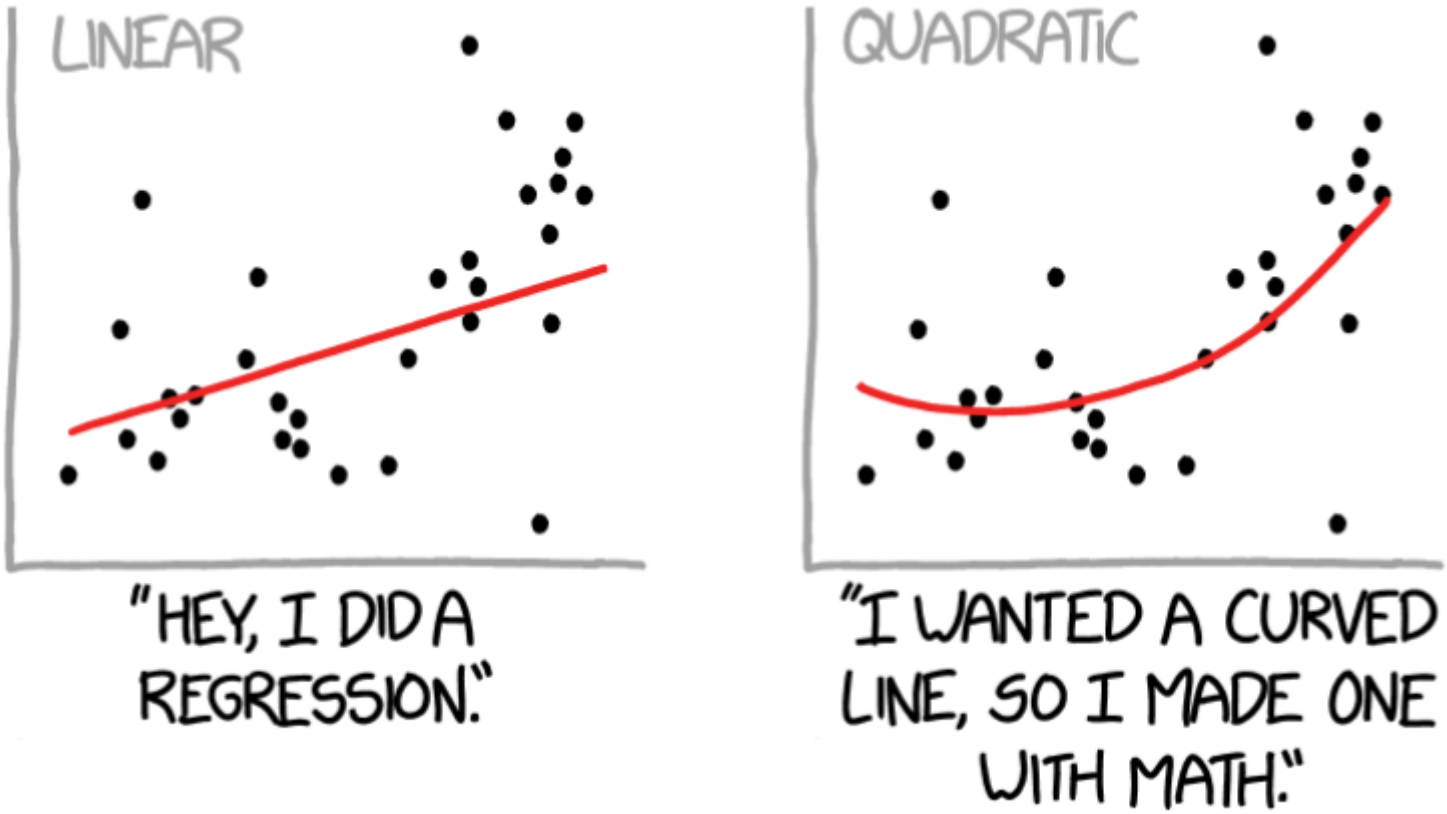
    - ~~Code verification: Check if code is bug-free and working as intended~~
    - Solution verification: **Estimate numerical uncertainty**

Numerical uncertainty estimation

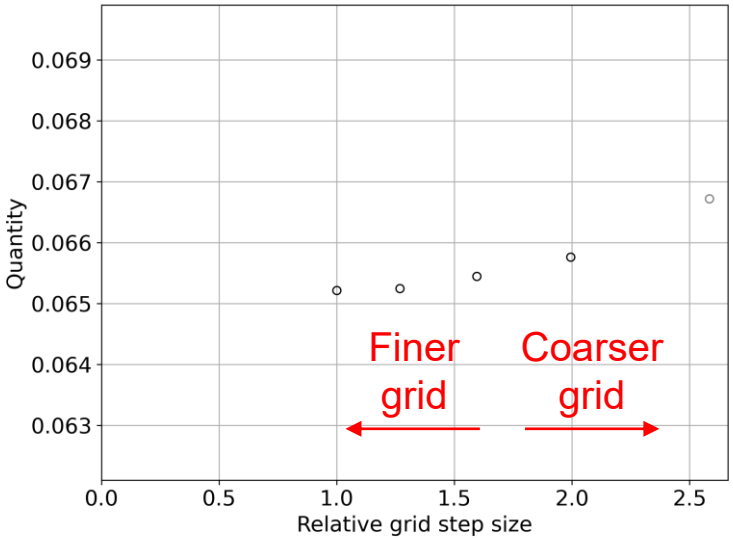
- Numerical **uncertainty** is calculated from numerical **error**, considering safety factor and scatter in data
  - Updated 2023 procedure (Rentschler et al., 2025)
  - Free Verification Tools (https://www.marin.nl/en/research/free-resources/verification-and-validation/verification-tools)
  - Python pre- & postprocessing script (https://github.com/blueOceanSustainableSolutions/wrapyNUA)
- Round-off error and iterative error are neglected, only relevant contribution from **discretization error**
  - Estimated from grid (and time) refinement study
  - Fit simulation data to extrapolate solution for infinitesimal fine grid

