Understanding natural variability of extreme North Sea waves and storm surges using long synthetic data

Waves Workshop 2025

Paulina Kindermann, José A. Antolínez, Daniel van der Hoorn, Valvanuz Fernández Quiruelas, Koen van Asselt, and Oswaldo Morales-Nápoles

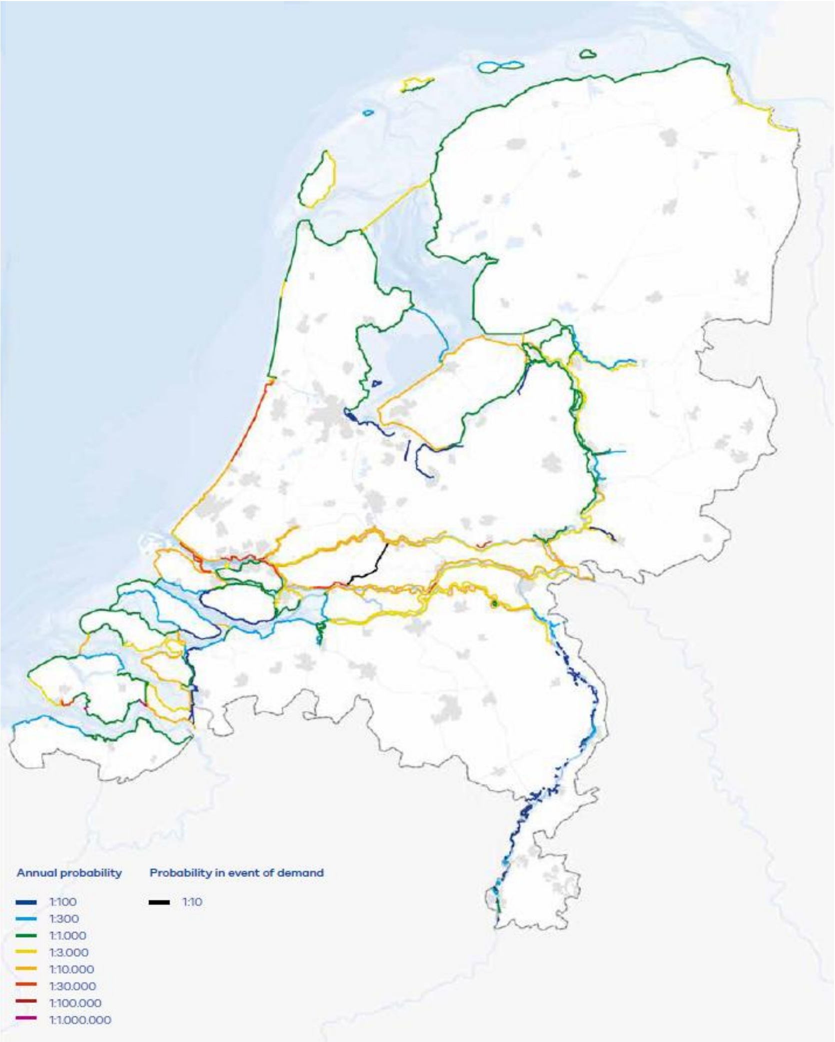
TU Delft

Relevance and context

60% of the Netherlands is prone to flooding from sea, lakes and rivers

- → Extreme storms over the North Sea are primary driver of coastal flood risk → high waves and storm surges
- → Protected by flood defenses (dikes, dunes, barriers)
- → Coastal flood defenses have strict safety standards: design hydraulic loads with 1,000 to 30,000 year return period
- → **Problem:** Difficult to extrapolate to such extreme events from 100 years of measurements

