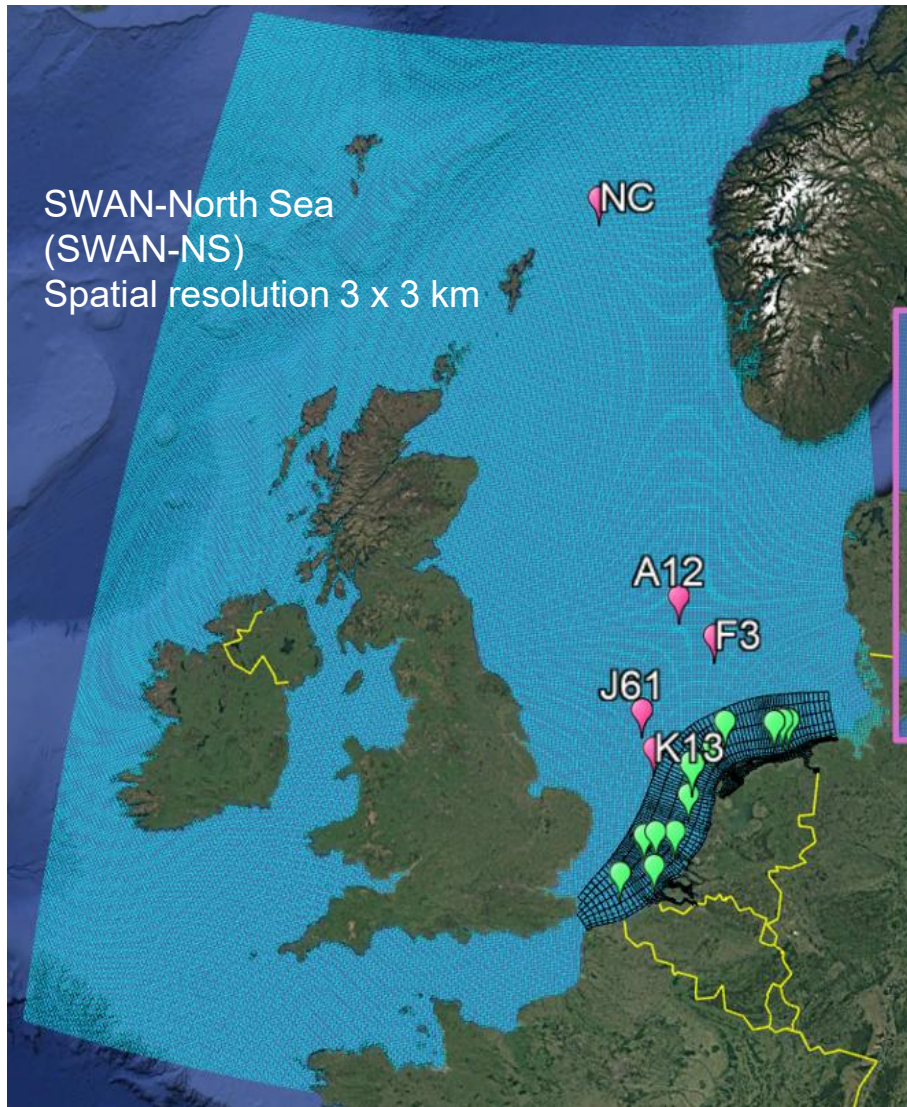# Lessons-learned: Evaluation of the operational spectral wave model with machine learning adjustments for spectral shape

