Changes in the North Sea extreme waves

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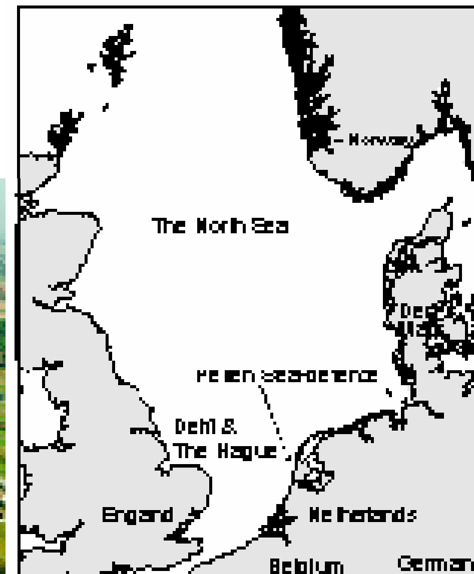


Motivation

The current approach to obtain hydraulic boundary conditions for the Dutch water defences involves the transformation of offshore wave conditions to nearshore. The transformation consist of defining the extreme offshore wave conditions and winds, and using these to run the wave model SWAN in stationary mode, computing the corresponding nearshore extreme waves.

There are two aspects in this approach that may have a negative effect on the quality of nearshore extreme value estimates:

1. The stationary assumption may not hold: either the modelled storm never occurs or occurs with a different return period.
2. No attention is paid to effects of climate variability on wave extremes.

Objectives

- Run SWAN in the non-stationary mode to produce a timeseries of nearshore long-term wave heights and analyse it using both stationary and a non-stationary extreme value models.

stationary vs non-stationary **extreme value models** (non-stationary SWAN)

- Compare the (stationary) extreme value estimates obtained using a non-stationary wave modelling approach with those obtained with the currently used stationary approach.

stationary vs non-stationary **SWAN** (stationary extreme wave model)

In all computations, ERA-40 data is used for the wind input and wave boundary conditions

Story line

- Brief description of SWAN
- Description of SWAN's sentitivity/calibration study
- Brief description of the extreme value models
- Results
- Conclusions

SWAN

Phase-averaging model that solves the spectral action balance equation, in Cartesian or spherical coordinates, without any *ad hoc* assumption on the shape of the wave spectrum.

$$\frac{\partial N}{\partial t}+\frac{\partial}{\partial x}\left(c_x N\right)+\frac{\partial}{\partial y}\left(c_y N\right)+\frac{\partial}{\partial \sigma}\left(c_\sigma N\right)+\frac{\partial}{\partial \theta}\left(c_\theta N\right)=\frac{S_{tot}}{\sigma}$$

S_{tot} =wind input+
wave-wave non-linear interactions (quadruplets &/+triads)+
whitecapping +
bottom friction+
depth induced wave breaking

Some of SWAN's source terms can be chosen from a couple of options.

Wave energy growth by wind input

linear + exponential term

Cavaleri and Malanotte-Rizzoli (1981)

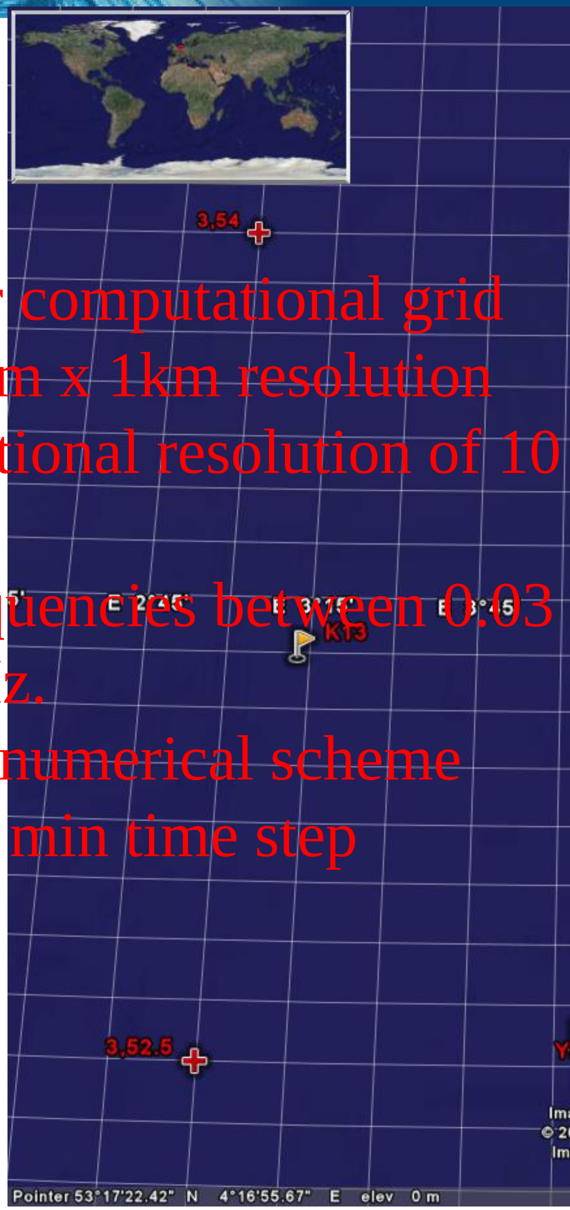
- Komen (1984) $\propto U_*/c_{ph}$
- Janssen (1991) $\propto (U_*/c_{ph})^2$
- Yan (1987) $\propto U_*/c_{ph}$ & $(U_*/c_{ph})^2$

Wave dissipation by whitecapping

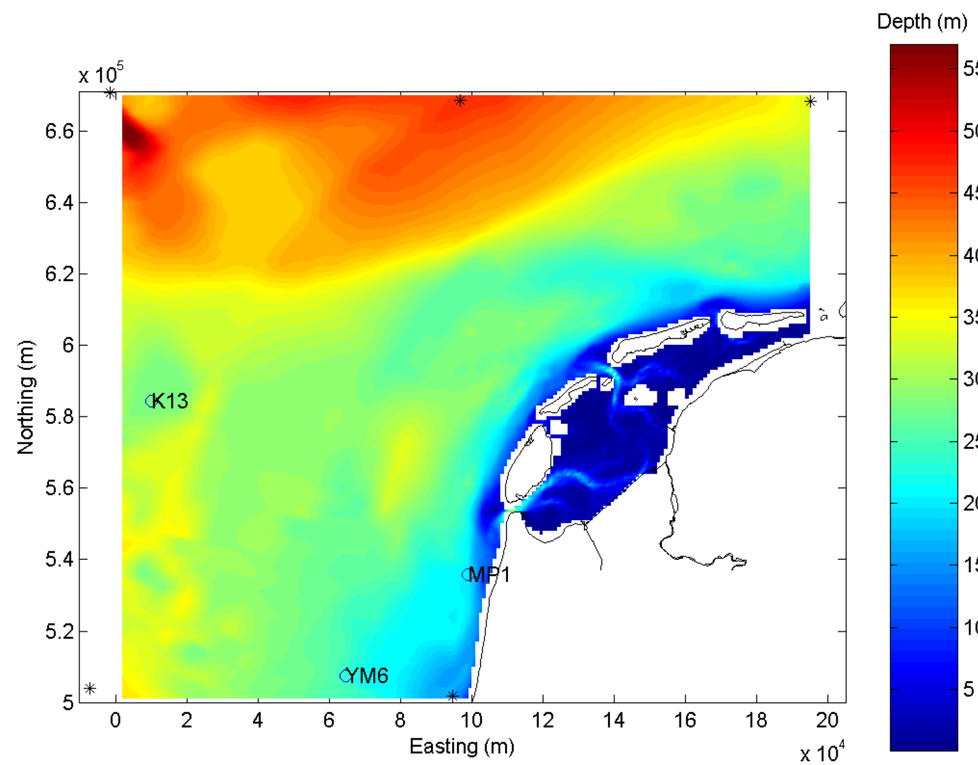
The parameters depend on the wind input formulation that is used and are determined by closing the energy balance of the waves in fully developed conditions

Wind input	Whitecapping	Configuration
Komen (1984)	$\propto \frac{k}{\overline{k}}$	WAM3
Janssen (1991)	$\propto \left(\frac{k}{\overline{k}}\right)^{1.5}$	WAM4
Yan (1987)	Alves and Banner (2003) (independent of the spectral mean quantities)	Westh

