



Norwegian
Meteorological
Institute

A data driven limited area storm surge model

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ML models at MET Norway

Multiple ML projects following the “ML revolution” in weather forecasting:

- AICE (Sea-ice, operational)
- Bris (atmosphere, operational)
- Unnamed chemistry model (atmospheric chemistry, dev)
- Unnamed wave model (Ocean, dev)
- HavBris (3D ocean, dev)
- Flo (Storm surge, dev)

Anemoi

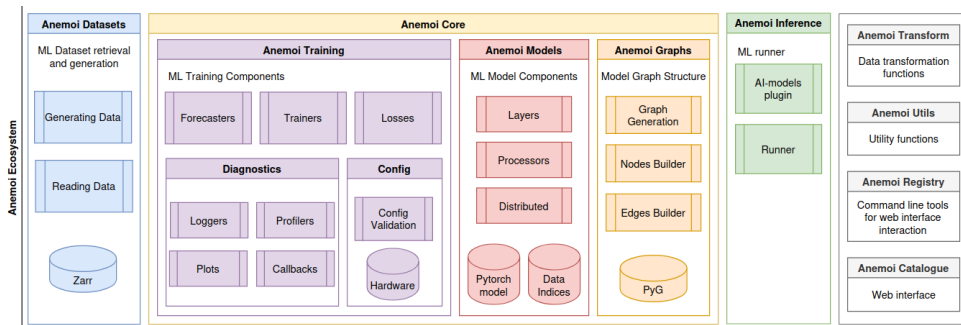
<https://anemoi.readthedocs.io/en/latest/>

An open-source framework developed at ECMWF (with partners) for data-driven weather models.

Graph Neural Network

Includes everything needed to create data driven model from scratch:

- anemoi-datasets
- anemoi-graphs
- anemoi-training
- anemoi-inference



- Encoder - processor - decoder architecture
 - Input data encoded to compact latent representation.
 - Processed forward in time
 - Decoded back to input grid.
- The graph is central
 - “Nodes” representing points in input grid and latent space
 - “Edges” connecting the nodes together.

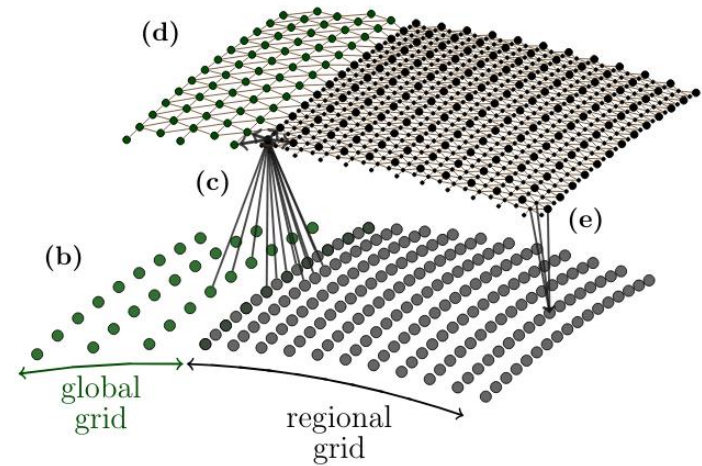
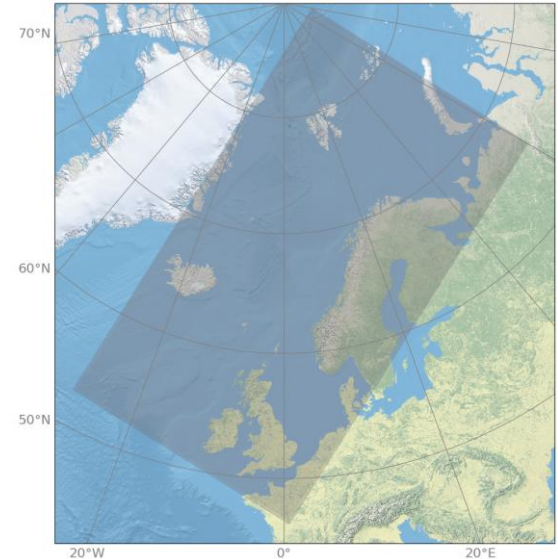


Figure 1 from Nipen, T. N., Haugen, H. H., Ingstad, M. S., Nordhagen, E. M., Salihi, A. F. S., Tedesco, P., ... & Chantry, M. (2024). Regional data-driven weather modeling with a global stretched-grid. *arXiv preprint arXiv:2409.02891*.