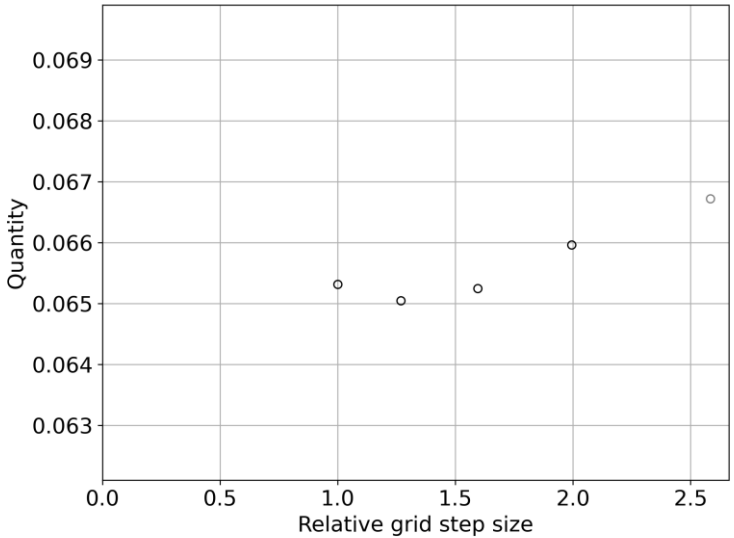


https://imgs.xkcd.com/comics/curve_fitting.png

Numerical uncertainty estimation

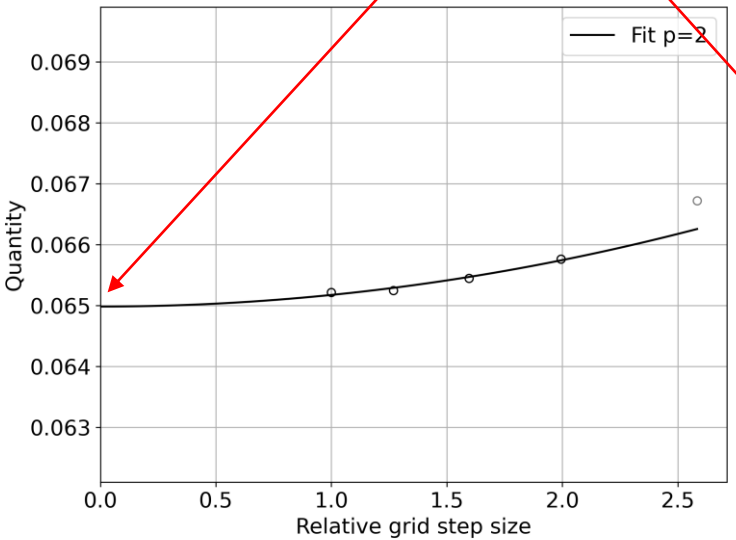
- Simulation data: Monotonic convergence vs. non-monotonic

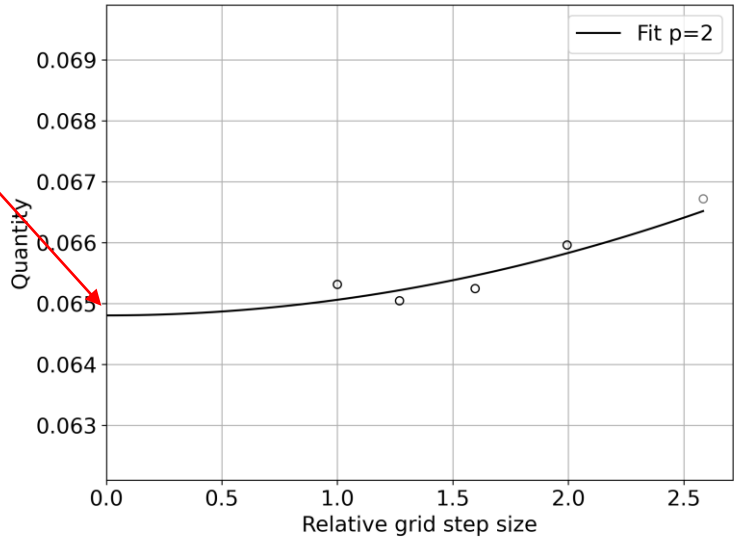




Numerical uncertainty estimation

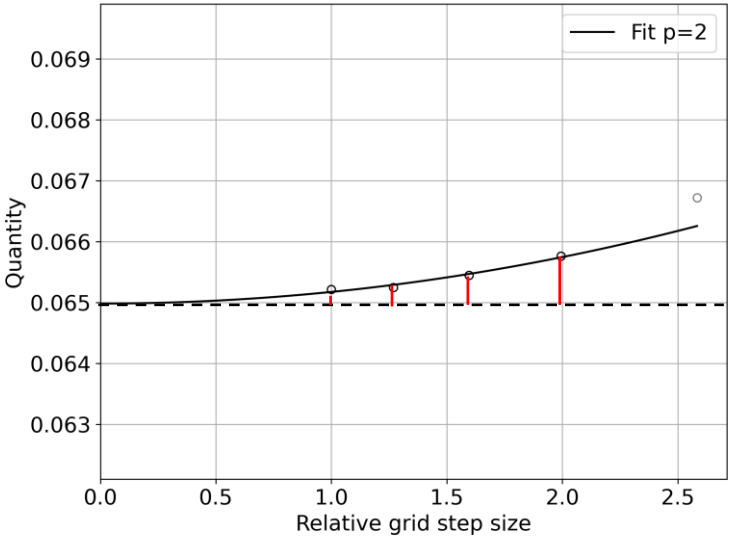
- Least-squares fit: $\phi_i = \phi_0 + \alpha \cdot r^p$ with $0.5 \leq p \leq 2.05$
  - Similar fit with $p = 2$
  - Similar ϕ_0

