Extreme Sea State Prediction at E.C.M.W.F

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Motivations:

- There has been quite some recent progress in the understanding of freak waves.
- There is now a theoretical framework for deterministic simulation of freak waves.
- In operational forecasting, a stochastic approach is used, hence only statement of a probabilistic nature can be made.
- Janssen (2003) showed that the Kurtosis (*C4*) of the surface elevation (η), which is a measure of the deviation from the Normal Gaussian probability distribution of η, can be expressed in terms of 6^{th} order integral of the wave action density to 3^{rd} power.
- For operational implementation, a computationally tractable approximation was found, including shallow water effects and directionality.

Methodology:

- Following Janssen (2003), the expression for the Kurtosis of the sea surface elevation (*C4*) is simplified using the narrow band approximation (both in frequency and direction).
- It was extended to include the stabilizing effect in shallow water (Janssen and Onorato 2007).
- For operational implementation, a fit to the derived expression is used.
- It requires a proper evaluation of the relative spectral width at the peak both in frequency (δ_ω) and in direction (δ_θ).
- New output parameters, the maximum individual wave height H_{max} and the associated maximum period T_{max}
- Comparison with buoy data is attempted.

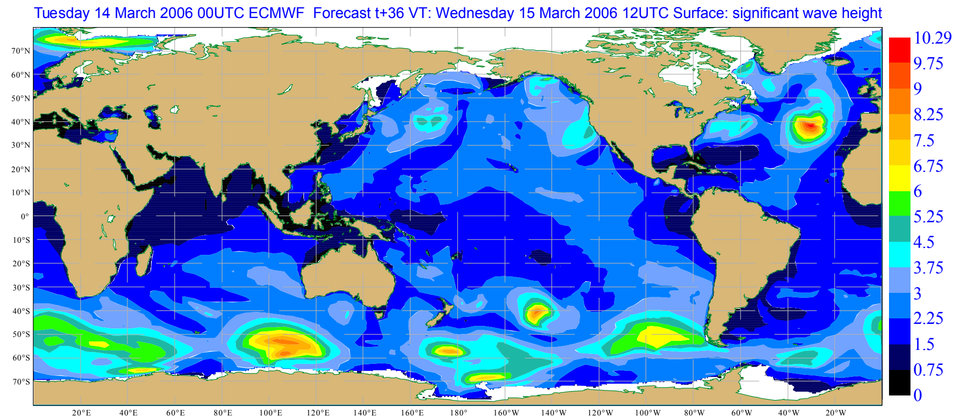
Conclusion:

- The freak wave warning system has been extended by including effects of directionality and shallow water in the estimation of $C4$.
- H_{max} provides a simple measure for extreme sea state.
- Preliminary validation of H_{max} is satisfactory.

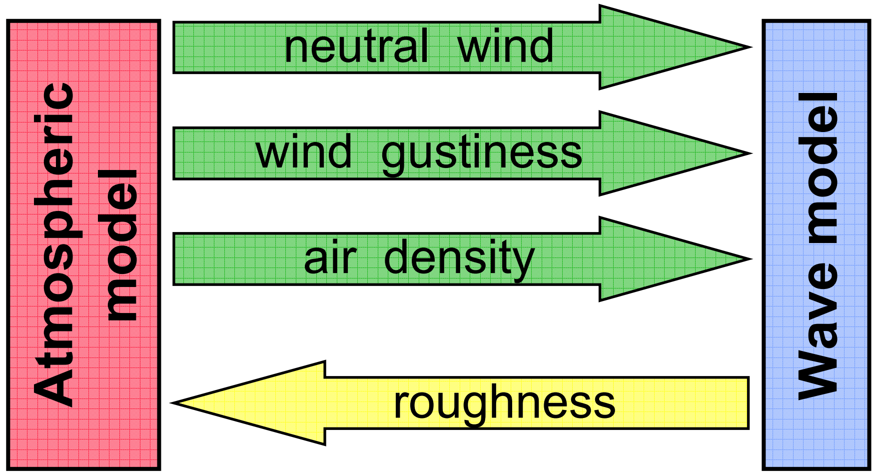
Introduction:

ECMWF global wave model, ECWAM:

- **Global from 81°S to 90°N**
- **Coupled to the atmospheric model with feedback of the sea surface roughness change due to waves.**
- **The interface between WAM and the IFS has been generalised to include air density and gustiness effects on wave growth and more recently neutral winds.**
- **Latest model changes (Sep. 2009) include a formulation for swell damping.**



Forecast wave height on 15/03/2006 12UTC.