Flo

- Storm surge: weather effect on sea surface height.
- Barotropic process, barotropic 2D ocean models.
- Total water level: combined tides based on obs, and weather effect.
- MET Norway forecasts total water level daily, and releases “warning levels” based on expected impact.
- Flo: regional data-driven 2D model for simulating storm surge.
- “None-ML-expert’s attempt at creating a ML model”



Training data

- NORA-Surge hindcast
- Forced by the NORA3 atmospheric hindcast
- 4 km horizontal resolution and 1 hour temporal resolution
- 43 years of data available

NORA-Surge: A storm surge hindcast for the Norwegian Sea, the North Sea and the Barents Sea

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ABSTRACT

Knowledge about statistics for water level variations along the coast due to storm surge is important for the utilization of the coastal zone. An open and freely available storm surge hindcast archive covering the coast of Norway and adjacent sea areas spanning the time period 1979–2022 is presented. The storm surge model is forced by wind stress and mean sea level pressure taken from the non-hydrostatic NORA3 atmospheric hindcast. A dataset consisting of observations of water level from more than 90 water level gauges along the coasts of the North Sea and the Norwegian Sea is compiled and quality controlled, and used to assess the performance of the hindcast. The observational dataset is distributed in both time and space, and when considering all the available quality controlled data, the comparison with modelled water levels yield a mean absolute error (MAE) of 9.7 cm and a root mean square error (RMSE) of 12.4 cm. Values for MAE and RMSE scaled by the standard deviation of the observed storm surge for each station are 0.42 and 0.54 standard deviations, respectively. When considering the geographical differences in characteristics of storm surge for different countries/regions, the values of MAE and RMSE are in the range 5.7–13.9 cm and 7.6–17.8 cm respectively, and 0.33–0.46 and 0.42–0.59 standard deviations for the scaled values. The minimum and maximum values for water level in the hindcast are −2.60 m and 3.92 m. In addition, 100-year return level estimates are calculated from the hindcast, with minimum and maximum values of, respectively, −2.73 m and 3.98 m. All minimum and maximum values are found in the southern North Sea area.

1. Introduction

Storm surges are driven by the passing of synoptic weather systems. A simple rule of thumb states that a reduction of 1 hPa in surface air pressure leads to an increase of 1 cm in water level from the inverse barometric effect alone. In addition, frictional forces in combination with the Coriolis effect will lead to Ekman transport which can cause convergence and divergence of water masses along coastlines. More generally, such perturbations of the sea surface will tend to manifest themselves as Kelvin waves, traveling with the coast to their right in the northern hemisphere. As these waves have spatial and temporal scales comparable to the astronomical tides, they have historically been known as tidal surges, but their generating mechanism is of course very different. More importantly, storm surges are only as predictable as the synoptic weather phenomena that cause them. There exists a number of well-documented water level forecast systems in Europe and elsewhere (e.g. Glahn et al. 2009, Zijl et al. 2013, Kristensen et al. 2022). The

simplest represent the ocean as a two-dimensional barotropic field with a free surface. This is also how we model the water level in this study. As Kelvin waves propagate as shallow-water waves whose phase and group speed are \sqrt{gH} , where H is the local depth and $g = 9.81 \text{ m s}^{-2}$ the earth's gravitational acceleration, the amplitude and propagation speed of storm surges is sensitive to errors in both the gradient and the mean level of the bathymetry.

The availability of storm surge hindcasts for the Norwegian Sea, the North Sea and the Barents Sea region with sufficient spatial resolution, and spatiotemporal coverage is scarce, as shown by Ferrelnaud, Monthane et al. (2020). Long hindcast integrations are necessary to assess water level extremes in coastal regions. To do this realistically requires high-quality and high-resolution atmospheric forcing and sufficiently high spatial resolution for the storm surge model. Storm surge hindcast archives serve mainly three practical applications. The first is