Model schematization

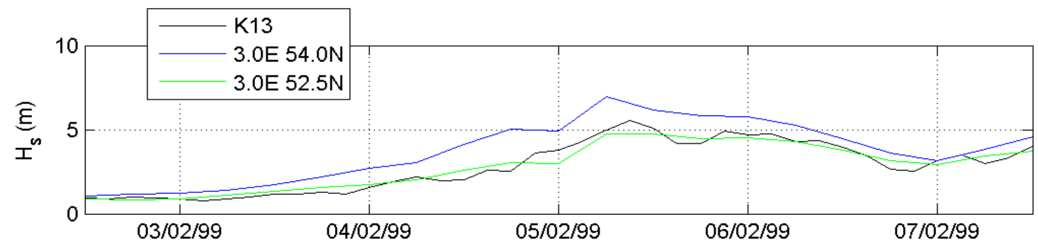


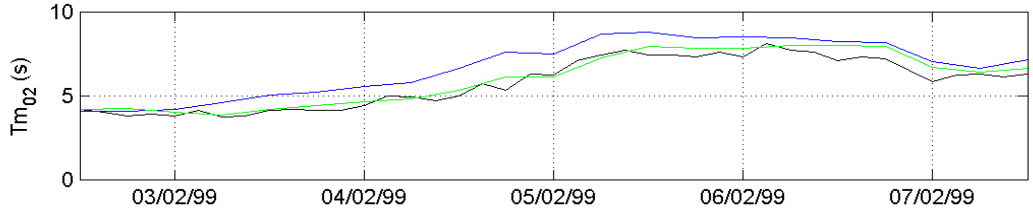
- regular computational grid with 1km x 1km resolution
- a directional resolution of 10 degrees
- 37 frequencies between 0.03 and 1 Hz.
- BSBT numerical scheme with 20 min time step

