Ocean Wave Forecasting

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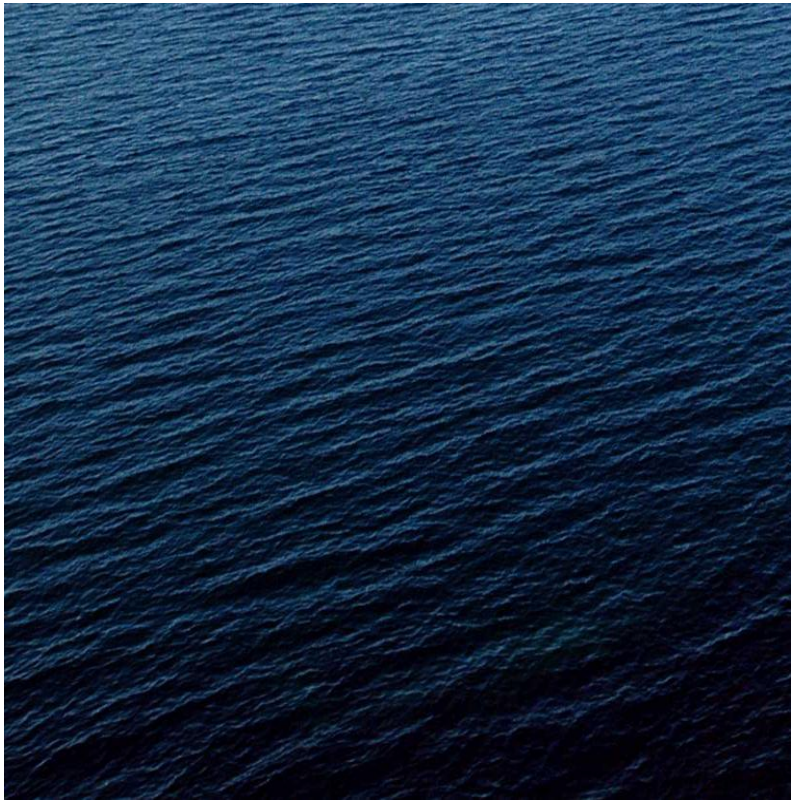
*** With contributions from my colleagues in the JCOMM/ Expert Team in Waves and Coastal Hazards**

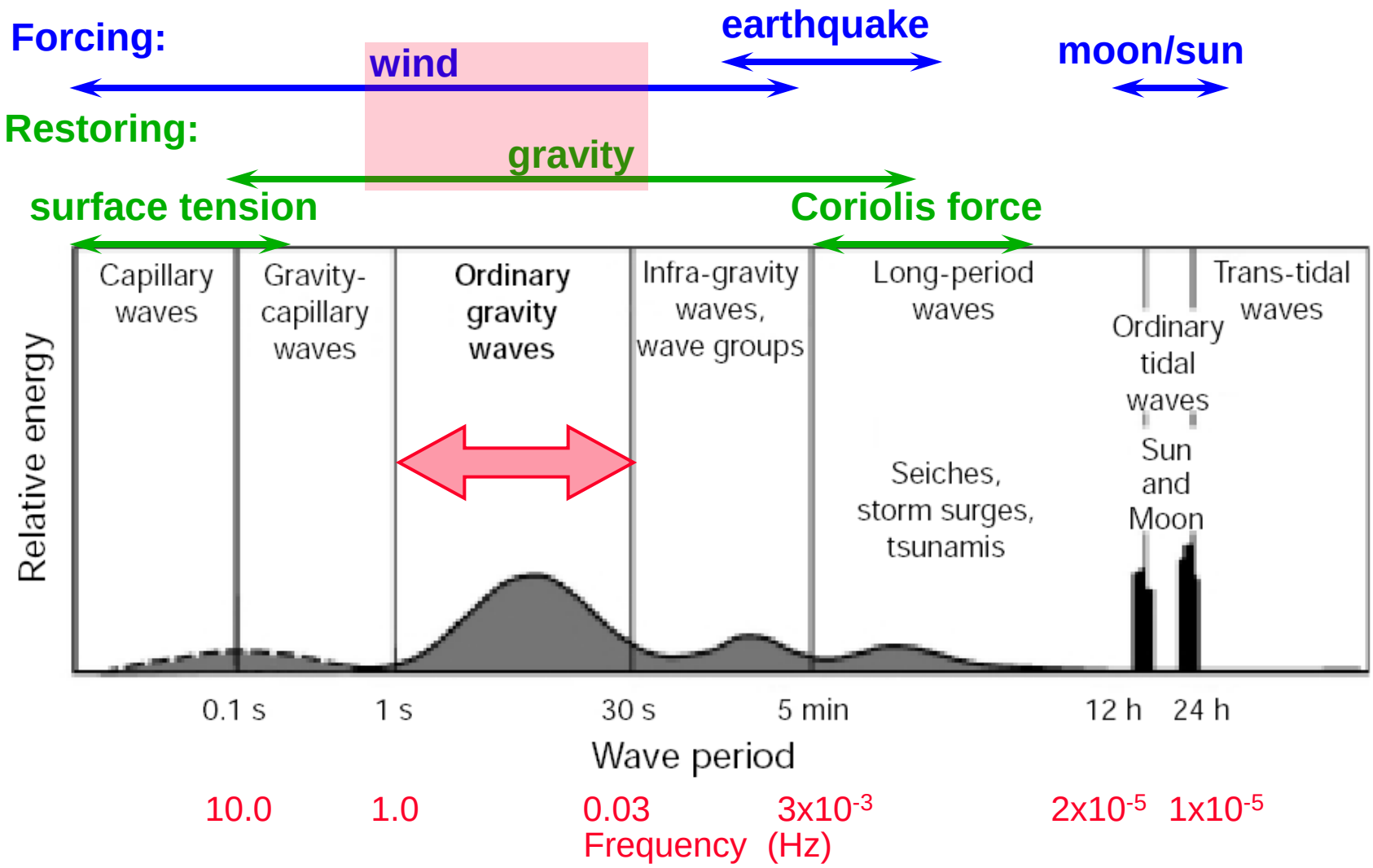
ECMWF

Ocean waves:

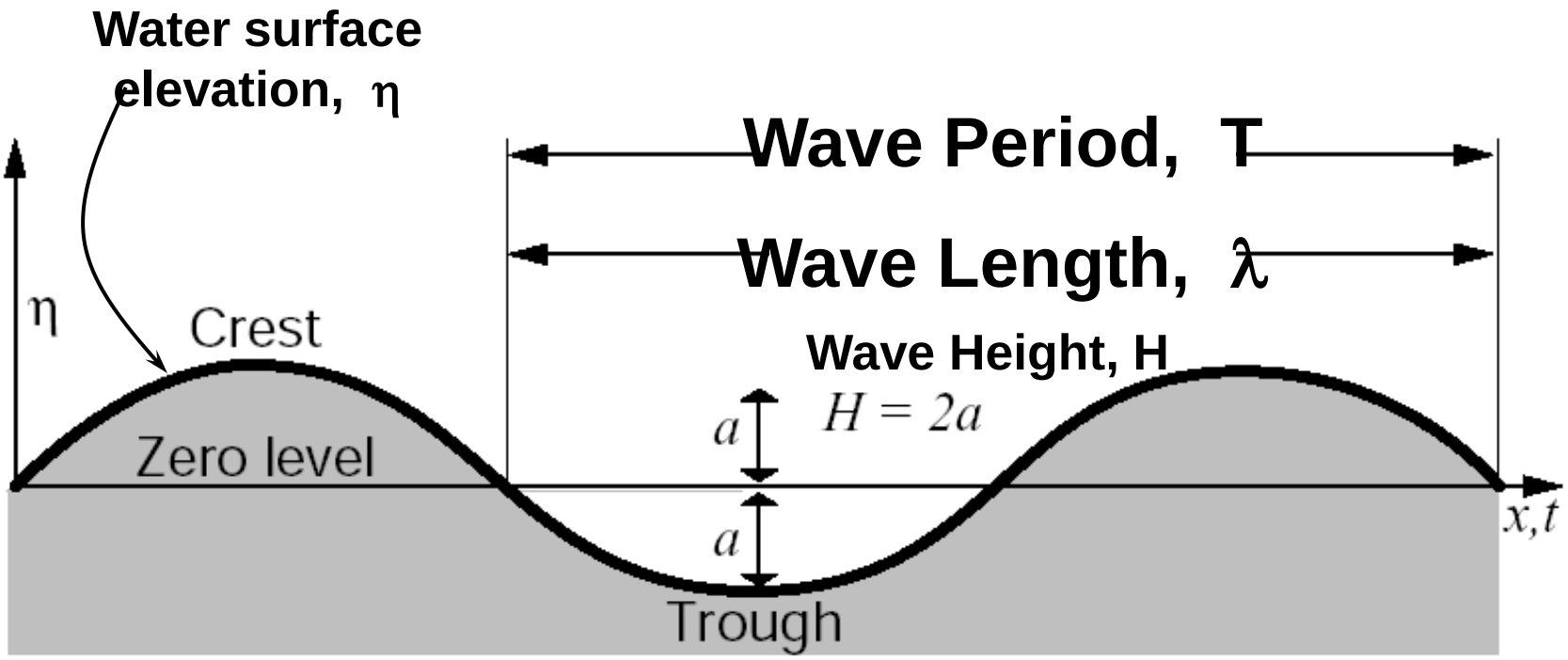
We are dealing with wind generated waves at the surface of the oceans, from gentle to rough …



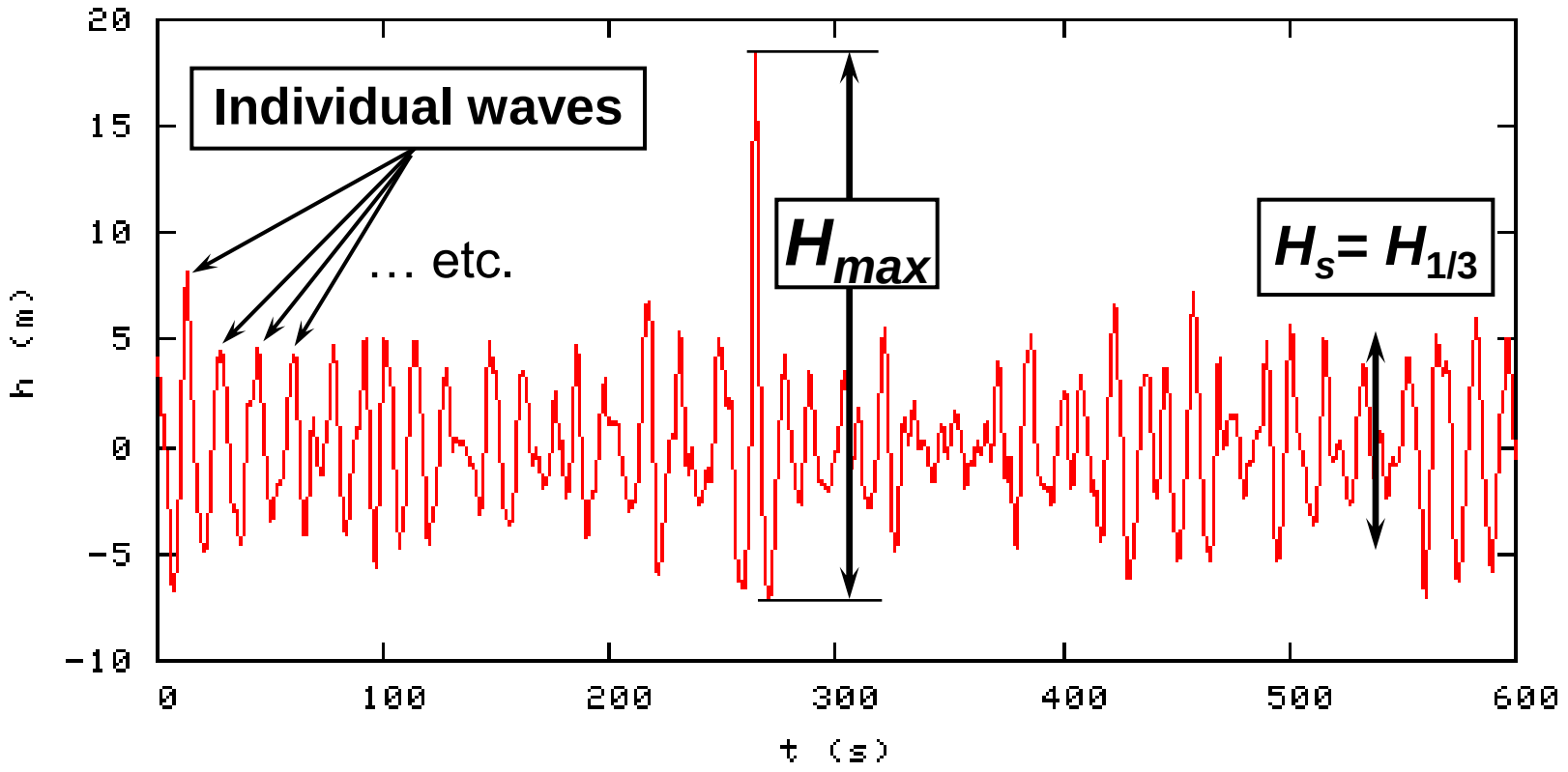
Ocean Waves


Forcing:
wind
earthquake
moon/sun
Restoring:
gravity
surface tension
Coriolis force
Capillary waves
Gravity-capillary waves
Ordinary gravity waves
Infra-gravity waves, wave groups
Long-period waves
Ordinary tidal waves
Trans-tidal waves
Seiches, storm surges, tsunamis
Sun and Moon
Relative energy
0.1 s
1 s
30 s
5 min
12 h
24 h
Wave period
10.0
1.0
0.03
3x10-3
2x10-5
1x10-5
Frequency (Hz)

What we are dealing with?

