Improving Storm Surge Modeling Accuracy: A Sensitivity Analysis of Sea Surface Drag Parameterization

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Introduction

What are storm surges?

- Unusual rise of water that occurs during a significant storm.
- Strong winds will push large waves towards the coastline, causing water to swamp the landscape, sometimes for kilometers inland.

Why are storm surges important?

- Coastal flooding
- Life-threatening hazard
- Amplification of storm impacts

The 1953 North Sea Flood. Credit: Rijkswaterstaat

How does climate change impact storm surges?

- **Sea Level Rise:** Rising sea levels due to ice melting, setting a higher starting point for storm surges [1].
  - Rapid melting of mountain glaciers and land ice (on Antarctica and Greenland).
- **Reduced Sea Ice:** Contributing to stronger Arctic winter storms and potentially resulting in higher storm surges [2].
- **Increased Storm Intensity:** Warming temperatures fuel more intense storms, resulting in more destructive storms and storm surges [3].
- **Altered Storm Tracks:** Shifts storm paths, leading to more storms in some regions [4].
- **Precipitation and Flooding:** Heavy rainfall and storm surges together can lead to disastrous flooding in coastal regions [5].

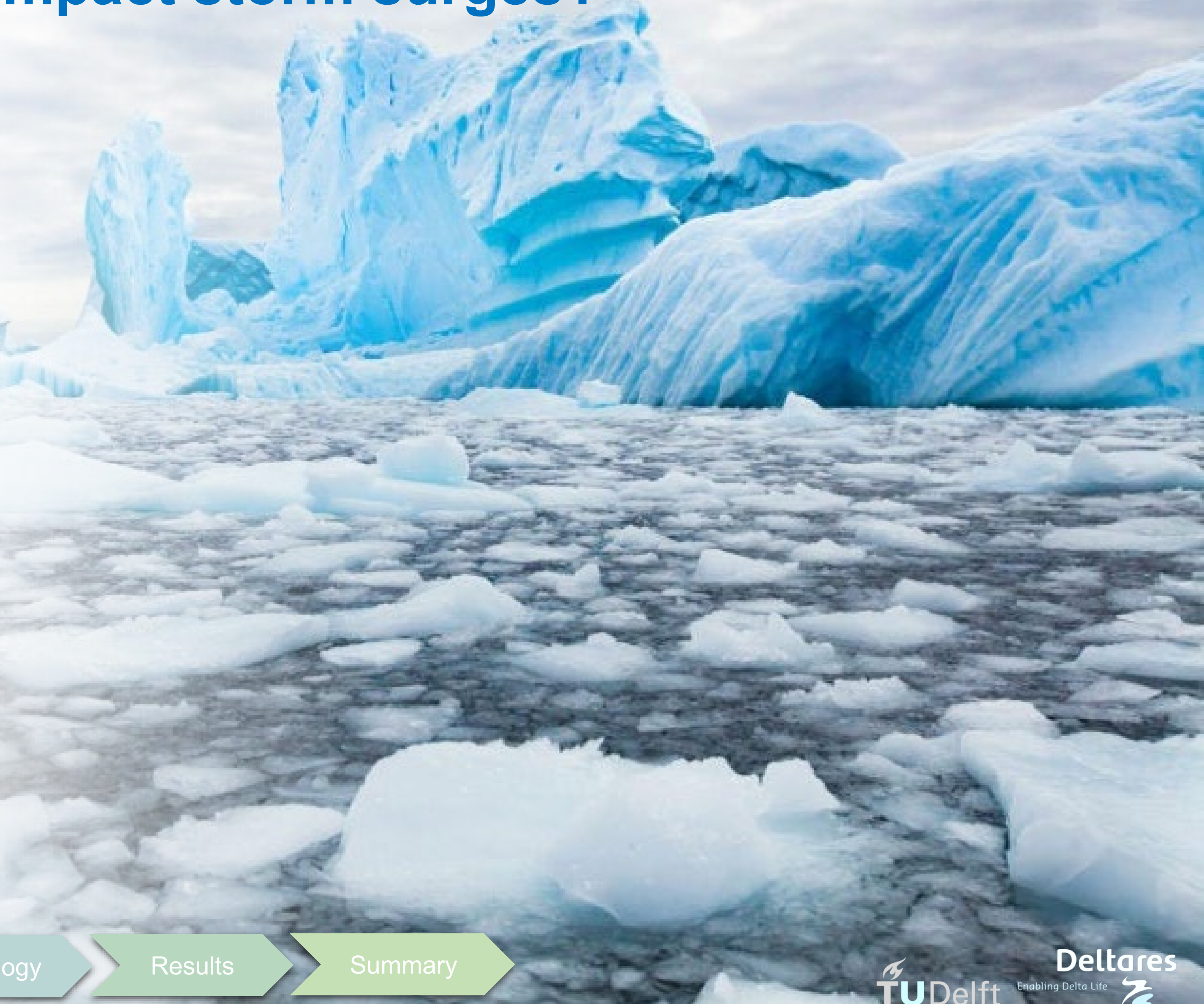

IMAGE: Melting glacial ice in Antarctica. CREDIT: Anya Berkut/iStock

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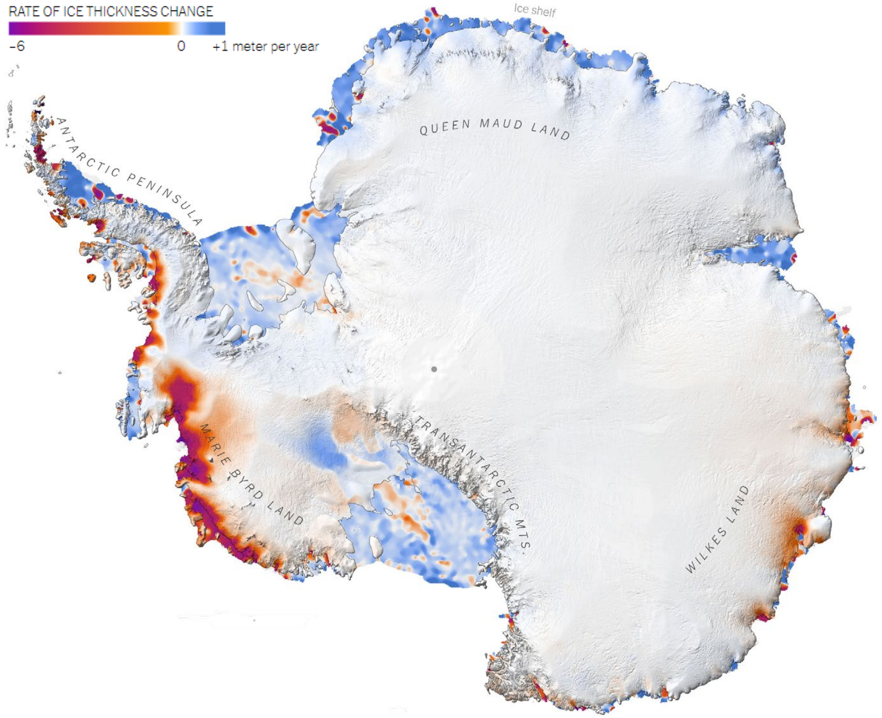
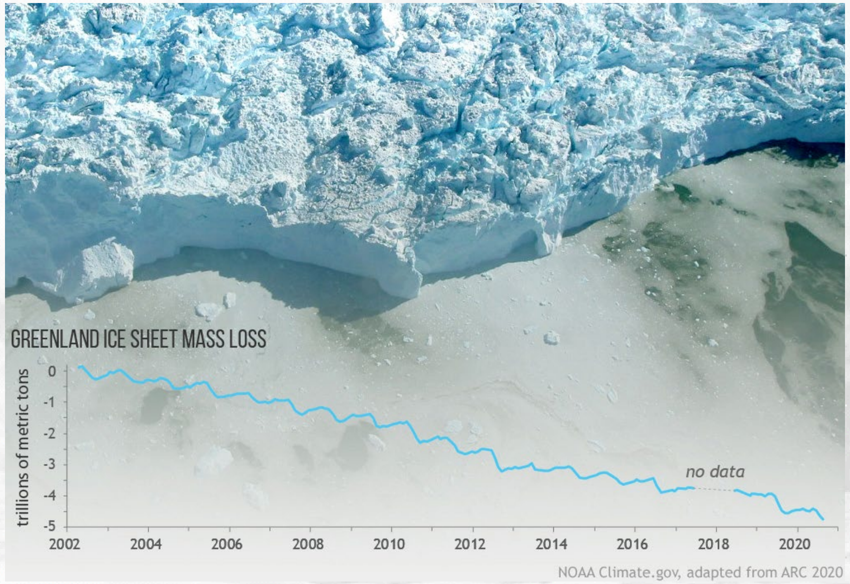
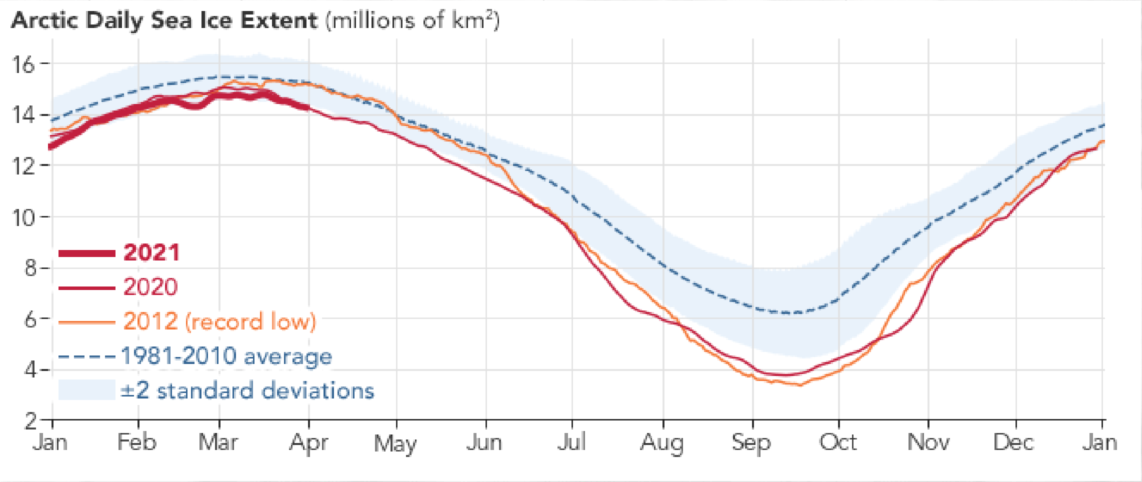