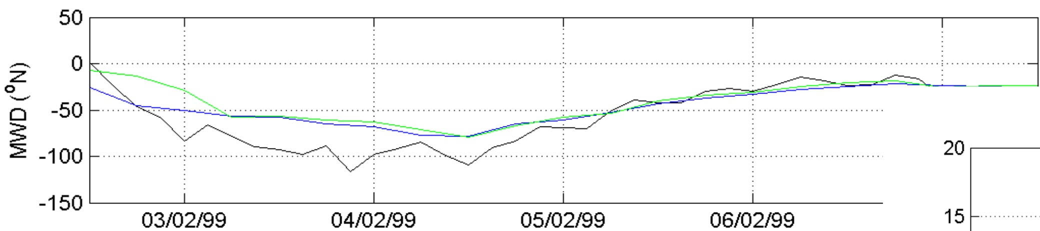


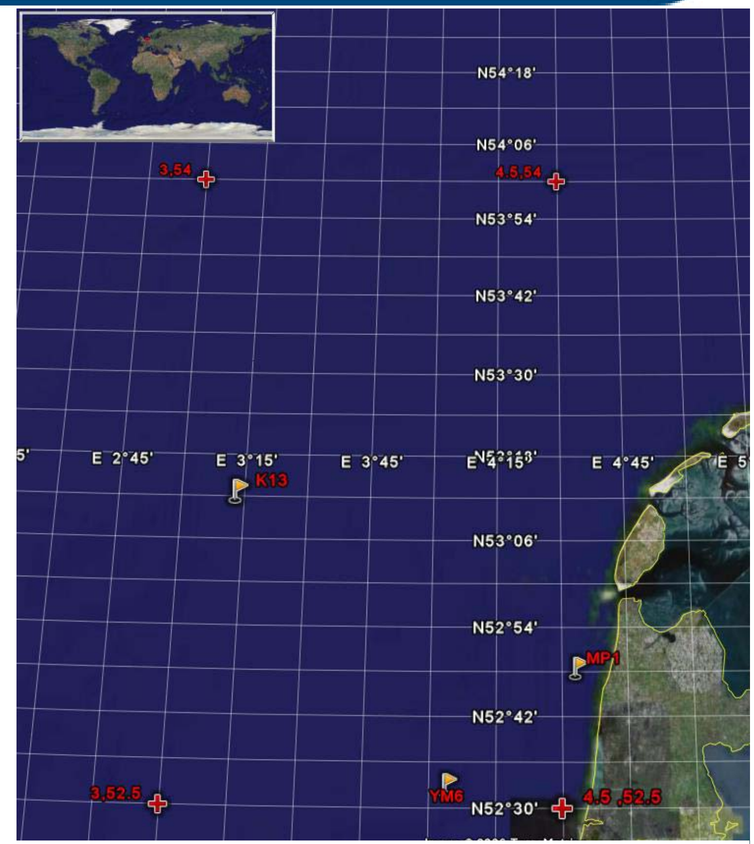
ERA40 vs measuremts

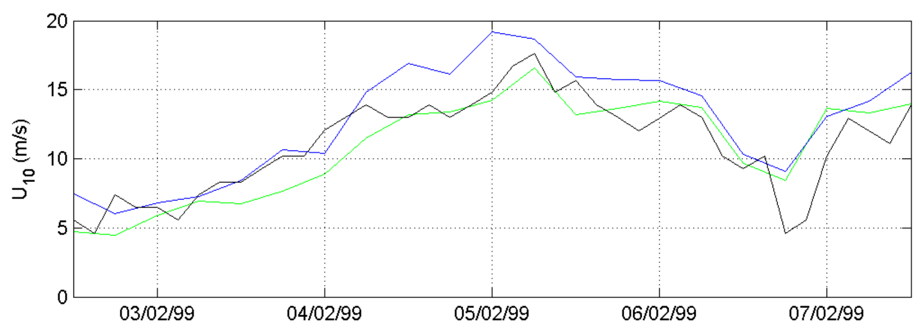
1999 storm



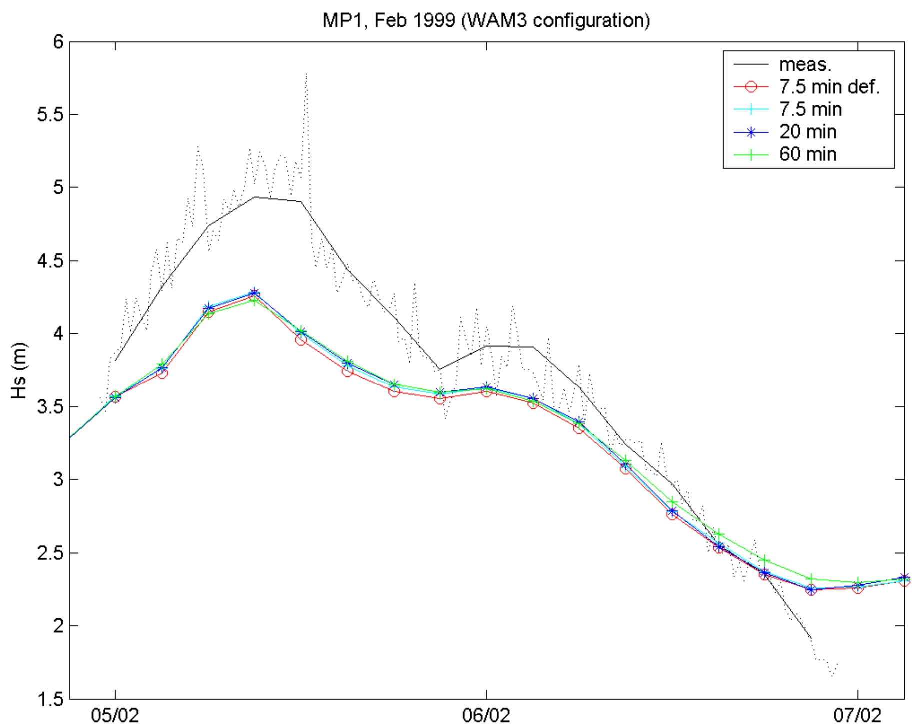


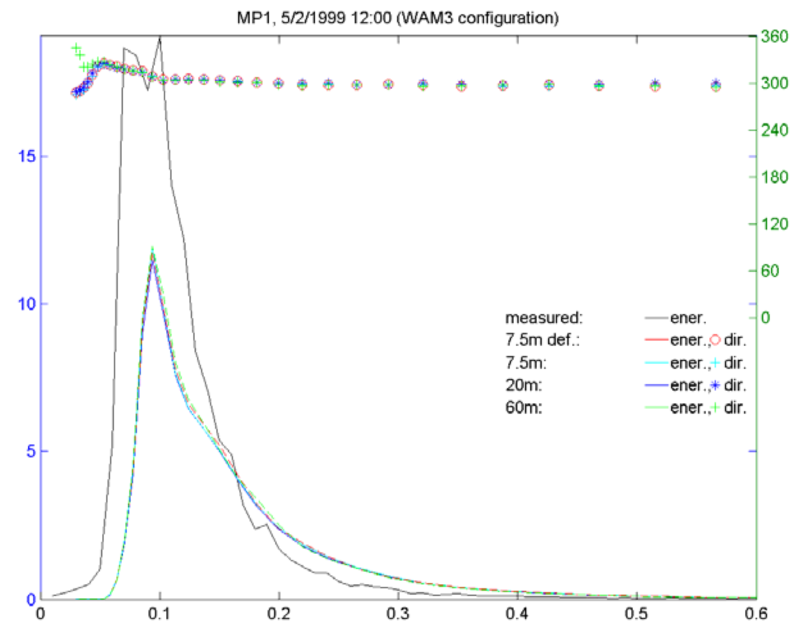




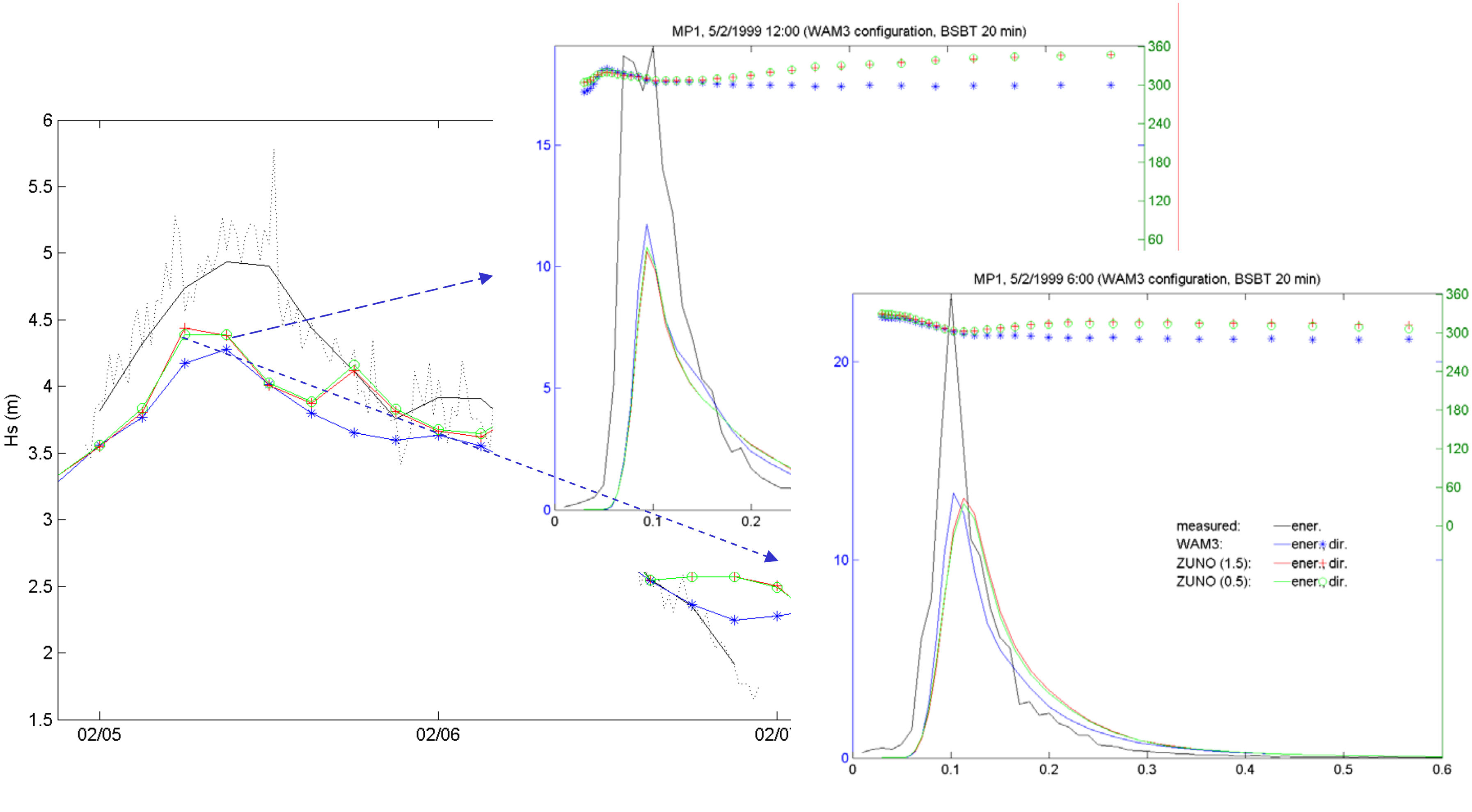


Numerics


MP1, Feb 1999 (WAM3 configuration)
Hs (m)
meas.
7.5 min def.
7.5 min
20 min
60 min
05/02
06/02
07/02

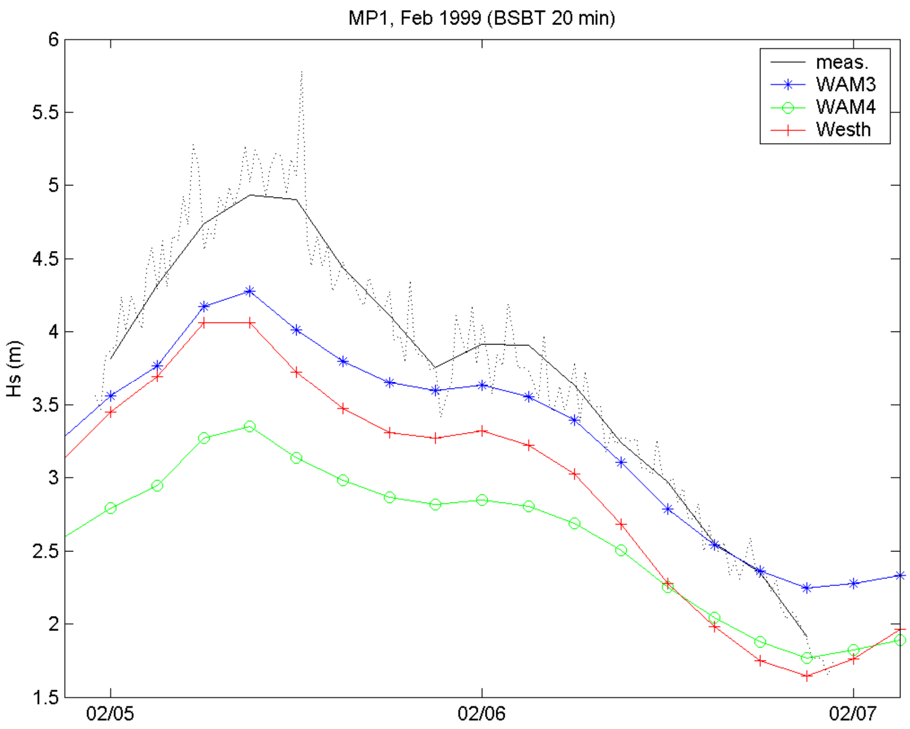

MP1, 5/2/1999 12:00 (WAM3 configuration)
measured:
7.5m def.:
7.5m:
20m:
60m:
ener.
ener., dir.
ener., dir.
ener., dir.
ener., dir.