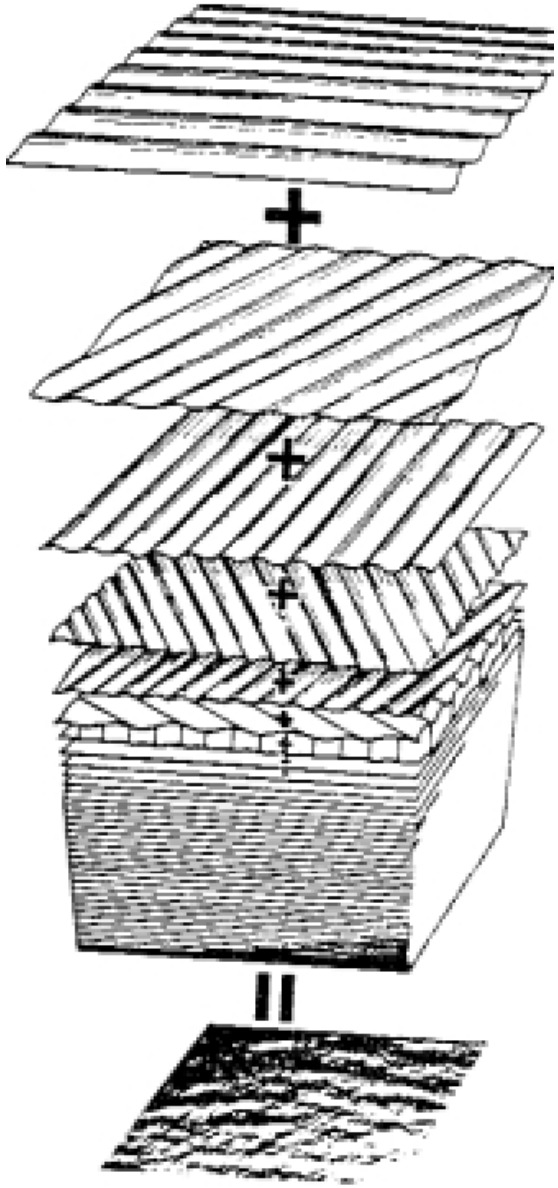


A Wave Record
Individual Waves,
Significant Wave Height, H_s,
Maximum Individual Wave Height, H_{max}



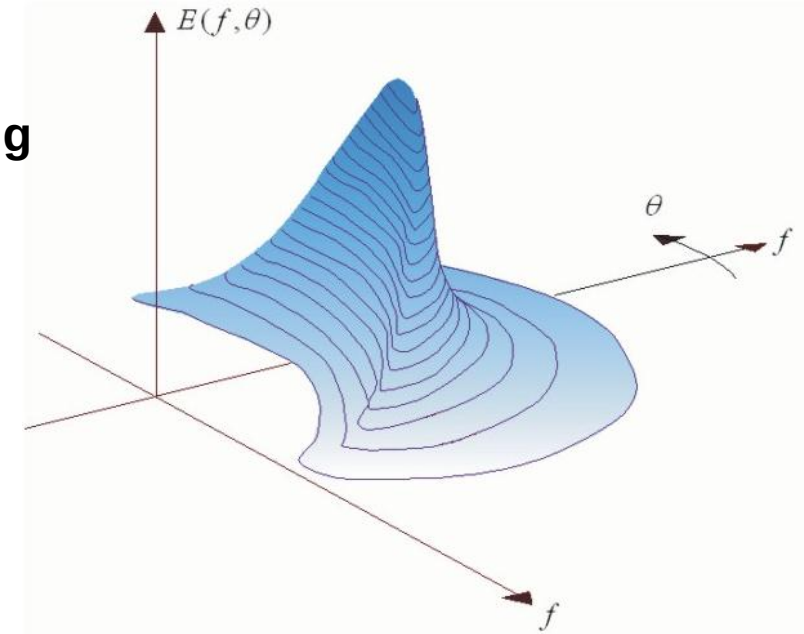
Surface elevation time series from platform Draupner in the North Sea

Wave Spectrum



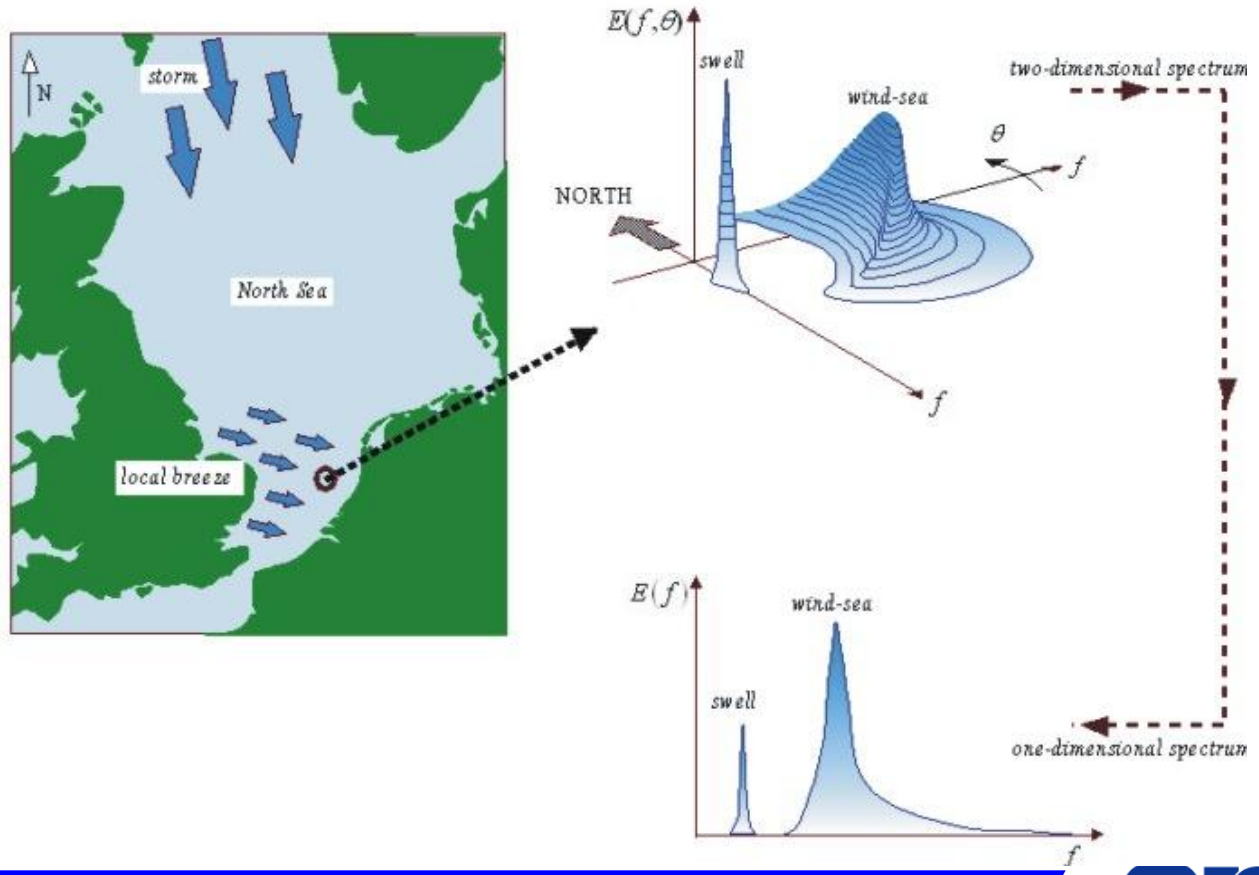
- The irregular water surface can be decomposed into (*infinite*) number of simple sinusoidal components with different frequencies (*f*) and propagation directions (θ) and amplitudes.

- The distribution of wave energy among those components is called: "wave spectrum", F(f,θ).



- **Modern ocean wave prediction systems are based on statistical description of oceans waves (i.e. ensemble average of individual waves).**

- **The sea state is described by the two-dimensional variance spectrum F(f, θ) of the surface elevation.**



Ocean Wave Modelling

- Once the spectrum is known, information about the sea state can be derived.
- For example, the mean variance of the sea surface elevation η due to waves is given by:

$$\langle \eta^2 \rangle = \iint F(f,\theta) df d\theta$$

- The statistical measure for wave height, called the significant wave height (H_s):

$$H_s = 4\sqrt{\langle \eta^2 \rangle}$$

The term significant wave height is historical as this value appeared to be well correlated with visual estimates of wave height from experienced observers. It can be shown to correspond to the average 1/3rd highest waves ($H_{1/3}$).

Ocean Wave Modelling

- **The 2-D spectrum follows from the energy balance equation (in its simplest form: deep water case):**

$$\frac{\partial F}{\partial t} + \vec{V}_g \cdot \nabla F = S_{in} + S_{nl} + S_{diss}$$

Where the group velocity V_g is derived from the dispersion relationship which relates angular frequency and wave number:

$$\omega^2 = g\,k$$

S_{in}: wind input source term (generation).

S_{nl}: non-linear 4-wave interaction (redistribution).

S_{diss}: dissipation term due to whitecapping (dissipation).

Wind input in pictures

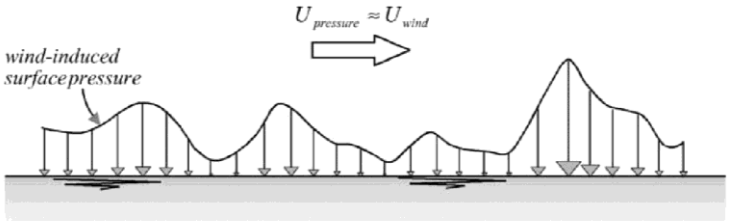


Figure 6.15 The normal wind-induced pressure moving as a (nearly) frozen distribution across the water surface.

Linear growth

But once waves are present, they distort the air flow above:

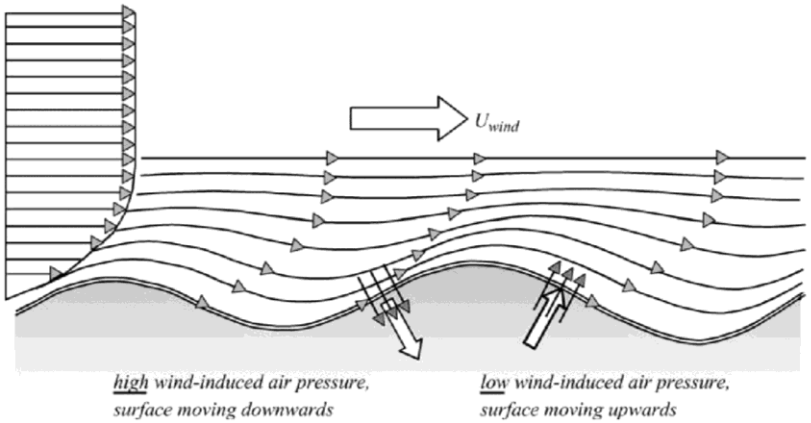


Figure 6.16 The wave-induced wind-pressure variation over a propagating harmonic wave.

the wave grows by this mechanism, the mechanism becomes more effective, so the wave can therefore grow faster, which in turn makes the mechanism even more effective, etc.

exponential growth

Figures from "Waves in Oceanic and Coastal Waters" by Leo Holthuijsen. Cambridge University Press

Non-linear inter-action in pictures

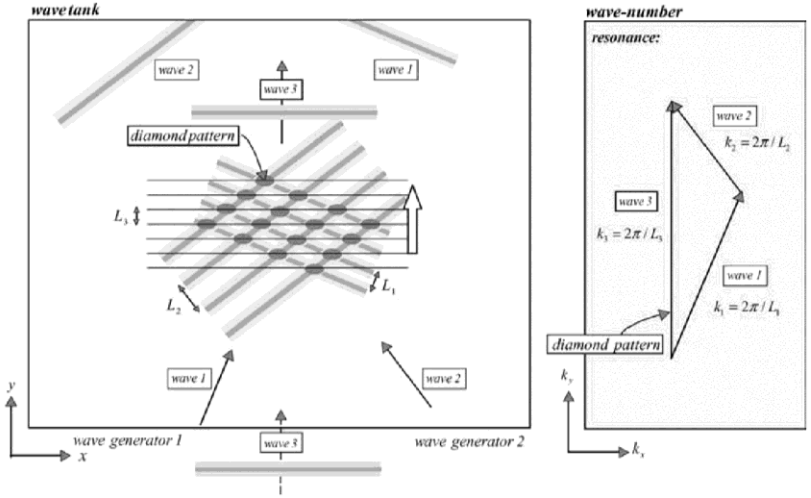


Figure 6.19 *Triad* wave–wave interactions (*not realisable in deep water*). A hypothetical wave-tank experiment with one pair of mechanically generated, freely propagating waves, interacting with a third, freely propagating wave. The wave-number vectors of the three wave components and of the diamond pattern are shown in the right-hand panel in wave-number space: the wave-number vector of the third wave is equal to the wave number of the diamond pattern, which is equal to the sum of the wave numbers of the original two wave components: $\vec{k}_3 = \vec{k}_1 + \vec{k}_2$. (For the concept of wave-number vectors, see Section 3.5.8).

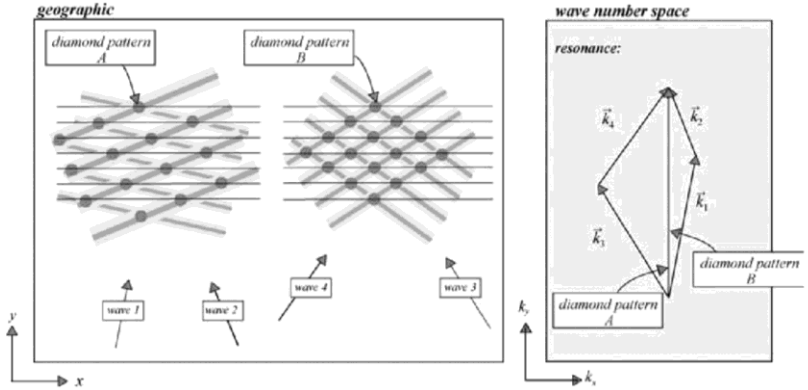


Figure 6.20 *Quadruplet* wave–wave interactions (realisable in deep water). Two pairs of wave components can create two diamond patterns with identical wave lengths and directions and therefore identical wave numbers. When the four waves are superimposed (not shown here), they can thus resonate. The wave-number vectors of the four wave components are shown in the right-hand panel in wave-number space with $\vec{k}_1 + \vec{k}_2 = \vec{k}_3 + \vec{k}_4$.

3-waves interaction (triad)
not possible in deep water

4-waves interaction (quadruplet)
possible in deep water

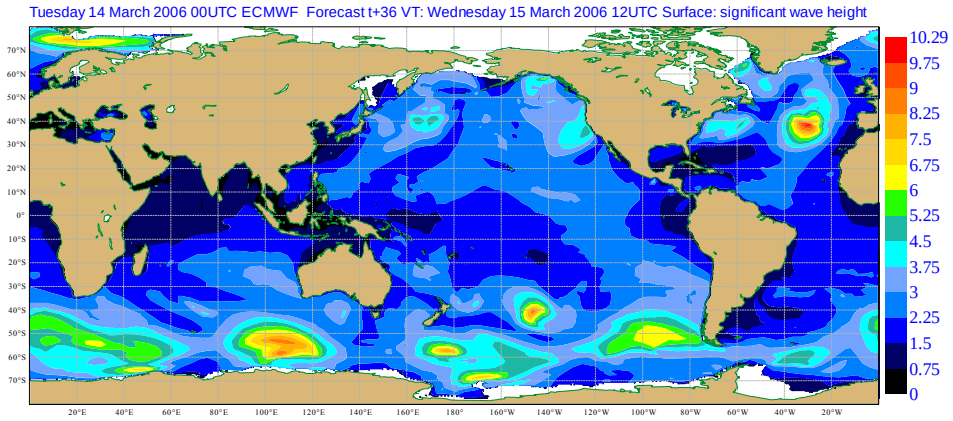
Figures from "Waves in Oceanic and Coastal Waters" by Leo Holthuijsen. Cambridge University Press

whitecapping dissipation

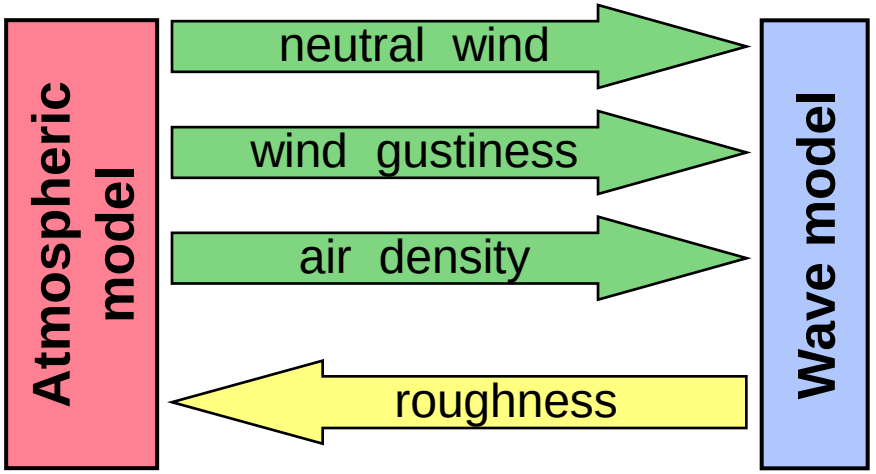
Wave Model Configurations

ECMWF Global models

- **Global from 81°S to 90°N, including all inland seas.**
- **<u>Coupled</u> to the atmospheric model (IFS) 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 neutral winds.**
- **Data assimilation Jason-2 altimeter wave heights.**



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



ECMWF Wave Model Configurations

Deterministic model

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

Probabilistic forecasts

(EPS)

- **55 km grid spacing.**
- **30→ 25 frequencies *.**
- **24 → 12 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

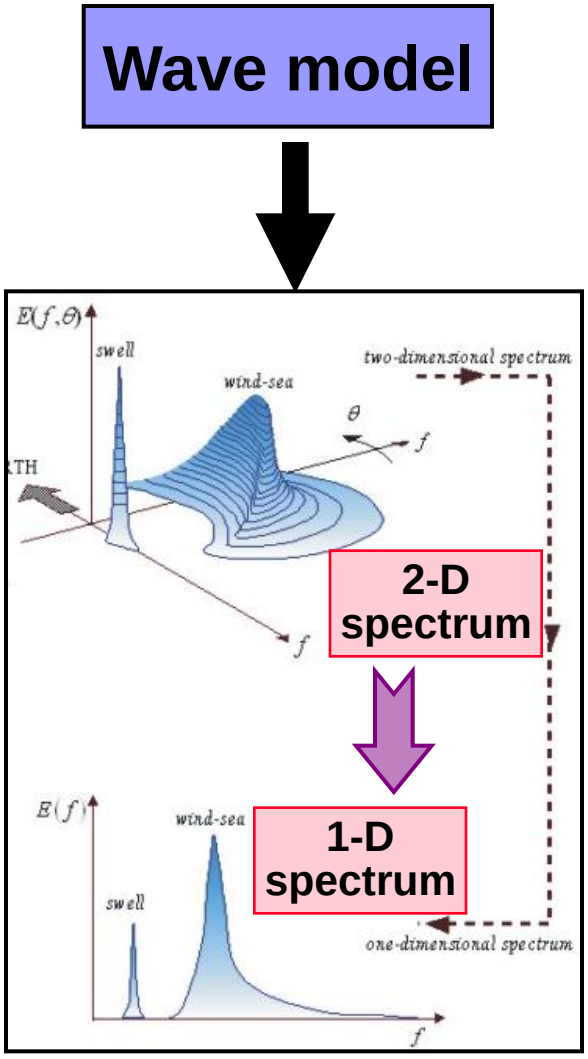
NB: also in seasonal forecast at lower resolutions

Wave Model Products

The complete description of the sea state is given by the 2-D spectrum, however, it is a fairly large amount of data *(e.g. 1296 values at each grid point in the global model (36x36)*.

