# **FORESEE** project update: Establishing a workflow at MET Norway for modelling non-stationary environmental extremes

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## Motivation

Marine standards recommend approaches to calculate return levels and exceedance probabilities for extreme values of marine key variables (such as wind, wave, surge). However, some approaches date back many decades. Examples include: the initial distribution method using a Weibull distribution for marginal models on all data; modelling directional wave heights using independent models for a each sector; and the Weibull log-normal model for joint probability [1,2]. While they have a practical appeal, these approaches do not take into account developments in extreme value (EV) theory during recent decades. When extrapolating far into the tail in particular, empirical models should be informed by EV theory.

Stakeholders are increasingly using non-stationary EV modelling, as well as joint EV modelling of response variables. Unified non-stationary modelling of extreme values allow for flexible, consistent, and theoretically justified modelling of extreme events and full uncertainty quantification (UQ).

The NFR-project **FORESEE** facilitates building knowledge within MET Norway, to apply and develop novel techniques for the purpose of seasonal forecasting extreme sea states. Moreover, increased competence with these techniques is important so that MET Norway is well placed to evaluating offshore reports, increasingly incorporating sophisticated modelling strategies.

We illustrate an example workflow to arrive at 100 year return values of significant wave height (Hs) and individual maximum wave (Hmax) as well as joint extremes of Hs and the peak period (Tp).

## Conclusion

The approach presented here provides a framework for applying non-stationary extreme value analysis including UQ for our metocean variables of interest. The impact of variables on return variables and exceedence probabilities can be investigated as all dependencies are traceable through the model.

## Plans

- Incorporate metocean variables for seasonal and climate prediction (see poster from Sophia Groninger)
- Expand on joint extremes
- Incorporate space-time extremes model for Hmax
- Create package and make publicly available

## Acknowledgements

FORESEE (Nr. 334188) is funded by the *Researcher Project for Young Talents (FRIPRO)* granted by the Norwegian Research Council.

## Non-stationary modelling

A hierarchical statistical modelling approach has evolved over the last 20 years [3] allowing modular characterisation of the occurrence and severity of storm events, for within-storm evolution, and hence for individual waves and the fluid loading they induce. The approach seeks to be model the full system in a consistent fashion, avoiding inconsistencies when modelling only part of the data compared to all data.

A suitable methodology to impose arbitrary smooth, covariate based non-stationarity is penalized regression splines. UQ can be performed using Bayesian or frequentist approaches, the latter via bootstrap resampling of storms. The underlying assumption is that observations are i.i.d. given threshold and covariates, so that EV theory can be applied. We model occurrences of storm peaks with a non-stationary additive point process model [4] and threshold exceedences with a non-stationary additive GPD model [5]. The extreme value threshold for storm peaks is also non-stationary, described using an asymmetric Laplace distribution within quantile regression [5]. Our *covariates* of choice are *peak direction* and *day of the year*. Including storm models and closed form conditional distribution for the individual wave height, the distribution of maximum individual wave height (Hmax) can be modelled for any given return period assuming a stationary climate integrating:

$$p(Hmax) = \int\int p(Hmax|Hs^{SeaState})p(Hs^{SeaState}|Hs^{StormPeak})p(Hs^{StormPeak})dHs^{SeaState}dHs^{StormPeak}$$