  → introduces large uncertainty



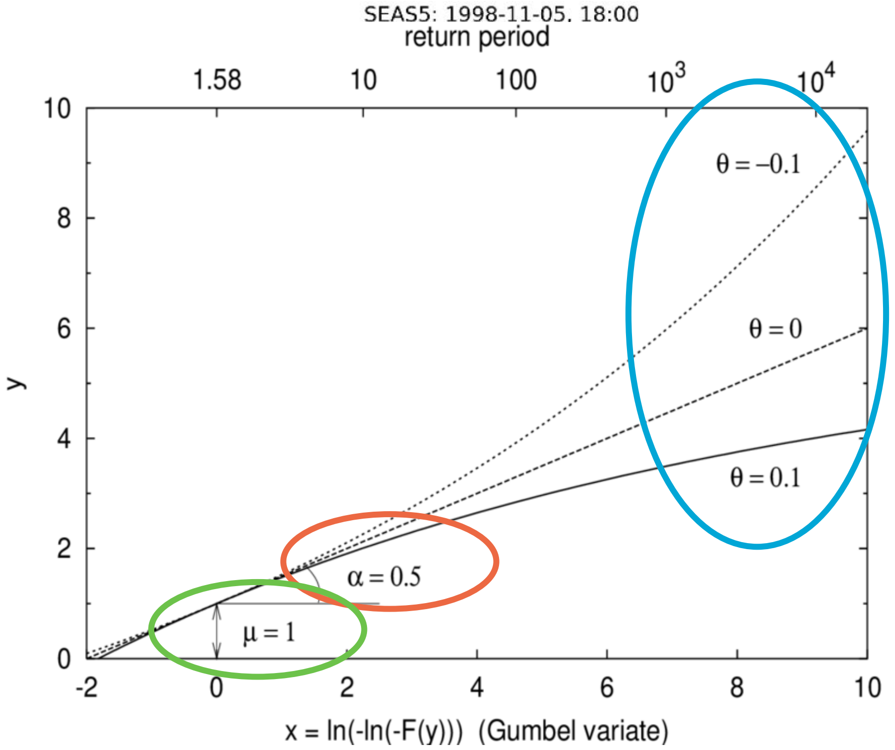
ENW (2016). Fundamentals of Flood Protection

Relevance and context

Solution = use of seasonal ensemble forecast data from ECMWF (SEAS5)

- → KNMI modelled sea levels for SEAS5 wind fields using WAQUA-DCSMv5
- → Adds up to ~9,000 years of plausible wind+sea level conditions in current climate
- → Hybrid approach for extreme value distribution: use synthetic data to fit shape parameter & use observations to fit scale and location parameter

Result = new estimates of wind speeds and sea levels for design with large return periods



Objective

What?

1. Create a consistent set of hydraulic boundary conditions for design of Dutch coastal flood defenses
2. Improve our understanding of the natural variability of waves during extreme storm conditions

How?

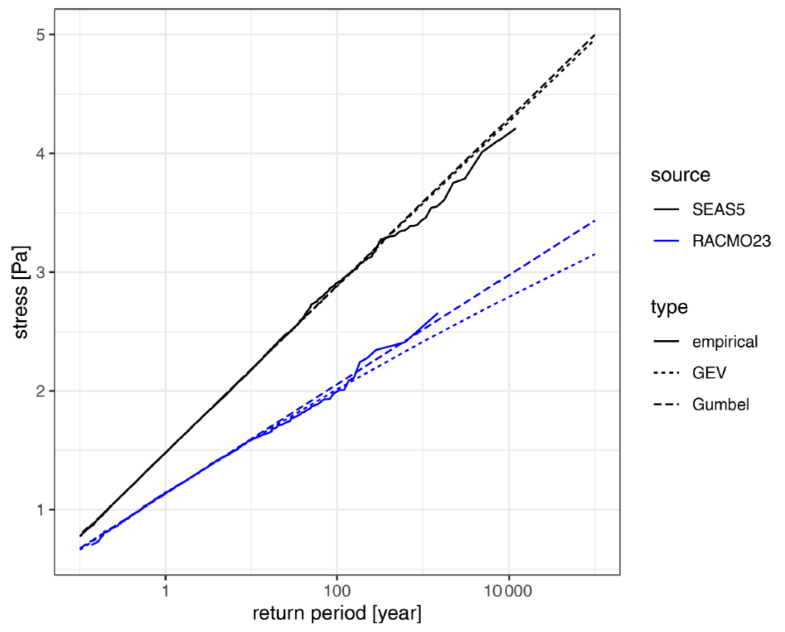
- Use the SEAS5-WAQUA dataset (9,000 years of synthetic data) to model waves
- Explore the impact of storm characteristics such as duration, wind rotation, size of the depression etc.
- Compare marginal wave statistics to observations and other models