It is therefore reduced to integrated quantities:

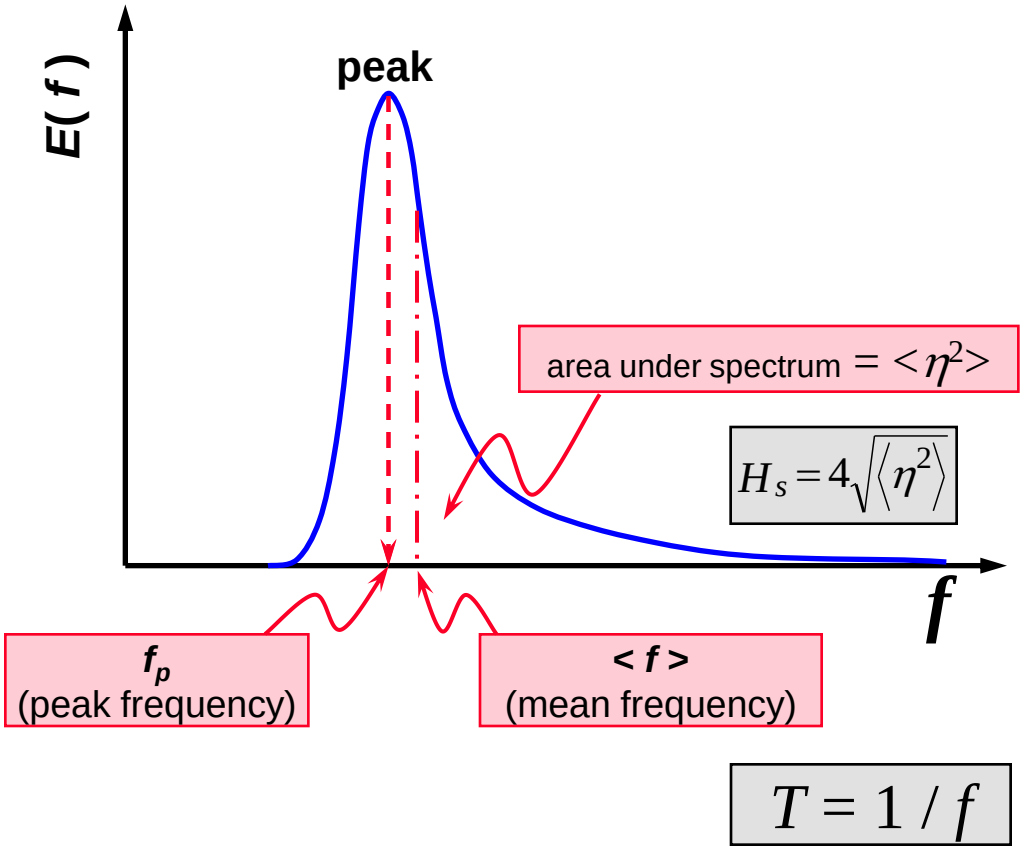
- **1-D spectrum obtained by integrating the 2-D spectrum over all directions and/or over a frequency range.**



Wave Model Products

When simple numbers are required, the following parameters are available:

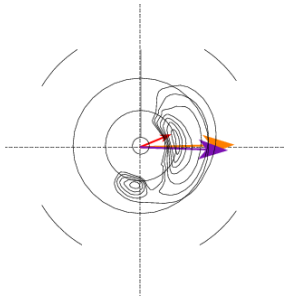
- **The significant wave height (H_s).**
- **The peak period (period of the peak of the 1-D spectrum).**
- **Mean period(s) obtained from weighted integration of the 2-D spectrum.**
- **Integrated mean direction.**
- ***Few others.***



Complete list at: http://www.ecmwf.int/services/archive/d/parameters/order=/table=140/

Wave Model Products

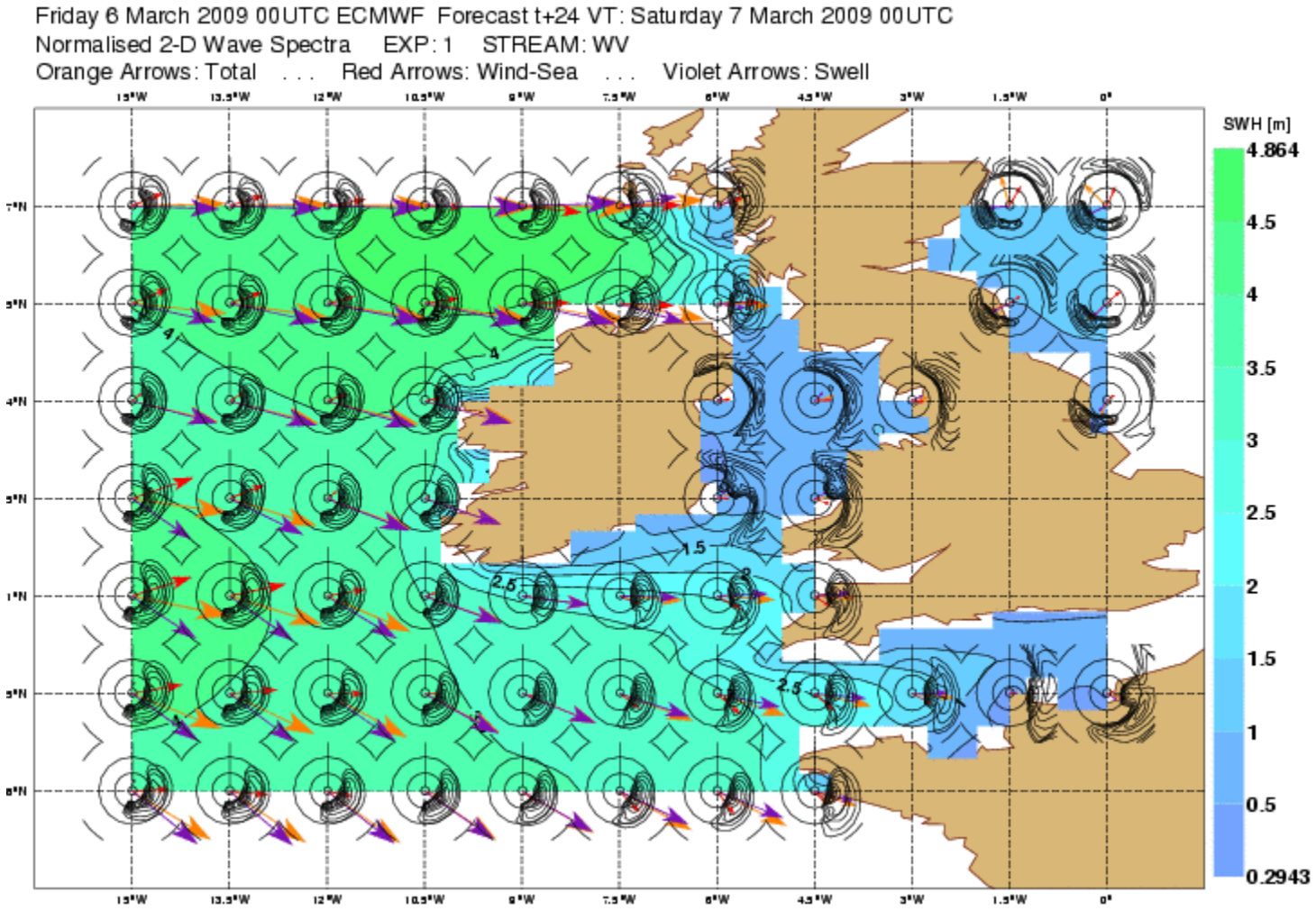
Plot of 2-D spectrum can become very busy !



windsea

swell

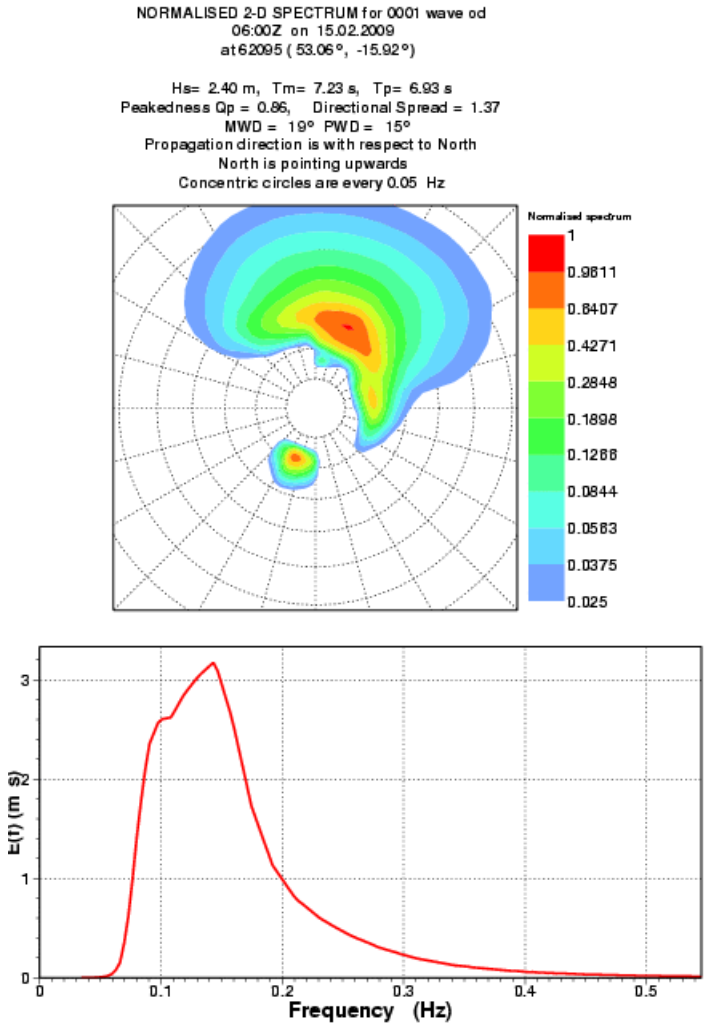
total sea



ECMWF

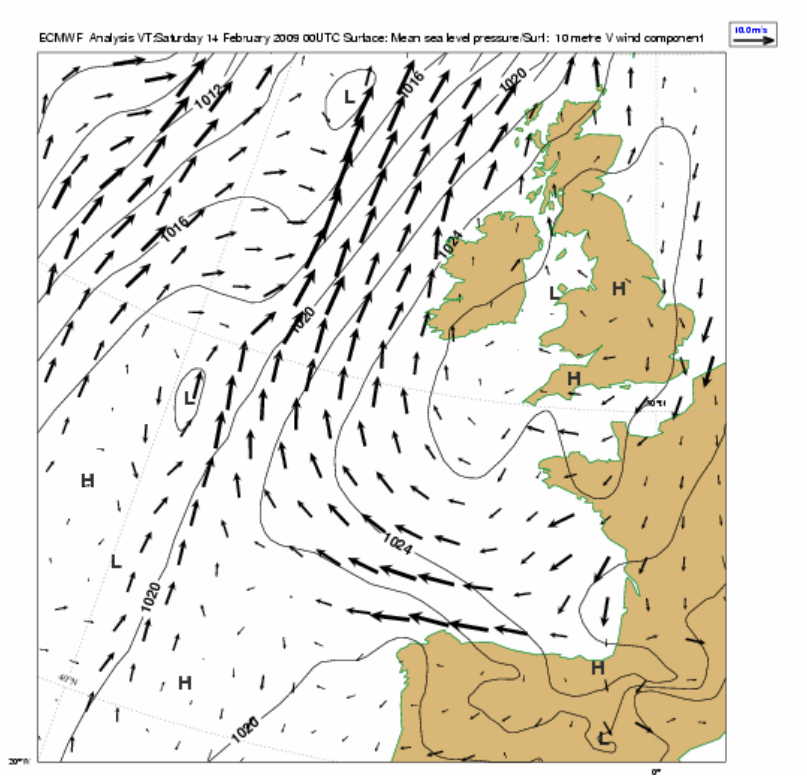
Wave Model Products

Except if you only look at one location …

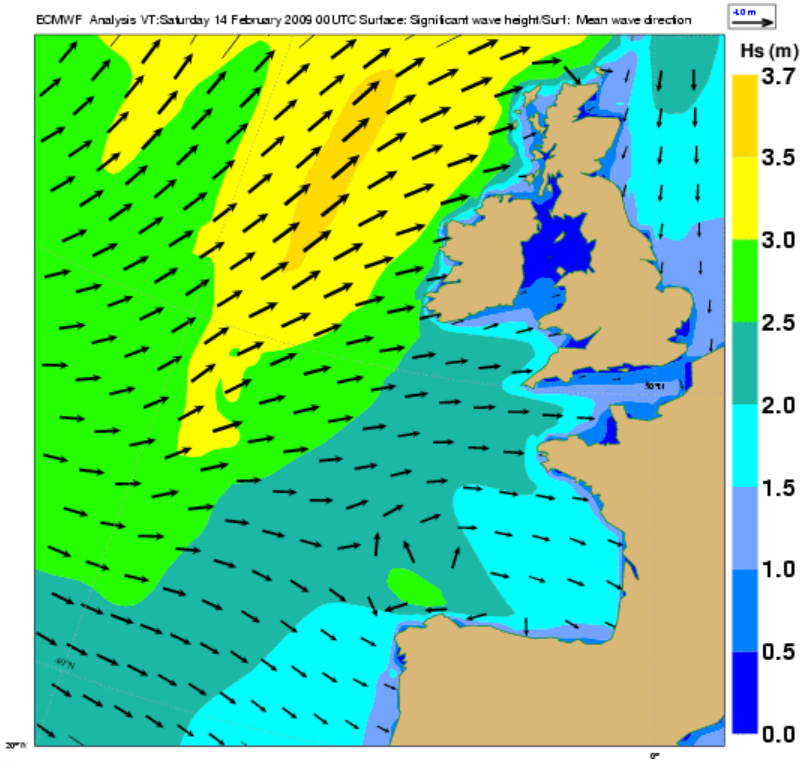


Wave Model Products

Use simple parameters:
total wave height and mean propagation direction

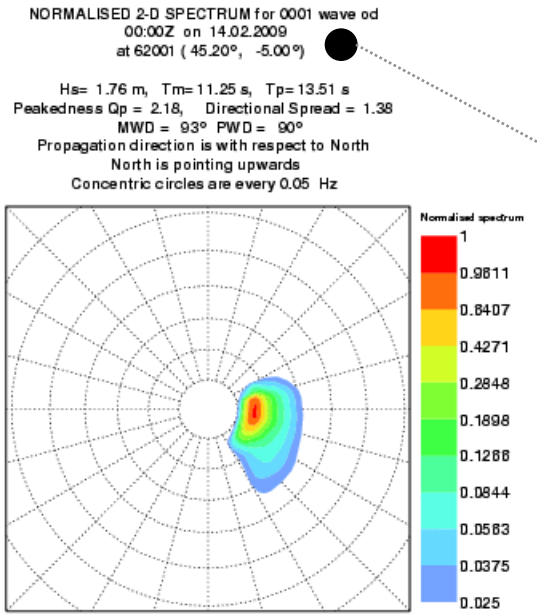


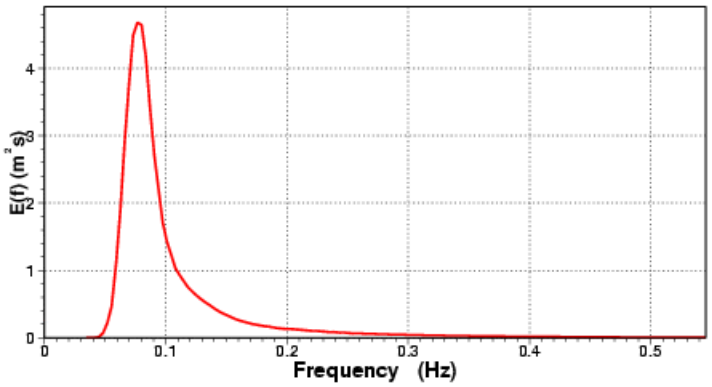
10m winds and mean sea level pressure:
Analysis : 14 February 2009, 00 UTC