Credit: NASA ICESat and ICESat-2



Credit: NOAA Climate gov



Credit: National Snow & Ice Data Center/NASA Earth Observatory

IMAGE: Melting glacial ice in Antarctica. CREDIT:

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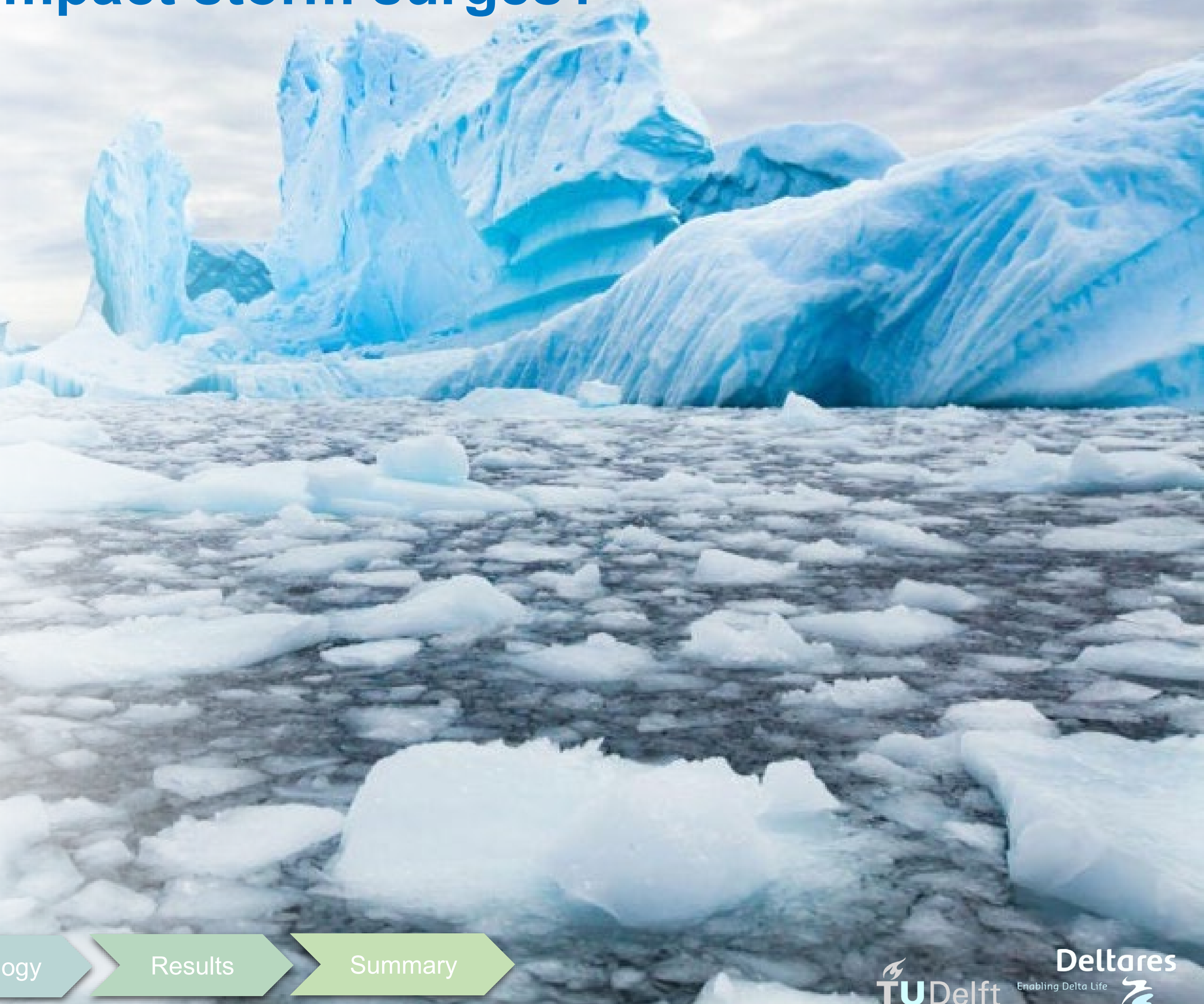
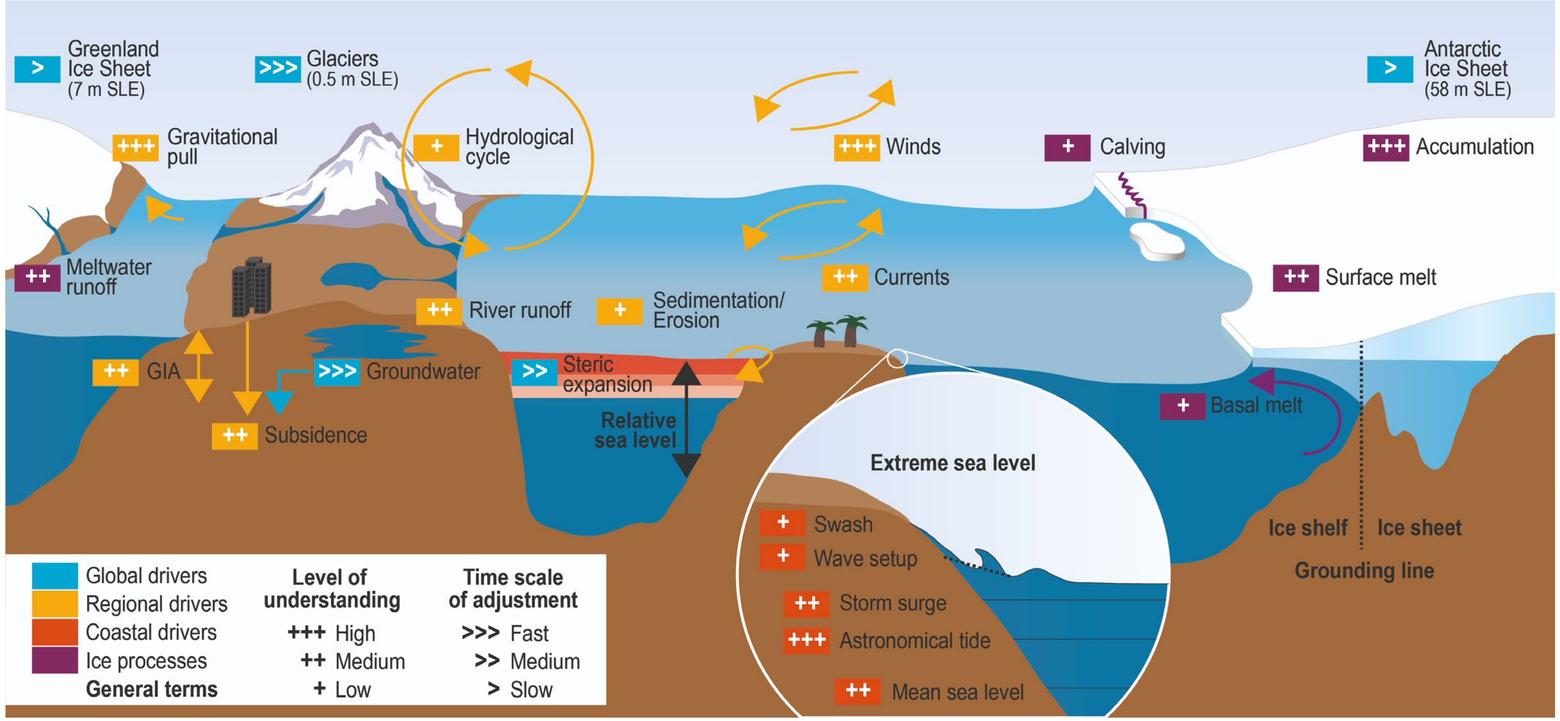


IMAGE: Melting glacial ice in Antarctica. CREDIT: Anya Berkut/iStock

Dutch Polar Cryosphere and Climate Change Consortium (DP4C)

- Stands for contributing to modeling efforts for coupled ice-sheet climate simulations.
- 5 PhD students and 2 Post Docs
- Aims to contribute to research from sea ice changes, ocean circulation in the Arctic, changes in Greenland and Antarctica to relative sea level, and extreme sea level.