ECMWF Wave Model Configurations

Deterministic model

- 40 km grid spacing .
- 30 frequencies.
- 24 directions.
- Coupled to the TL799 model (25km).
- Analysis every 6 hrs and 10 day forecasts from 0 and 12Z.

Probabilistic forecasts

(EPS)

- 110 km grid spacing.
- 30→ 25 frequencies *.
- 24 → 12 directions *.
- Coupled to TL399 → TL255 model *.
- (50+1) (10+5) day forecasts from 0 and 12Z (monthly once a week).

* Change in resolutions after 10 days

NB: also in seasonal forecast at lower resolutions

ECMWF Wave Model Future* Configurations

Deterministic model

- 28 km grid spacing .
- 36 frequencies.
- 36 directions.
- Coupled to the TL1279 model (16km).
- Analysis every 6 hrs and 10 day forecasts from 0 and 12Z.

Probabilistic forecasts

(EPS)

- 55 km grid spacing.
- 36 → 30 frequencies *.
- 36 → 24 directions *.
- Coupled to TL639 → TL319 model *.
- (50+1) (10+5) day forecasts from 0 and 12Z (monthly once a week).

* Change in resolutions after 10 days

*: resolution increase planned later in the year

Extension of the freak wave warning system:

Kurtosis of the sea surface elevation η: $C_4 = \dfrac{\langle \eta^4 \rangle}{3\langle \eta^2 \rangle^2} - 1$

$$C_4 = C_4^{dyn} + \alpha\,\varepsilon^2$$

For deep water,
with the narrow band approximation,
we use the fit:

$$C_4^{dyn} = \beta \frac{BFI^2}{\delta_\theta}$$

BFI: Benjamin Feir Index:

$$BFI = \sqrt{2}\,\frac{\varepsilon}{\delta_\omega}$$

δ_ω: relative frequency width at the peak

δ_θ: relative directional width at the peak

integral steepness ε:

$$\varepsilon = k_0 \sqrt{m_0}$$

$$m_0 = \langle \eta^2 \rangle = \iint E(\omega,\theta)\,d\omega\, d\theta$$

$E(\omega,\theta)$: 2D wave spectrum
k_0: peak wave number

Extension of the freak wave warning system:

$$C_4 = C_4^{dyn} + \alpha\,\varepsilon^2$$

$$C_4^{dyn} = \beta\,\frac{BFI^2}{\delta_\theta} \qquad \alpha = 6$$

$$\beta = 0.062\,\frac{\pi}{3\sqrt{3}} \qquad BFI = \sqrt{2}\,\frac{\varepsilon}{\delta_\omega}$$

$$\delta_\omega = \frac{1}{\pi}\frac{1}{Q_p}$$

peakedness: $Q_p = \frac{2}{m_0^2}\int_D \omega E^2 d\omega d\theta$

D: E(ω) > 0.4 E(ω_0)

$$\delta_\theta = \sqrt{2(1-M_1)} \qquad M_1 = \frac{1}{m_0}\int \cos(\theta) E(\omega,\theta)\, d\omega d\theta$$

δω and δθ are also determined from parabolic fit around the peak of the frequency and direction spectra respectively.

Maximum wave height:

Expectation value of H_{max}

$$\langle H_{max} \rangle = \int H_{max}\, p_m(H_{max})\, d H_{max}$$

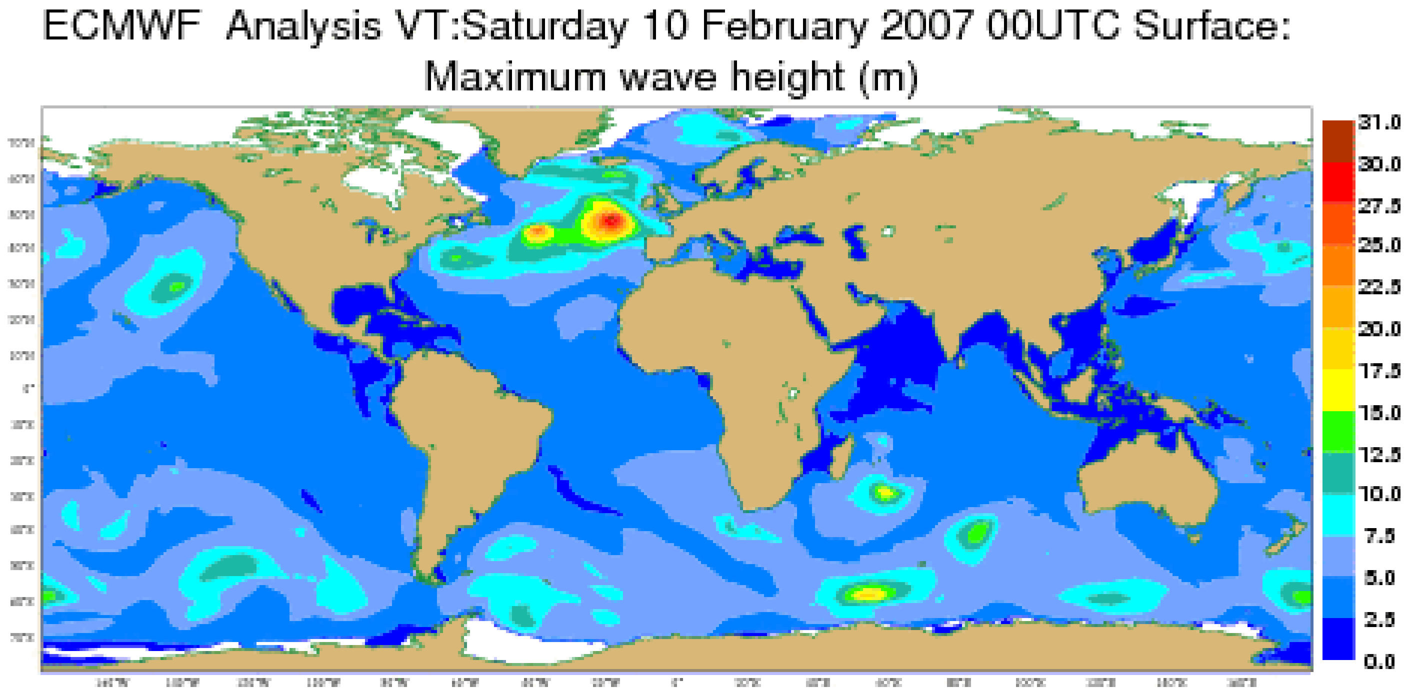
Starting from the pdf of the surface elevation which depends on skewness and kurtosis (Cram-Charlier expansion), $p_m(H_{max})$ is derived from the pdf of the wave height, defined as twice the envelop of the wave train:

$$\frac{\langle H_{max} \rangle}{H_{sig}} = \sqrt{z}$$

$$z = z_0 + \frac{\gamma}{2} + \frac{1}{2}\log\left[1 + C_4\left\{2 z_0 (z_0 - 1) - \gamma(1 - 2 z_0) - \frac{1}{2}(\gamma^2 + \frac{\pi^2}{6})\right\}\right]$$

$z_0 = \frac{1}{2}\log(N)$ $\gamma = 0.5772$ Number of waves $N = \frac{duration}{T_p}$