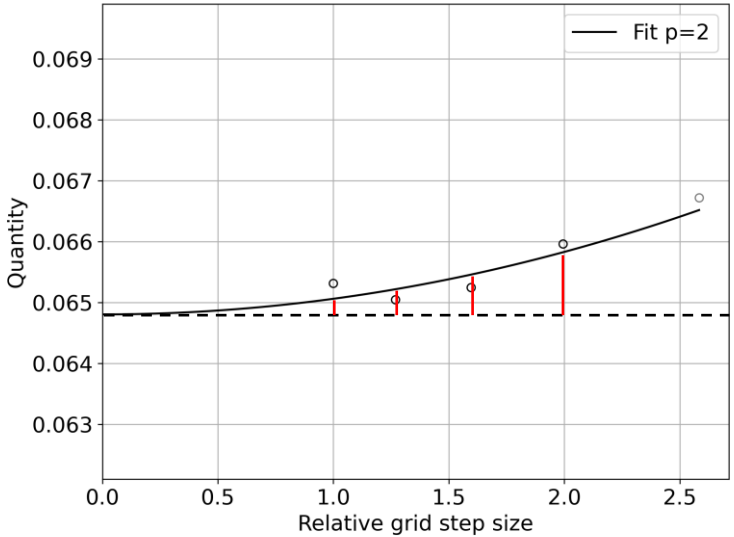




Numerical uncertainty estimation

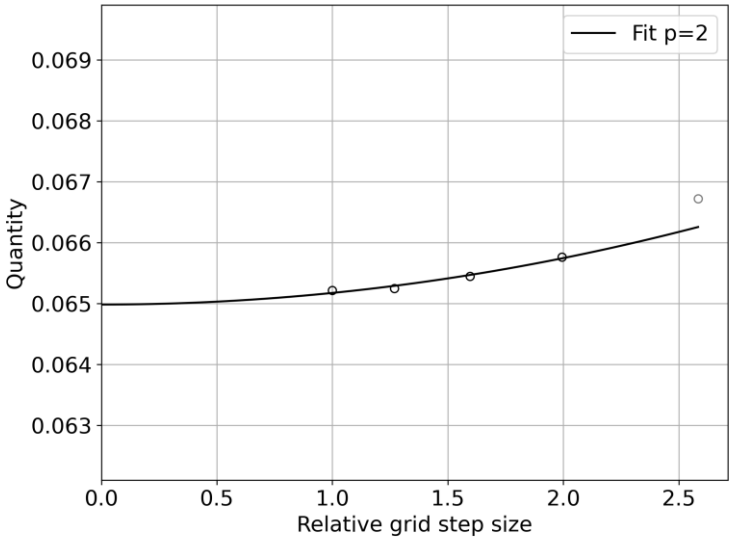
- Discretization error: Difference between fit and extrapolated solution
  - Similar discretization errors in the two examples!

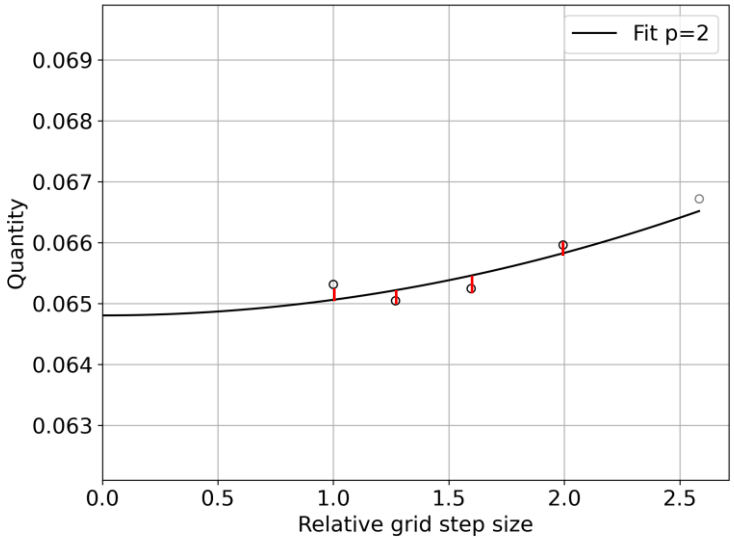




Numerical uncertainty estimation

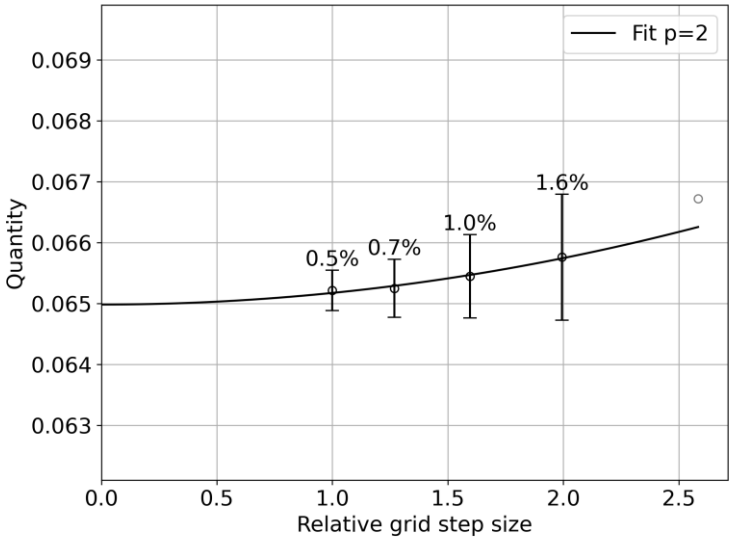
- Scattered data on the right graph

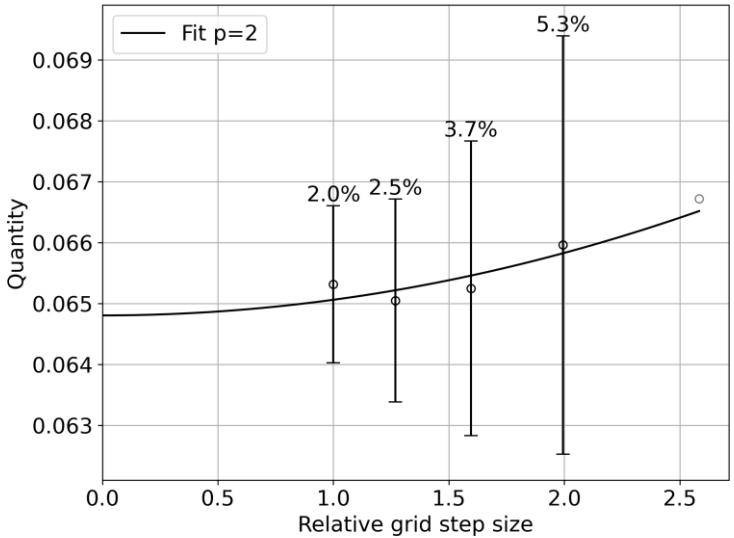




Numerical uncertainty estimation

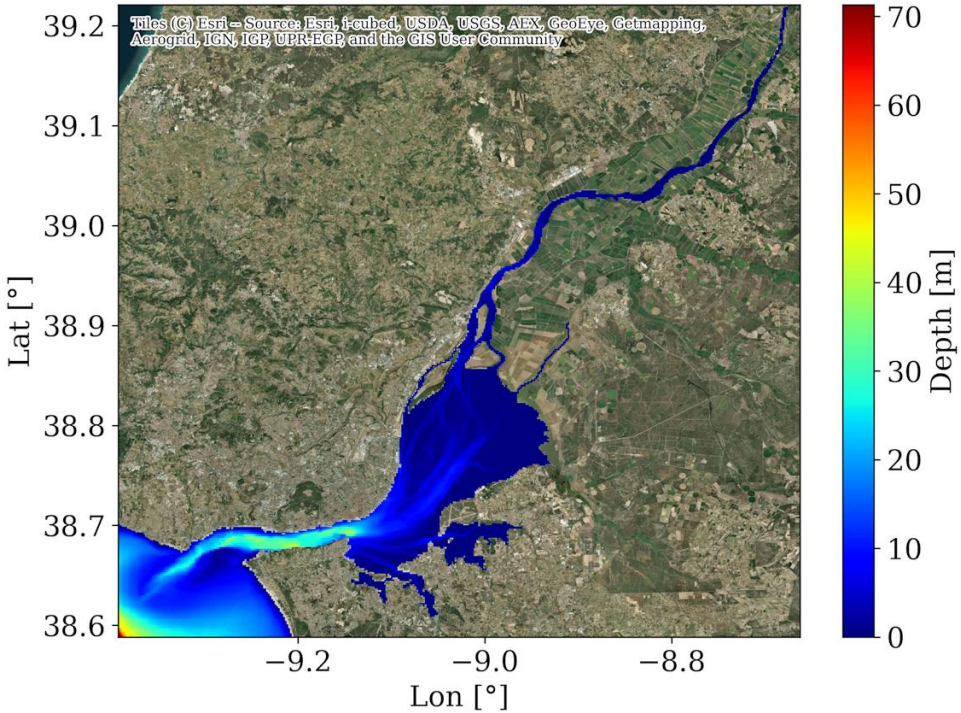
- Numerical uncertainty
  - Scatter is penalized!