Joana van Nieuwkoop, Menno de Ridder, Joost den Bieman, Marisol Irias Mata

22 September 2025 – Wave Workshop 2025, Santander

SWAN North Sea, operational wave models RWsOS

SWAN-North Sea
(SWAN-NS)
Spatial resolution 3 x 3 km

Models use:
- Harmonie wind
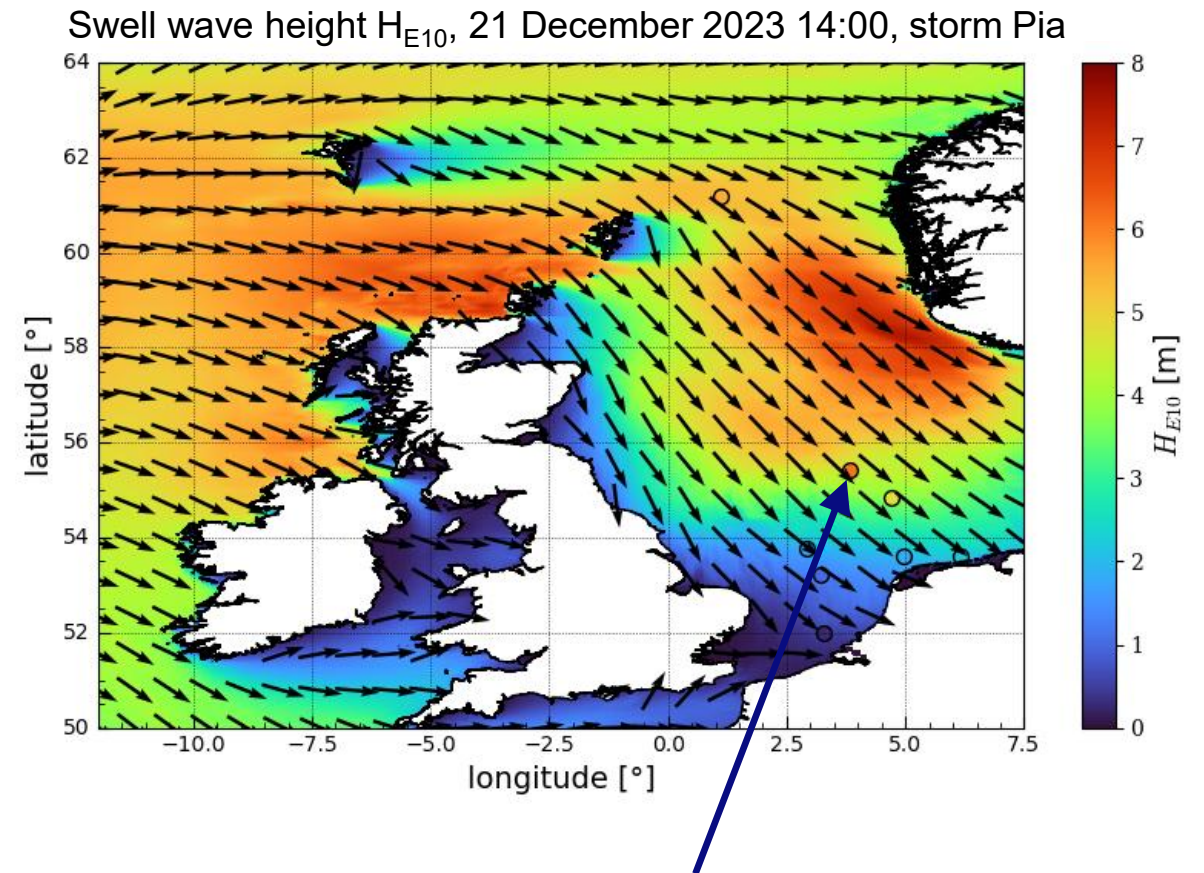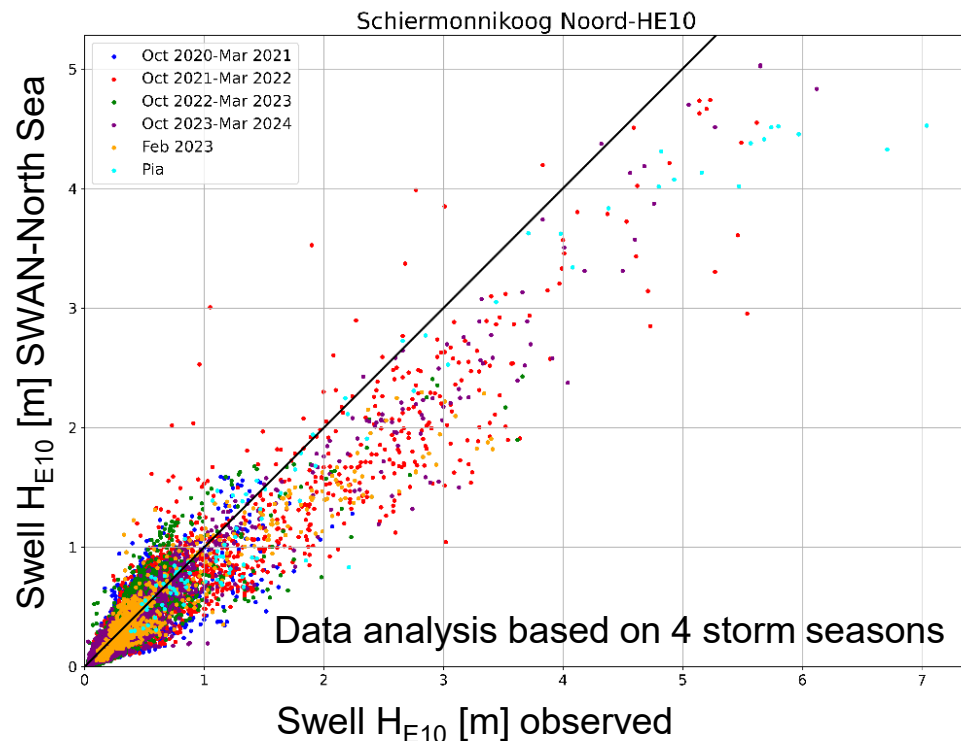- ECMWF WAM boundary conditions
- D-Flow FM hydrodynamic conditions