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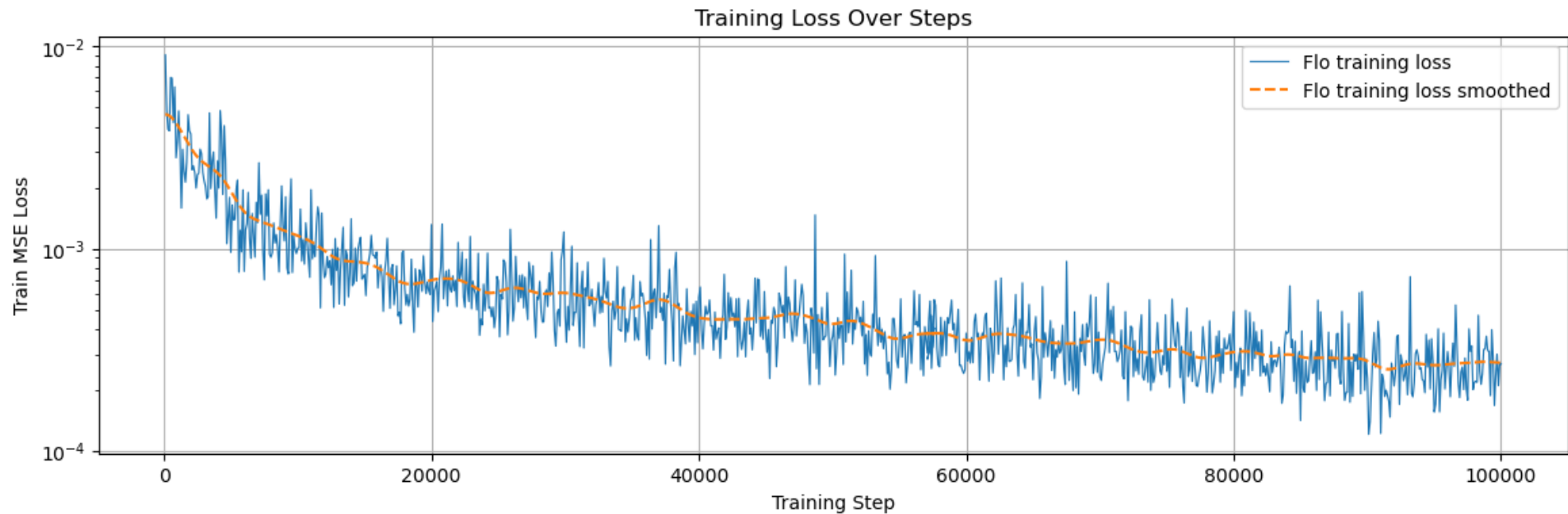
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Variable	Source	Type
SSH (residual water level)	NORA-Surge	Prognostic
10 meter wind (U10m and V10m)	NORA3	Forcing
MSLP	NORA3	Forcing
Bathymetry	NORA-Surge	Forcing (static)
Land-sea mask	NORA-Surge	Forcing (static)
Coriolis parameter	NORA-Surge	Forcing (static)
Solar insolation	Anemoi	Forcing (static)
Sine of latitude	Anemoi	Forcing (static)
Sine of longitude	Anemoi	Forcing (static)
Sine of local time	Anemoi	Forcing (static)
Sine of Julian day	Anemoi	Forcing (static)
Cosine of latitude	Anemoi	Forcing (static)
Cosine of longitude	Anemoi	Forcing (static)
Cosine of local time	Anemoi	Forcing (static)
Cosine of Julian day	Anemoi	Forcing (static)

Training the model

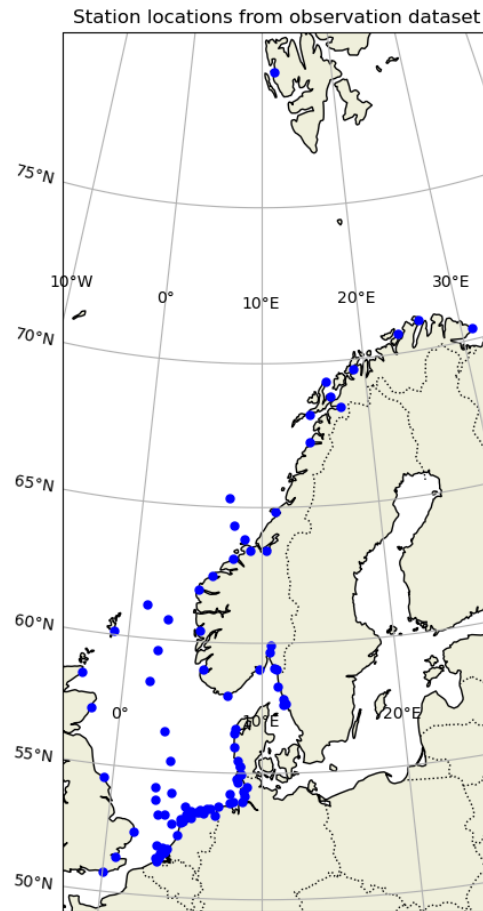
- 1x H200 GPU
- Limited to 100k steps in the interest of time... (took ~7 days)
- Channels: 256
- Trained on data for 1990-2005 ~ 3 epochs
- 2010–2022 (13 years) reserved for evaluation