Tagus estuary model

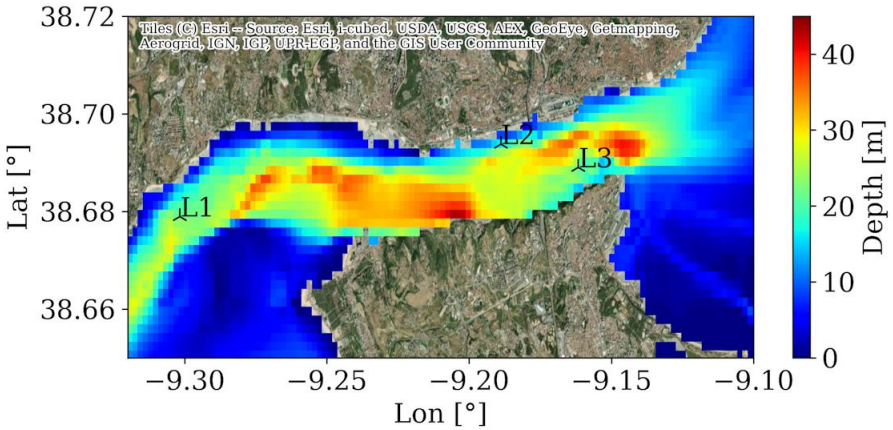
- Baroclinic 3D model, 21 layers
- FES2014 tide, river discharges, WRF meteo, GOTM turbulence
- Single domain
  - Base resolution ~200m
  - 11-22m bathymetry in channel/mouth from EMODnet

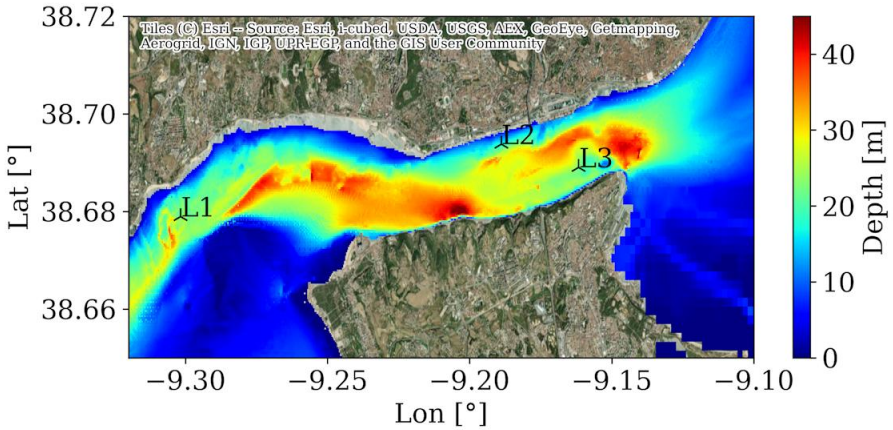


- How reliable are simulated current velocities?

Grid refinement study

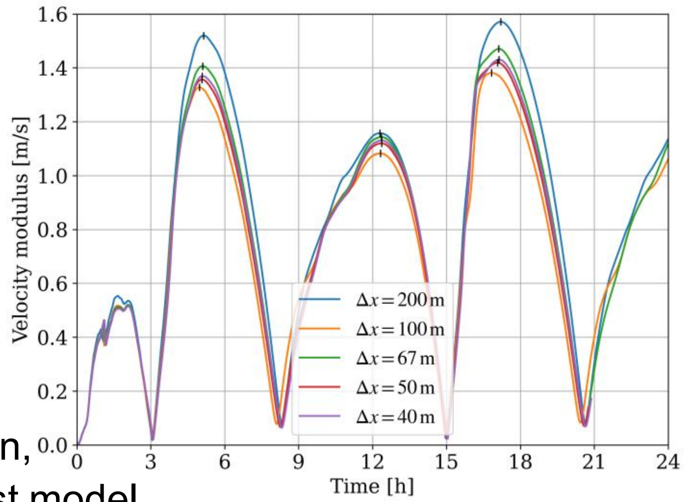
- 5 discretizations: 200…40m (3…75e+06 cells)
- 3 potential locations for tidal turbines (Hoofd et al., 2023)

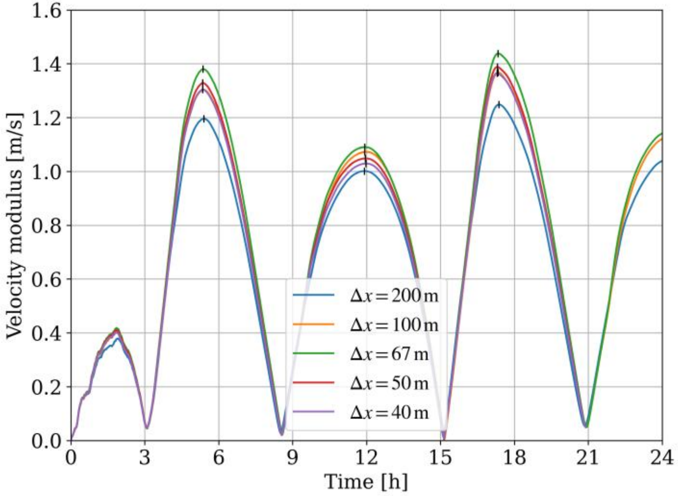


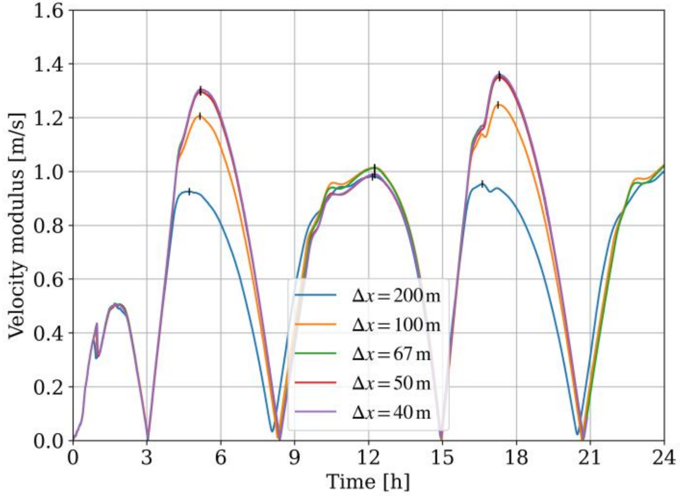


Grid refinement study

- Velocity modulus time series at L1, L2, L3
  - Not monotonically converging!
  - Careful! Nearest-cell value vs. linear interpolation, interpolation error can reach > 0.1m/s in coarsest model