SWAN-Kuststrook (SWAN-KS) – every 10th gridline
Spatial resolution varies from 35 m to 2.6 km

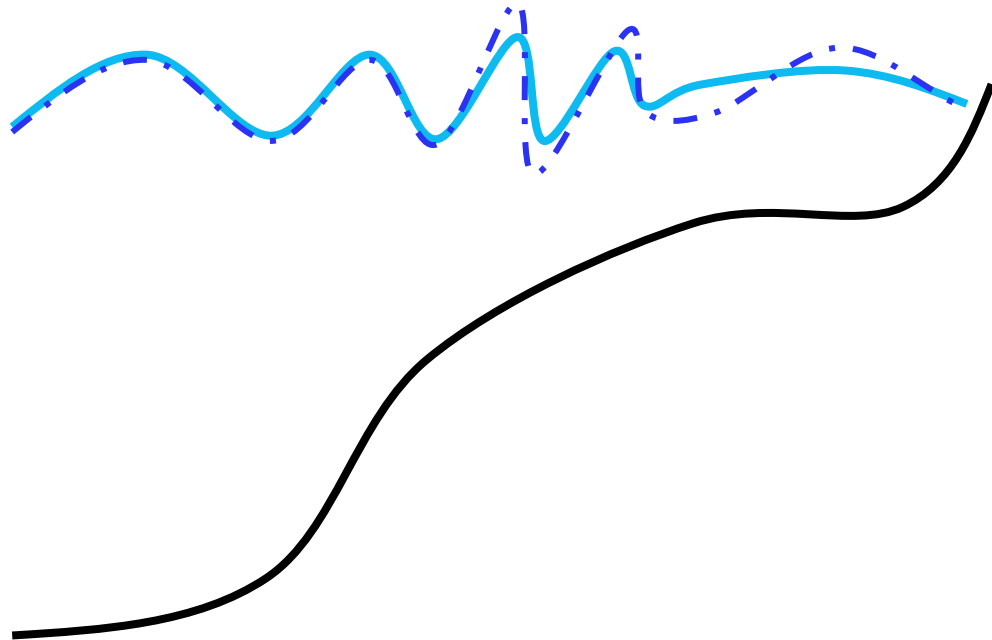**Deltares**

Performance operational wave models

- Generally good performance for significant wave height

- For swell wave height large scatter

- Large swell events from the northwest severely underestimated

Swell wave height H_{E10}, 21 December 2023 14:00, storm Pia

Coloured dots: wave measurements swell wave height

Schiermonnikoog Noord-HE10

- Oct 2020-Mar 2021
- Oct 2021-Mar 2022
- Oct 2022-Mar 2023
- Oct 2023-Mar 2024
- Feb 2023
- Pia