Credit: IPCC

Develop a new parametrization for sea-ice related physics within the Global Tide and Surge Model (GTSM) for global projections of extreme sea levels and perform future scenarios to investigate the impacts of changes resulting from climate change in the polar regions on coastal regions.

Improving the understanding of the role of sea surface drag parametrization in storm surge dynamics and reproduction within the Global Tide and Surge Model (GTSM).

Global Tide and Surge Model

- Depth-averaged hydrodynamic model
- Global coverage with an unstructured grid that spatially varying resolution increasing towards the coast:
  - 25 km in the ocean
  - 2.5 km along the coast - 1.25 km in Europe

- Delft3D Flexible Mesh software by Deltares
- Simulates water levels caused by tides and storm surges
- Applications;
  - Operational forecasting
  - Reanalysis of historical extremes
  - Future climate projections

Credit: publicwiki.Deltares.nl

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Previous Studies with GTSM

- Previous studies have validated GTSM and have confirmed the accuracy of GTSM in modeling water levels, notably aligning well with observations in studies [6], [7] where a constant wind drag value from Charnock [8] was utilized.
- This constant does not consider variations in sea state, thereby limiting its accuracy and applicability.
- Recent studies [9] and [10] highlight the significance of integrating dynamic drag formulations into storm surge models, rather than depending on constant values.

Credit: publicwiki.Deltares.nl

Surge Modeling in GTSM

The wind field is transformed into wind stress to capture the necessary air-sea momentum exchange for storm surge, utilizing a drag coefficient that accounts for air density and wind speed at a given location.

The wind stress is modeled as the following equation:

$$\tau_s = \rho_a C_D U_{10}^2$$

Logarithmic velocity profile law: $$\frac{u_{10}}{u_*} = \frac{1}{k}\left(ln\frac{z}{z_0}\right)$$

The drag coefficient C_D: $$C_D = \frac{u_*^2}{u_{10}^2}$$

Charnock (1955) z_0's dependence on u_* : $$z_0 = \frac{\propto u_*^2}{g}$$

Credit: publicwiki.Deltares.nl

Experimental Design

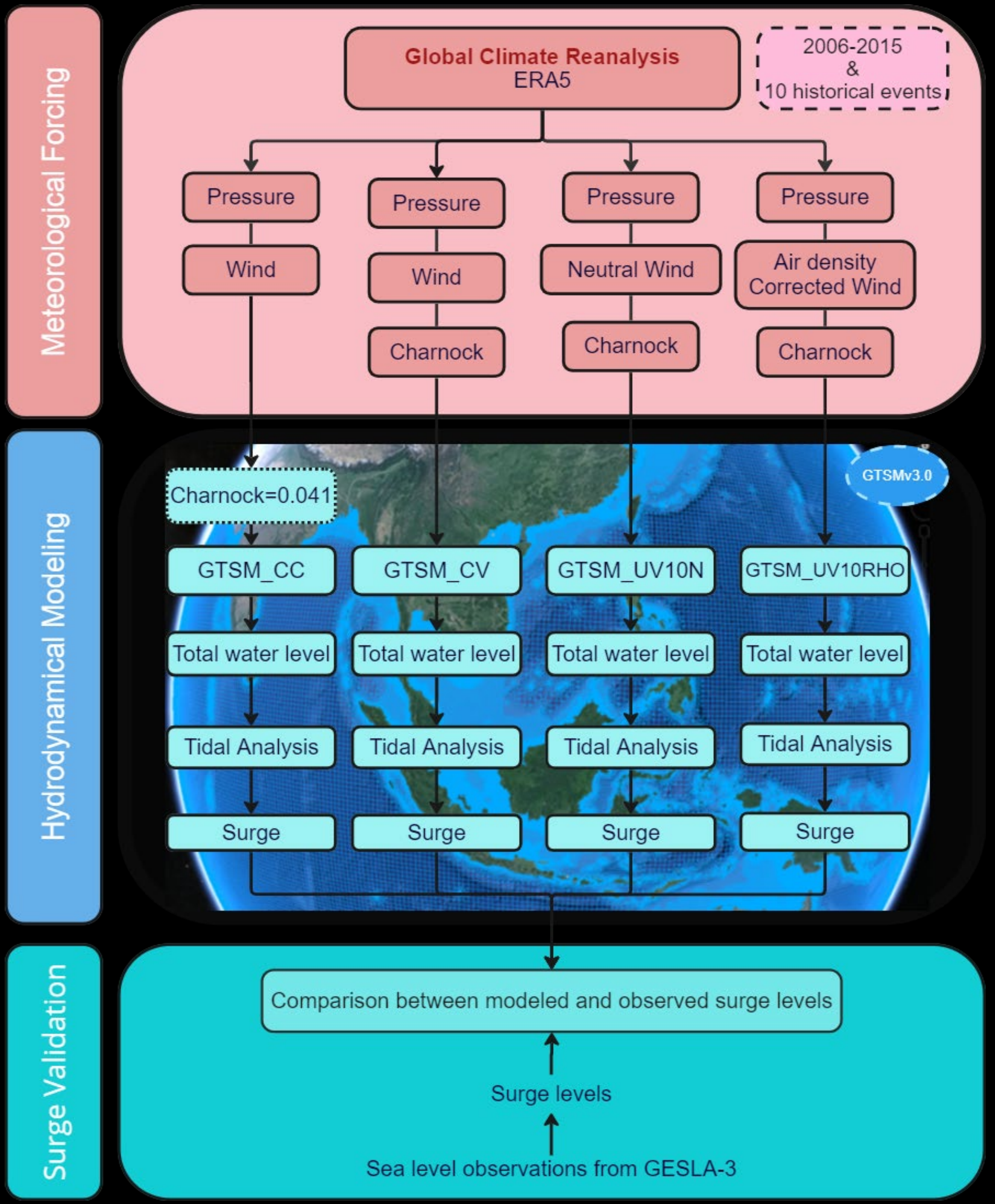
To evaluate the effects of implementing a wave-state-dependent drag coefficient, which offers a more realistic representation, four model experiments are hold:

1. GTSM_CC
2. GTSM_CV
3. GTSM_UV10N
4. GTSM_UV10RHO

Experiments:

- Total water levels produced from tidal and meteorological forcing
- Covers 2006-2015 including 10 historical extreme events
- Time series at 10-minute resolution
- ~ 44,000 output points

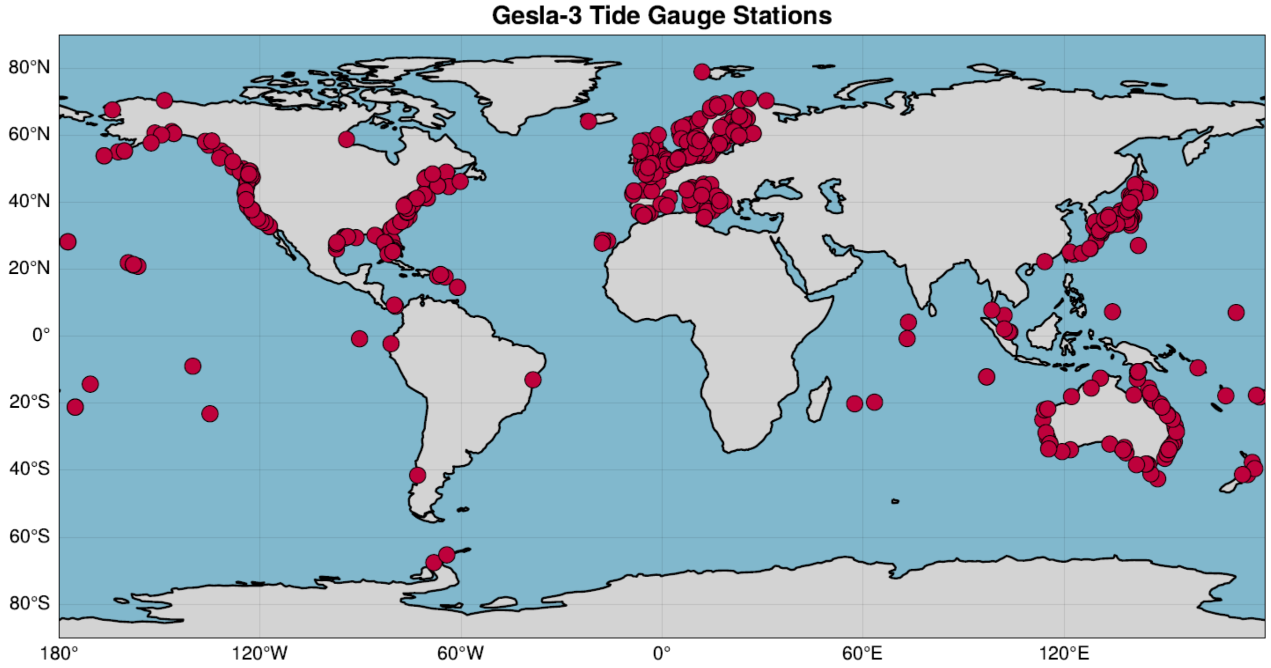
The non-tidal residual, known as surge, remains in the total water level once the tidal contribution is subtracted.