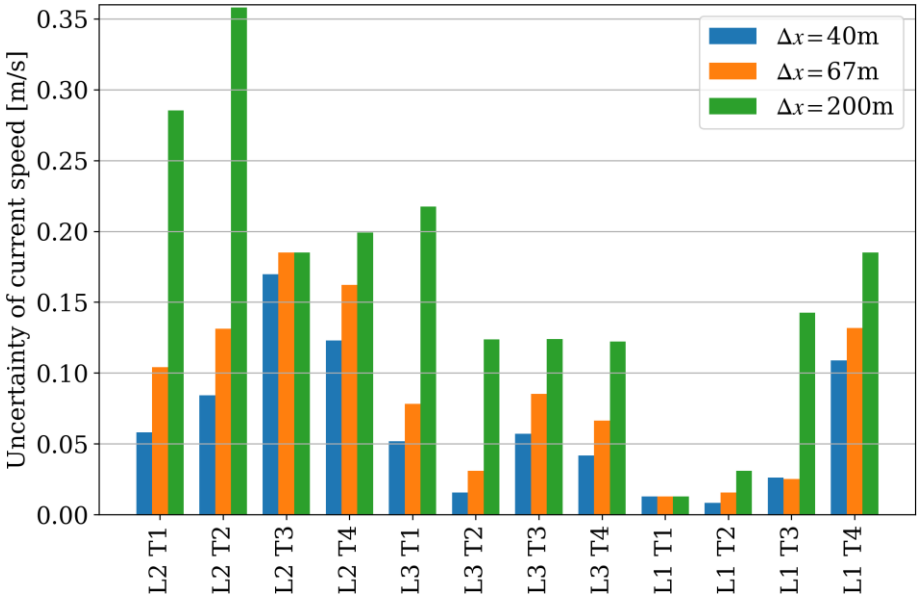






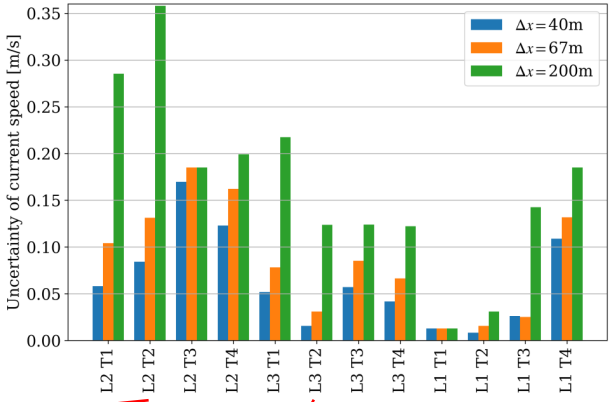
Numercial uncertainty analysis

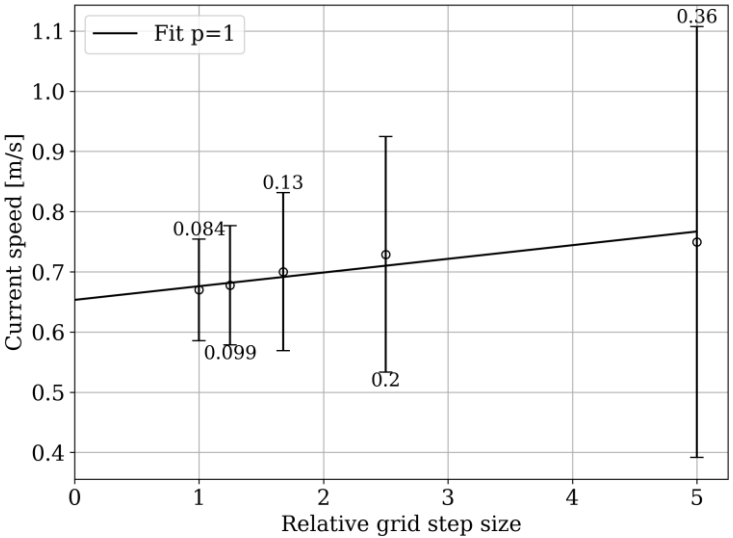
- 4 tests per location → 12 samples
- Large uncertainties for coarsest model, still significant uncertainties for finer resolutions
- Largest uncertainties at L2 (closest to land…)

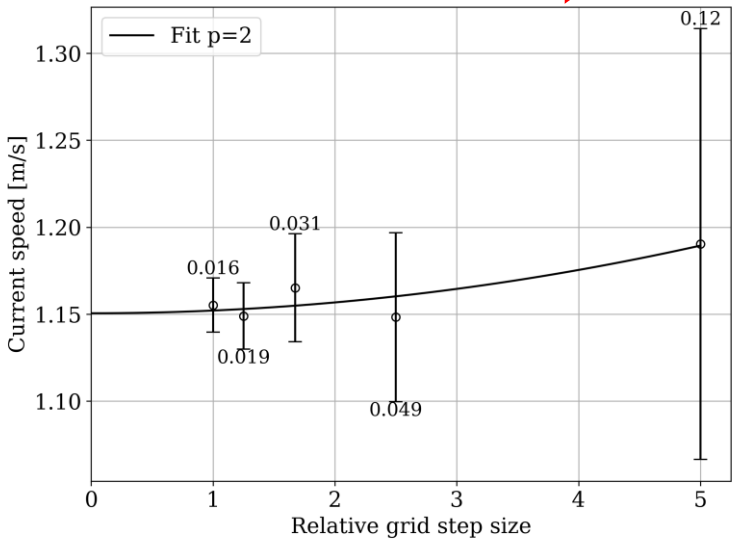


Numercial uncertainty analysis

- Large data range, non-monotonic behavior, scatter
  → very conservative uncertainty estimates