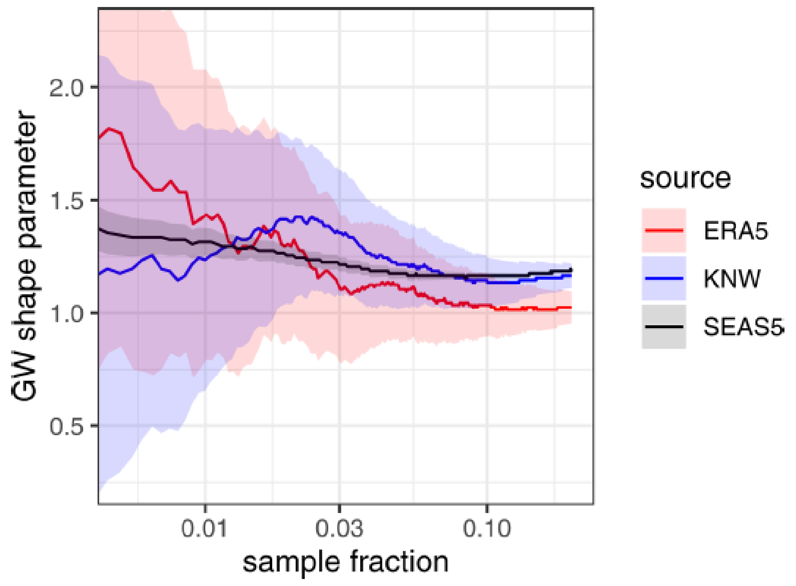
Method

- Use HurryWave model by Deltares: Similar to SWAN, but faster due to simplifications:
  - Explicit first-order uplift scheme
  - Stationary water level fields
  - No wave-triad interactions
  - → Using Snellius, 1 year of ERA5 wind fiels above North Sea takes 01:07 – 01:08 h computational time on one GPU H100
  - → **Hypothesis:** suitable to model waves from 9.000 years of SEAS5 wind conditions in deep to intermediate waters
    - → Test by validating wind data and wave model

SEAS5 wind stress validation

- Validation by KNMI: distributions of annual maxima of stress from 3-hourly RACMOv2.3 and 6-hourly SEAS5 data:
  - Tails clearly differ in scale → likely as a result of differences in boundary layer parameterization
  - However, the shapes agree closely → both are nearly exponential.
- Comparison of GW shape parameter for various thresholds:
  - SEAS5 is most stable and always within uncertainty bound of other climate models