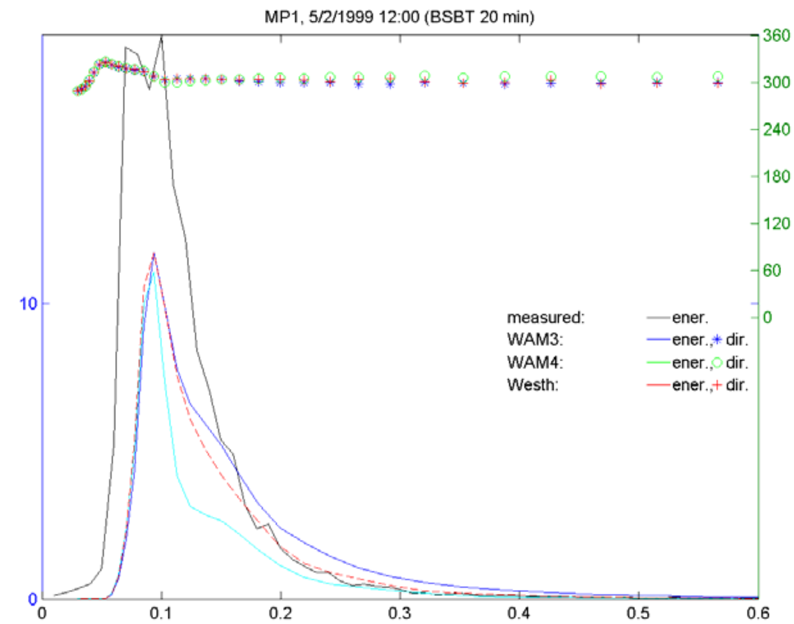
Sensitivity to currents and water level



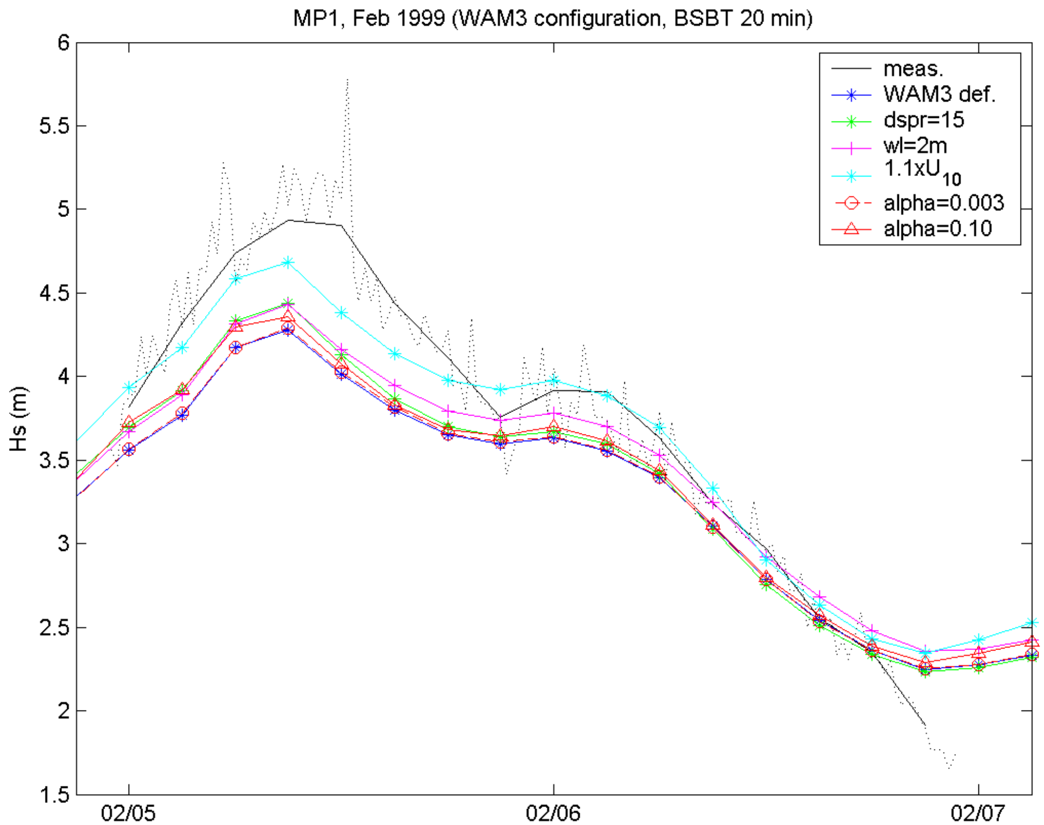
Currents and water levels: ZUNO (hourly) using ERA-40 winds and SLP as input

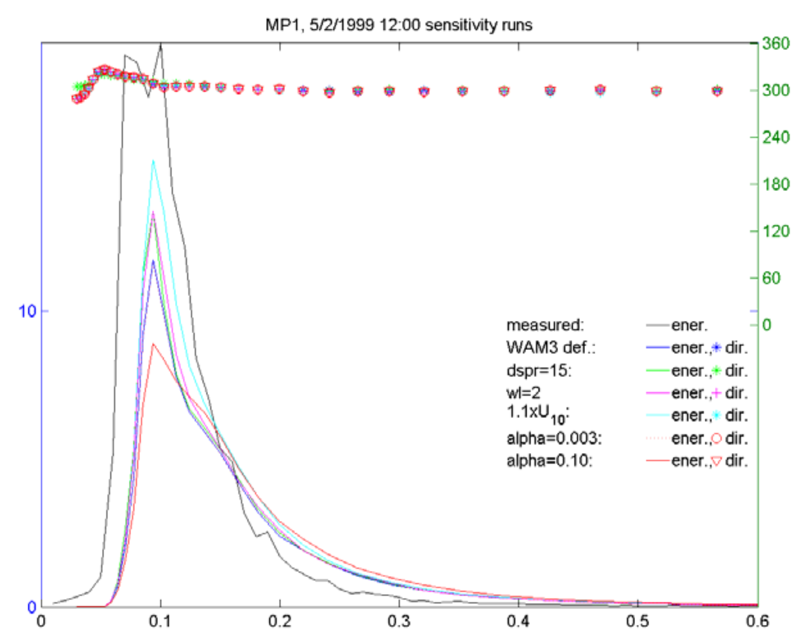
Physics


MP1, Feb 1999 (BSBT 20 min)
meas.
WAM3
WAM4
Westh
Hs (m)
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
02/05
02/06
02/07


MP1, 5/2/1999 12:00 (BSBT 20 min)
measured: ener.
WAM3: ener., dir.
WAM4: ener., dir.
Westh: ener., dir.
360
300
240
180
120
60
0
10
0
0
0.1
0.2
0.3
0.4
0.5
0.6

Sensitivity runs (WAM3 configuration)





- ➢increase wind speed
- ➢decrease DSpr

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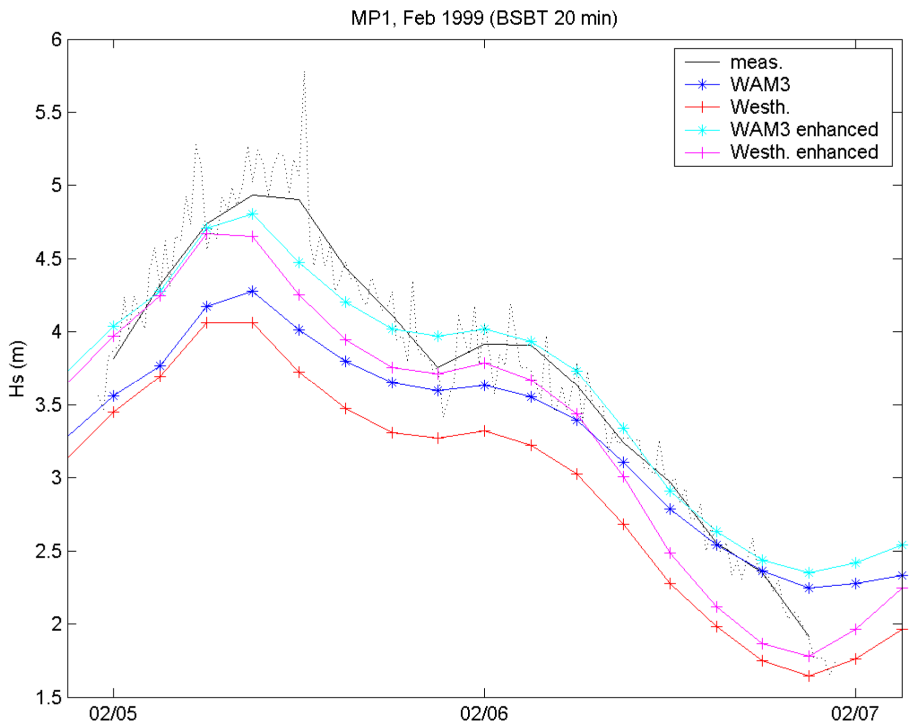
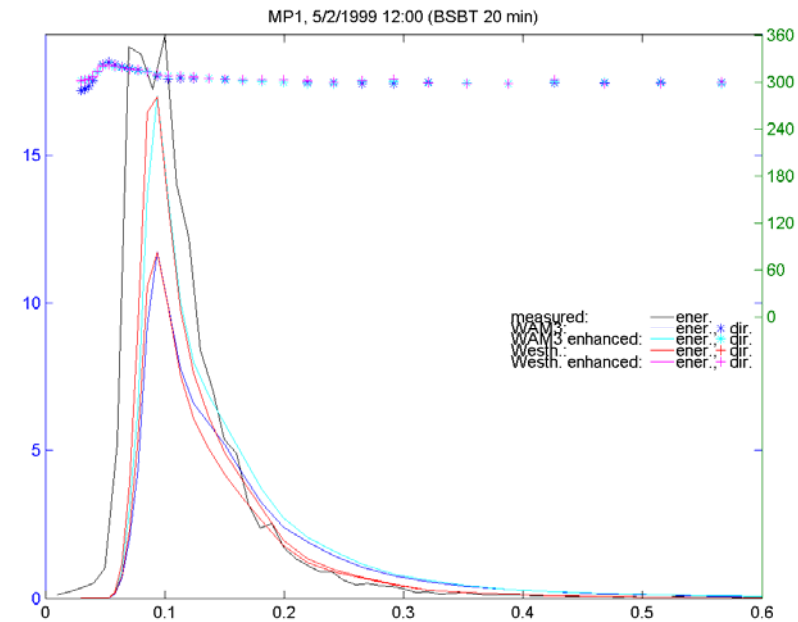
Enhanced