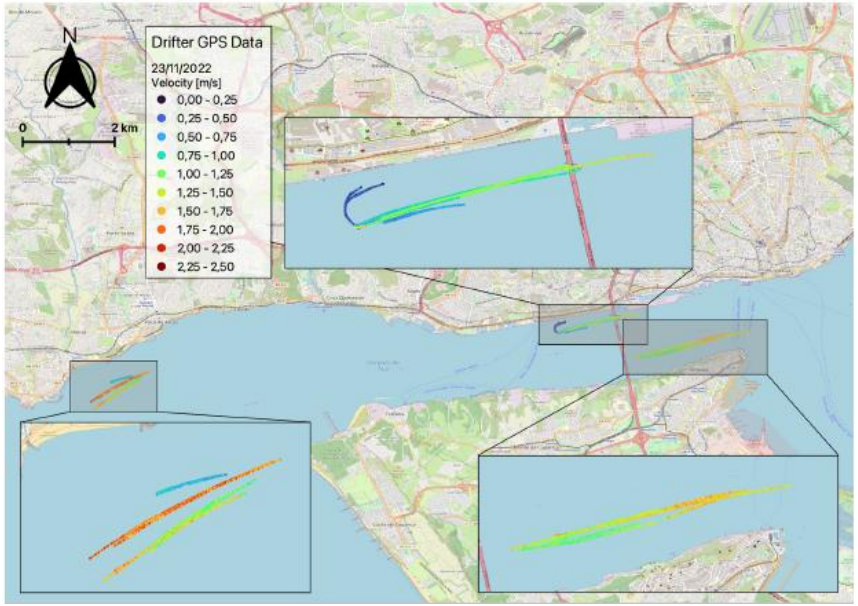






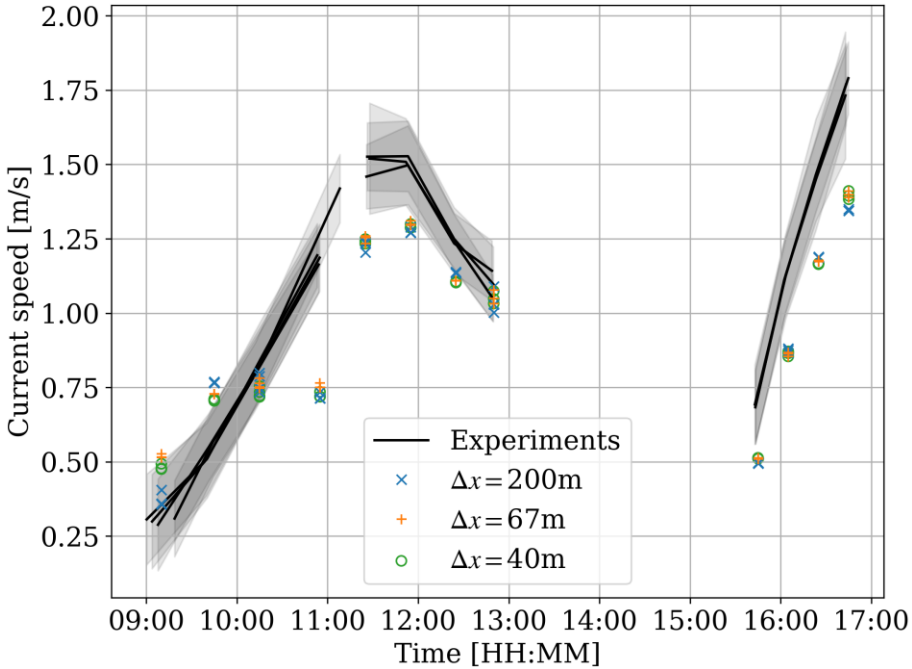
Experimental campaign

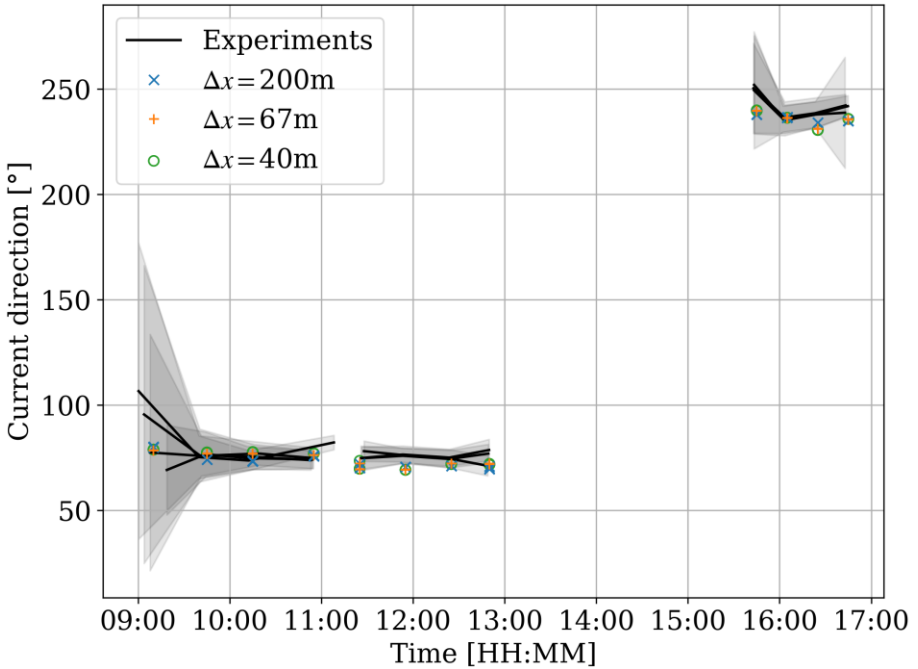
- Self-built, low-cost GPS drifters (Hoofd et al., 2023)
- Large experimental uncertainty ~0.3m/s



Validation

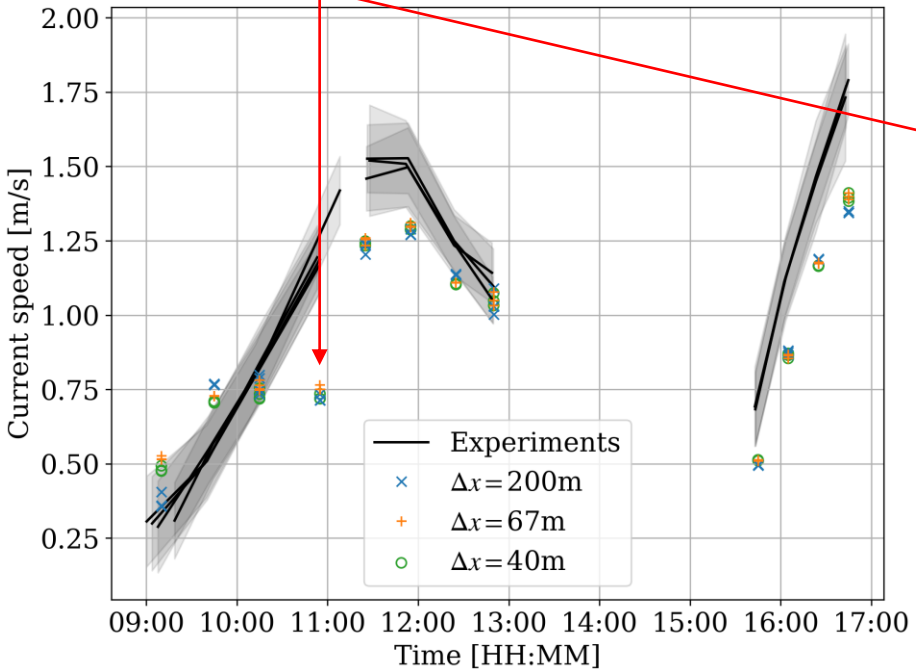
- Drifter averages and stdevs vs. linearly interpolated simulation results