Training loss



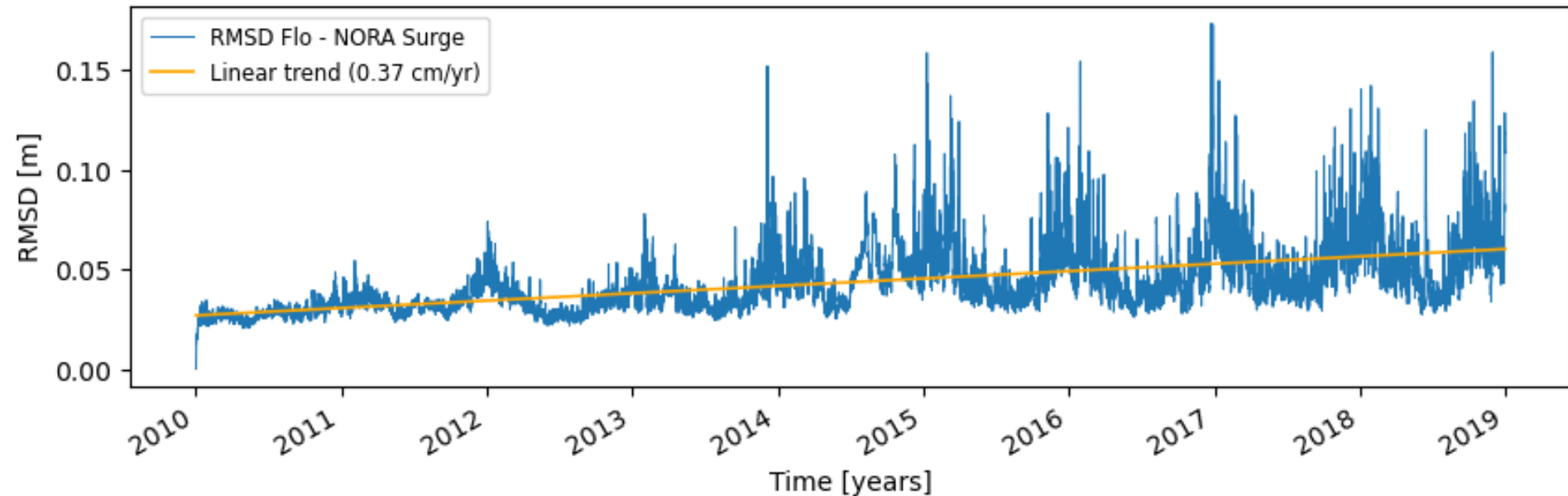
Evaluation

- Inference was run as a hindcast for 9 years (2010–2018)
- Flo is evaluated through comparison against observations and NORA-Surge
- De-tided observational dataset, evaluation focuses on *residual water level*.



Comparison against NORA-Surge

RMSD time series



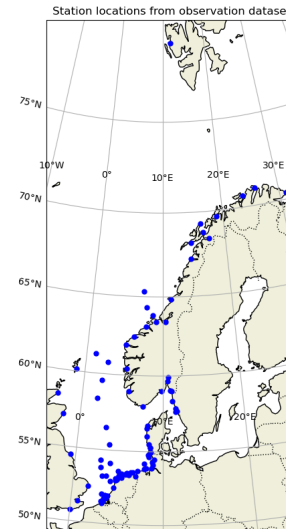
Gridpoint by gridpoint comparison (RMSD) averaged over entire model domain