Global Observations

Global Extreme Sea Level Analysis Version 3 (GESLA-3) [11]:

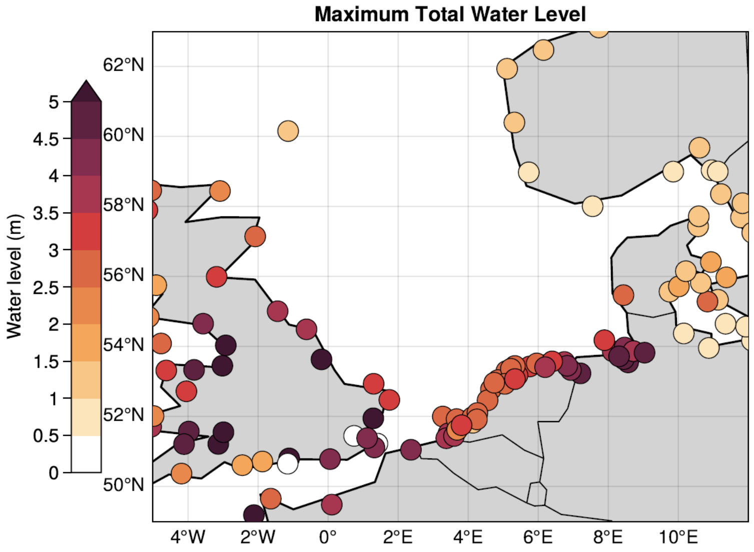
- Public stations cover most of the world
- Better coverage in the Northern Hemisphere, particularly in North America, Europe, Japan, and Australia.

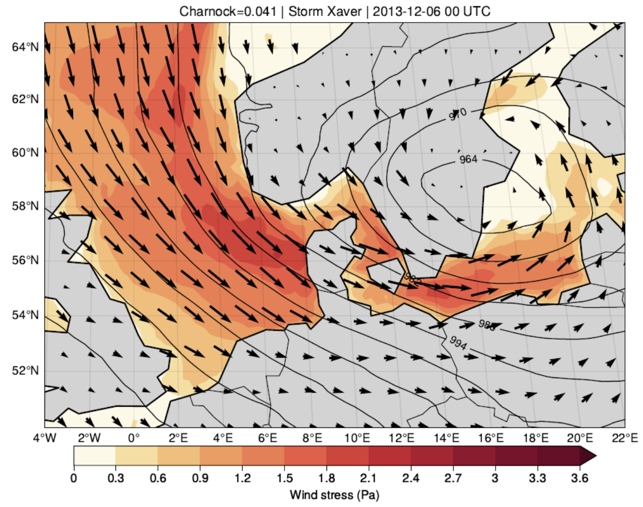


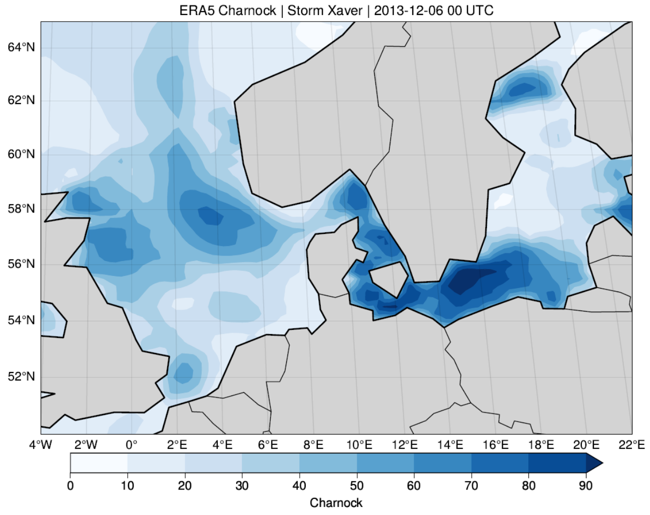
Preliminary Results: Case Study 1 - Storm Xaver

- Severe storm Xaver, moving across northern Europe in early December 2013,
  - Caused severe winds with gusts of hurricane force across the UK, Netherlands, northern Germany, and higher latitudes.
  - At least 7 fatalities

Credit: AFP







Water levels up to:
- 4m along the Netherlands coasts
- 5m along German coasts

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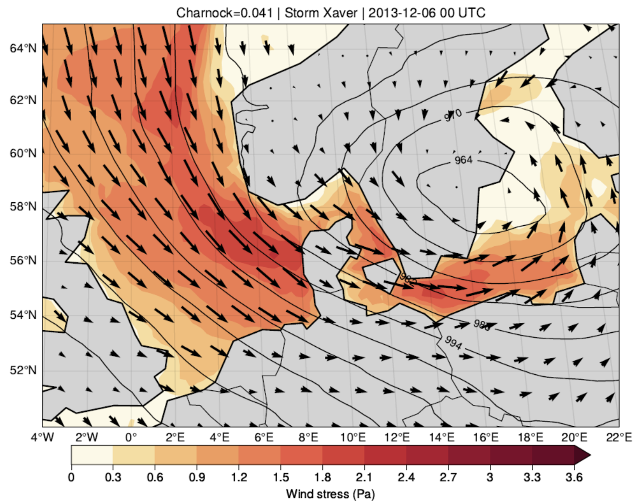