Example : expected Hmax within 3 hours



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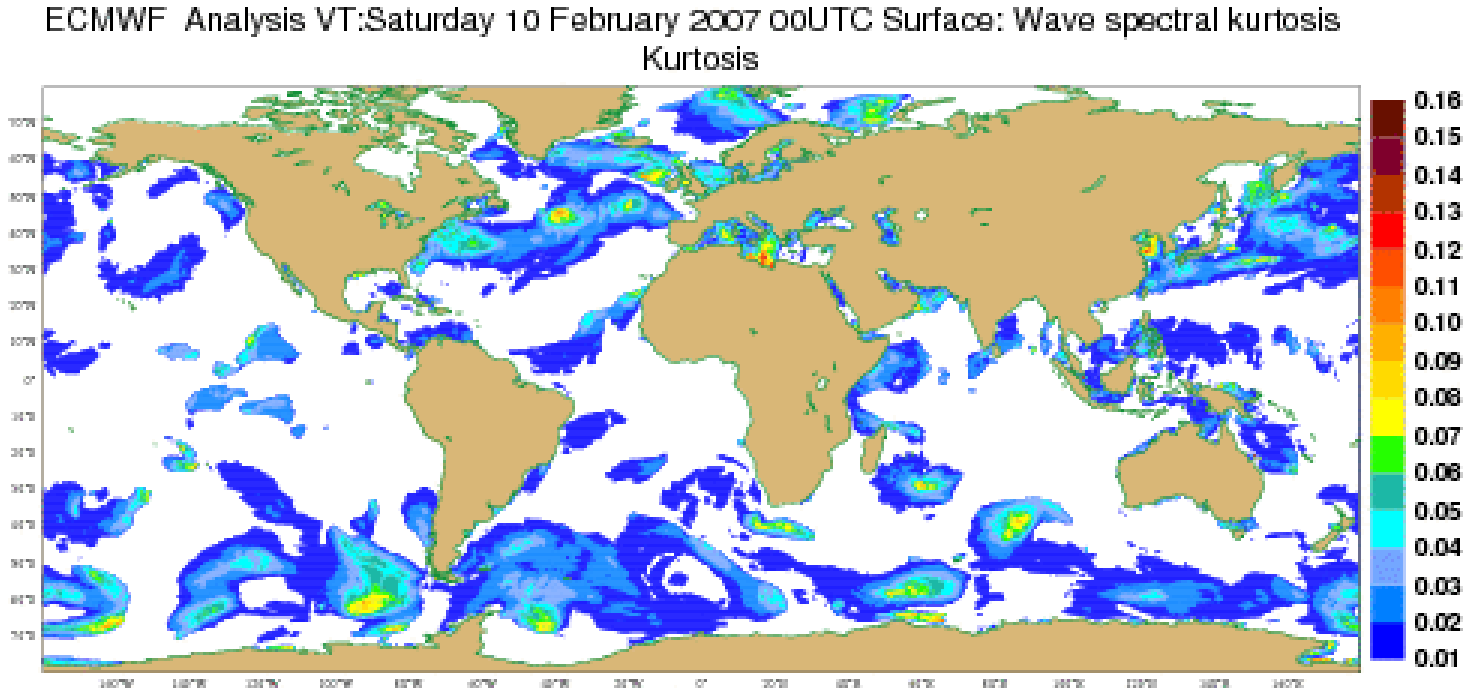
Example : corresponding kurtosis