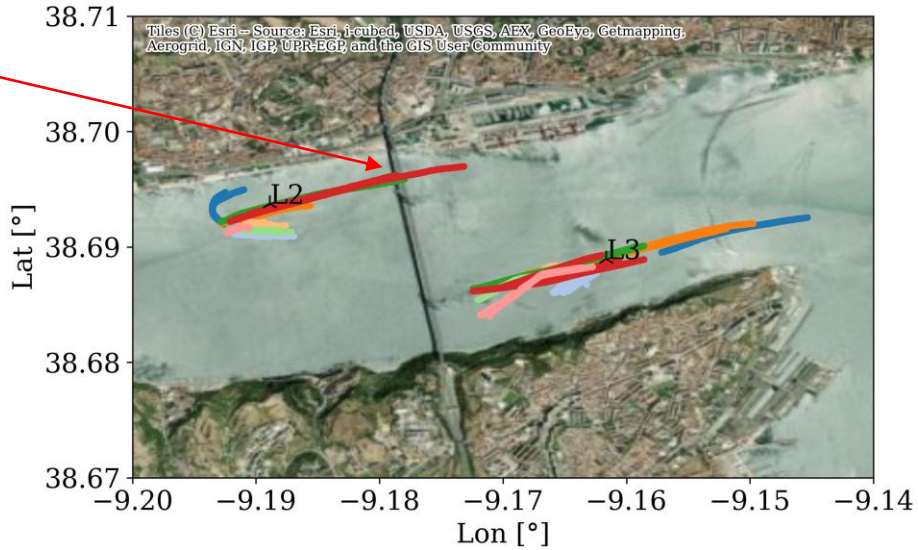




Validation

- Outlier due to flow acceleration near 25 de Abril bridge? Not modelled…





Conclusions

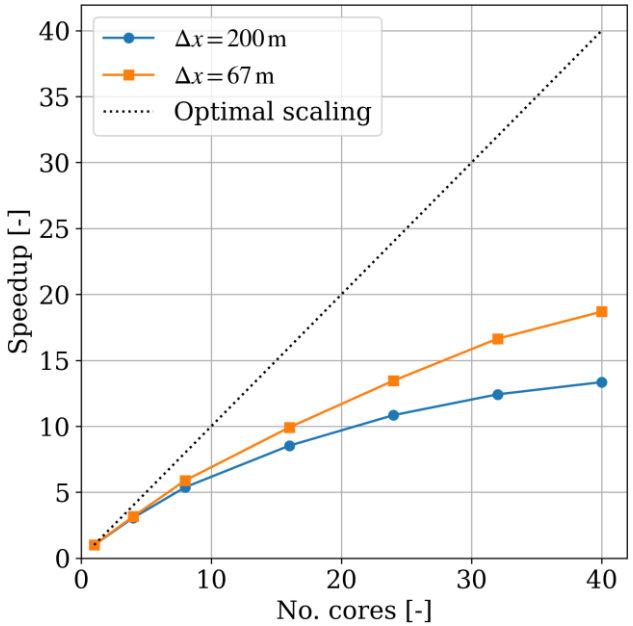
- Finer discretizations achieve uncertainty estimates well below 0.1m/s
- Despite larger uncertainties, the coarsest model performs respectably well with suitable post-processing methodology (interpolation!)
- Non-monotonic convergence behavior and scatter render uncertainty analysis overly conservative

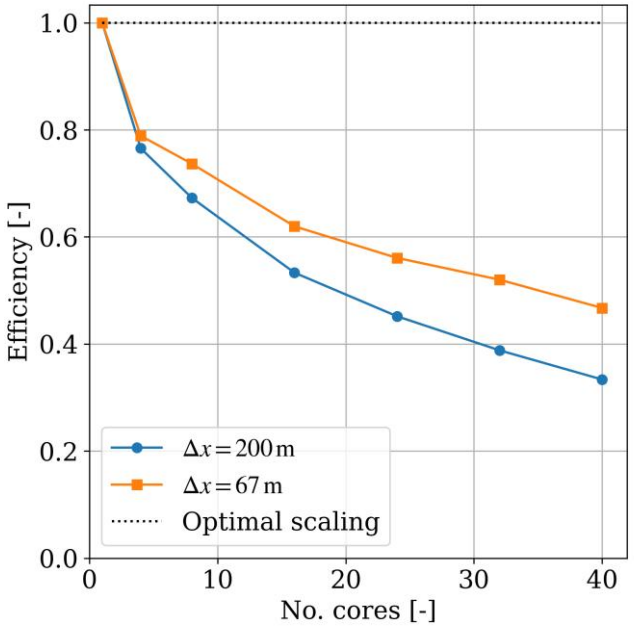
Future work

- What is the source of the non-monotonic behavior and scatter?
  - High-resolution bathymetry and geometry? Rather not…
  - Non-linearities from numerical schemes, turbulence, filters, …?
- Azores nested model
  - Use in EU projects
  - Coupling with SWAN, REEF3D, …
  - Digital Twin
- Higher quality experimental data
  - Spotter/Hydrotwin buoy with water level and current sensors (https://www.sofarocean.com/products/spotter, https://hydrotwin.pt/)