Swell H_{E10} [m] SWAN-North Sea

Swell H_{E10} [m] observed

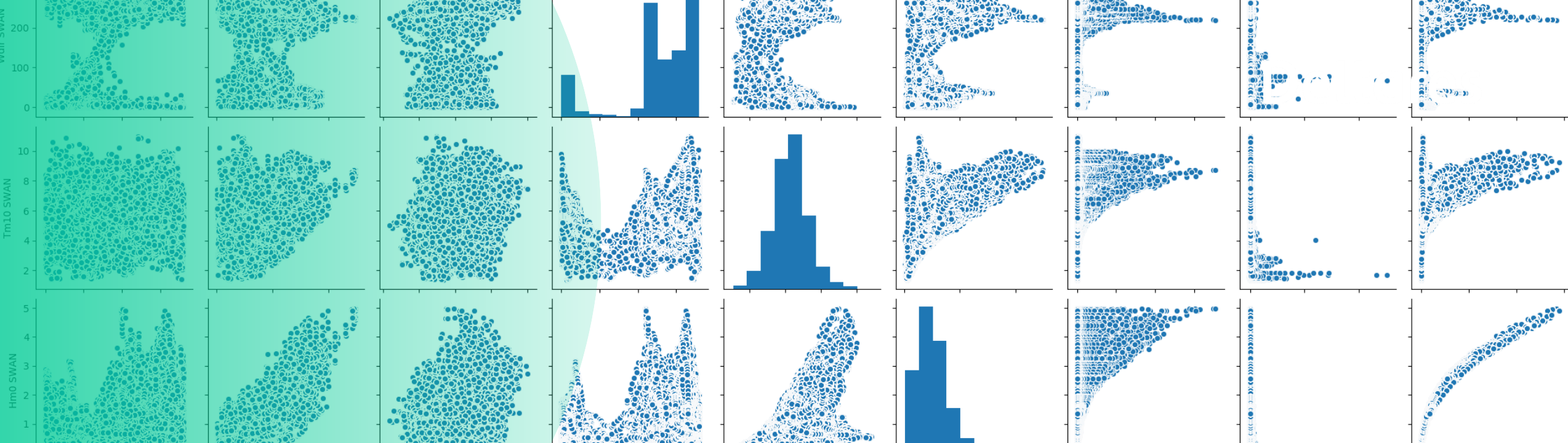Data analysis based on 4 storm seasons

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Options to improve results

Deviation in model

1) *Improve model*

2) *Correct model based on patterns in the data (machine learning model)*

Model correction

Machine Learning (XGBoost) to improve the SWAN-Kuststrook results

Correct the SWAN-results with data driven model

Training XGBoost model based on 15 months of data

Operational machine learning correction

Wind velocity	as used in SWAN
Wind direction	as used in SWAN
Water level	as used in SWAN
Significant wave height	predicted by SWAN
Spectral wave period	predicted by SWAN
Deep water wave steepness	predicted by SWAN
Wave direction	predicted by SWAN
Energy density in frequency bin	predicted by SWAN
Main wave direction in frequency bin	predicted by SWAN

Difference between wave and wind direction
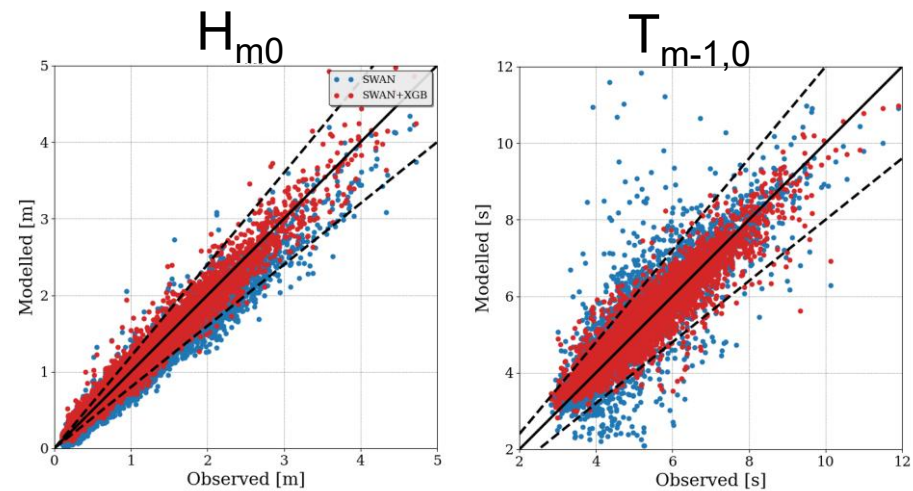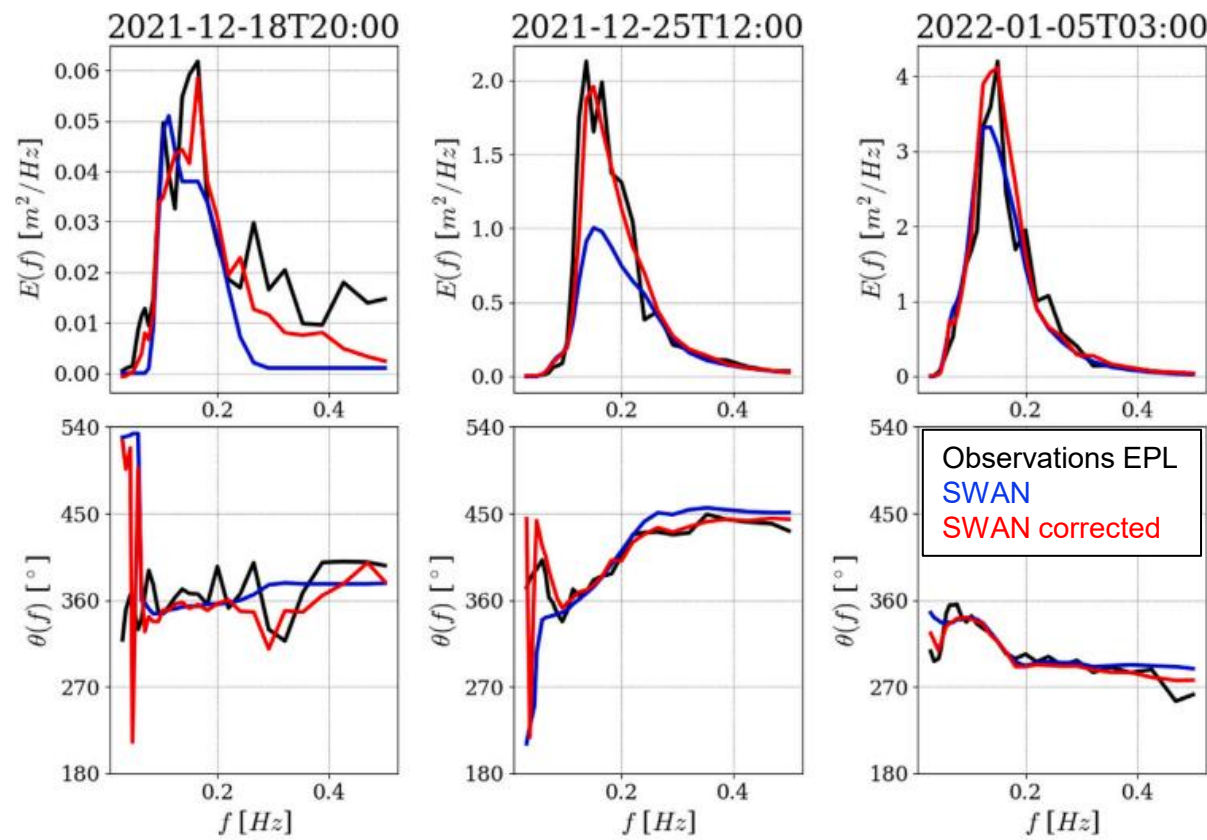
$$\Delta E(f) = \frac{E_{obs}(f) - E(f)}{E_{SWAN,total}} \quad ; \quad \Delta\theta(f) = \frac{\theta_{obs}(f) - \theta(f)}{360} \quad ;$$