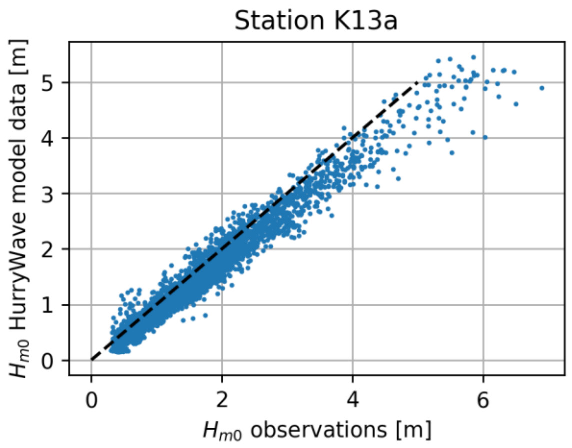


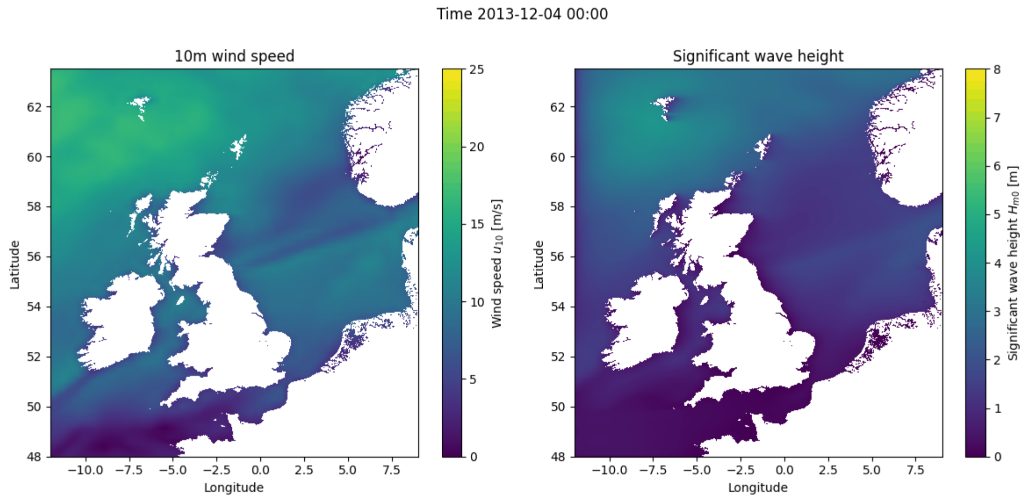
TU Delft

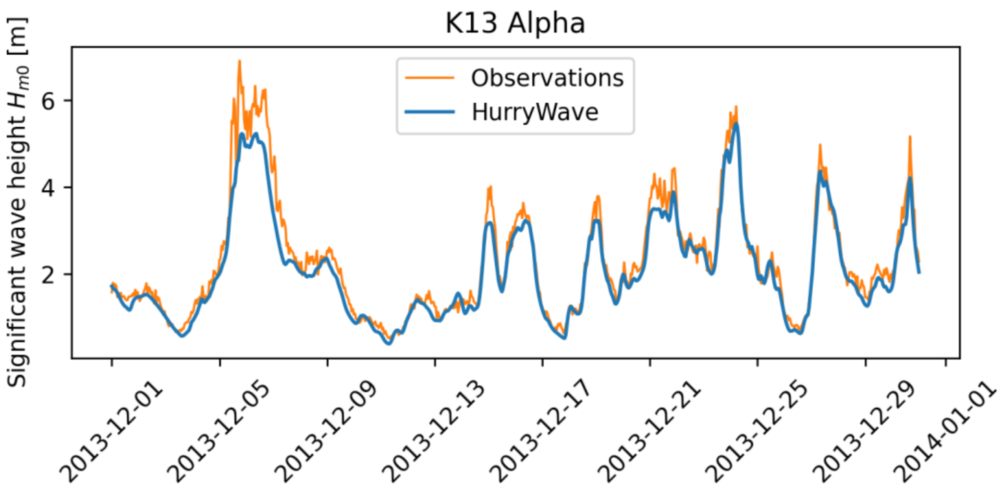
de Valk, C. & van den Brink, H. (2025): An appraisal of the value of simulated weather data for quantifying coastal flood hazard in the Netherlands

HurryWave model validation

- Checks on storm level, year and multiple years
- Comparison HurryWave waves (with ERA5 wind) vs. buoy data:
  - HurryWave underestimates high wave heights and long wave periods







Next steps

1. Further validation, calibration and sensitivity analysis of HurryWave
   - Use wind stress as input
   - Check on wave spectra
   - Boundary conditions
   - Effect of stationary water levels
2. Alternative using SWAN, to:
   1. Model only most extreme storms from SEAS5
   2. Include non-stationary water levels

$$U_*^2 = C_D U_{10}^2$$

$$C_D(U_{10}) = (0.55 + 2.97\tilde{U} - 1.49\tilde{U}^2) \times 10^{-3}$$

Thank you for your attention

Paulina Kindermann

p.e.kindermann@tudelft.nl

TU Delft Rijkswaterstaat HKV Deltares TNO