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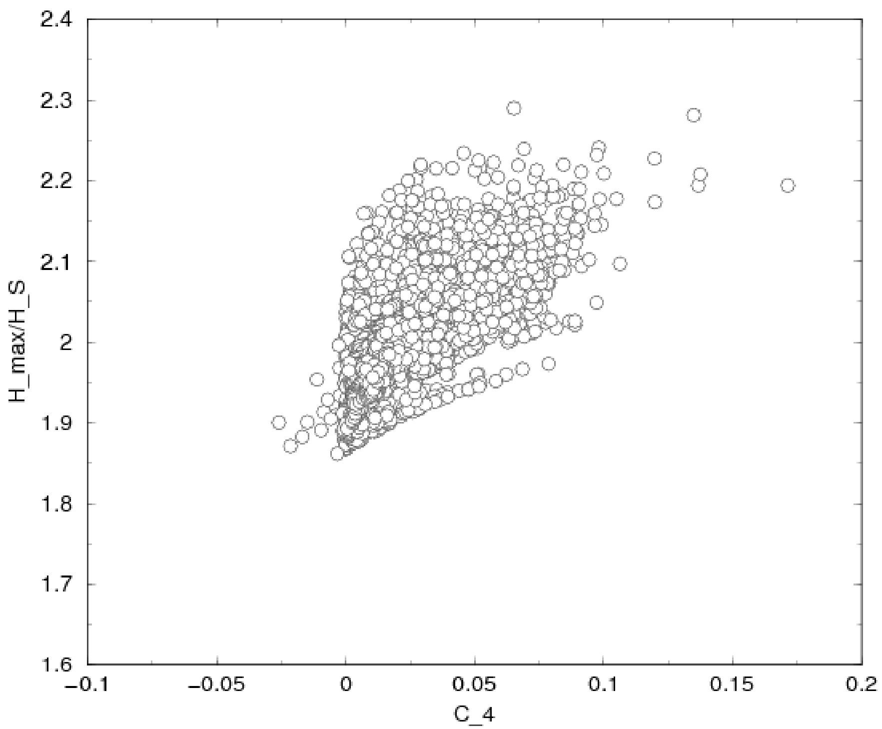
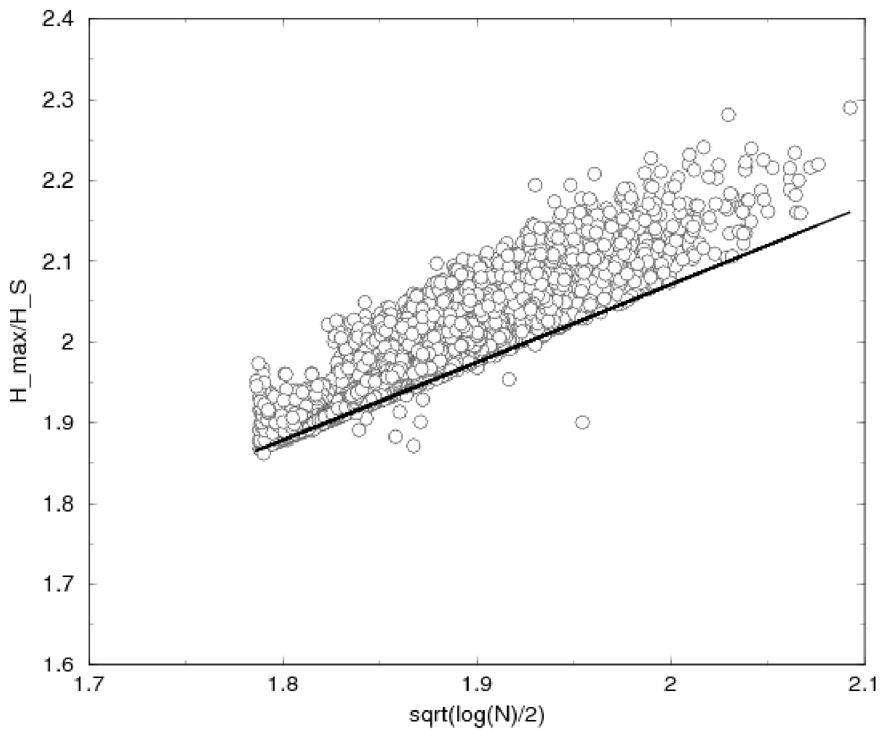
Results :



H_{max}/H_s vs *C4*
for all grid points of previous figures

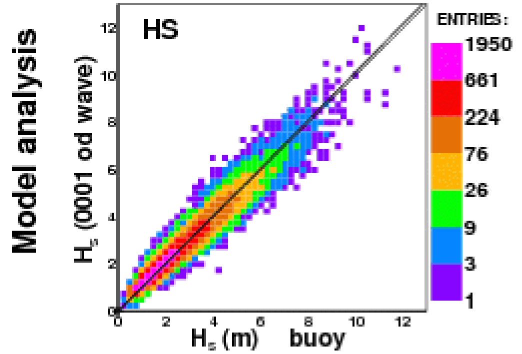


H_{max}/H_s vs *number of waves (N)*
for all grid points of previous figures

Comparison with buoy data :

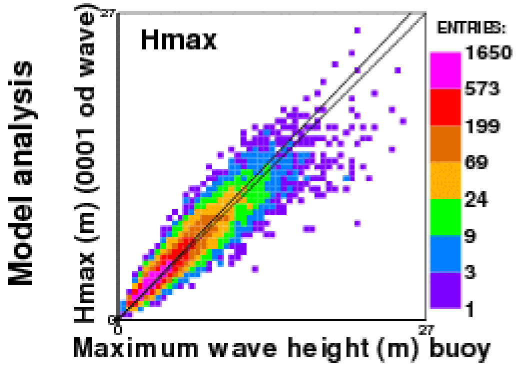
Comparison against Canadian (MEDS) and Norwegian (Oceanor) buoys:

All buoys 20060202 to 20080131



ENTRIES = 36520
MODEL MEAN = 2.44 STDEV = 1.273
BUOY MEAN = 2.37 STDEV = 1.325
LSQ FIT: SLOPE = 0.933 INTR = 0.228
RMSE = 0.324 BIAS = 0.069
CORR COEF = 0.971 SI = 0.134
SYMMETRIC SLOPE = 1.013

NB: Hs and Hmax as recomputed from archived spectra.