Extra: MOHID perfomance

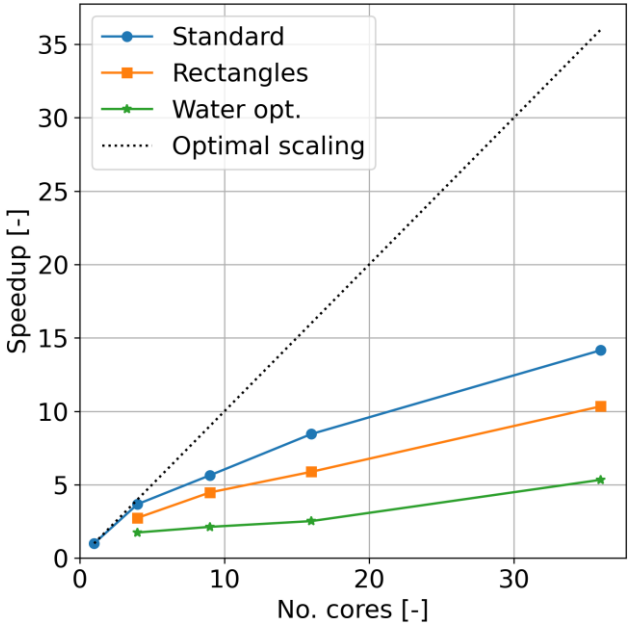
- Strong scaling study on Deucalion HPC cluster (Intel based) with MPI

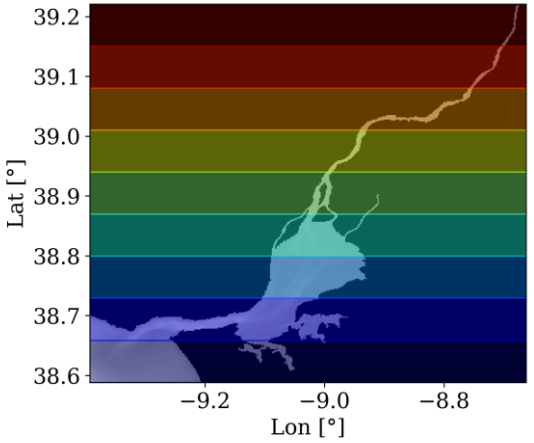


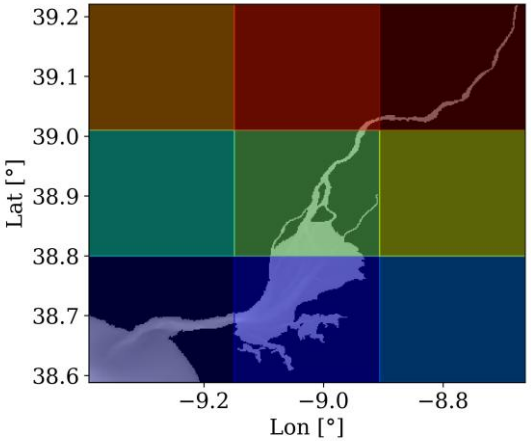


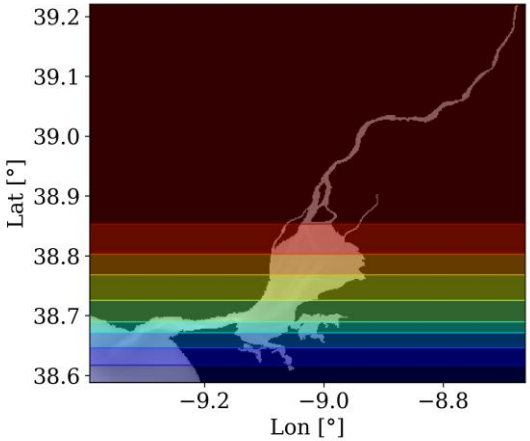
Extra: MOHID performance

- Influence of different domain decompositions



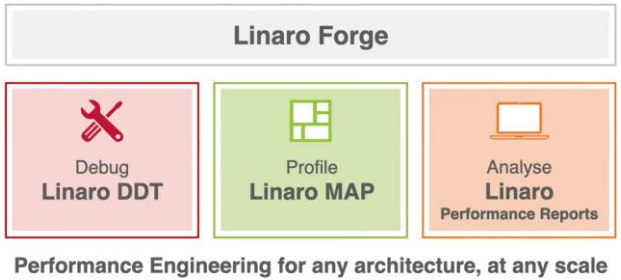


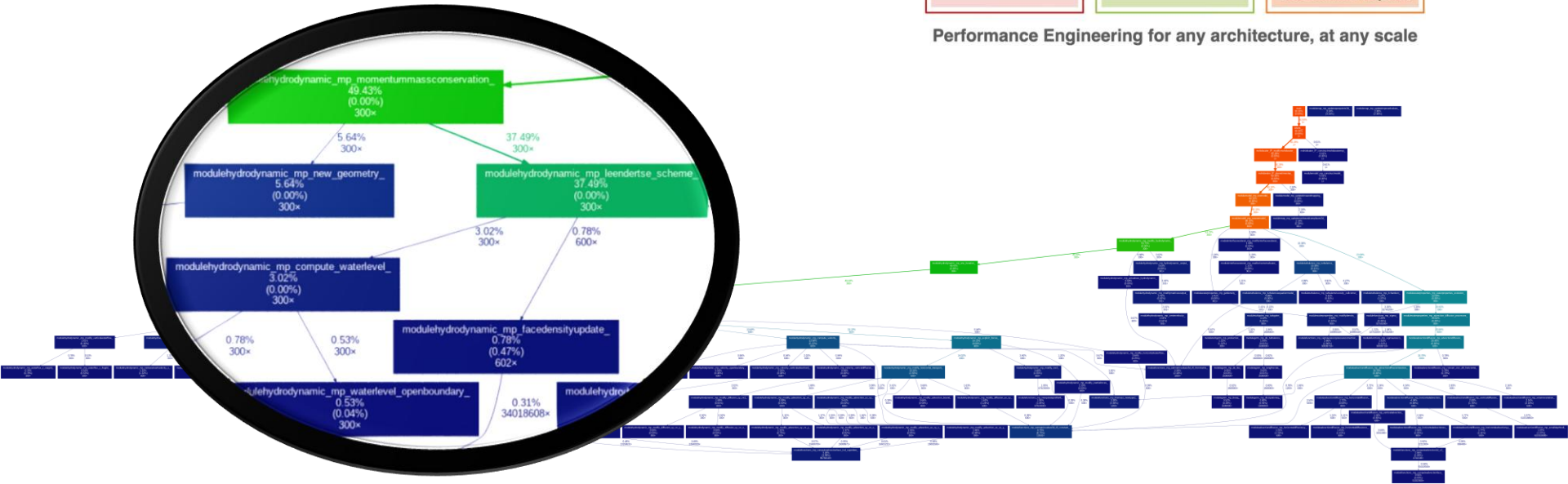




Extra: MOHID performance

- Suggestion: Code profiling
  - Paying: Linaro Forge (https://www.linaroforge.com/)
  - Free: gprof+gprof2dot





Acknowledgment & References

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- The authors acknowledge the use of the EuroHPC Deucalion High Performance Computing infrastructure (https://rnca.fccn.pt/en/deucalion/)
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