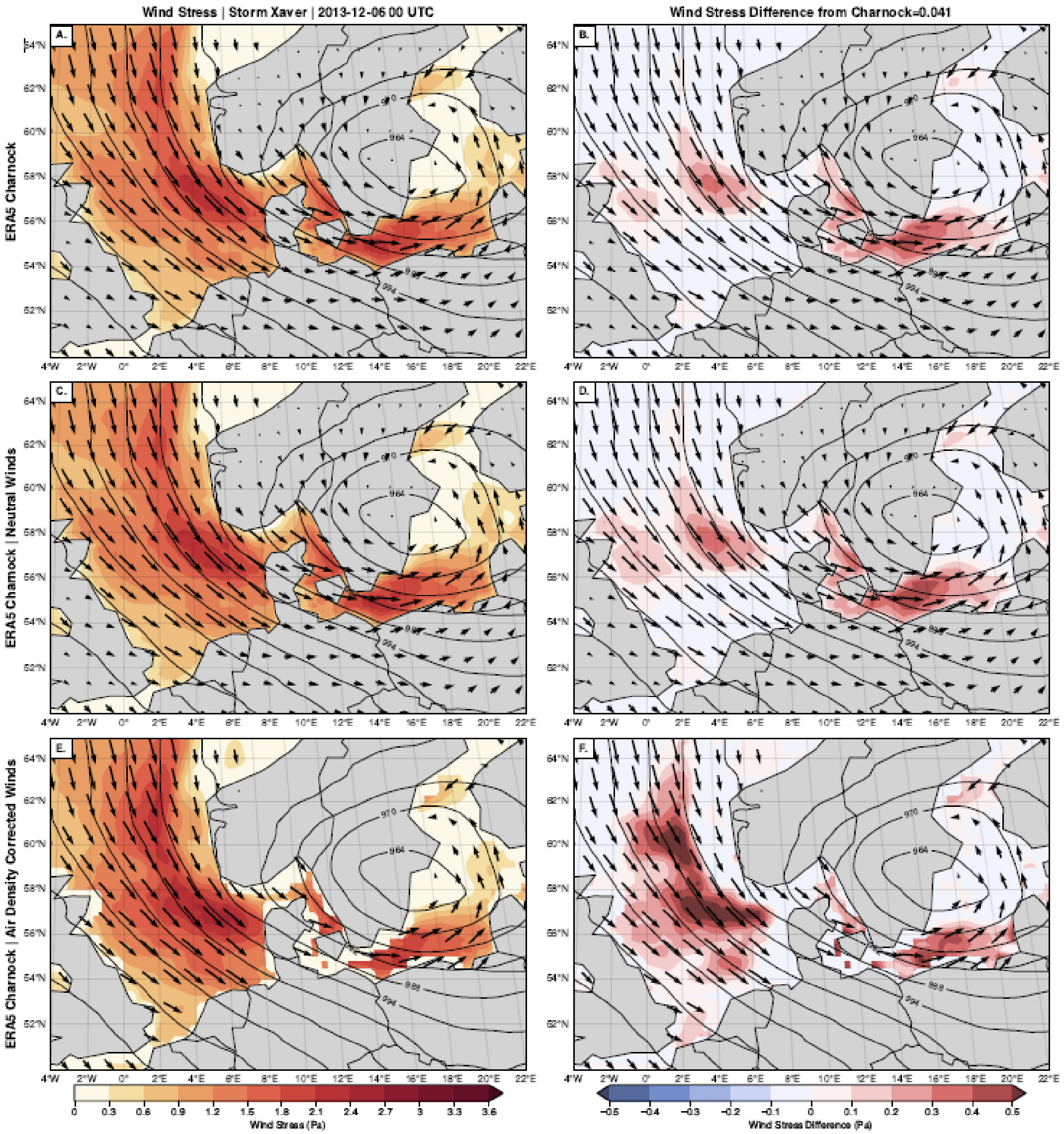

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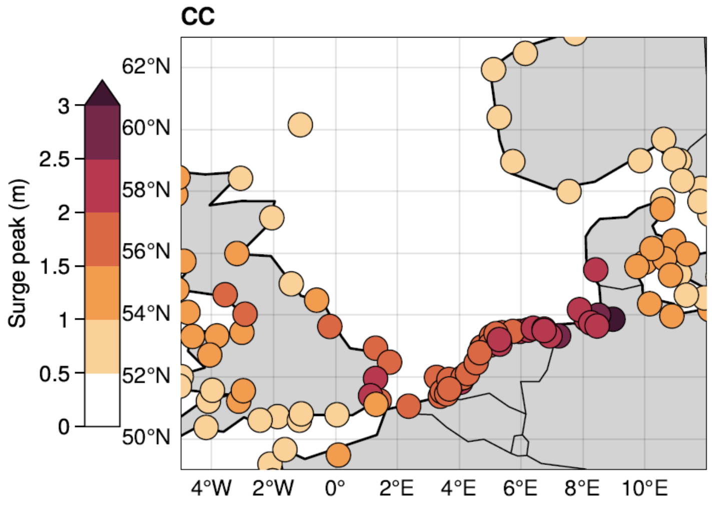

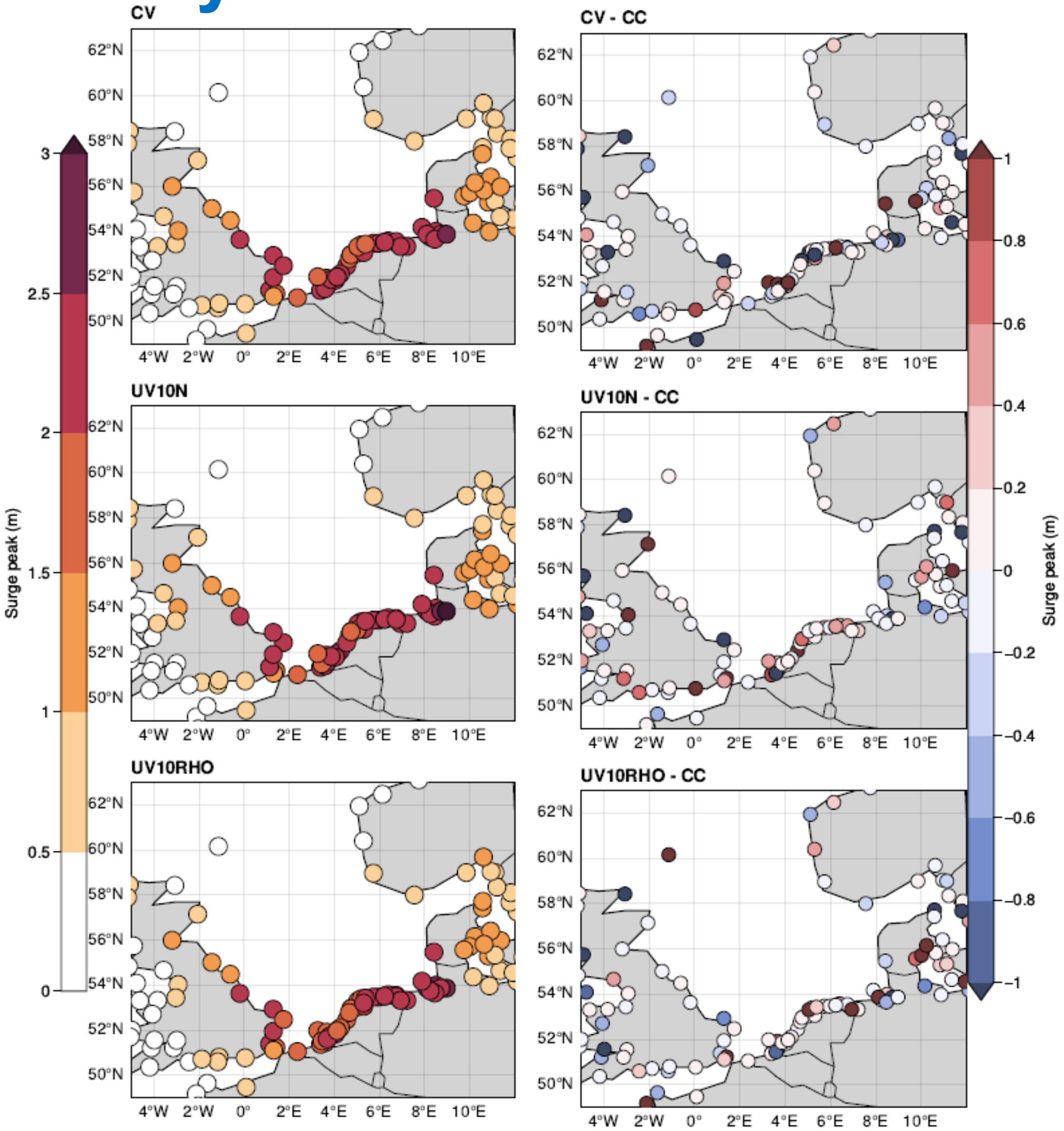

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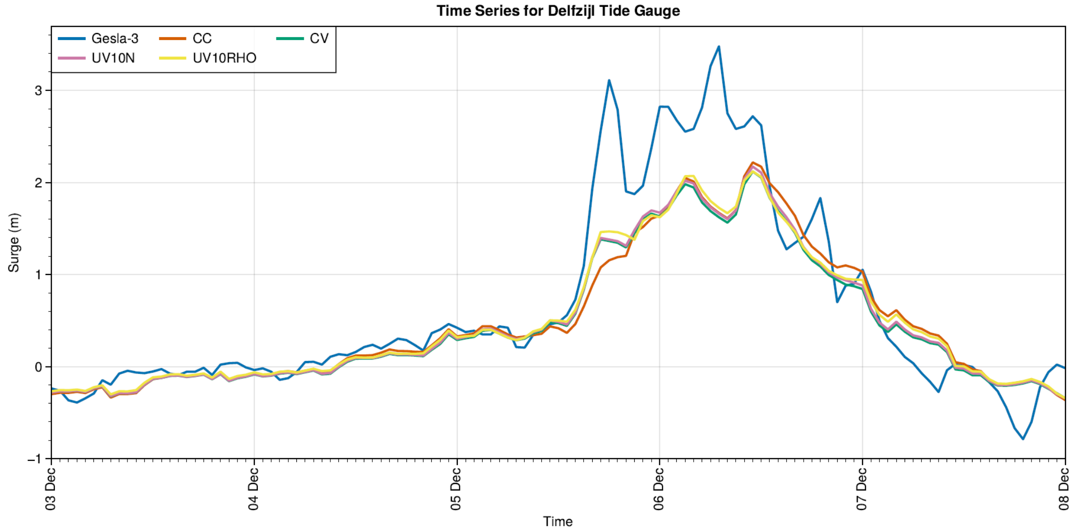
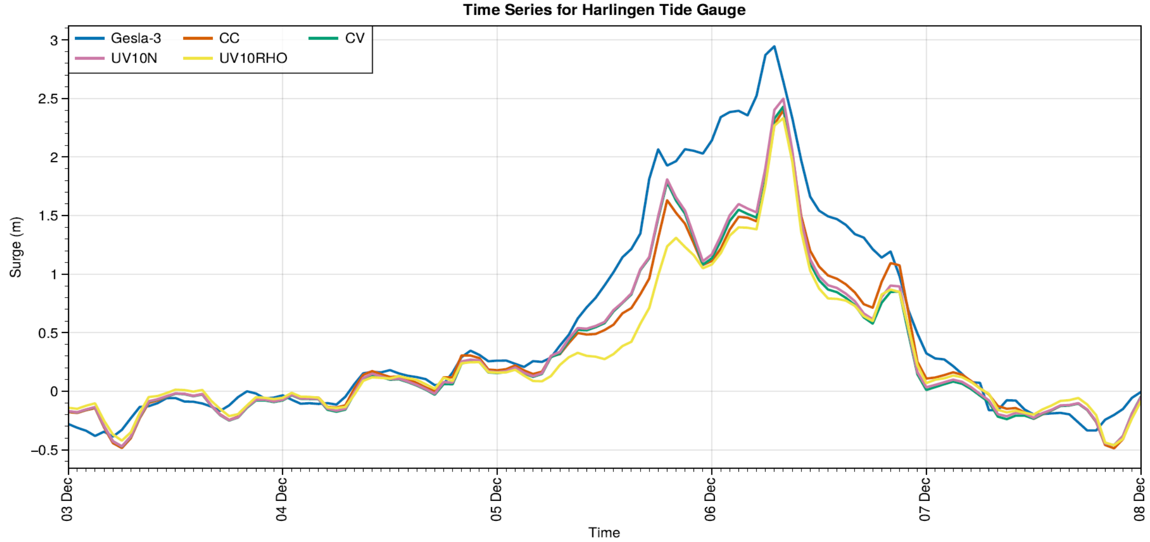
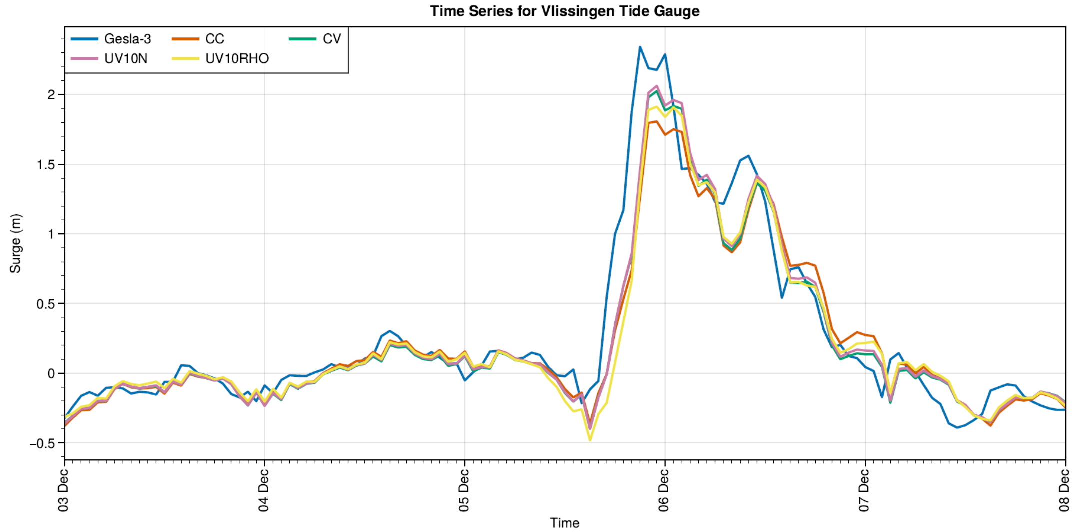