Comparison against observations

“Masked” means we have masked the data for the times when the observations are less than +/- 10 and 30 cm, to better evaluate the “extremes”

Exp. name		RMSE [cm]	RMSE/ σ [σ]	Correlation
NORA-Surge	All data	12.6	0.55	0.85
	Masked < $\pm 10cm$	13.4	0.58	0.90
	Masked < $\pm 30cm$	16.7	0.71	0.94
Flo	All data	12.4	0.54	0.86
	Masked < $\pm 10cm$	13.2	0.57	0.90
	Masked < $\pm 30cm$	16.6	0.70	0.94

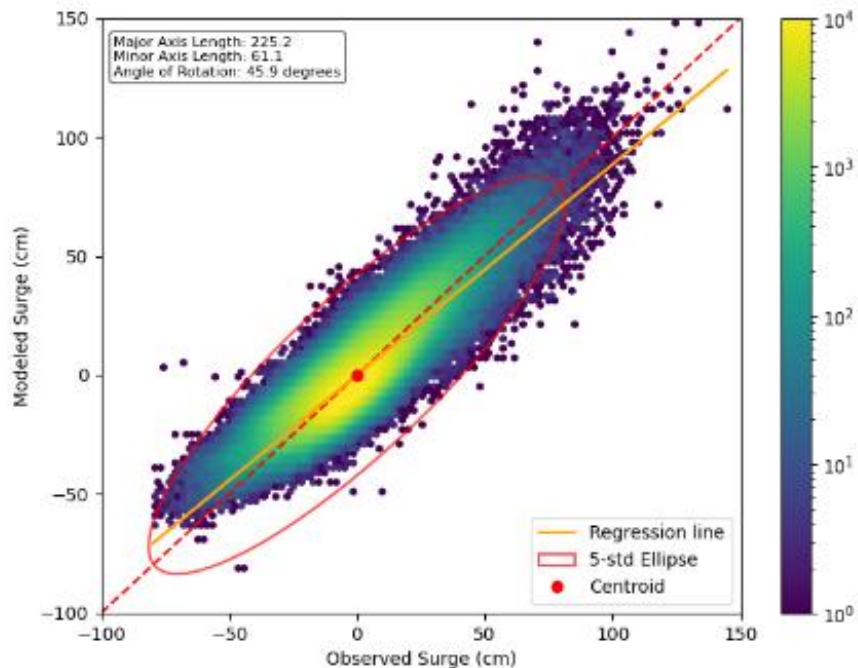
All stations



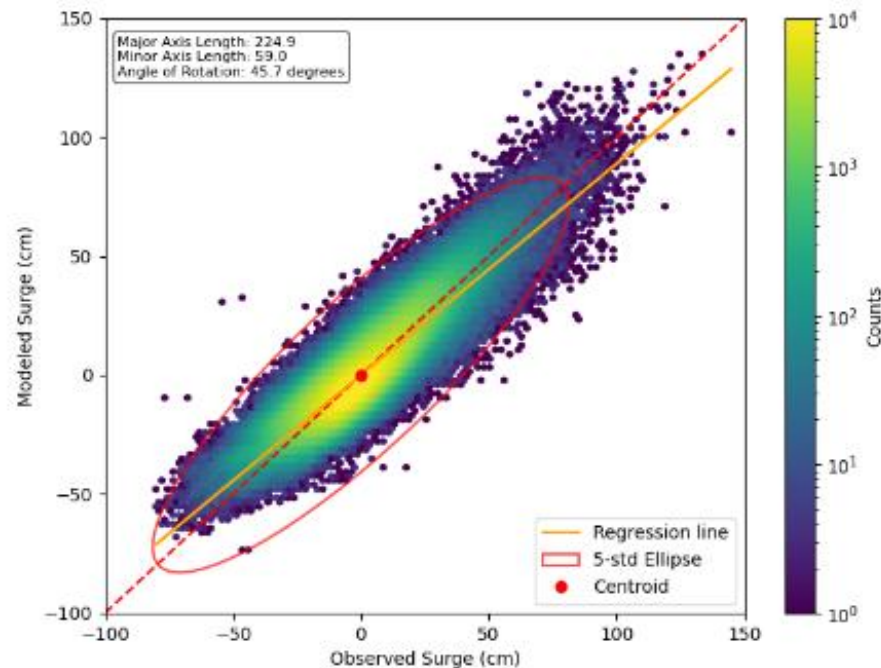
Norwegian stations only

Exp. name		RMSE [cm]	RMSE/ σ [σ]	Correlation
NORA-Surge	All data	8.4	0.53	0.87
	Masked < $\pm 10cm$	8.8	0.56	0.92
	Masked < $\pm 30cm$	10.3	0.65	0.97
Flo	All data	8.1	0.51	0.88
	Masked < $\pm 10cm$	8.5	0.54	0.93
	Masked < $\pm 30cm$	10.0	0.63	0.97

Comparison against Norwegian obs.