**Storm peaks**
$Hs^{StormPeak}$ | covariates
(e.g direction, period, season …)

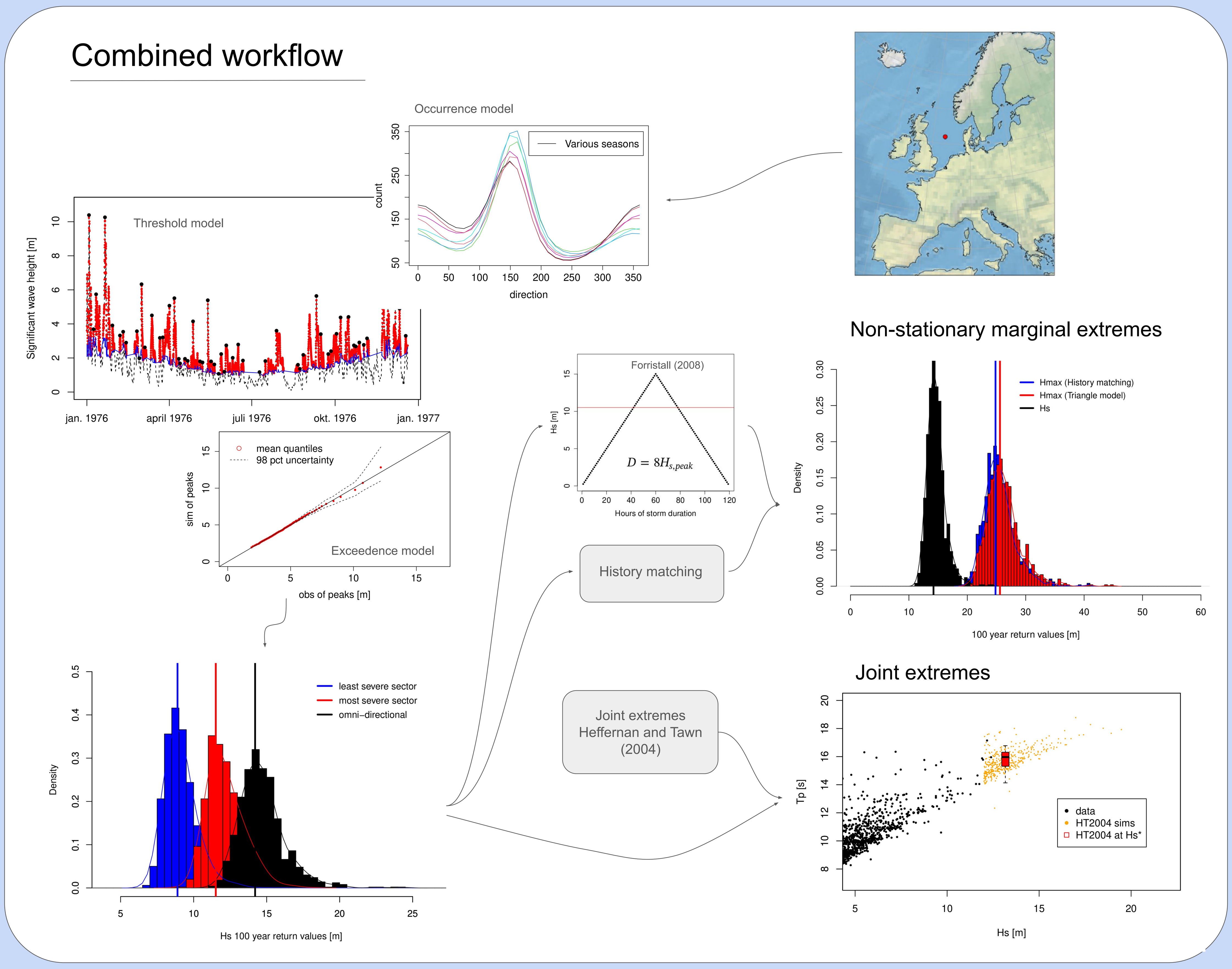
⇨

**Storm evolution**
$Hs^{SeaState}$ | $Hs^{StormPeak}$ , covariates
(e.g direction, period, season …)

⇨

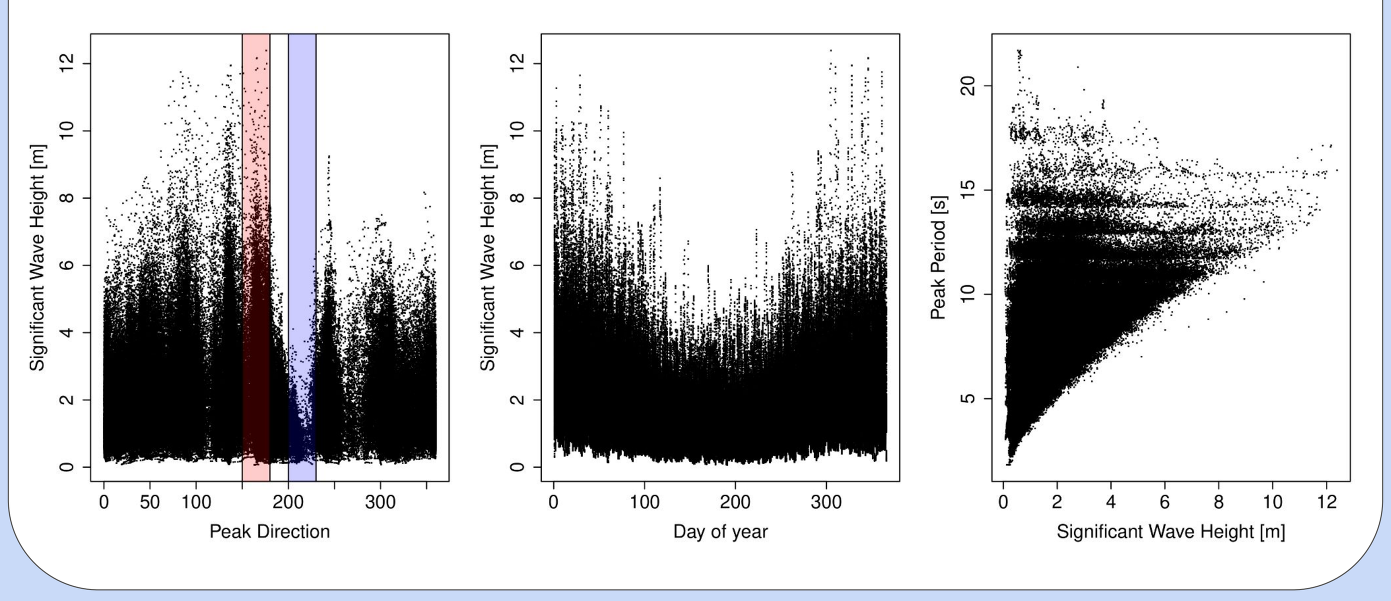
**Hmax**
Hmax | $Hs^{SeaState}$
e.g. Forristall

## Combined workflow




## Data

We use the NORA3 wave hindcast [6] covering the years 1976-2023. Hs depicts dependence on direction and season. It is also logical to assume that large Hs will be accompanied by large Tp. The data is from a location in the central North Sea.




## Joint extremes

We model joint extremes of multiple response variables with the conditional extremes model by Heffernan and Tawn (HT2004) [7] which on Laplace scale is defined as:

$$Y|(X=x) = \alpha x + x^{\beta} Z \quad \text{for} \quad x > u$$

$$Z = \frac{Y - \alpha x}{x^{\beta}} \qquad \alpha \in (0,1] \qquad \beta \in (-\infty, 1]$$

The HT2004 model has been proposed for modelling asymptotic independence and partly asymptotic dependence.

## References

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