ENTRIES = 32495
MODEL MEAN = 4.89 STDEV = 2.495
BUOY MEAN = 4.54 STDEV = 2.584
LSQ FIT: SLOPE = 0.911 INTR = 0.750
RMSE = 0.922 BIAS = 0.348
CORR COEF = 0.944 SI = 0.188
SYMMETRIC SLOPE = 1.051

Model Hmax is the expected value in a 3 hour record

Buoys used:
MEDS: 44137,44138, 44139, 44140, 44150, 44251, 44255, 46036, 46132, 46147,46184, 46205, 46206, 46207, 46208.
Oceanor: LFB1, LFB2

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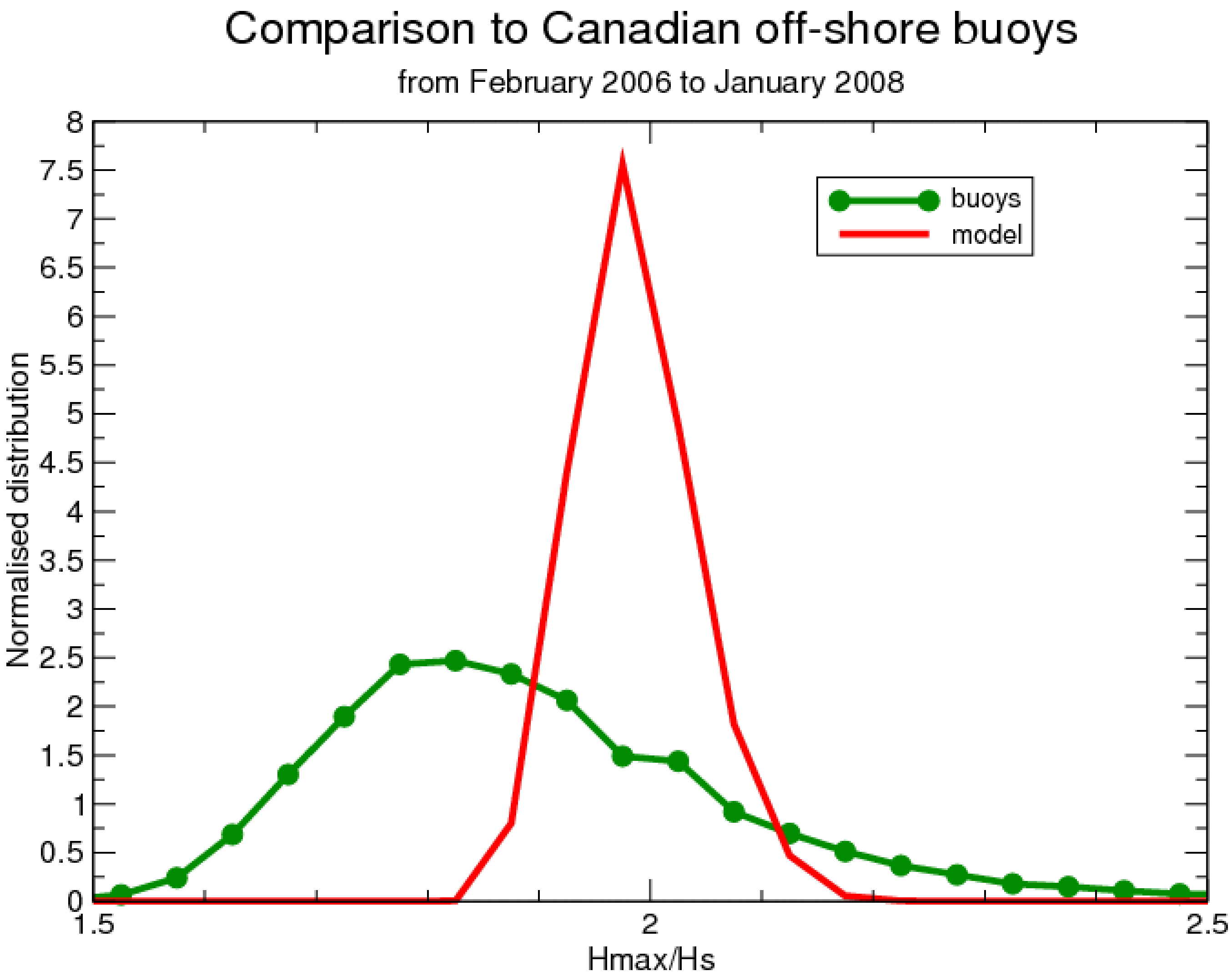
Comparison with buoy data :