(a) NORA-Surge




(b) Flo

Case study of Storm Xaver

- Large storm that hit Northern Europe in December 2013.
- Storm surge among the top 5 measured in 100 years in the German bight.
- Water levels Hamburg reached 6m above mean sea level.

NATURE AND ENVIRONMENT
Sabine storm surge floods Hamburg's fish market
A swell caused by storm Sabine flooded Hamburg's iconic fish market. Fish could now be swimming through the stalls where they are usually sold.

f x




Hamburg fish market

ADVERTISEMENT

Hamburg's famous fish market flooded on Wednesday after storm Sabine caused river Elbe water levels to rise by 2.76 meters.

Several other streets around the port city in northern Germany were also flooded by the storm surge, according to a statement from the police and some cars had to be rescued from the flood water.

A fifth and final storm surge is expected later on Wednesday afternoon, reported German broadcaster NDR.

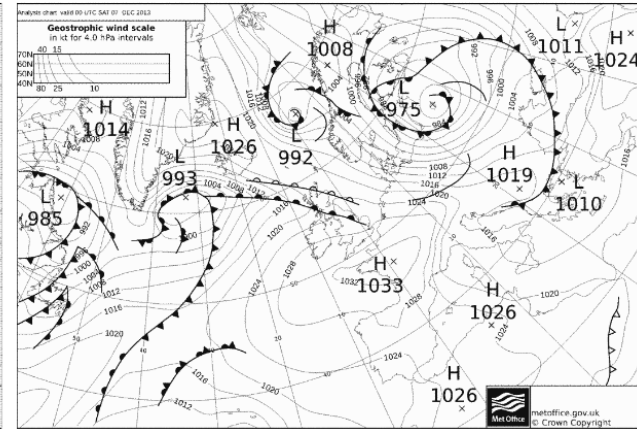
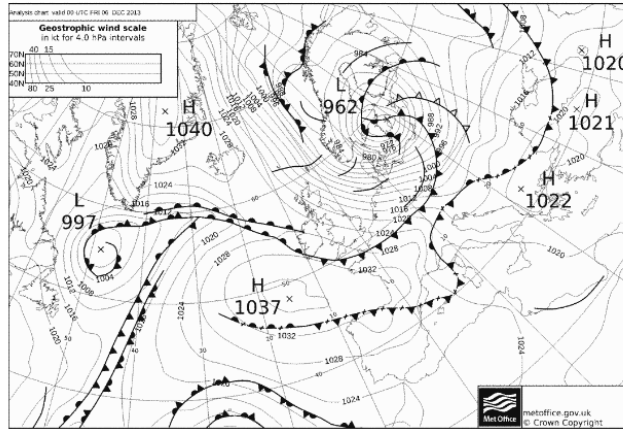
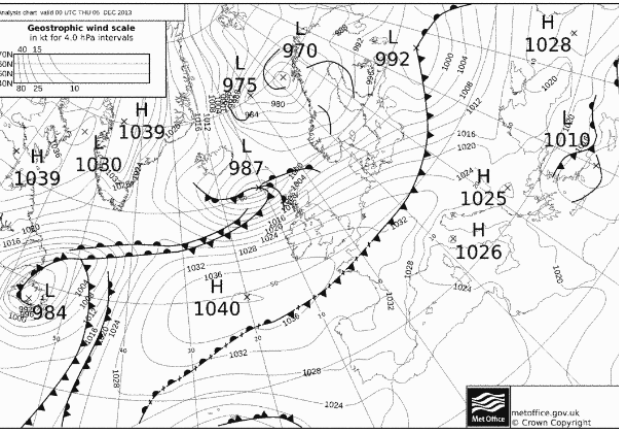


Storm Sabine caused a storm surge of 2.76 meters

Energy from the storm that followed in the wake of Sabine has pushed the water against the coast, causing the swells, said a spokesperson for the German weather service (DWD).