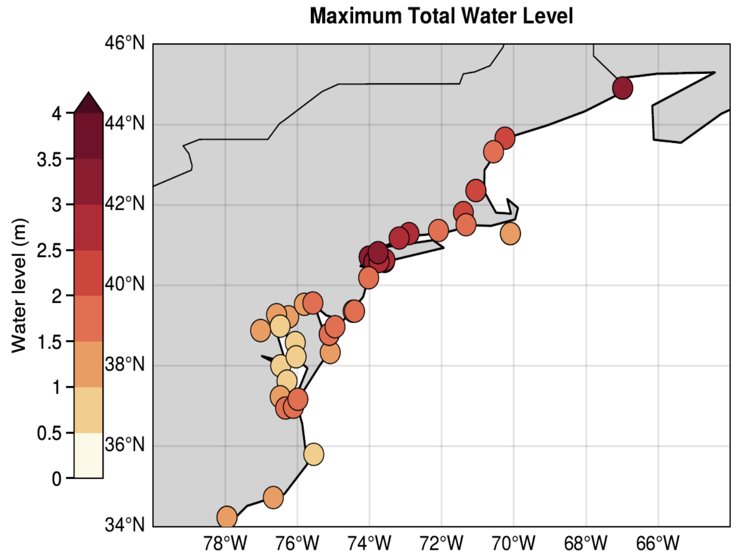


	Delftzijl			Harlingen			Vlissingen		
	RMSE	MAE	R2	RMSE	MAE	R2	RMSE	MAE	R2
CC	0.456	0.277	0.919	0.332	0.197	0.970	0.219	0.128	0.935
CV	0.437	0.268	0.945	0.327	0.204	0.974	0.195	0.114	0.950
UV10N	0.426	0.261	0.943	0.310	0.192	0.975	0.192	0.113	0.949
UV10RHO	0.418	0.259	0.946	0.400	0.253	0.964	0.225	0.126	0.930

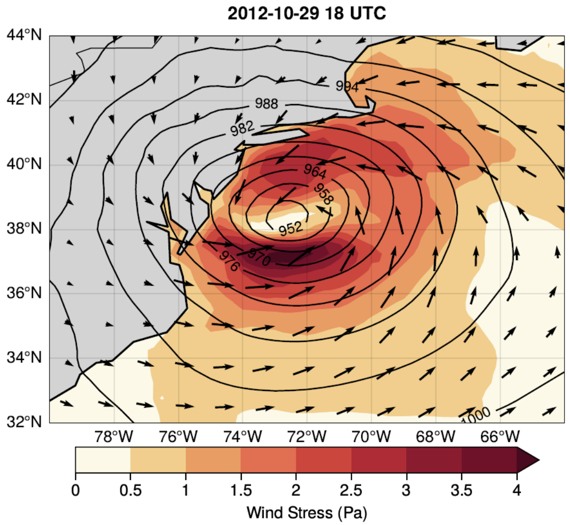
Preliminary Results: Case Study 2 - Post-tropical Cyclone Sandy

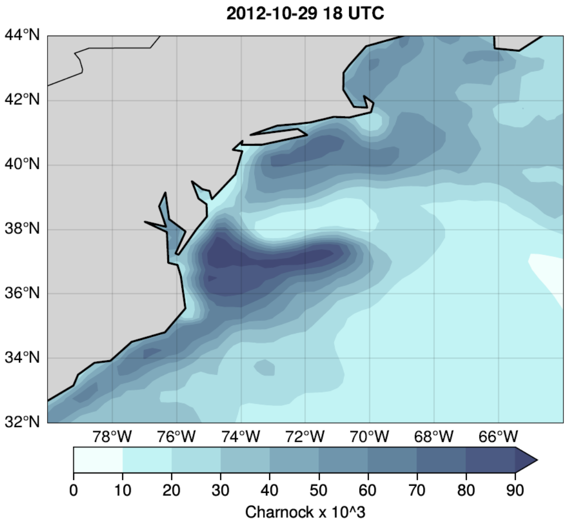
- Severe storm Sandy, an extremely destructive and strong Atlantic post-tropical cyclone in the USA in late October 2012:
  - At least 200 fatalities
  - Coastal flooding
  - Extensive wind damage inland

Credit: Bob Pool / Getty Images



Water levels up to:
- Storm tide along the coast was 4.5m





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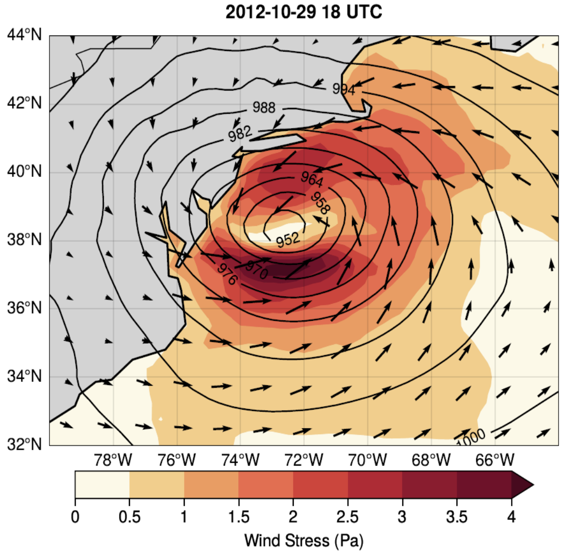