Europlatform

0.06 Hz

Hourly data from 2020-2022

Bieman et al (2023). Hybrid modelling to improve operational wave forecasts by combining process-based and machine learning models
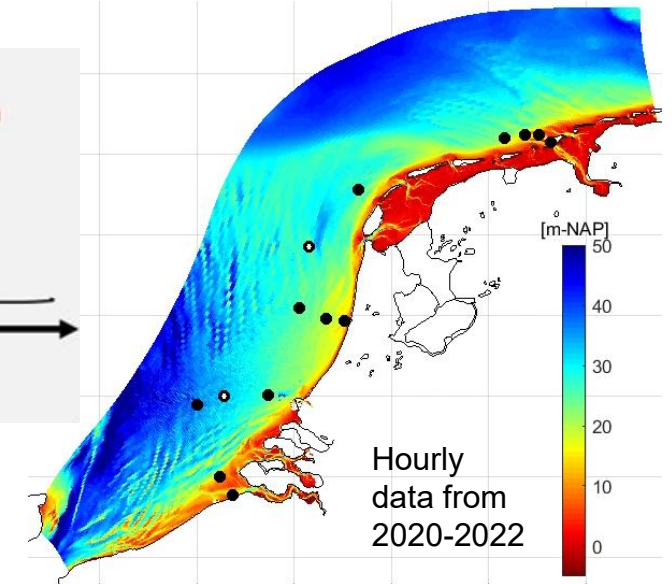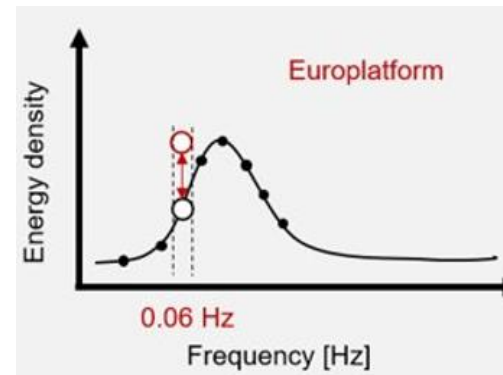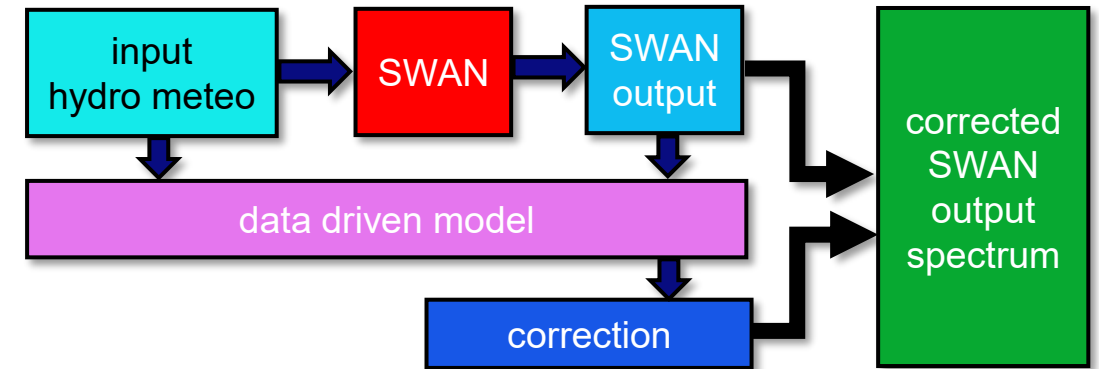
SWAN results after correction