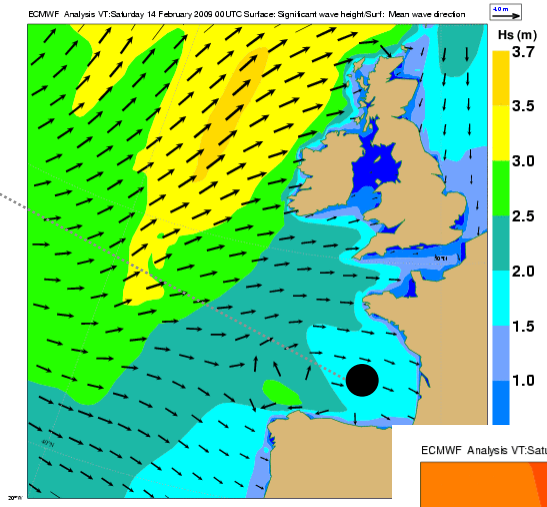


Wave height and mean direction:
Analysis : 14 February 2009, 00 UTC

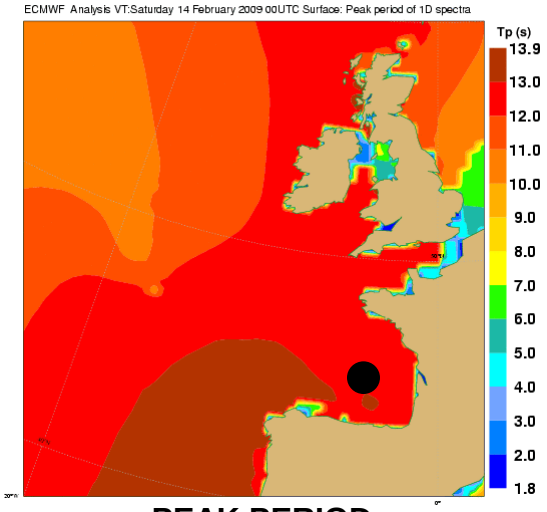
Wave Model Products







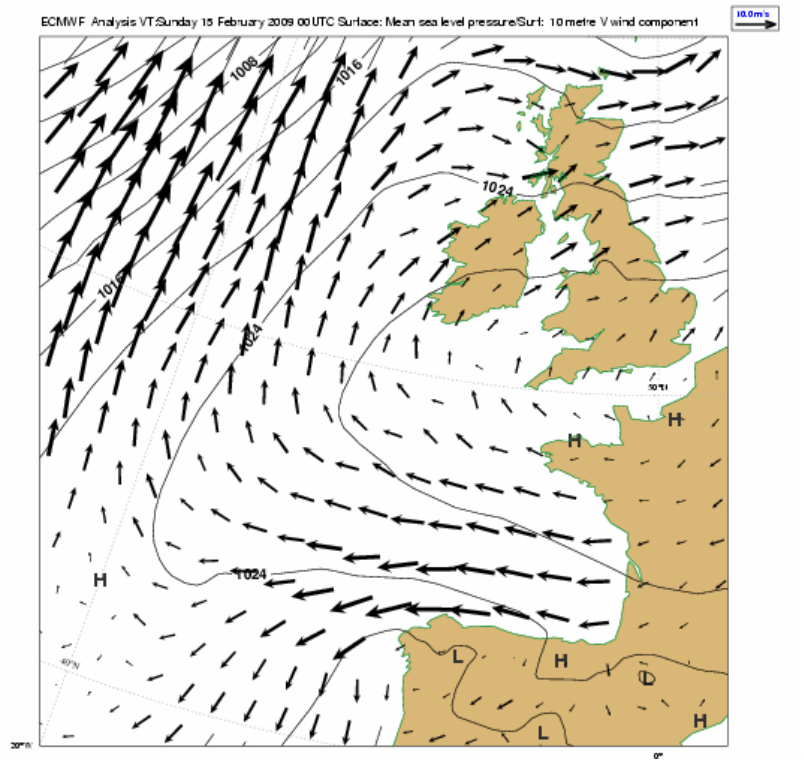
Wave height and me
Analysis : 14 February



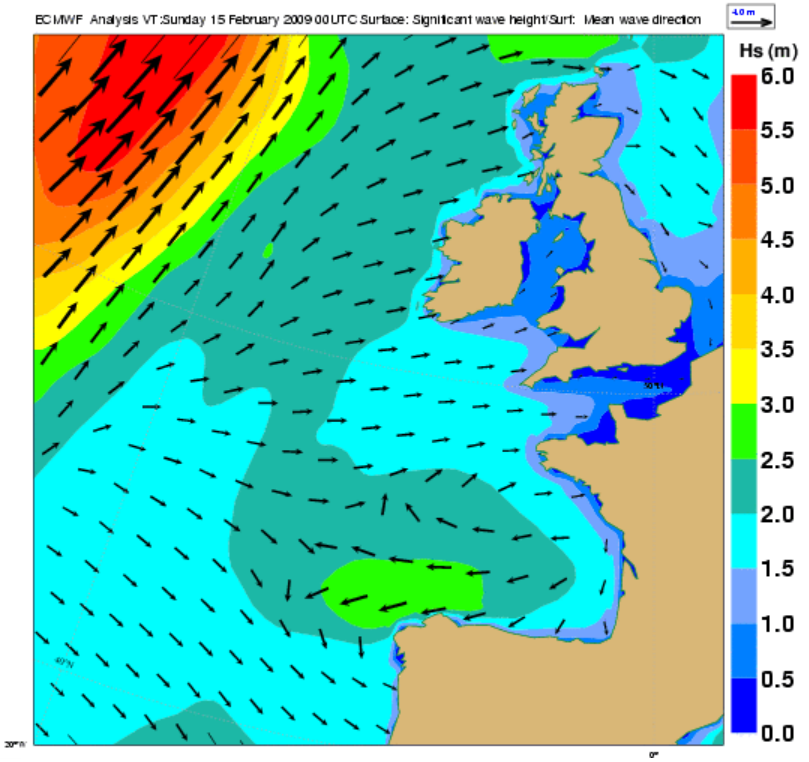
PEAK PERIOD:
Analysis : 14 February 2009, 00 UTC

Wave Model Products

Situation might be more complicated !



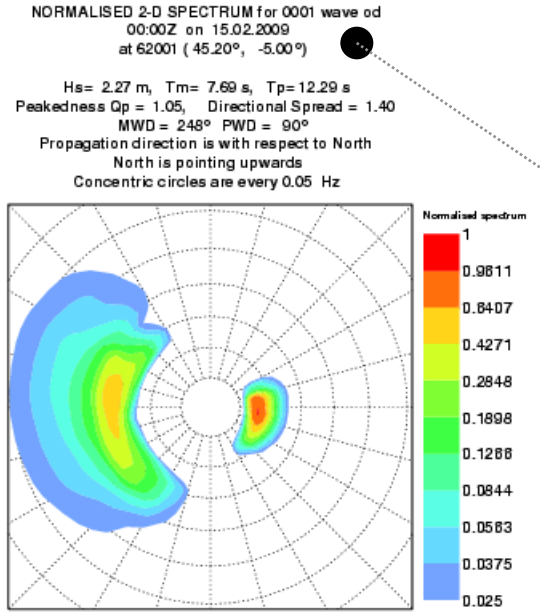
10m winds and mean sea level pressure:
Analysis : 15 February 2009, 00 UTC

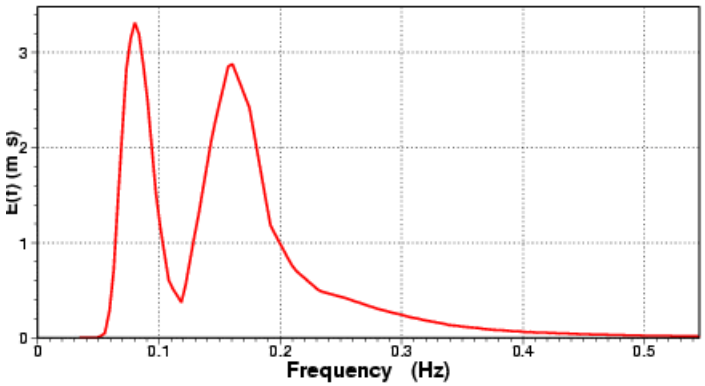


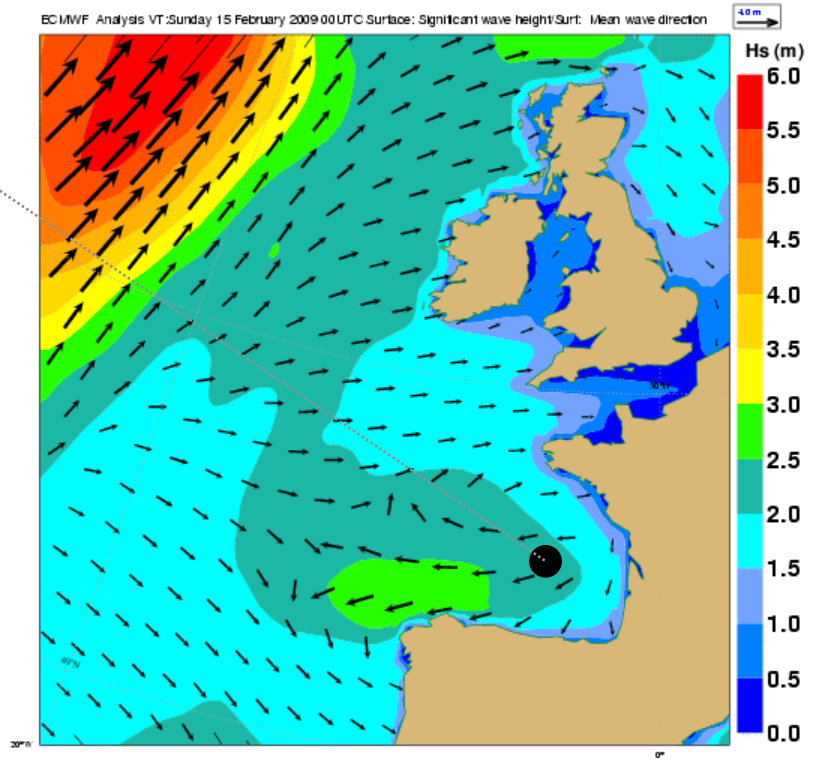
Wave height and mean direction:
Analysis : 15 February 2009, 00 UTC

Wave Model Products

Situation might be more complicated:



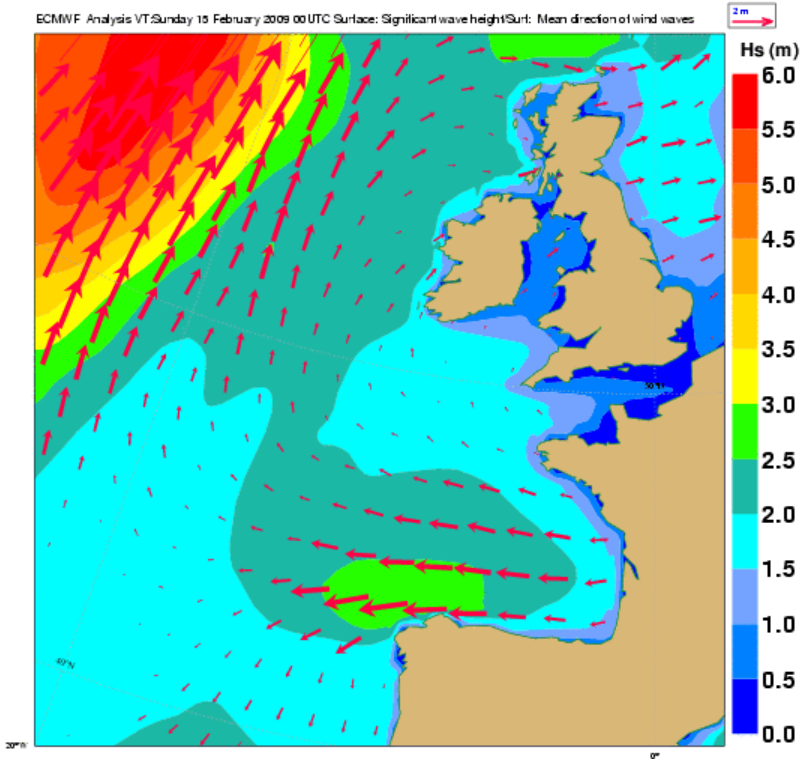




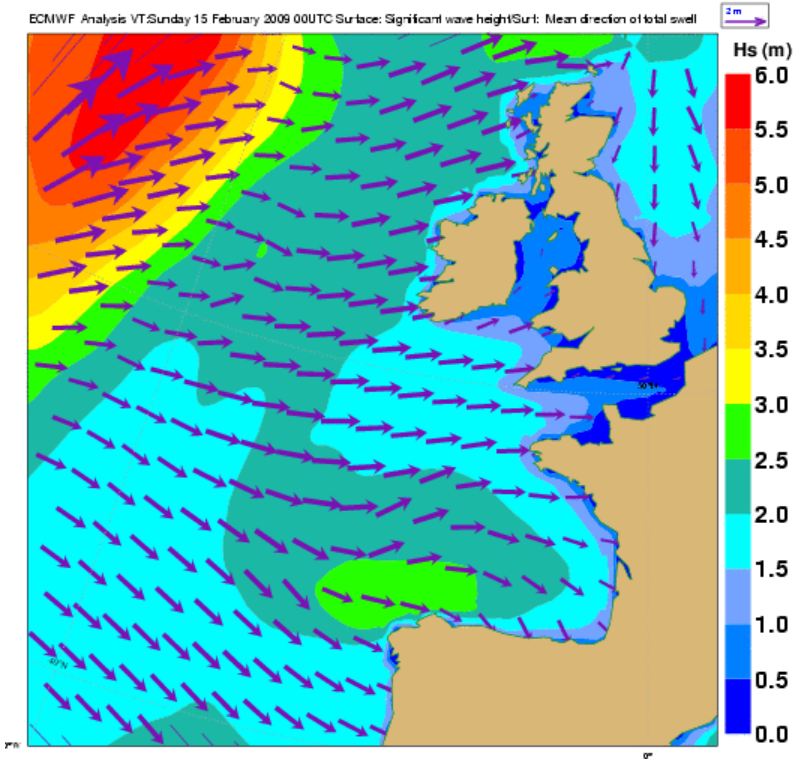
Wave height and mean direction:
Analysis : 15 February 2009, 00 UTC

Wave Model Products

A scheme is used to split the global wave fields into waves which are under the direct influence of the forcing wind, the so-called windsea or wind waves, and those waves that are no longer bound to the forcing wind, generally referred to as swell. Period and mean direction are also determined for these split fields.