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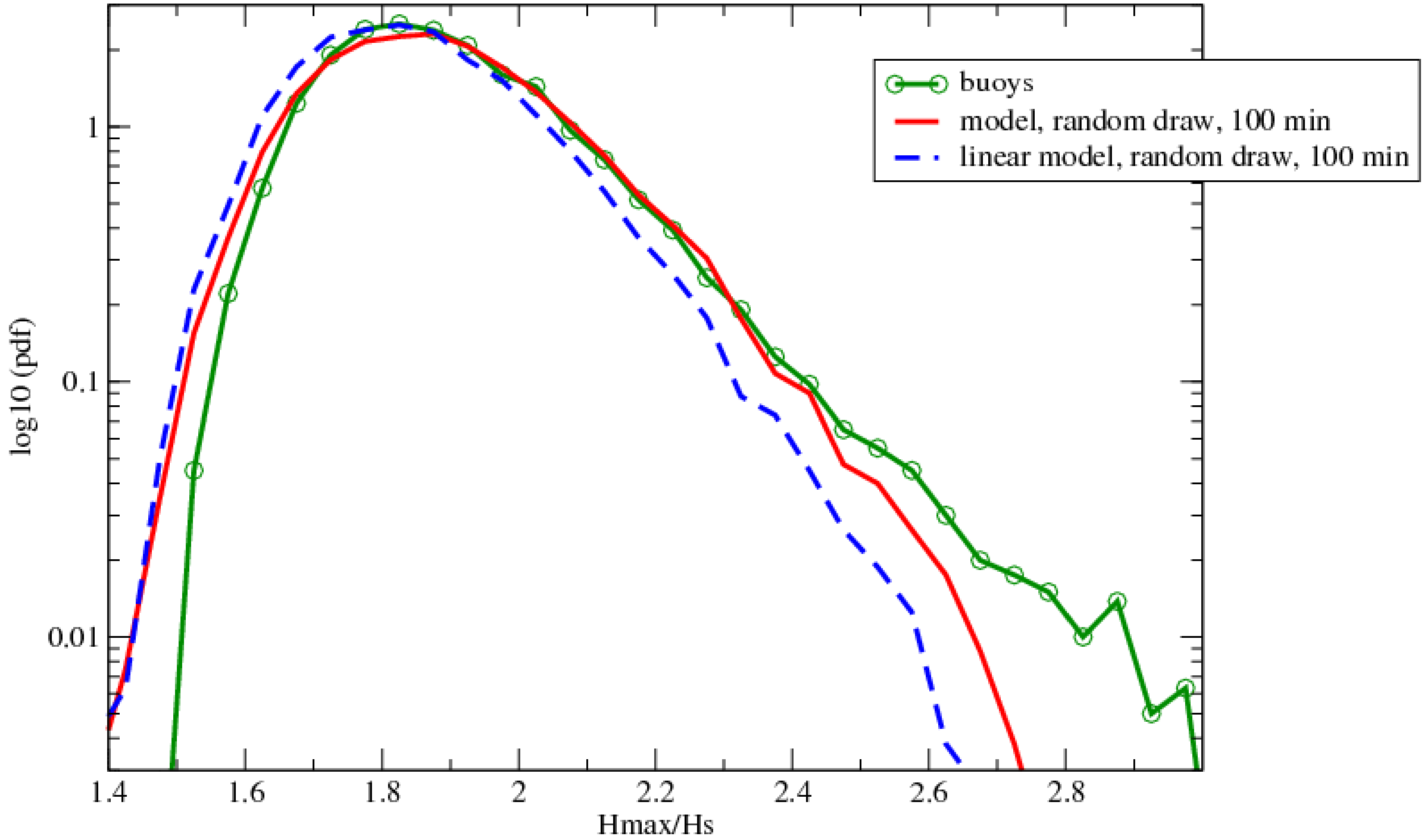
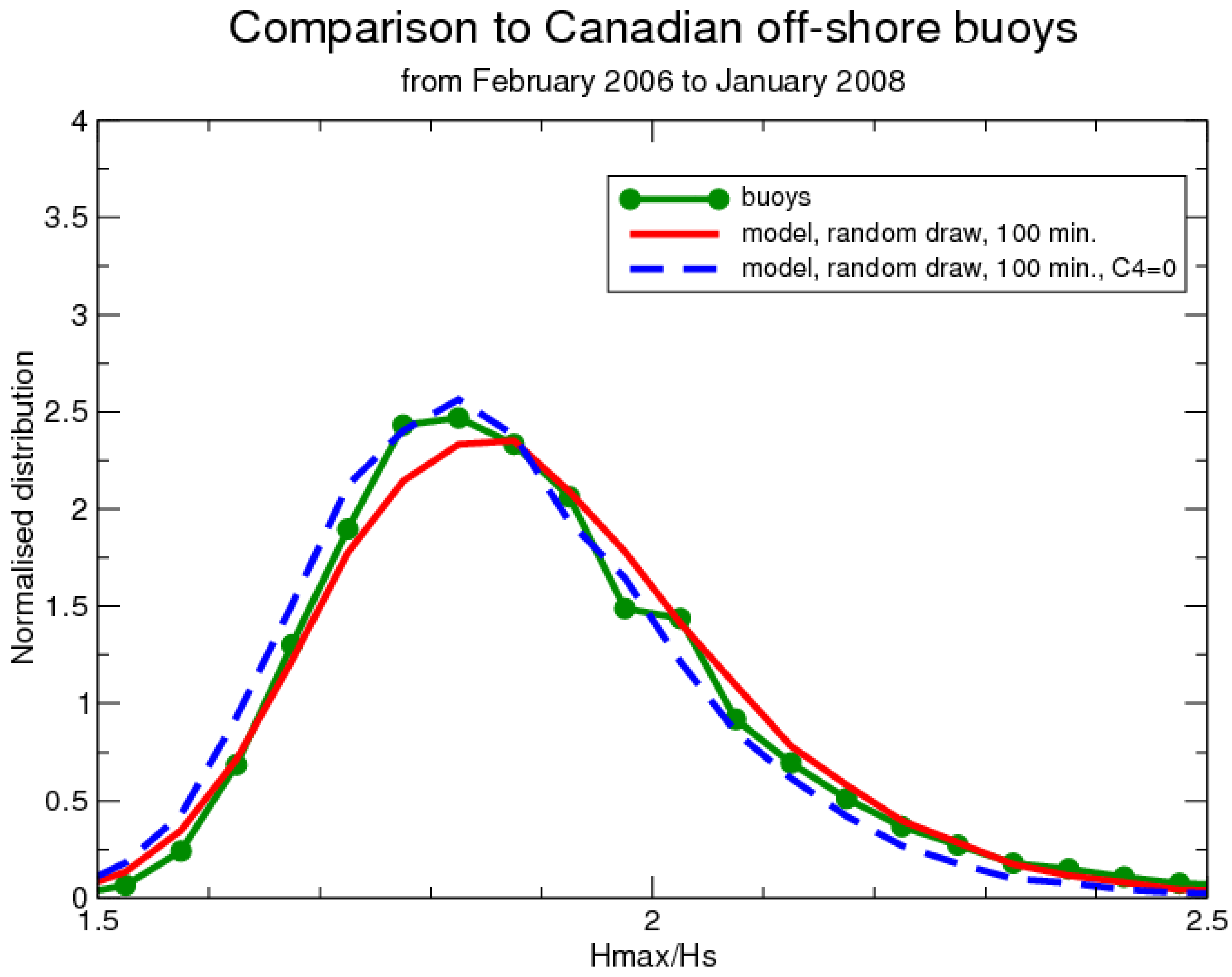
Comparison with buoy data :

- H_{max} observed is from a single realization, where as H_{max} modeled is the expectation value.
- Can the observed distribution be simulated?
- Yes, by generating a random draw from the theoretical $p_m(H_{max})$, with given N and C4.

Comparison with buoy data :



Comparison with buoy data :



ECMWF

Conclusion:

- The freak wave warning system has been extended by including effects of directionality and shallow water in the estimation of *C4*.
- H_{max} provides a simple measure for extreme sea state.
- H_{max} in operations since June 2008.
- Preliminary validation of H_{max} is satisfactory.