$1.1*U_{10}$ (to account for sub-grid scale variability)
DSpr=20

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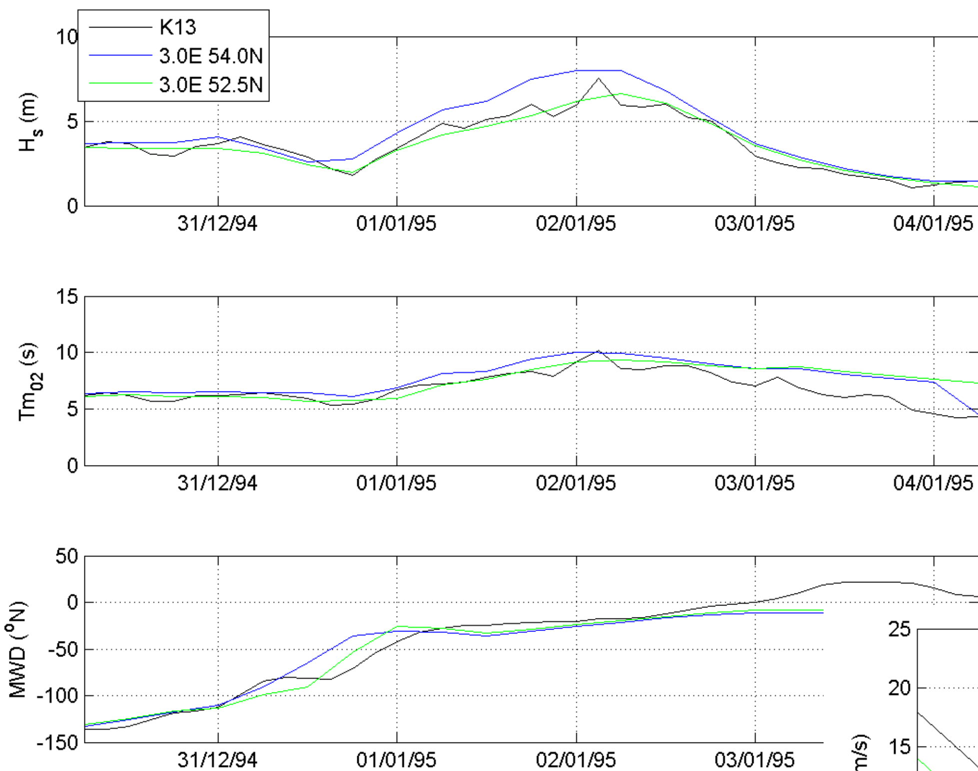
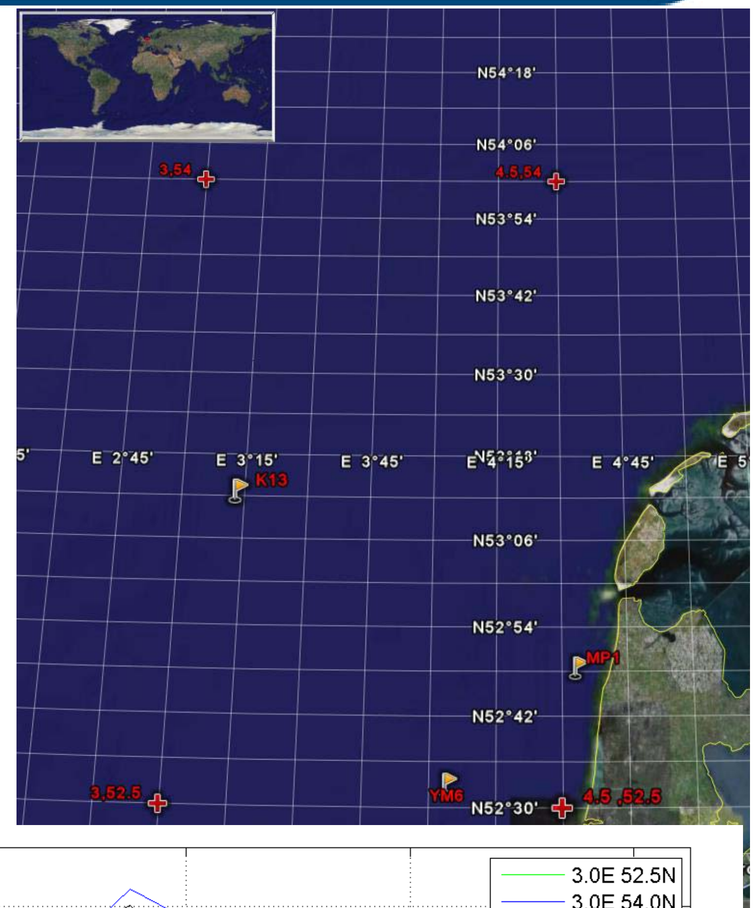
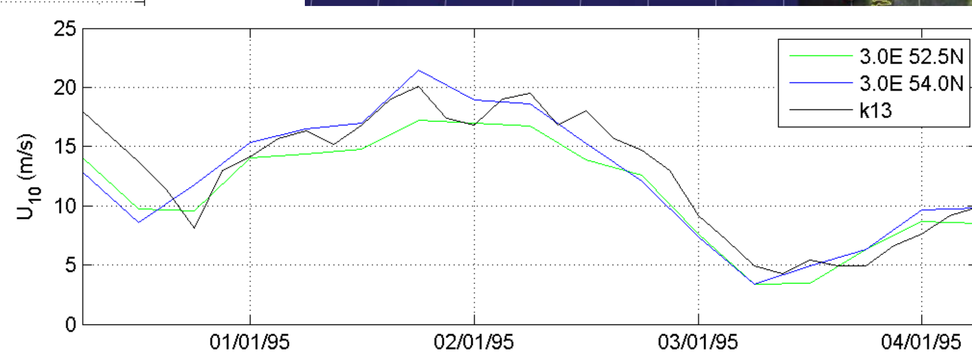
ERA40 vs measuremts

1995 storm







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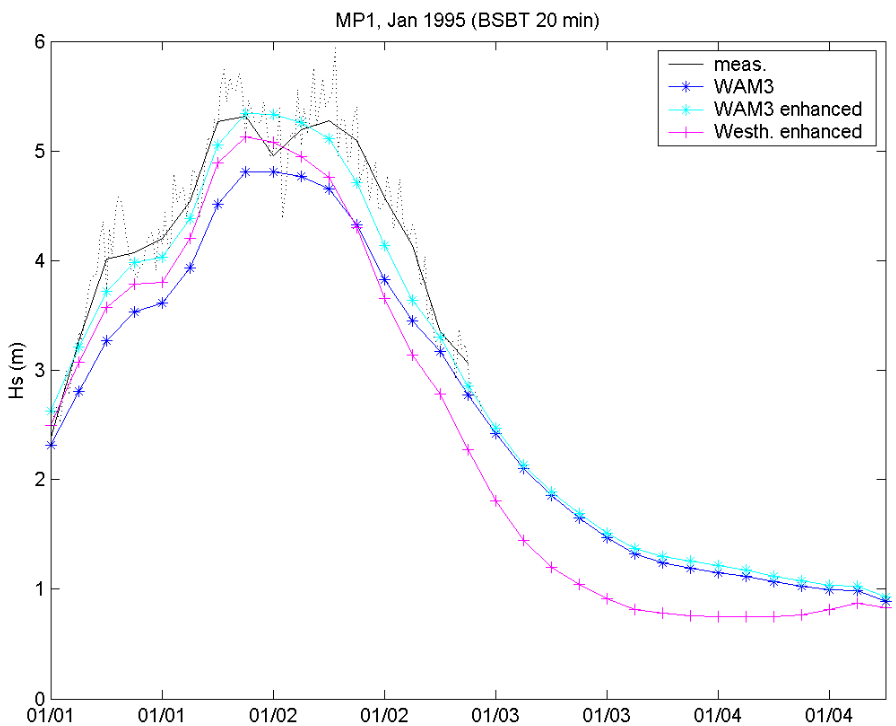
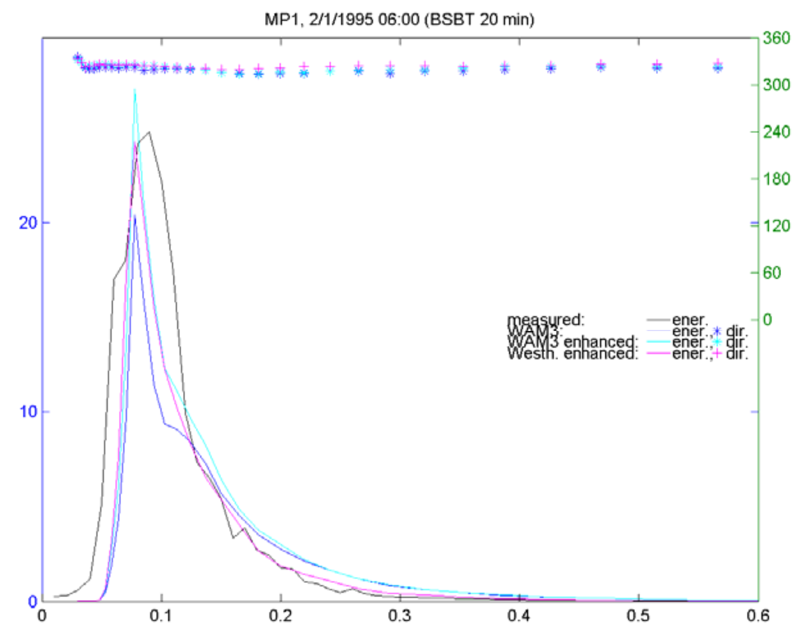
Enhanced





$1.1*U_{10}$ (to account for sub-grid scale variability)
DSpr=20

Results of the sensitivity analysis

1. The wind field and wave boundary conditions obtained from the ERA-40 data are suitable for SWAN computations in non-stationary mode.