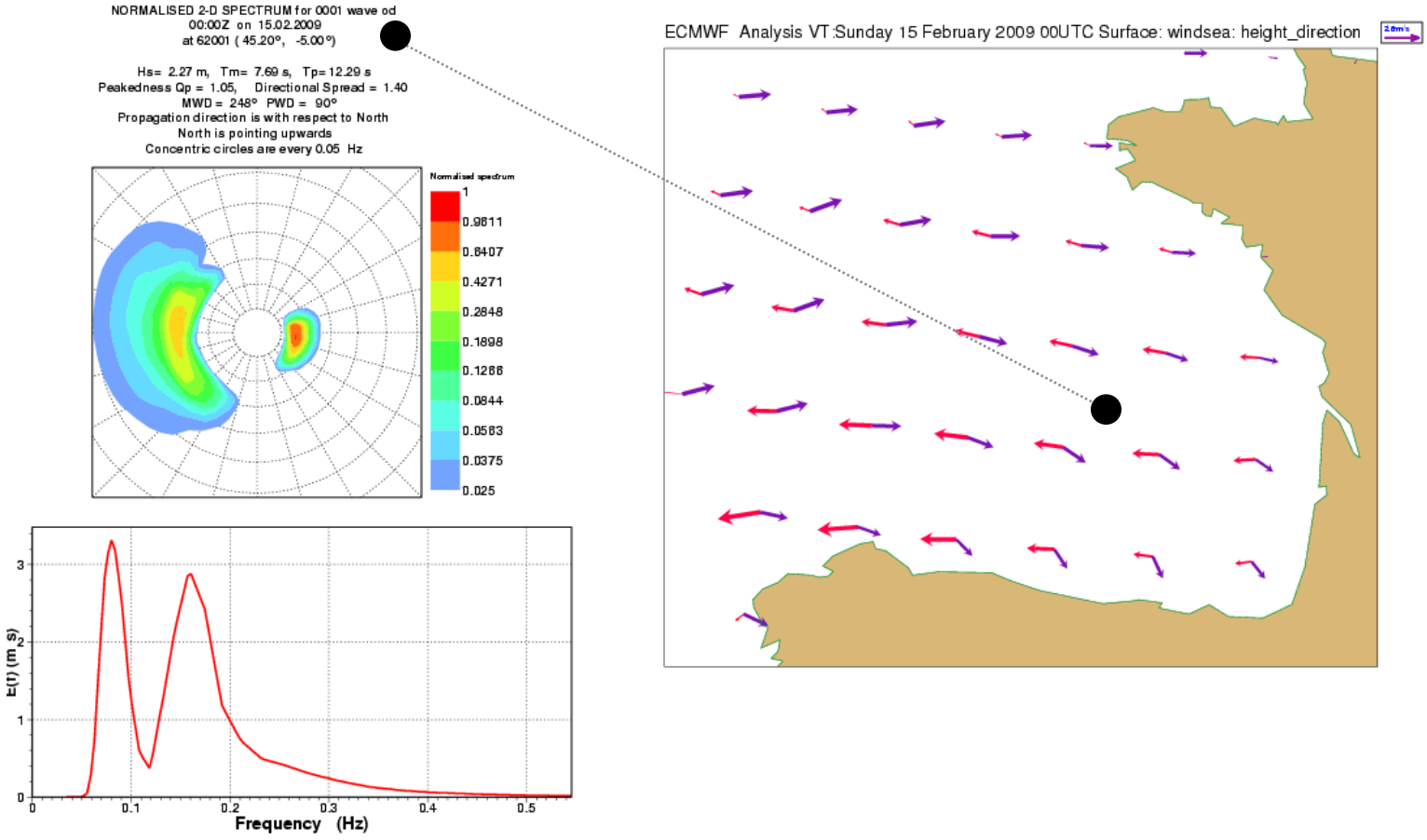
Wave height and windsea mean direction:
Analysis : 15 February 2009, 00 UTC



Wave height and swell mean direction:
Analysis : 15 February 2009, 00 UTC

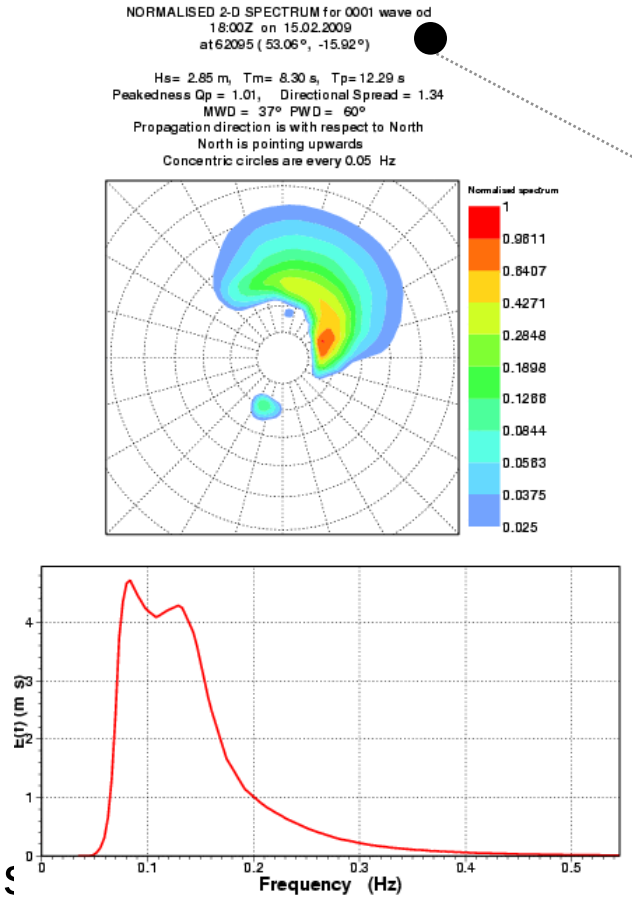
Wave Model Products

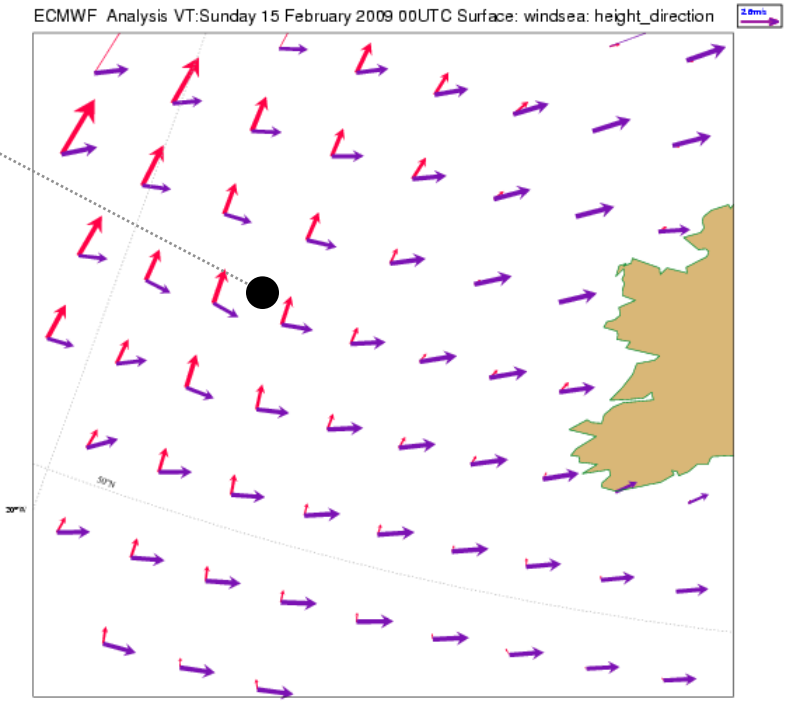
Windsea and swell: opposing sea



Wave Model Products

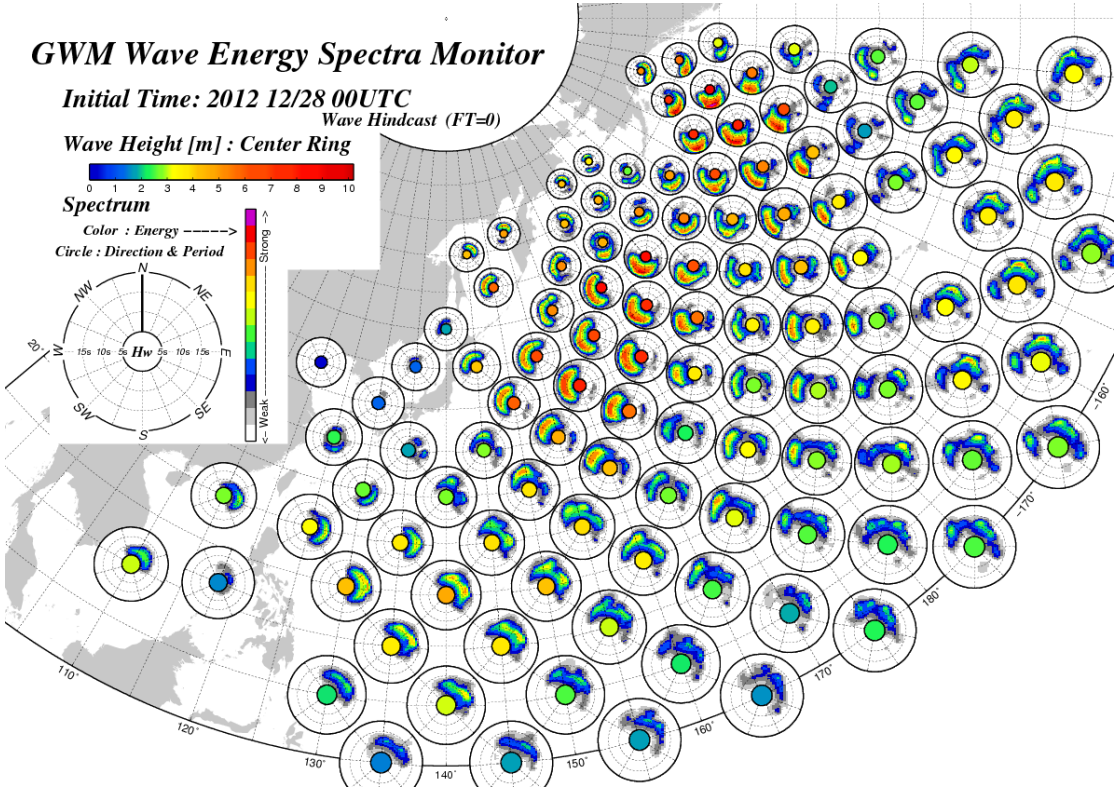
Windsea and swell: cross sea

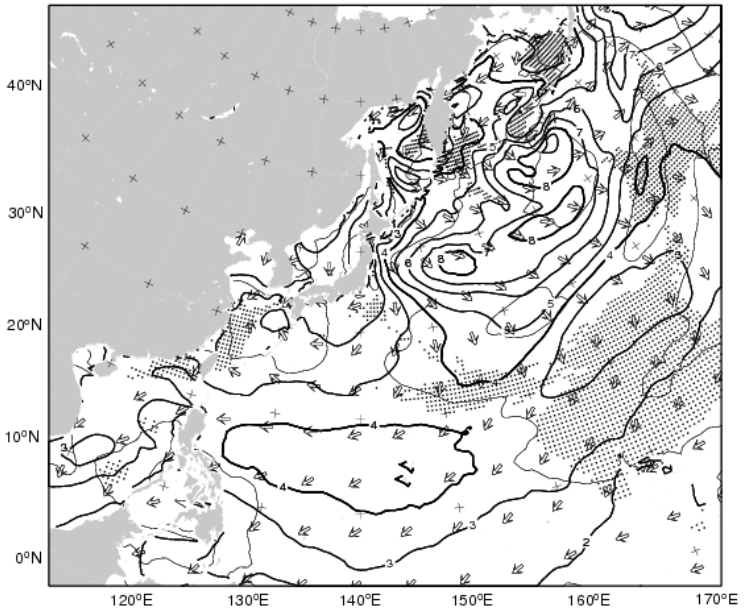




Wave Model Products

yet it has been introduced at JMA to indicate cross sea areas !



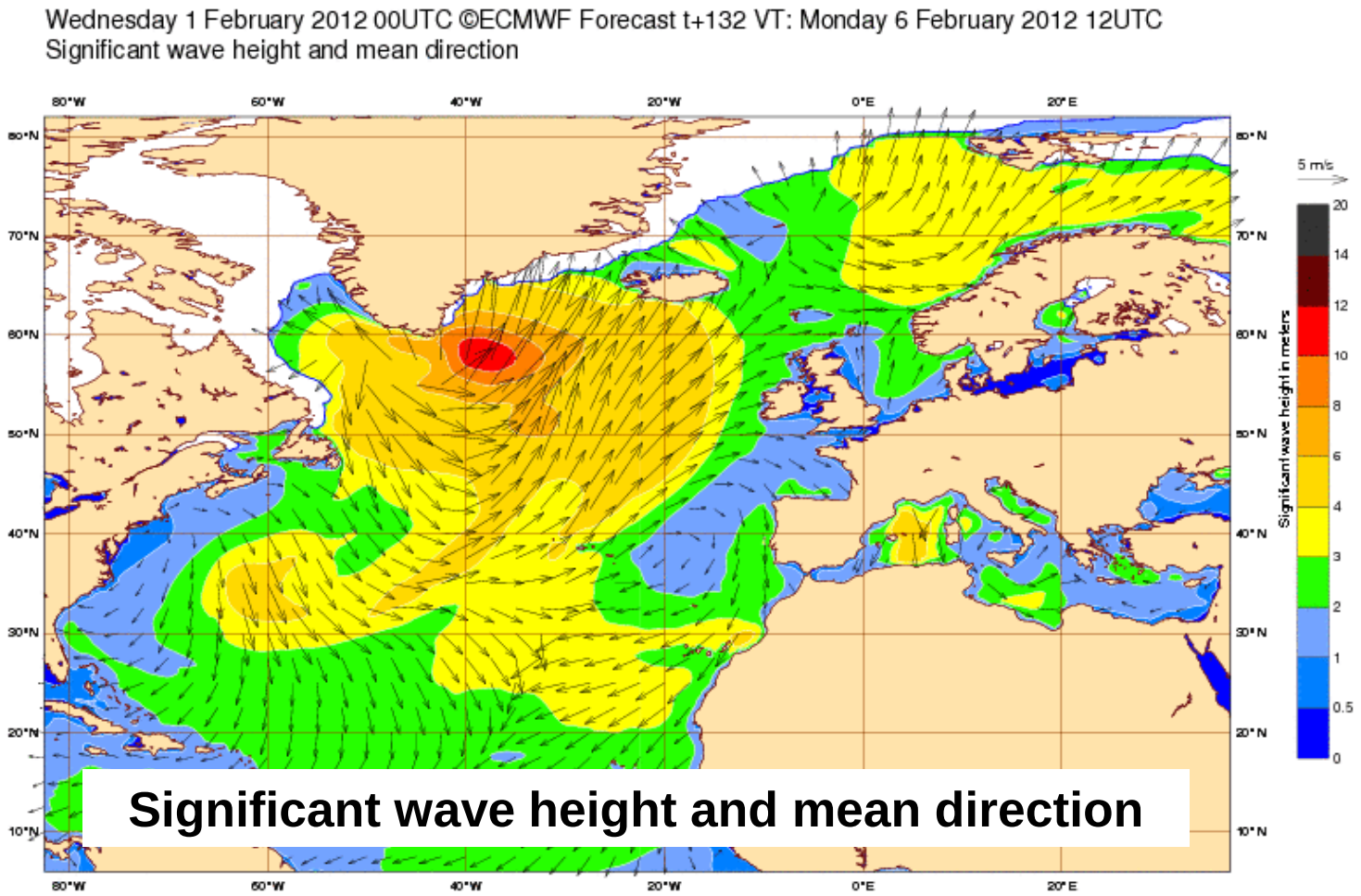


Predicted wave spectrum field (upper) and an image wave map in which crossing area is marked. (Source: JMA)