Observations EPL
SWAN
SWAN corrected

RMSE	SWAN	SWAN corrected	Improvement
H_{m0} [m]	0.21	0.14	-33% ⬇
H_{E10} [m]	0.08	0.06	-25% ⬇
$T_{m-1,0}$ [s]	0.67	0.41	-39% ⬇

Decision in 2022: implement machine learning correction in operational forecast suite Delft FEWS
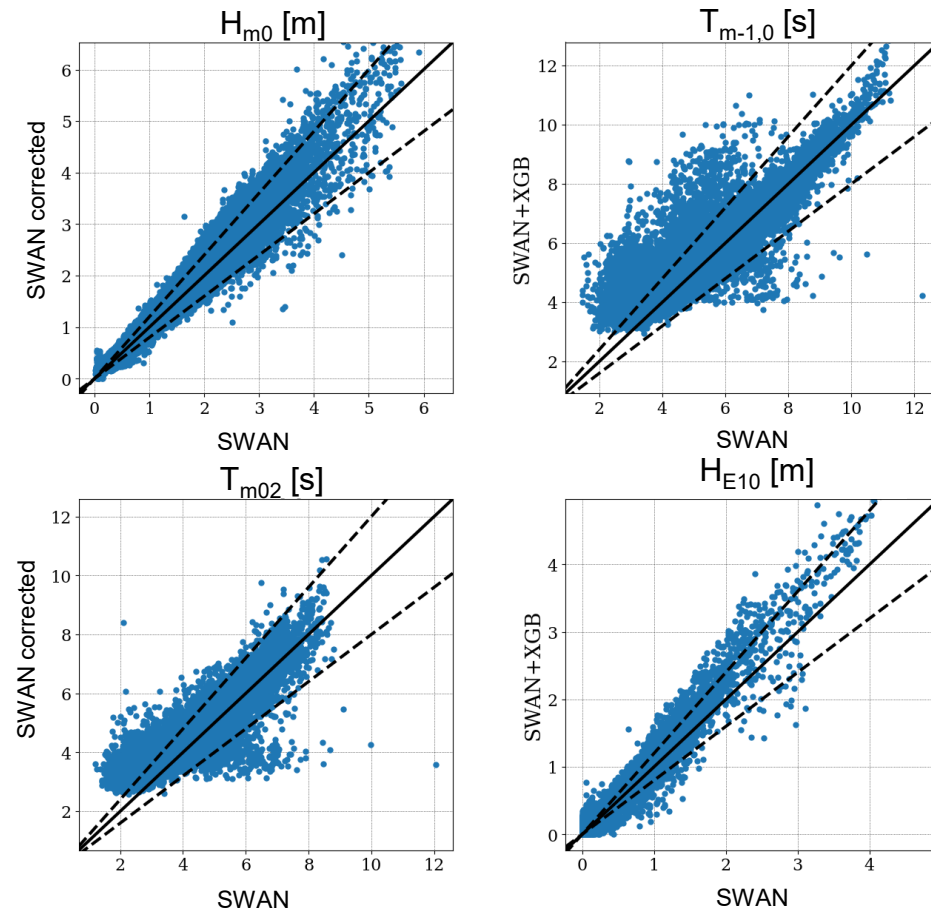
Observations EPL
SWAN
SWAN corrected
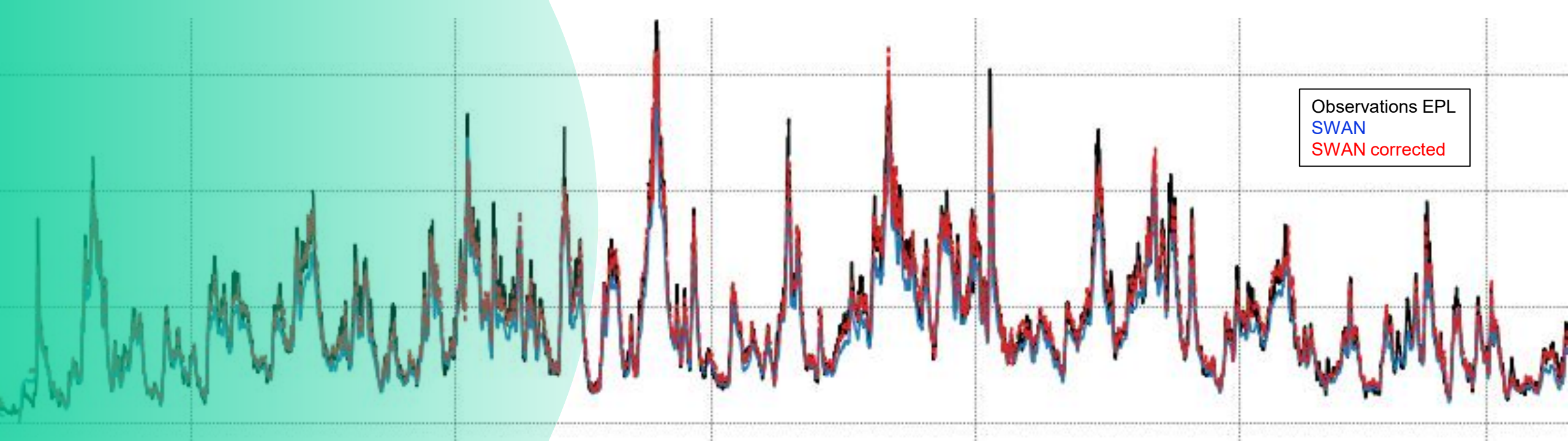
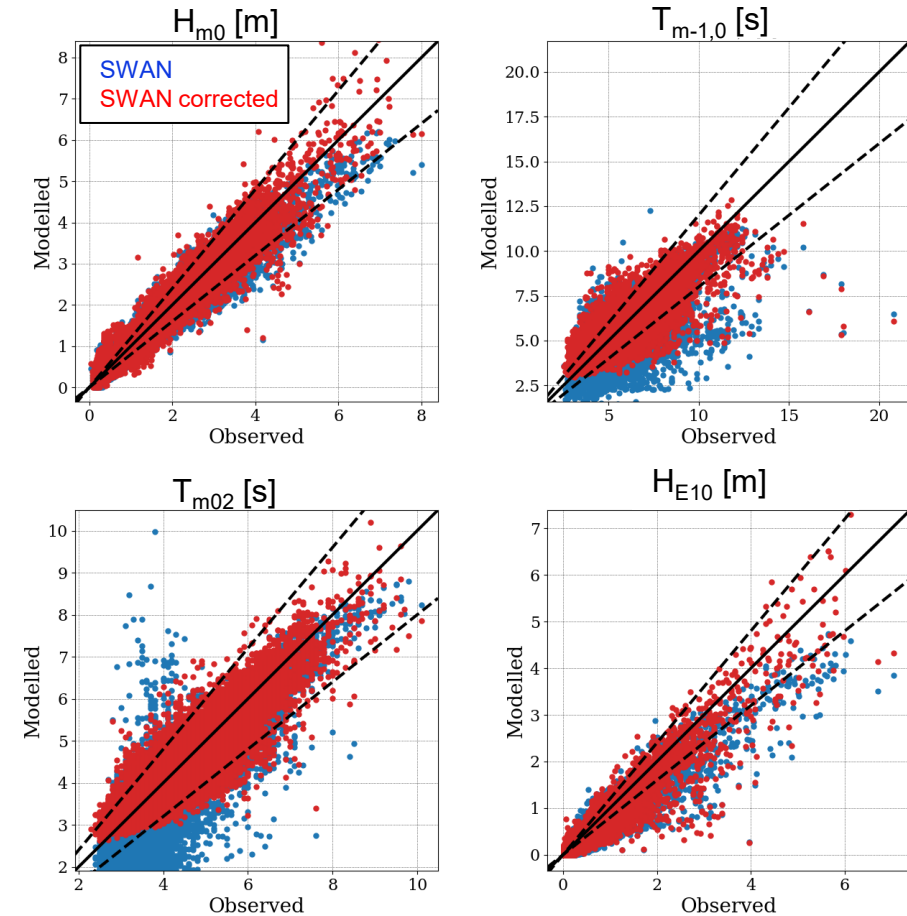# Evaluation after 1-year operational results