2. The choice of SWAN's integration time step and numerical scheme is not critical. Time steps of 1 hour can be used.

3. The use of ZUNO water levels and velocities does not improve the results.

4. The choice of the wind input and corresponding whitecapping configuration in SWAN is crucial.

5. The hindcasts based on the Westh. configuration describe the high frequency tail of the measured spectra and the measured mean wave periods rather well, but underestimate the wave heights and in particular overestimate the decay of wave energy following the storm peak.

6. The best hindcasts are obtained using the WAM3 configuration with properly calibrated ERA-40 data.

Extreme value analysis

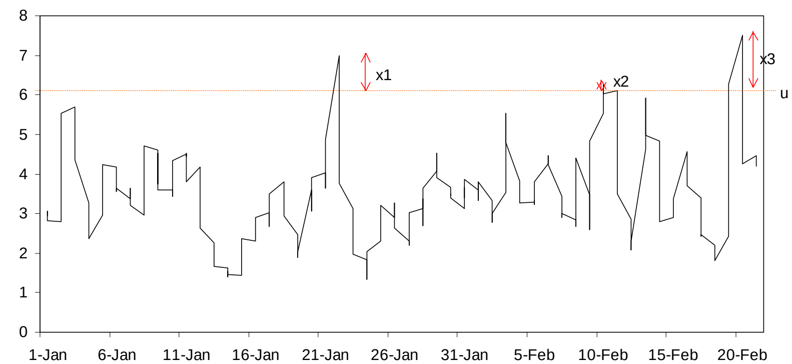
Stationary EVA – POT/GPD

Peak excesses over a high threshold *u* occur according to a Poisson process with rate λ_u and are independently distributed with a Generalized Pareto Distribution

$$F_u(x) = \begin{cases} 1-(1-\kappa x/\alpha)^{1/\kappa} & \kappa \neq 0 \\ 1-\exp(-x/\alpha) & \kappa = 0 \end{cases}$$

The *m*-year return value is given by

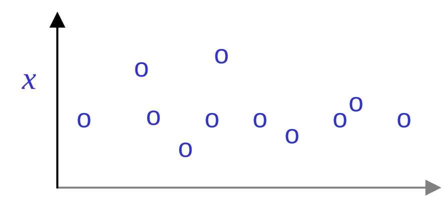
$$x_m^{(u)} = \begin{cases} u+\alpha/\kappa \log(1-(\lambda_u m)^{-\kappa}) & \kappa \neq 0 \\ u+\alpha \log(\lambda_u m) & \kappa = 0 \end{cases}$$



Non-stationary EVA - Non-homogeneous Poisson process

$$\lambda(t,x) = \frac{1}{\sigma(t)}\left(1+\xi(t)\frac{x-\mu(t)}{\sigma(t)}\right)_+^{-\frac{1}{\xi(t)}-1} \qquad (t,x)\in C$$

$$\rho(A) = \int_A \lambda(t,x)\,dt\,dx$$



$$C = \{(t,x) : x > u(t), 0 \leq t \leq T\}$$

$$\mu(t) = \mu_0 + \mu_1 t + \mu_2 t^2, \quad \sigma(t) = \sigma_0 + \sigma_1 t + \sigma_2 t^2, \quad \xi(t) = \zeta.$$

The *m*-year return value, x_m, is determined by solving

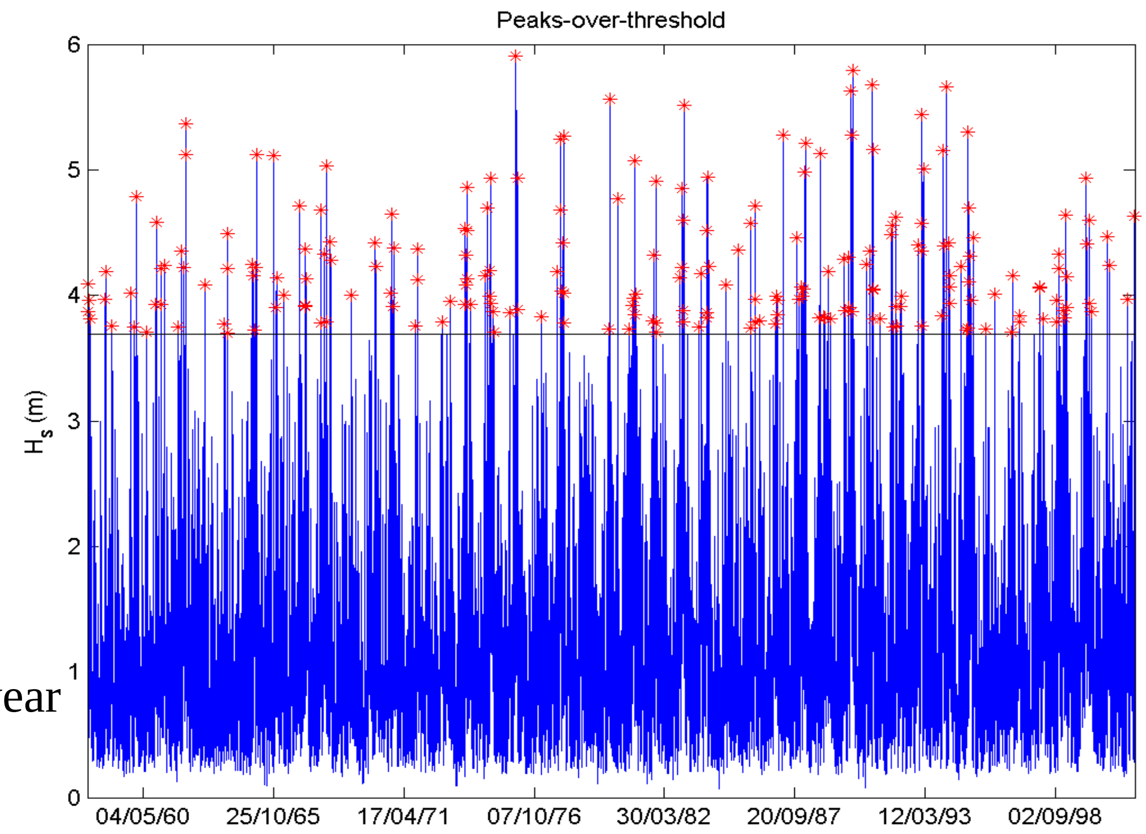
$$\int_0^m \left(1+\xi(t)\frac{x_m-\mu(t)}{\sigma(t)}\right)^{-\frac{1}{\xi(t)}} dt = 1$$

Non-stationary SWAN/ stationary EVA estimates

Final SWAN settings:
•1 hour time step
•WAM3 configuration
•ERA40 6-hourly fields (1958 to 2001) with $1.1 \cdot U_{10}$ and Dspr=20º

Computational details:
Linux cluster with 54 nodes
Per node:
CPU: 3.6 GHz
RAM: 4GHz
Computational time: 3 days/year