Wave model deterministic products on the web*

Wave products available <u>by default</u> on the centre's web pages:
(Home -> Products -> Forecasts -> Ocean Wave Forecasts :

http://www.ecmwf.int/products/forecasts/wavecharts/index.html#forecasts

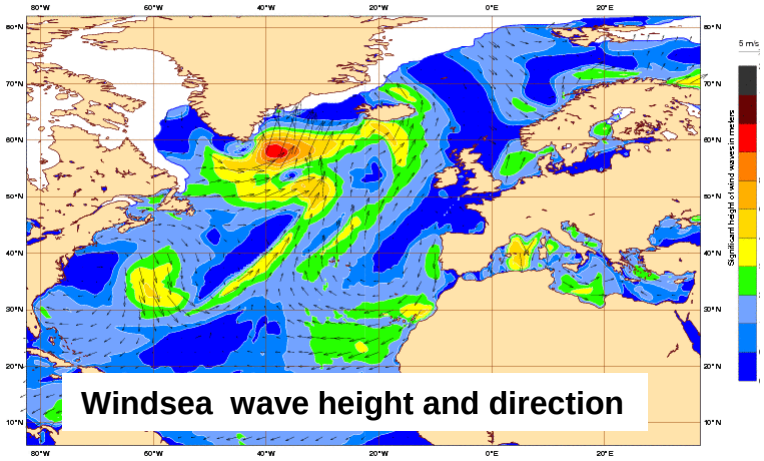


Significant wave height and mean direction

Wave model deterministic products on the web

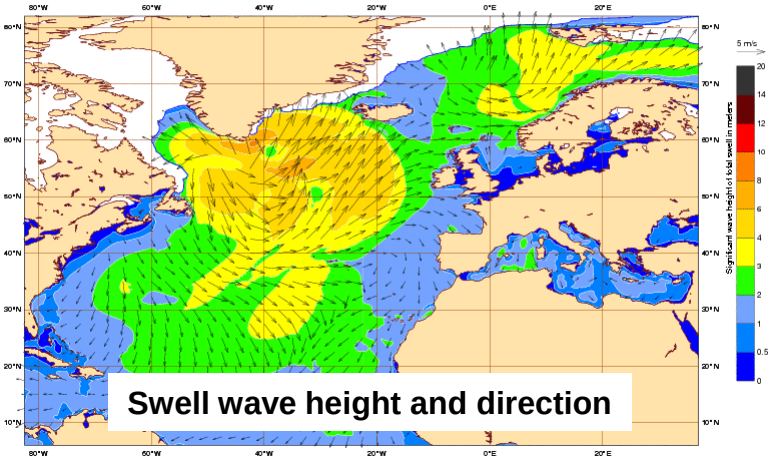
Also windsea and swell plots:

Wednesday 1 February 2012 00UTC ©ECMWF Forecast t+132 VT: Monday 6 February 2012 12UTC
Significant height of wind waves and mean direction



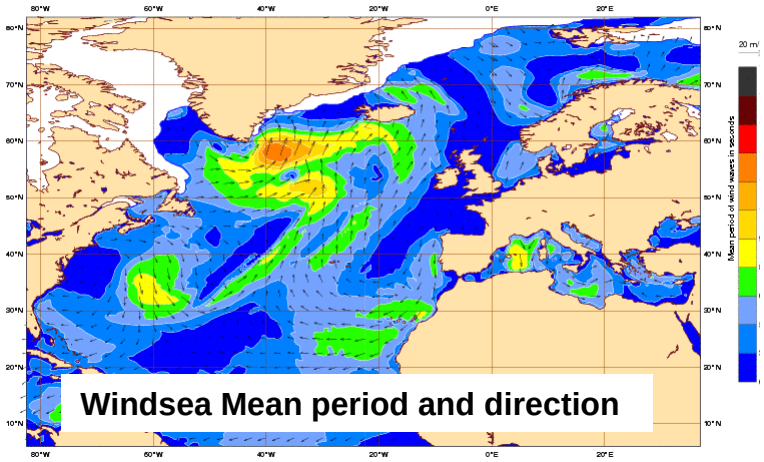
Windsea wave height and direction

Wednesday 1 February 2012 00UTC ©ECMWF Forecast t+132 VT: Monday 6 February 2012 12UTC
Significant wave height of total swell and mean direction



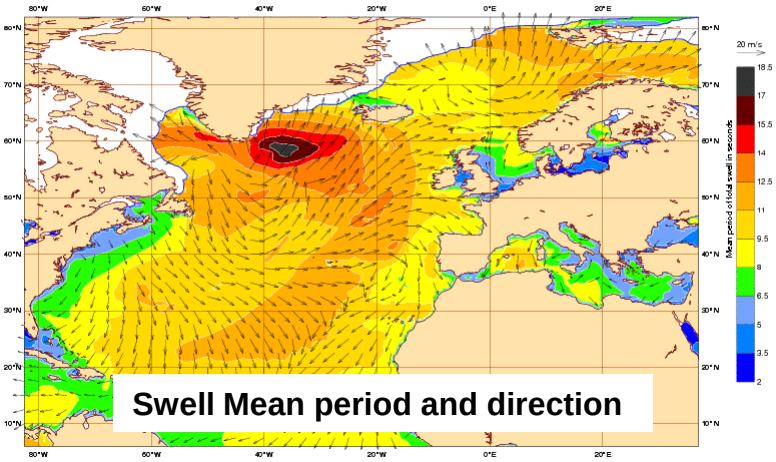
Swell wave height and direction

Wednesday 1 February 2012 00UTC ©ECMWF Forecast t+132 VT: Monday 6 February 2012 12UTC
Mean period of wind waves and direction



Windsea Mean period and direction

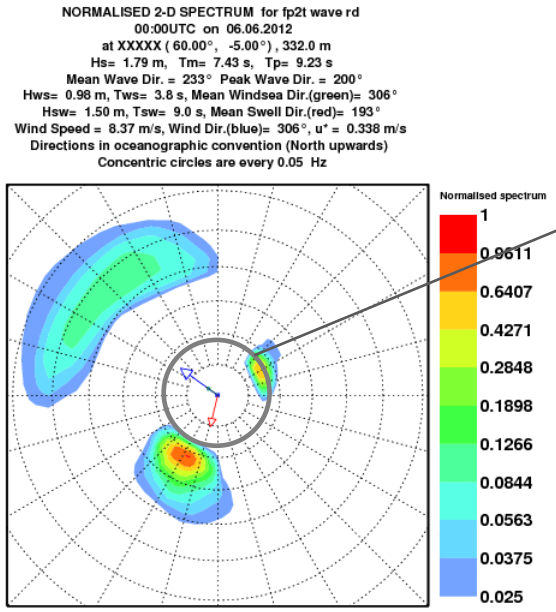
Wednesday 1 February 2012 00UTC ©ECMWF Forecast t+132 VT: Monday 6 February 2012 12UTC
Mean period of total swell and direction

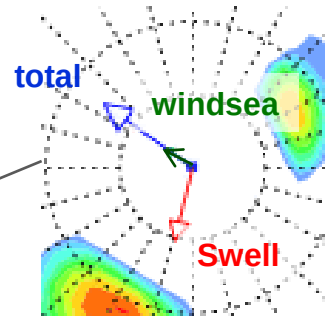


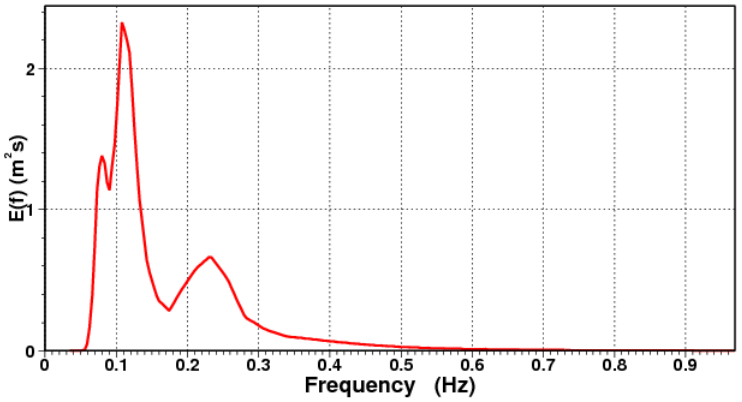
Swell Mean period and direction

spectral partitioning

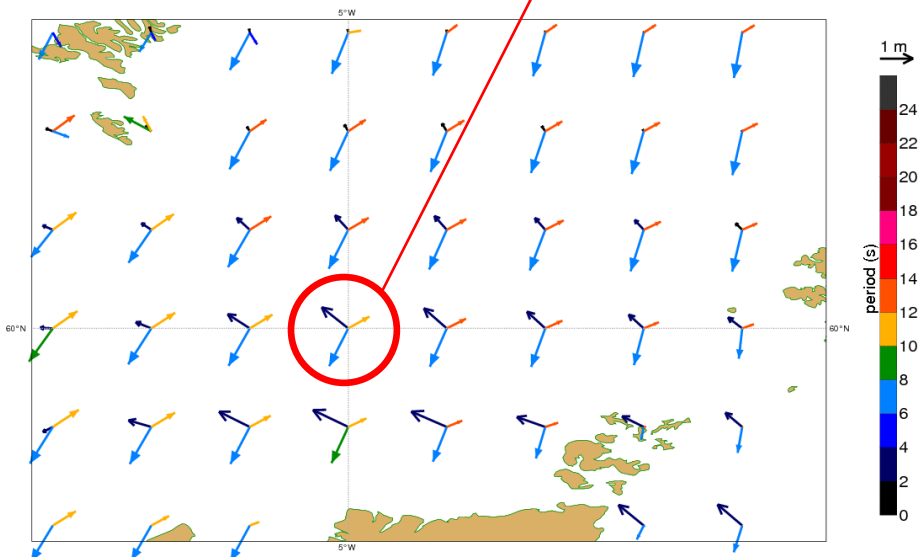
Operational:







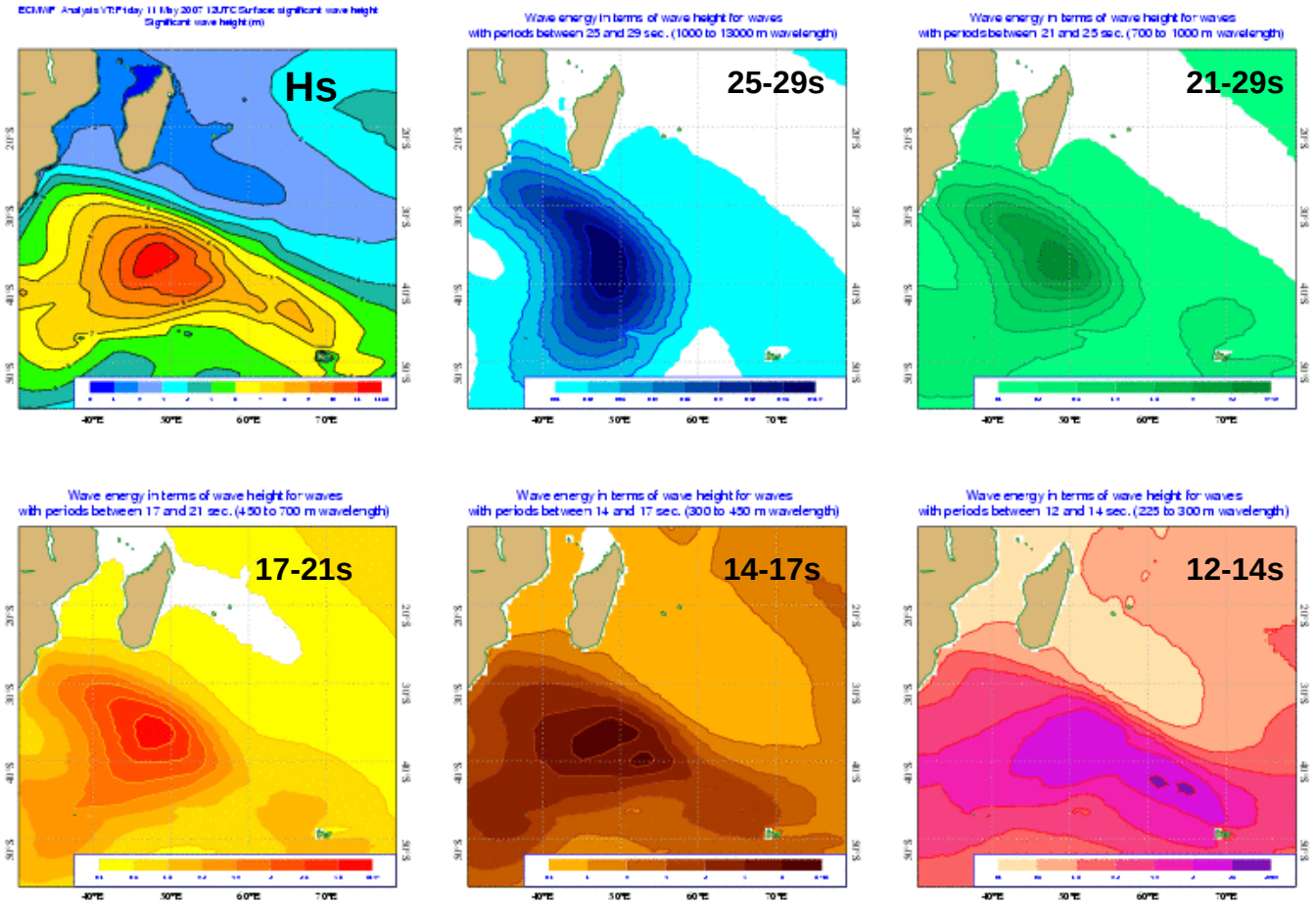
New decomposition:



Can we derive more information from the wave spectra?