<https://www.dw.com/en/sabine-storm-surge-floods-hamburgs-fish-market/a-52351376>

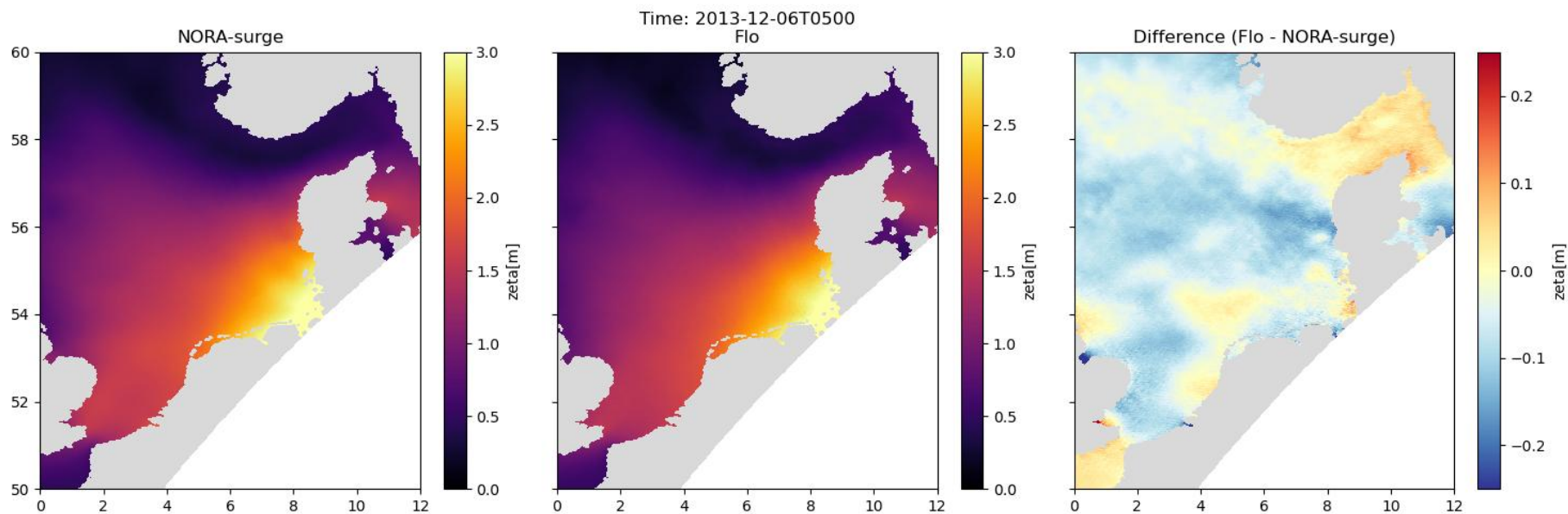
Weather situation during Storm Xaver



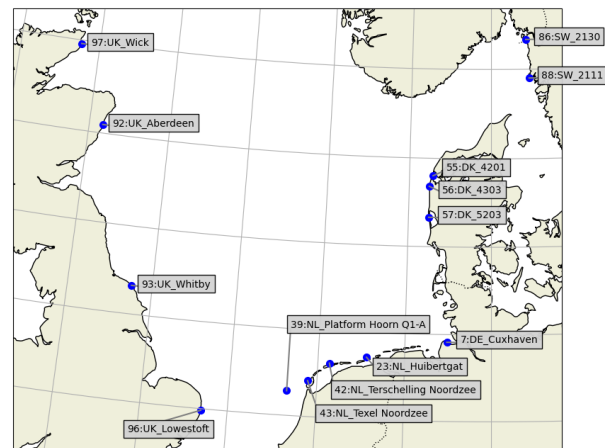
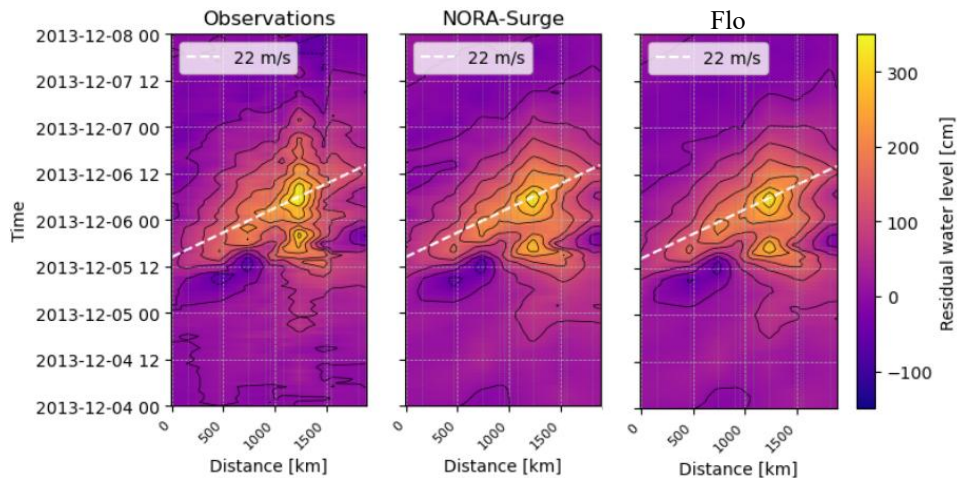
5-7 December 2013