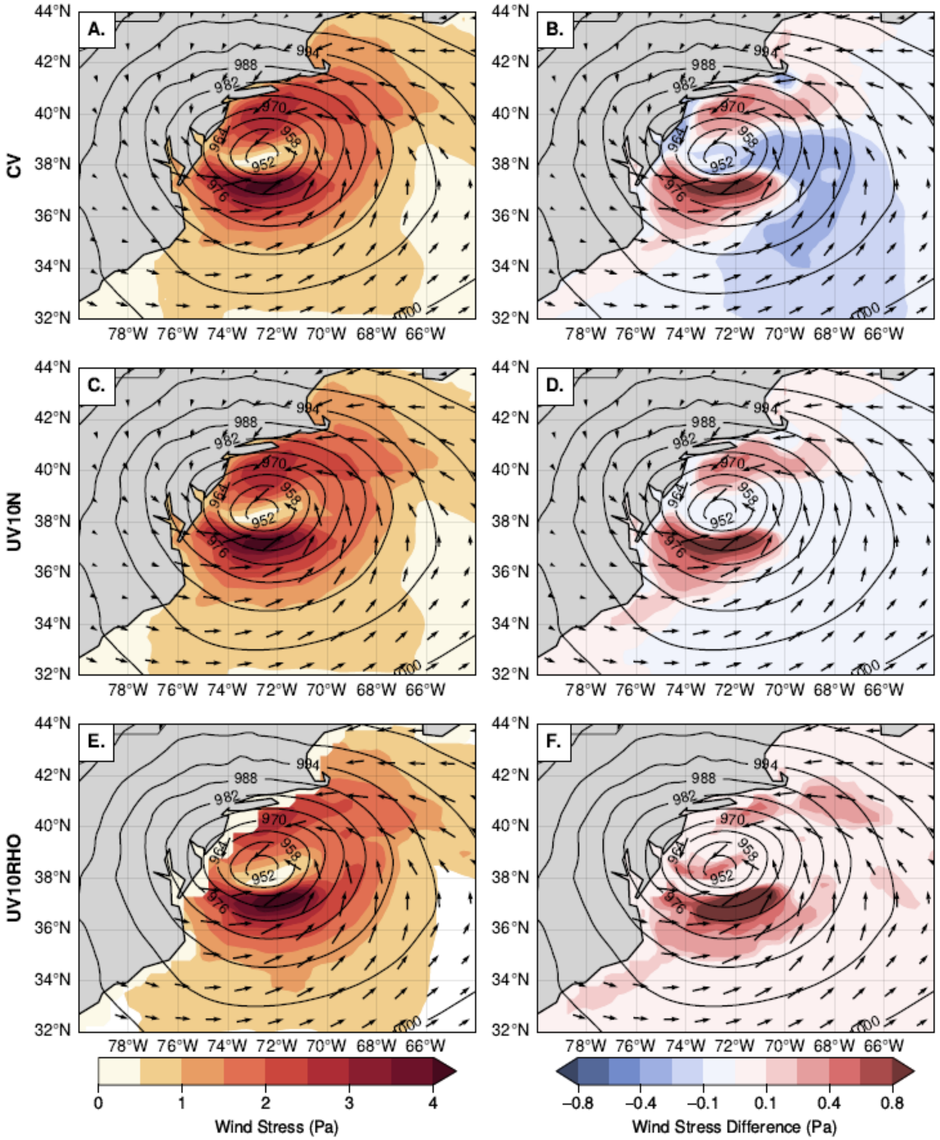

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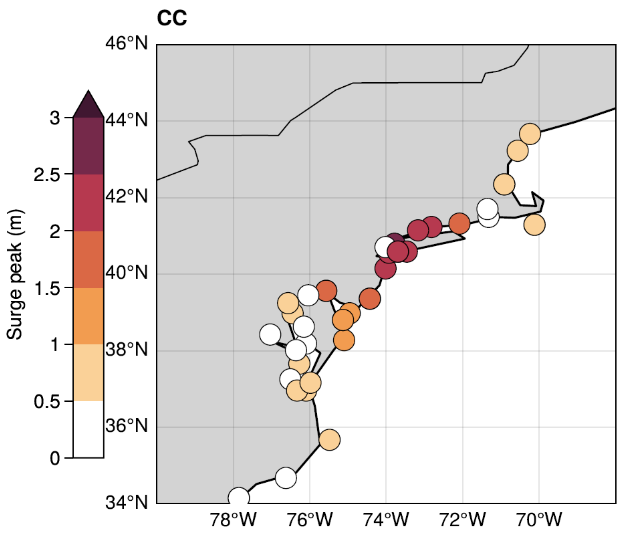