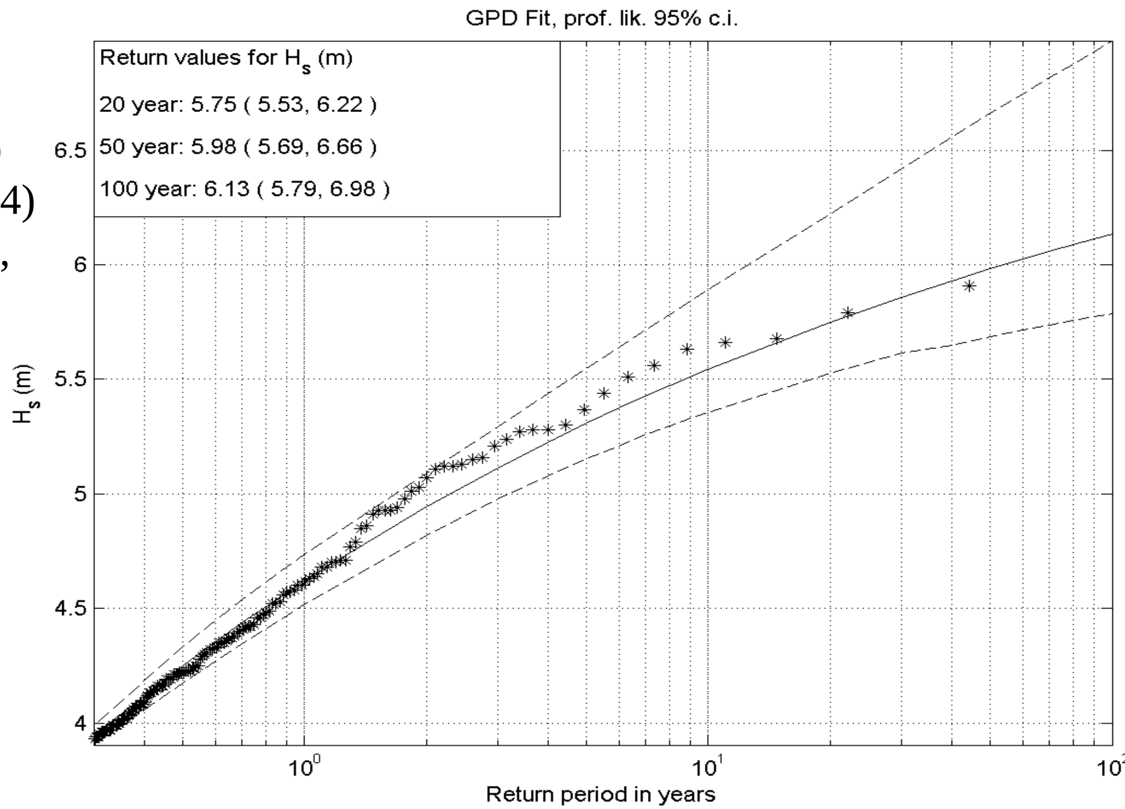
POT threshold:
u= 3.7 m, *n*=216 peaks



Timeseries of Hs hindcasts at MP1

Non-stationary SWAN / Stationary EVA estimates

scale parameter = 0.68 (0.56, 0.82)
shape parameter=-0.20 (-0.32, -0.04)
(distribution with bounded support, type III tail, with *endpoint* 7.13 m)



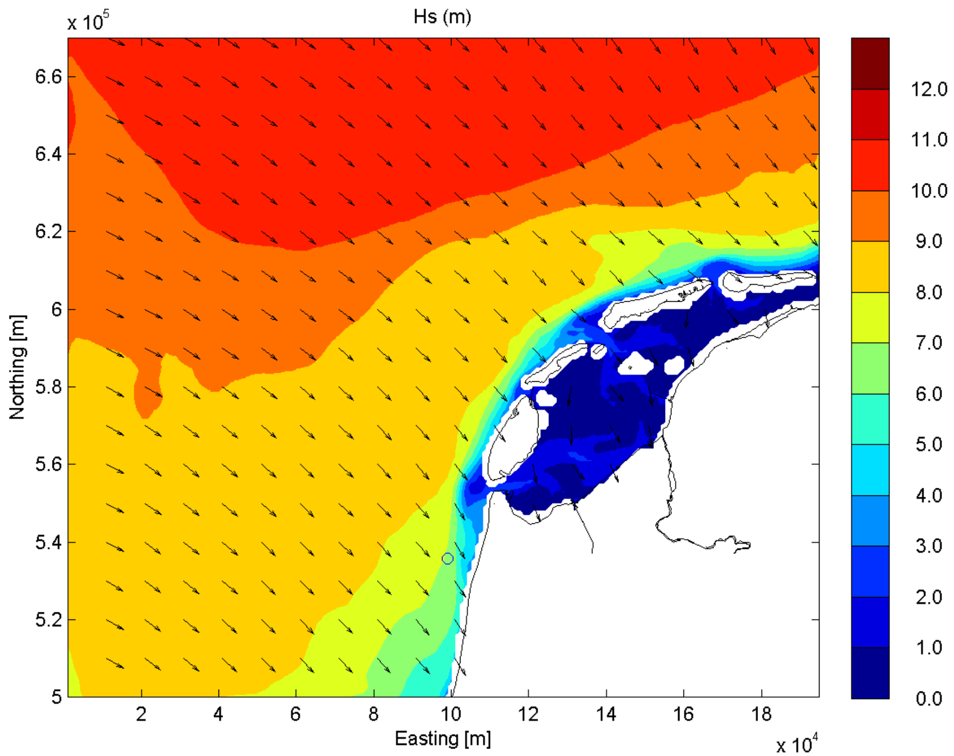
Hs 100-yr rv=6.13 (5.79, 6.89) m
(Tm02=6.0 (5.8, 6.4) s, MWD=300°N)

Stationary EVA estimates / Stationary SWAN

100-yr RV estimates from the ERA-40 data

U_{10}=26.0 (24.6, 30.7) m/s.

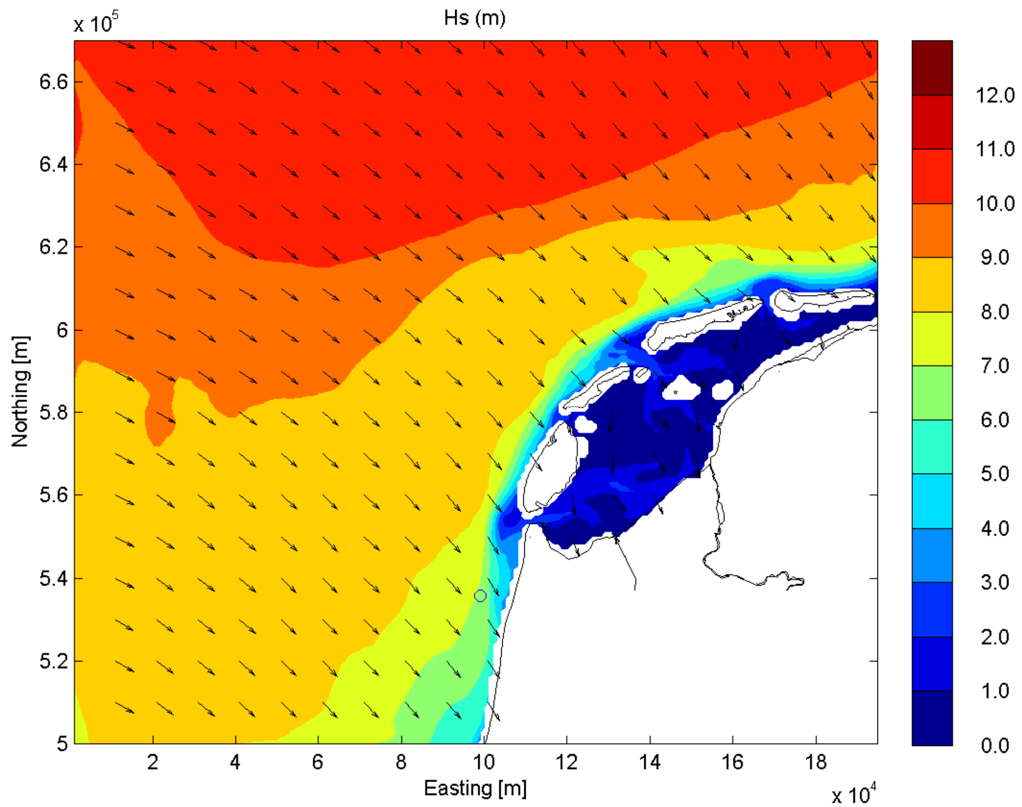
Location	H_s (m)	T_{m02} (s)	MWD (ºN)
3°E 52.5°N	7.95 (7.46, 9.63)	9.8	340
3°E 54°N	10.08 (9.14, 12.84)	10.4	340
4.5°E 52.5°N	7.70 (7.22, 9.35)	10.6	340
4.5°E 54°N	9.64 (8.86, 11.68)	10.4	330
6°E 54°N	9.86 (8.73, 12.80)	10.7	300