Resulted in top 5 ever recorded water level over the last 100 years in the German Bight

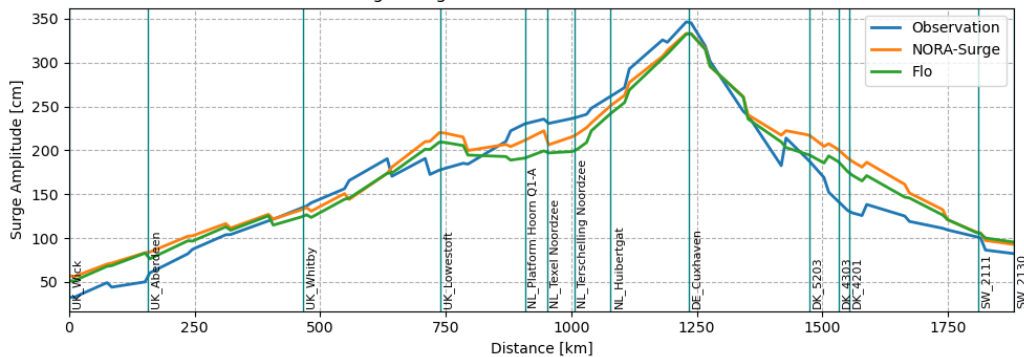
Flo and Storm-Surge Storm Xaver



Kelvin waves Storm Xaver



Amplitudes along the wave characteristic line ($c=22$ m/s)
Passing through max observed residual water level



Summary and conclusions

- Flo is capable of producing a continuous hindcast with similar error characteristics as its numerical counterpart.
- Flo is able to predict Kelvin wave propagation, indicating that the model has learned some physical properties which are not explicitly seen during training.
- We are working on operationalizing Flo and compare its forecast to the operational numerical model.
- To increase model performance we intend to add observational data to the training, as a way to simulate data-assimilation, which has not been included in NORA-Surge.

Thank you for your attention!

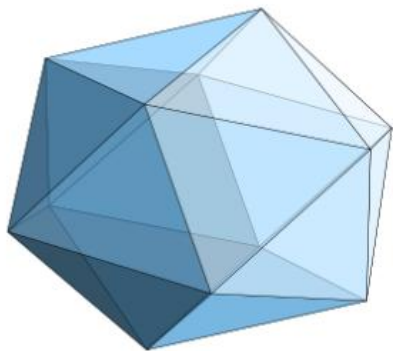
Preprint



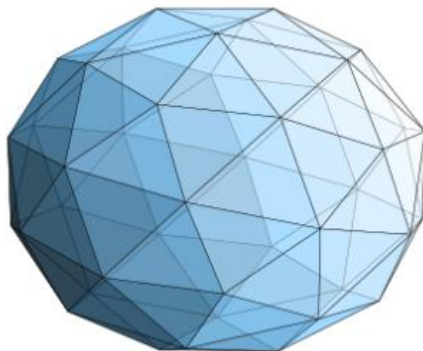
Extra slides

Graph creation

Refinement level=0



Refinement level=1



Refinement level=10