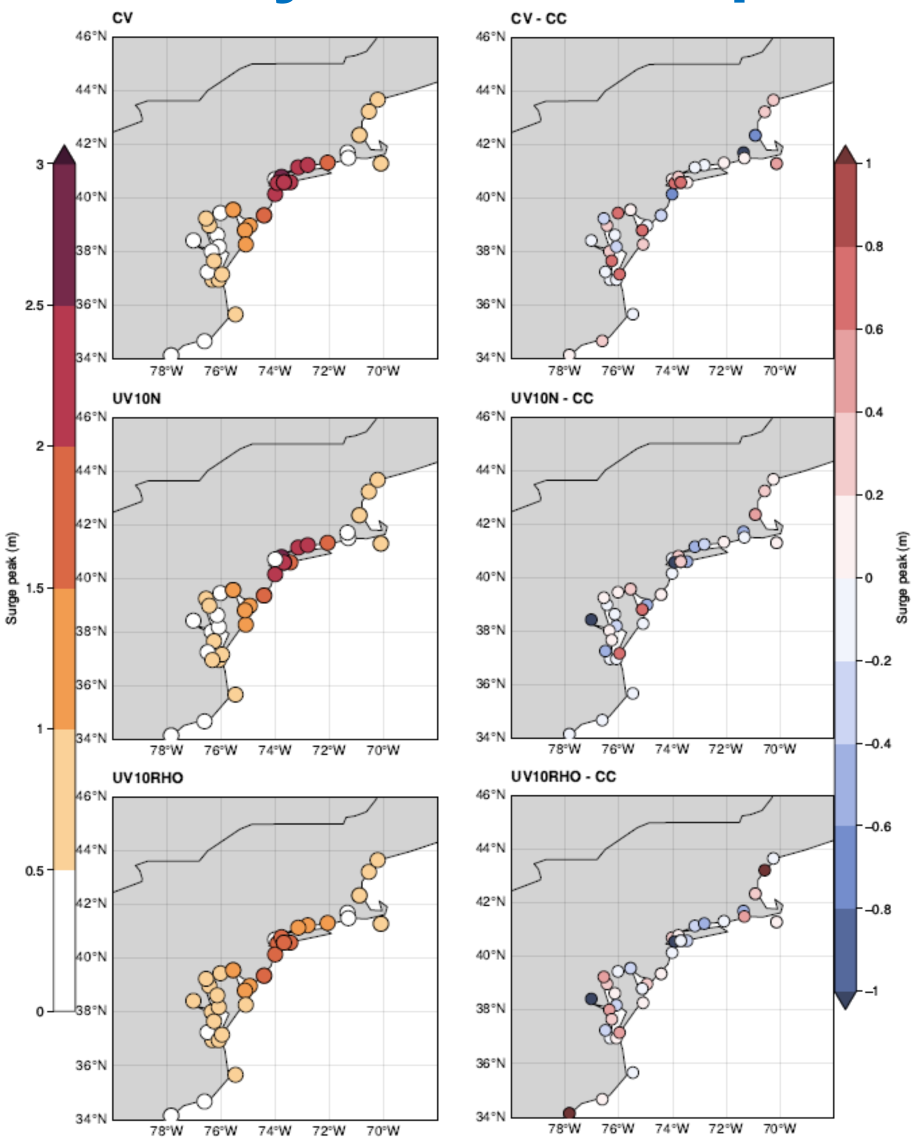

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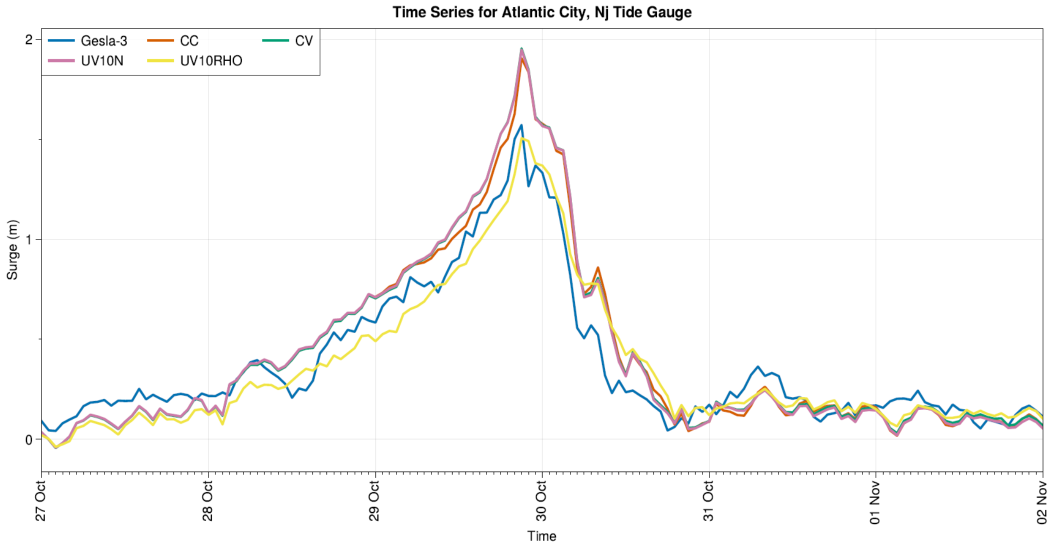
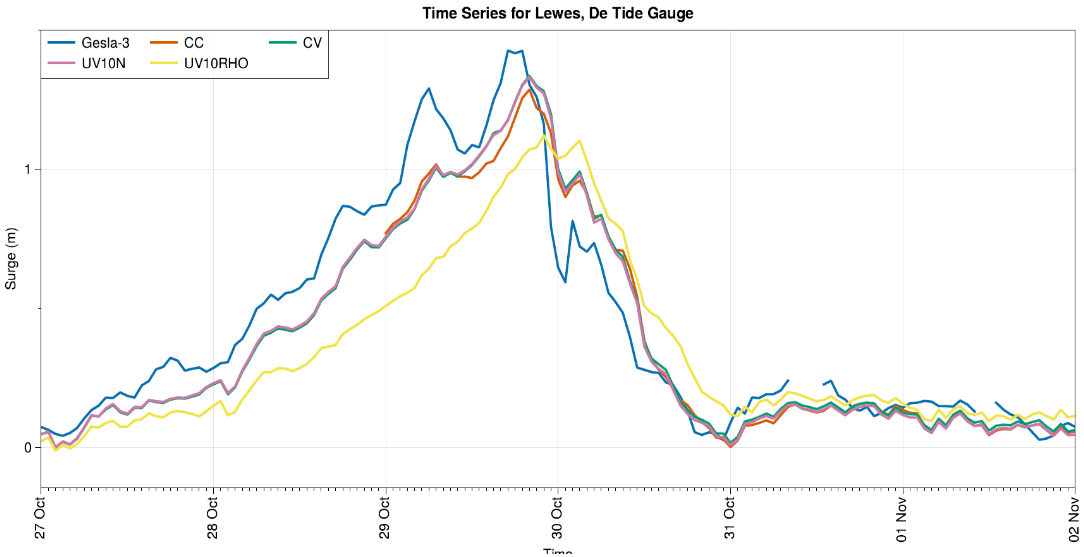
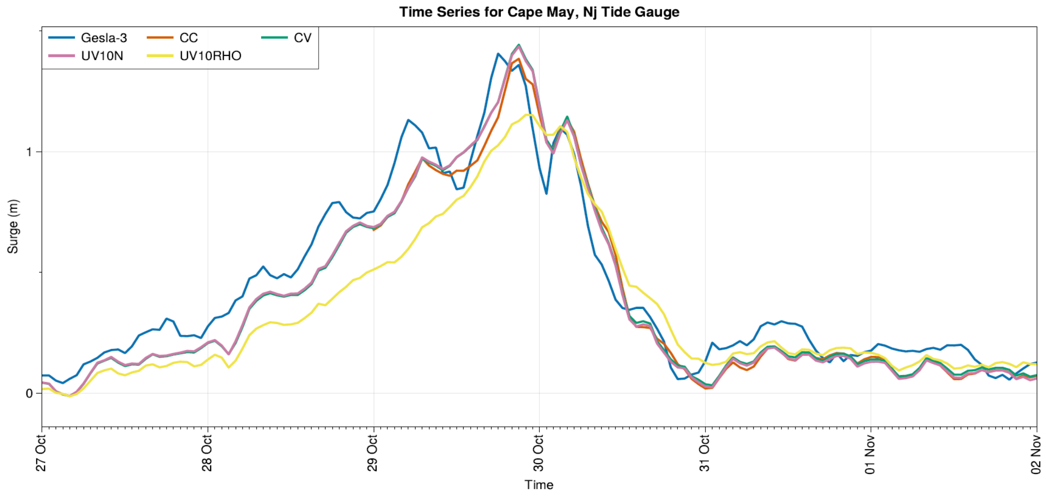
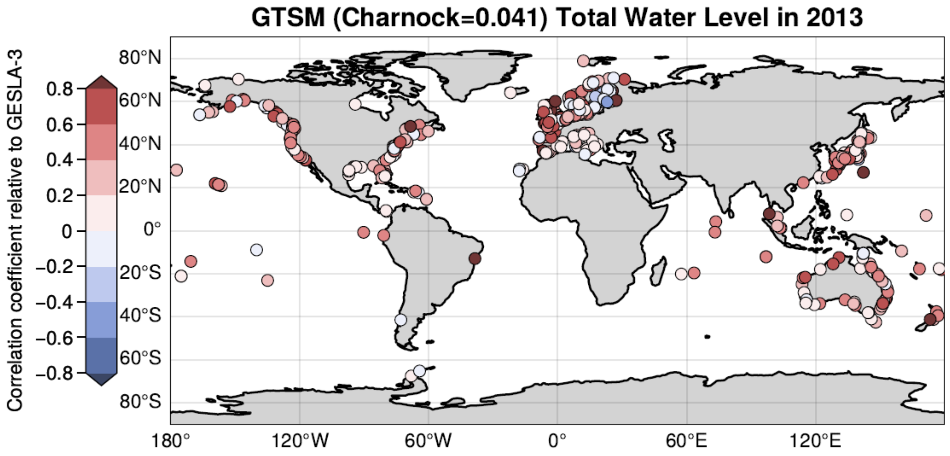
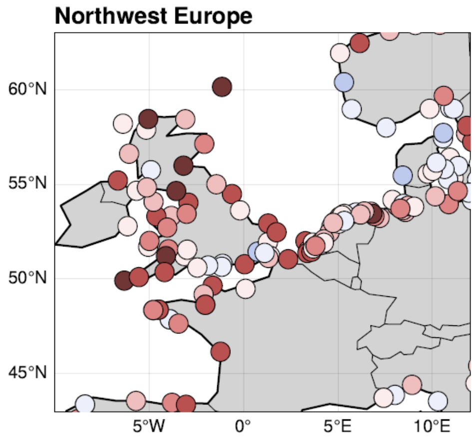


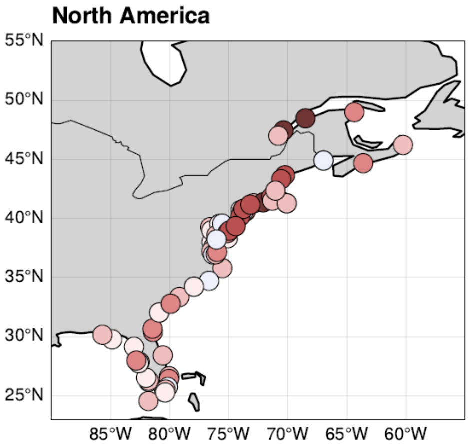


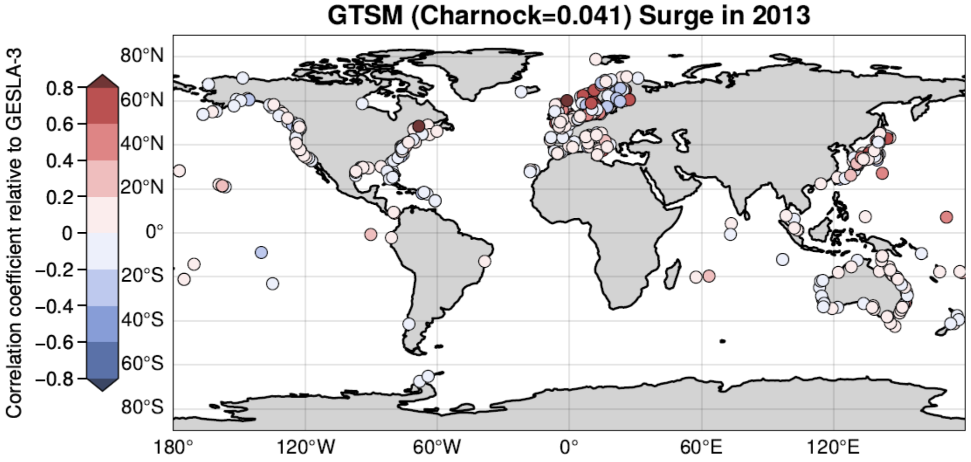


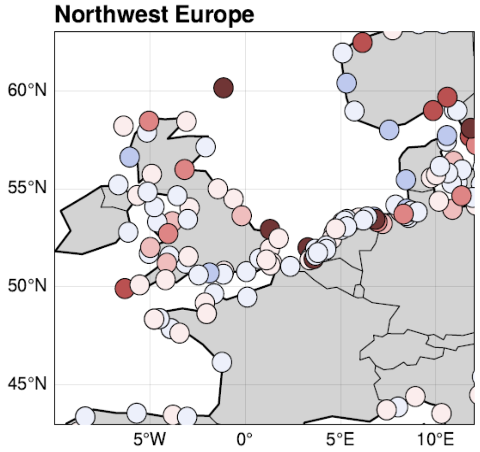
Preliminary Results: Yearly Simulation - 2013

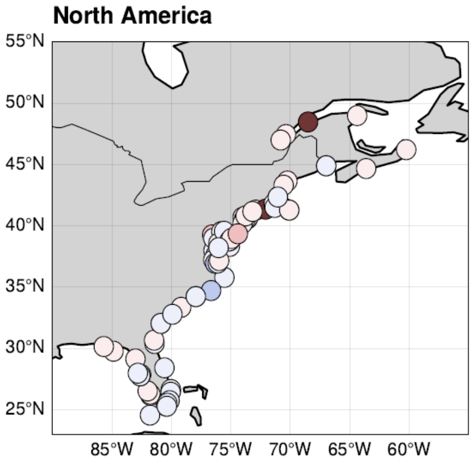












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Future Directions

- Long-term simulations of10 years (2006-2015)
- Validation of mean sea level pressure and wind values to observations
- Errors in the calculation of the astronomical tide and timing
  - Skew surge analysis
- Increasing the number of historical events:
  - Storm Xynthia, November 2011 Bering Sea cyclone etc.

- Implementing the sea-ice physics
  - Modeling surges without sea-ice cover
  - Modeling surges with sea-ice cover

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