Significant wave height and low frequency wave energy propagation, as derived by integrating the 2d spectra over directions and frequency bands (shown here in terms of equivalent wave height)

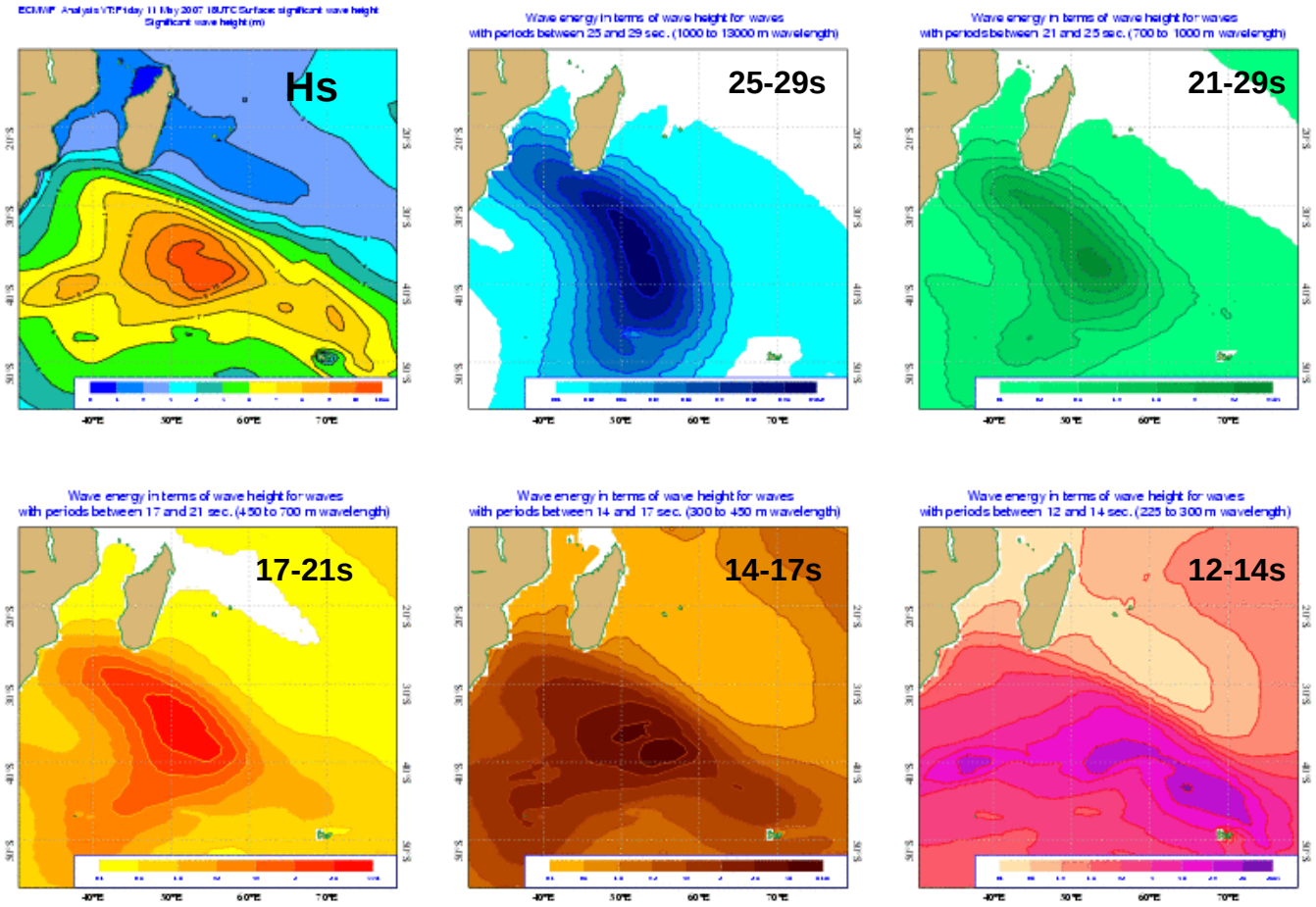
11 May, 2007, 12 UTC



Large swell reaching la Réunion: Can we derive more information from the wave spectra?

Significant wave height and low frequency wave energy propagation, as derived by integrating the 2d spectra over directions and frequency bands (shown here in terms of equivalent wave height)

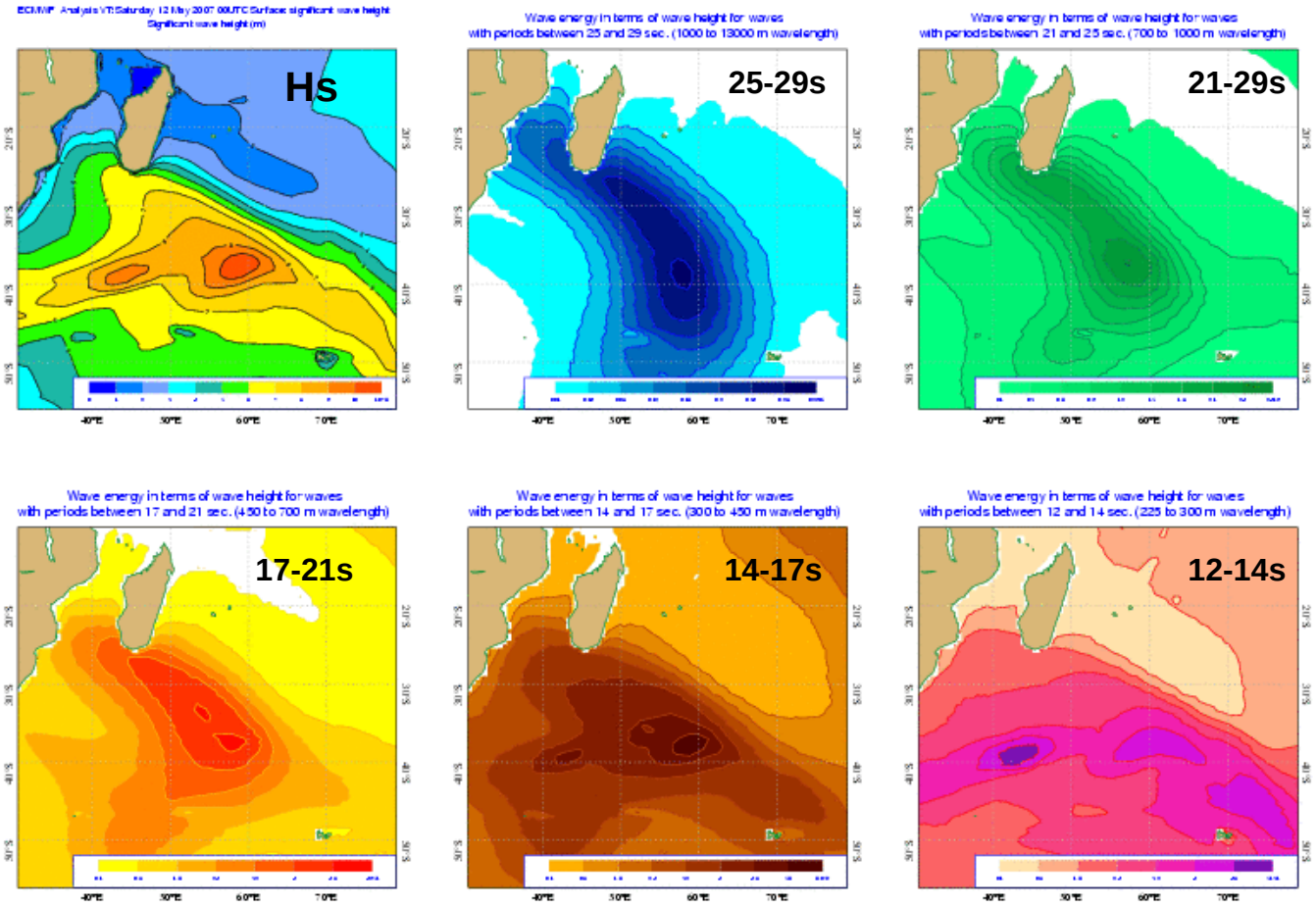
11 May, 2007, 18 UTC



Large swell reaching la Réunion: Can we derive more information from the wave spectra?

Significant wave height and low frequency wave energy propagation, as derived by integrating the 2d spectra over directions and frequency bands (shown here in terms of equivalent wave height)

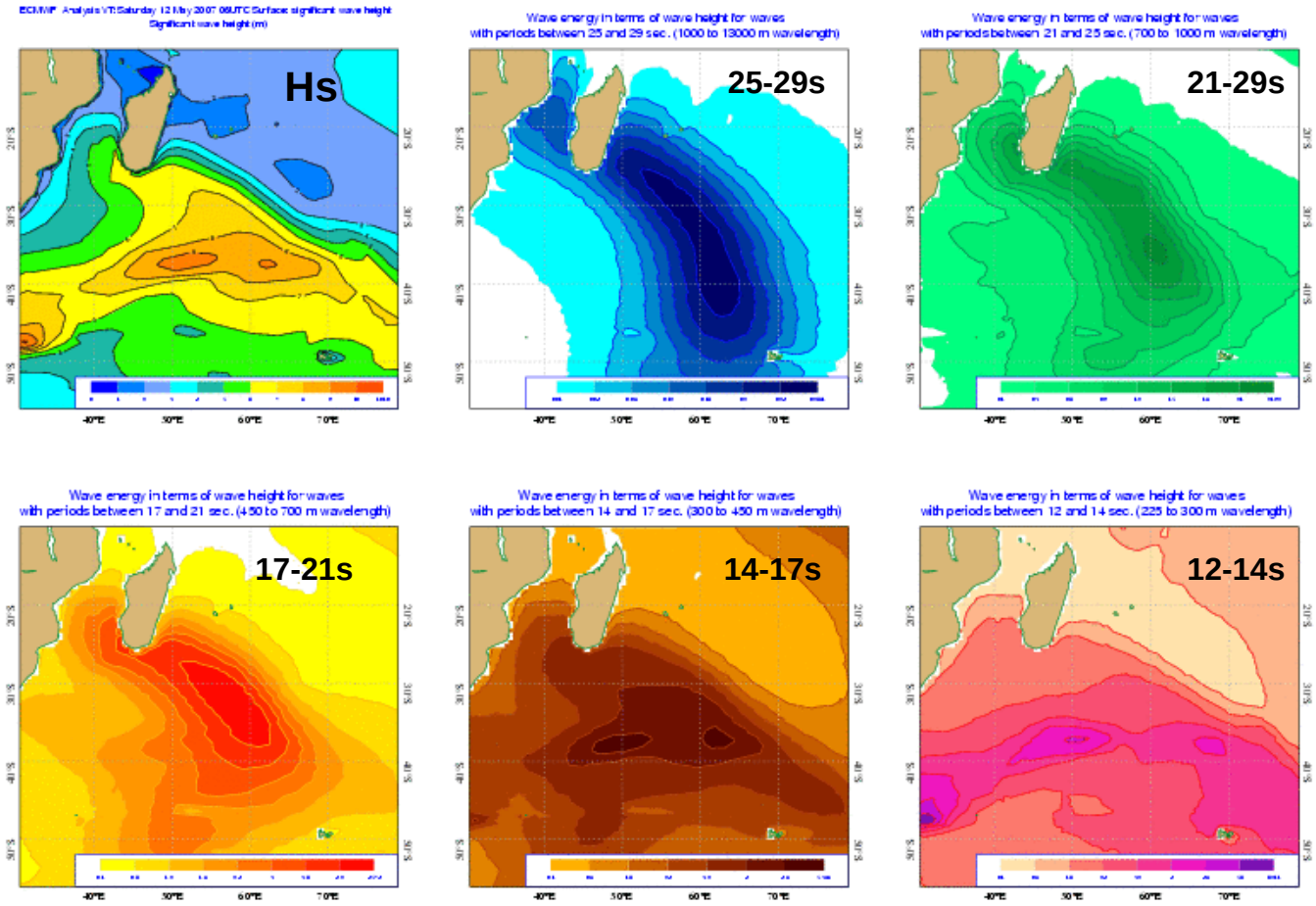
12 May, 2007, 0 UTC



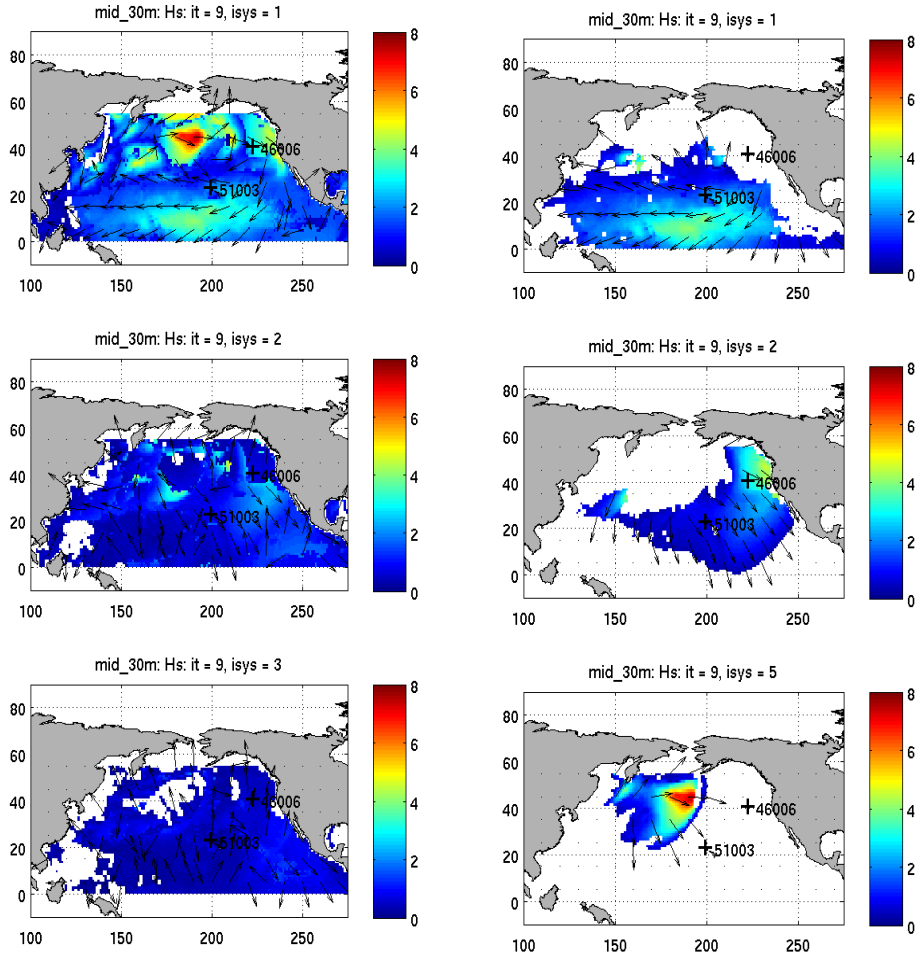
Large swell reaching la Réunion: Can we derive more information from the wave spectra?

Significant wave height and low frequency wave energy propagation, as derived by integrating the 2d spectra over directions and frequency bands (shown here in terms of equivalent wave height)

12 May, 2007, 6 UTC

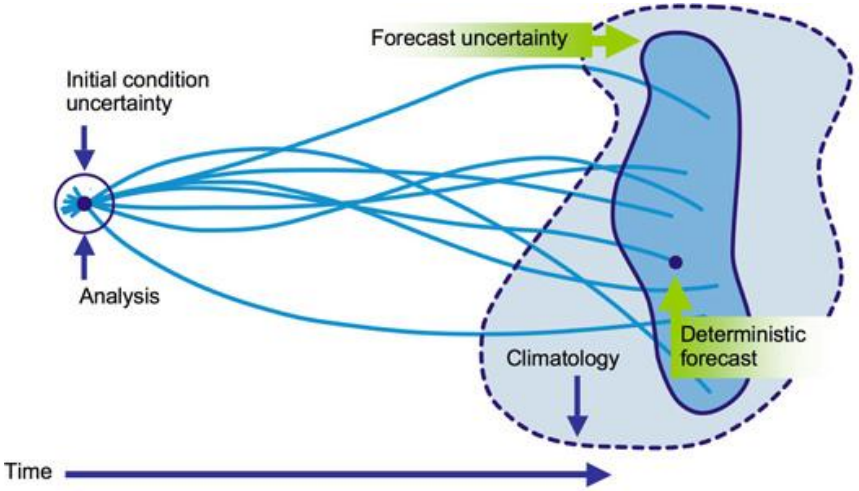


spectral partitioning



Transformation of topographically partitioned North Pacific significant wave height data (left) into systems (right) by NCEP's swell tracking routine. (Source: NCEP).