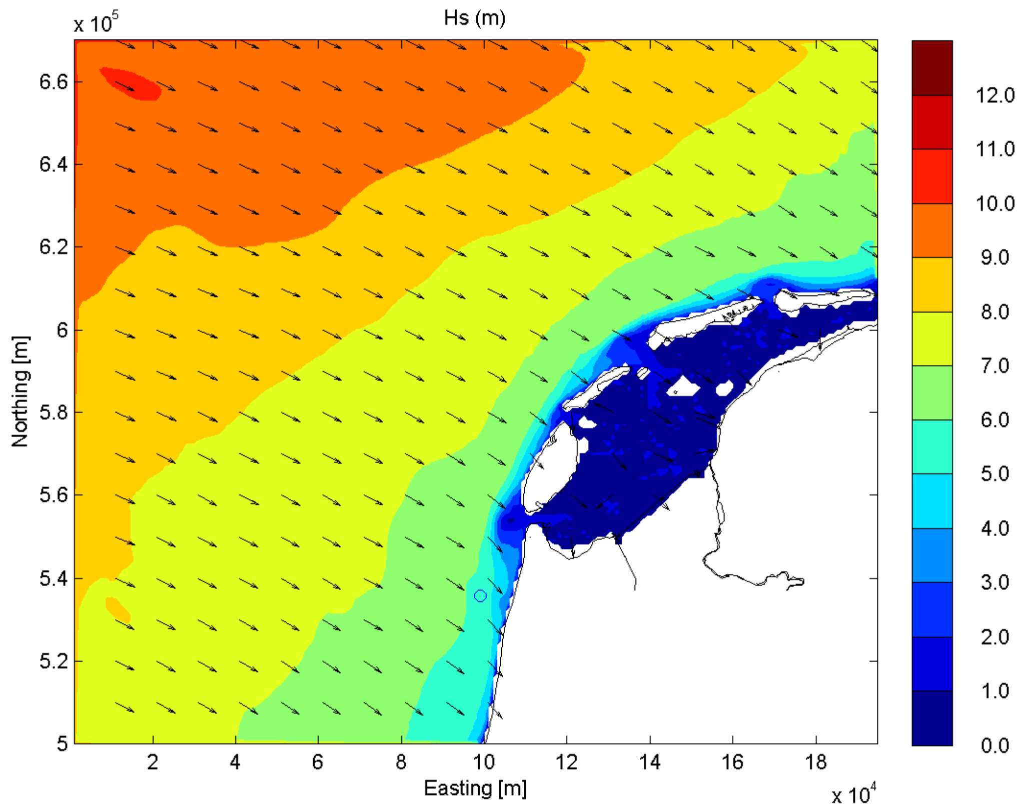
The associated 100-yr storm estimate at MP1 consists of Hs=6.86m, Tm02=6.9s and MWD=306°N.

NS-SWAN/S-EVA Hs 100-yr rv= 6.13 (5.79, 6.89) m, Tm02=6.0 (5.8, 6.4) s and MWD=300°N

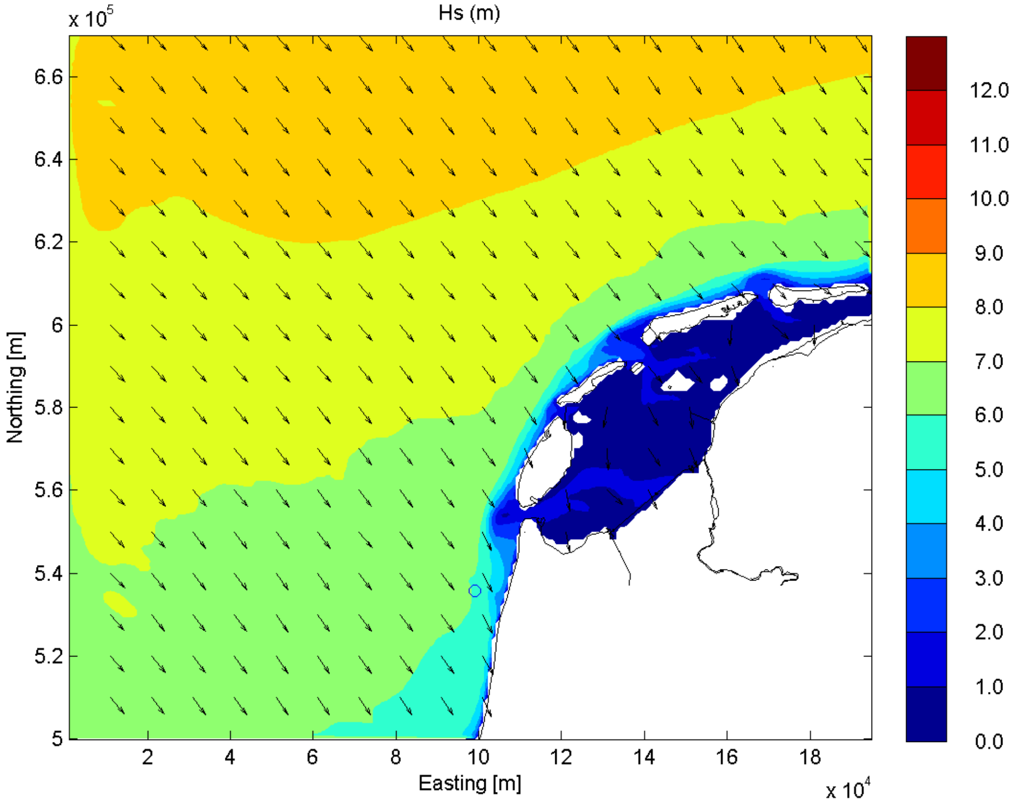
Stationary EVA estimates / Stationary SWAN
100-yr storm (6.86 m)



Non-stationary SWAN
1990/12/12 18h (5.68)



Non-stationary SWAN
1976/01/03 18h (5.91)



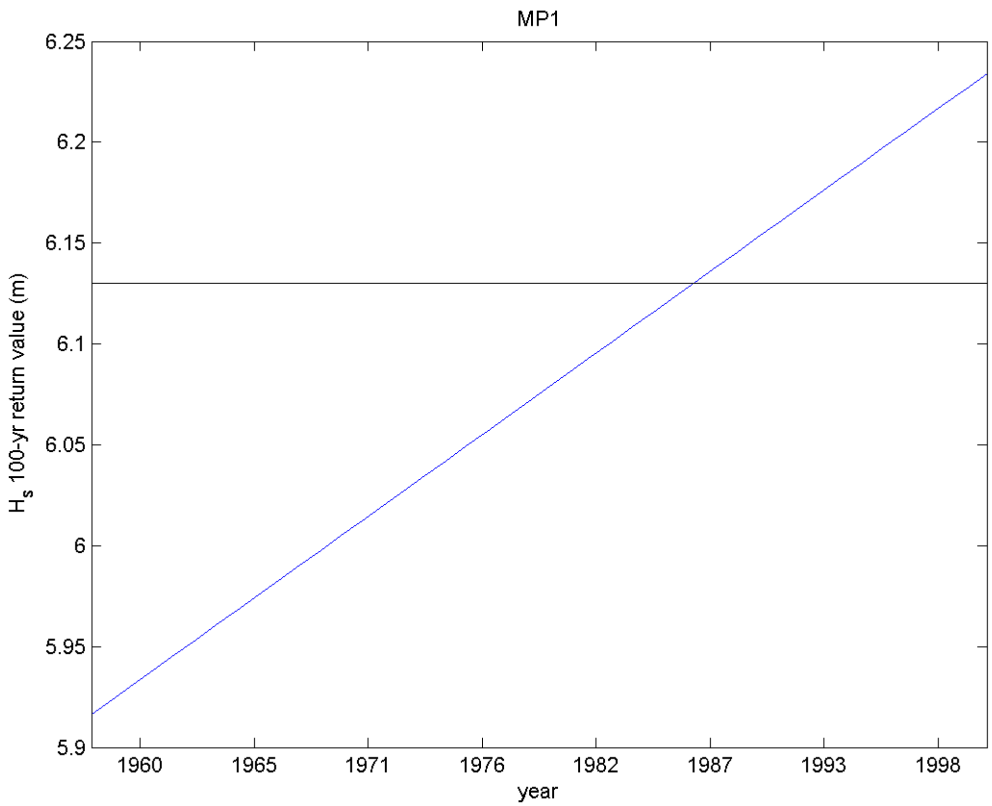
Non-stationary SWAN / Non-stationary EVA estimates

$\mu_0 = 4.46\,(4.30, 4.57)$,

$\mu_1 = 7.4\cdot 10^{-3}\ (0.6\cdot 10^{-3}, 14.5\cdot 10^{-3})$,

$\sigma_0 = 0.49\,(0.46, 0.56)$ and $\xi = -0.20\,(-0.30, -0.06)$

2001 100-yr rv= 6.23 (5.94, 6.99) m



(NS-SWAN/S-EVA=6.13 (5.79, 6.89) m,
S-SWAN/S-EVA=6.86 m)

Conclusions

Approach 1 - stationary SWAN/ stationary EVA estimates
Approach 2 - non-stationary SWAN/ stationary EVA estimates
Approach 3 - non-stationary SWAN/ non-stationary EVA estimates

- **The estimates obtained using Approach 2 are conservative when compared with those based on Approach 1.**
- **On the basis of this study we find that, for obtaining return value estimates at nearshore locations, Approach 2 is preferable to Approach 1.**
- **The estimates based on Approach 3 show that in the last 4 decades there has been a small linear increase in severity of the extreme wave systems.**
- **The estimated linear increase in severity of the extreme wave systems must be interpreted with care. Although it is a long-term trend (44 years) it may still be part of a longer-term cycle or affected by future changes in climate.**