August 2023 – August 2024

Evaluation operational Machine Learning model

SWAN-ML versus SWAN (all locs)

SWAN-ML/SWAN versus obs (all locs)

Performance comparison evaluation periods

RMSE	Evaluation training period 2020 - 2022			Operational evaluation period 2023 – 2024		
	SWAN	SWAN corrected	Improvement	SWAN	SWAN corrected	Improvement
H_{m0} [m]	0.21	0.14	-33%	0.23	0.18	-22%
H_{E10} [m]	0.08	0.06	-25%	0.13	0.11	-15%
$T_{m-1,0}$ [s]	0.67	0.41	-39%	0.65	0.53	-12%
Wavedir [°]	50	38	-25%	34	29	-15%

- Machine learning models improves the SWAN-Kuststrook results
- But operational machine learning performance suboptimal

Reasons deterioration in performance

- There have been several model changes (bug in wave boundary conditions, change model physics, transition wind input: Harmonie model version)

- The machine learning model has been trained on 15 months of data → limited amount extreme conditions and swell conditions.

Evaluation dataset

Training dataset

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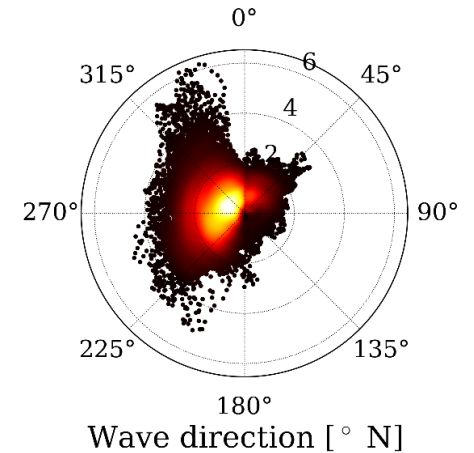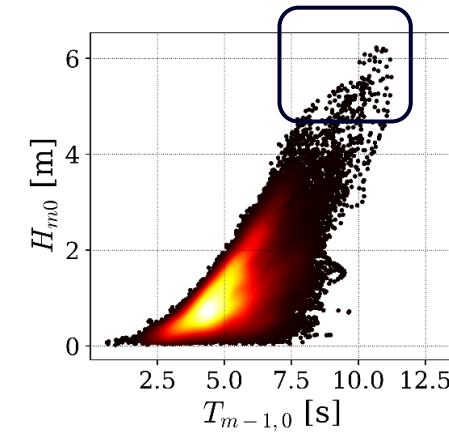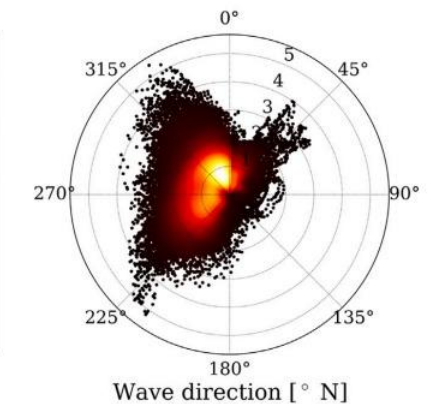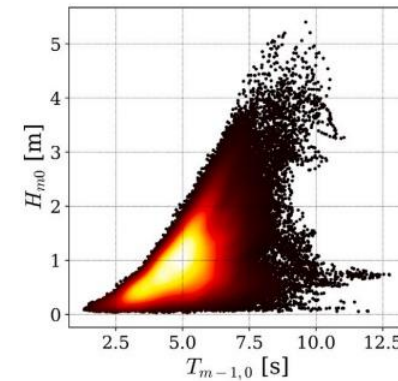
Lessons-learned

- A hybrid approach (in which a numerical model is corrected by machine learning) requires **regular retraining** if the numerical model changes.

- Aim for a sufficient **long training dataset**, ~ length in our case of minimal 5 years to include 'more extreme' conditions.

- In case the machine learning model is run in an operational setting, it is important to **check the operational implementation**.

- It is important to think about the **data management** system for operationalization.

- **Take along the client/ users** in 'trusting' the model outcomes of the machine learning model and the added effort when retraining is necessary.

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Questions, discussion

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