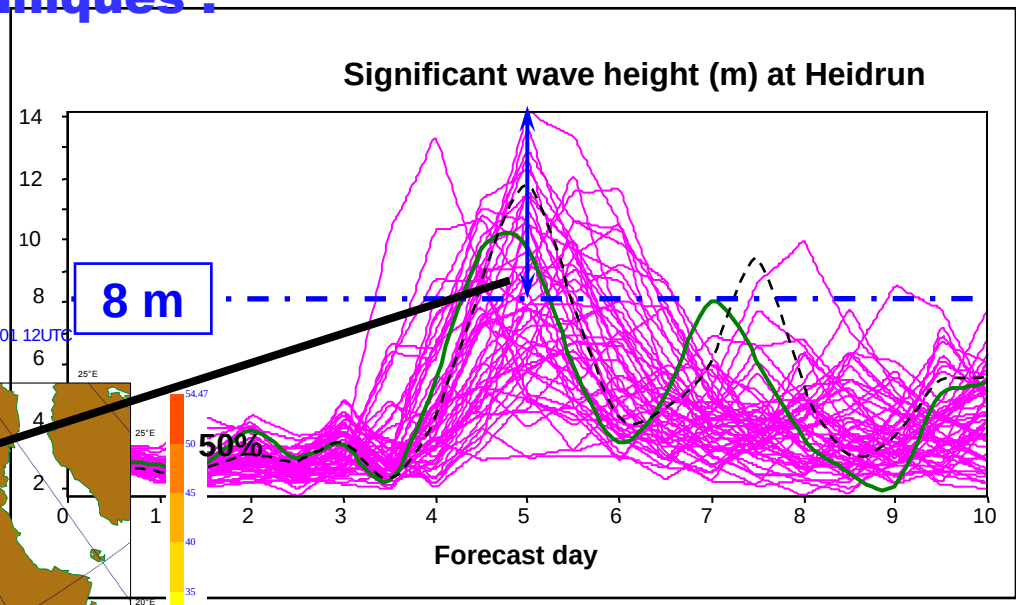
Ensemble forecasting:

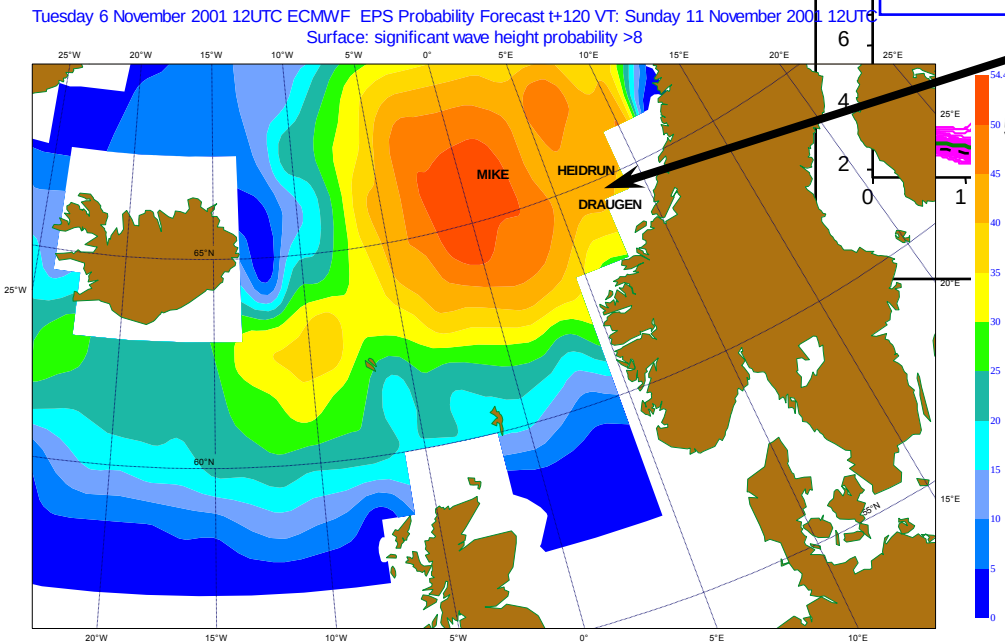


Click here if you know what ensemble forecasting means:

So far, everything has been presented as output from the deterministic forecast system. BUT, forecast should actually be more probabilistic. Nowadays, weather centres rely on ensemble techniques :

From an ensemble of wave forecasts it is possible to derive probabilities for certain wave conditions.





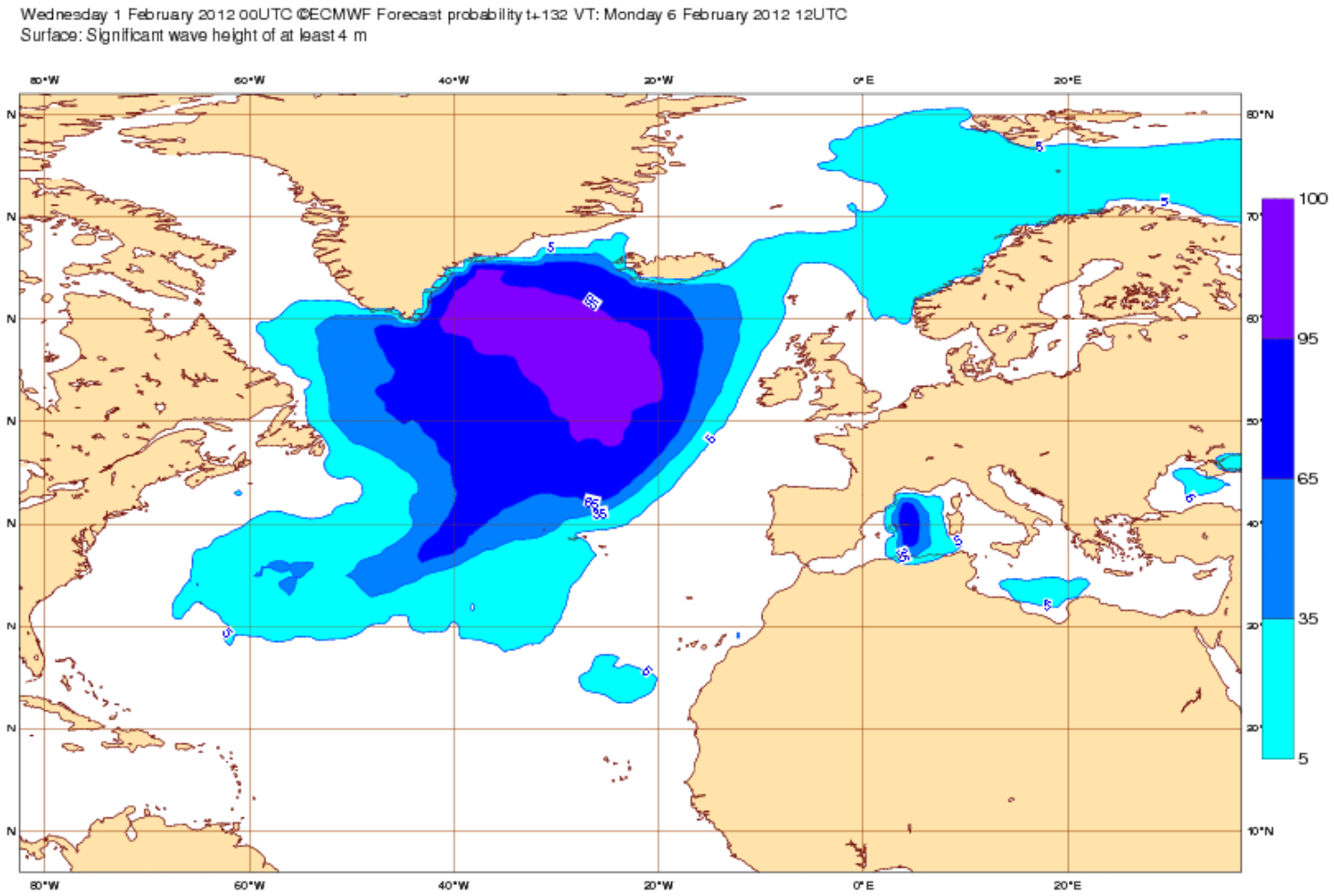
06 Nov. 2001 12 UTC ECMWF EPS probability forecast t+120

Significant wave height above 8 m

ECMWF Newsletter 95 – Autumn 2002

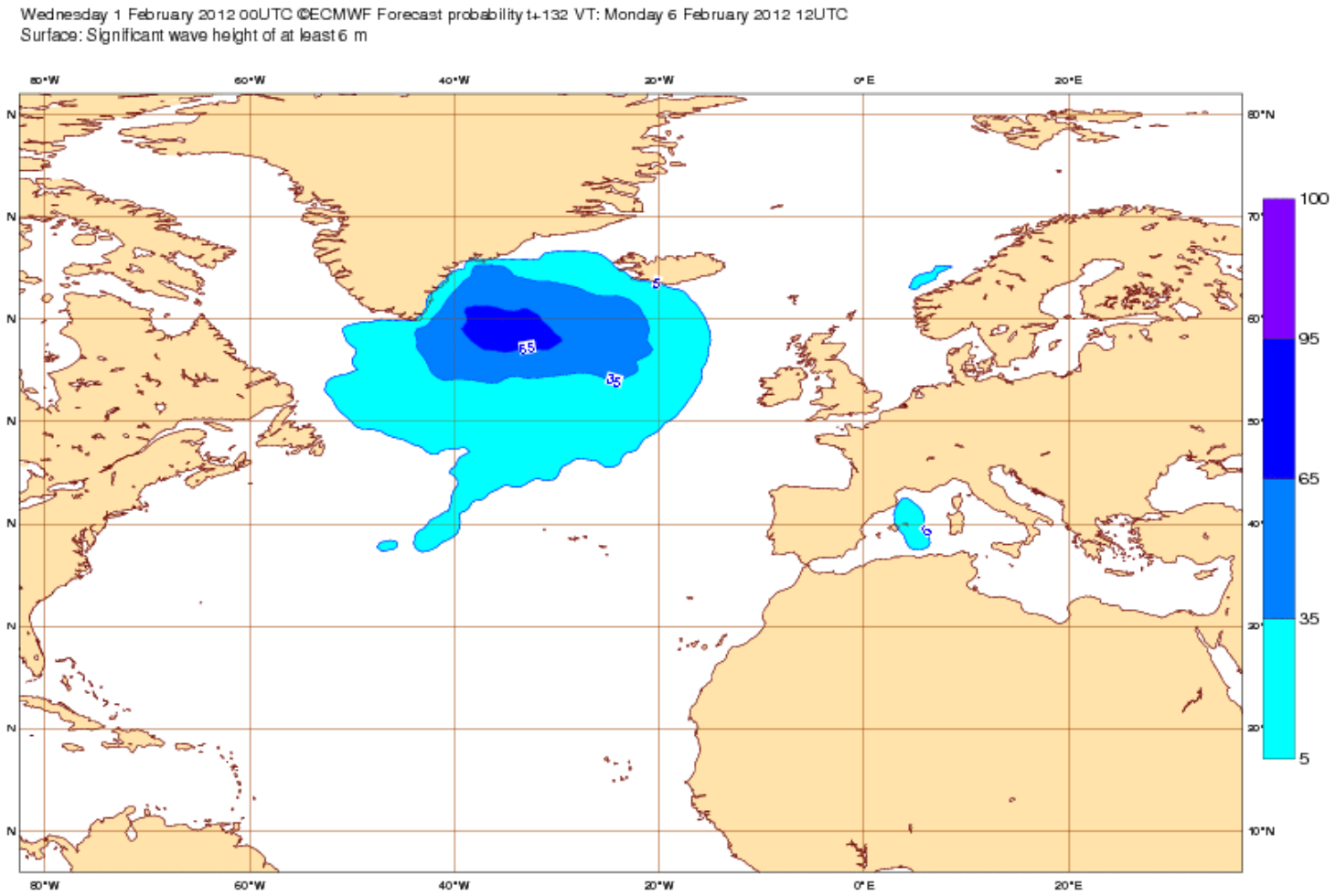
Basic EPS Wave Model Products

probability for set thresholds (4m)



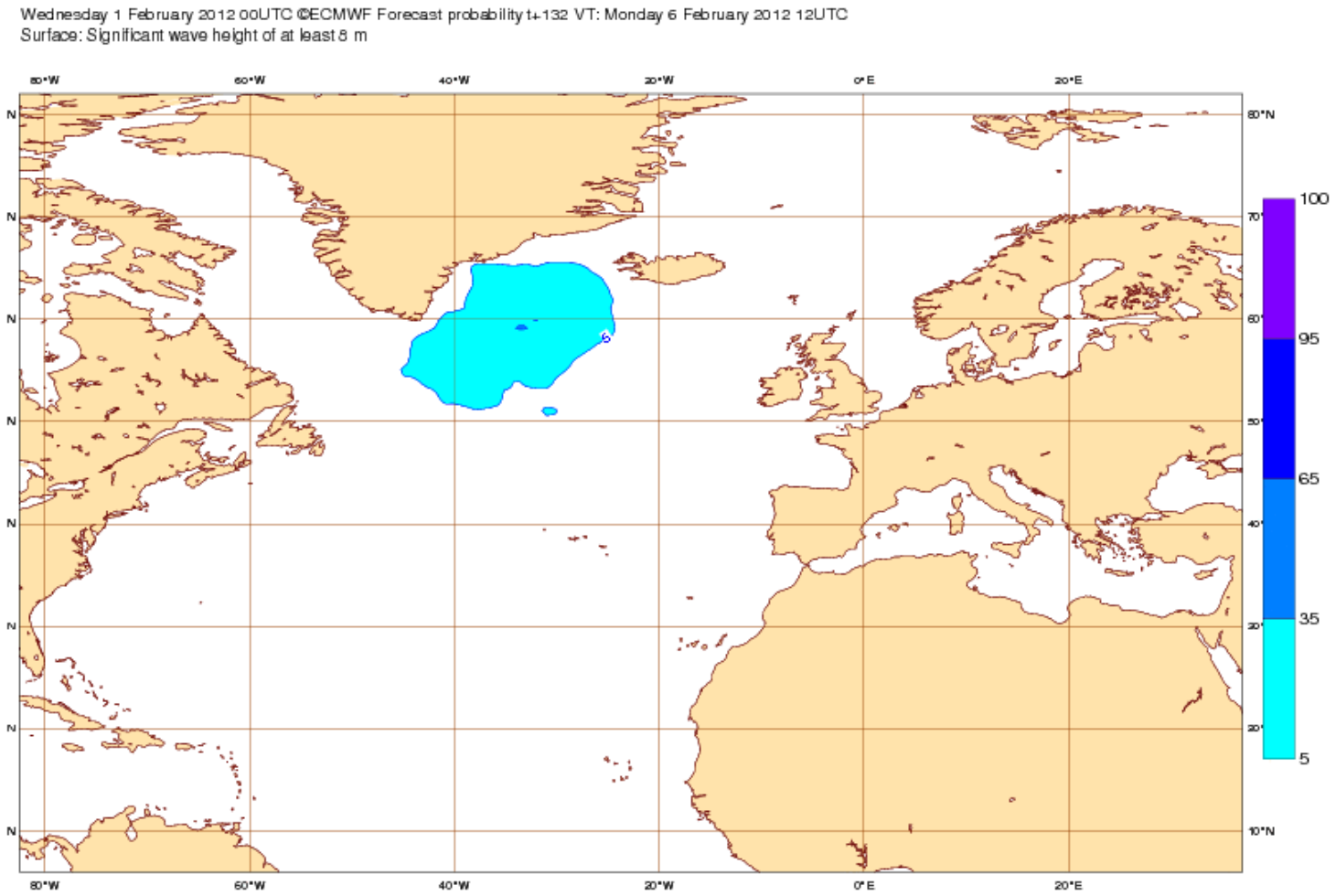
Basic EPS Wave Model Products

probability for set thresholds (6m)

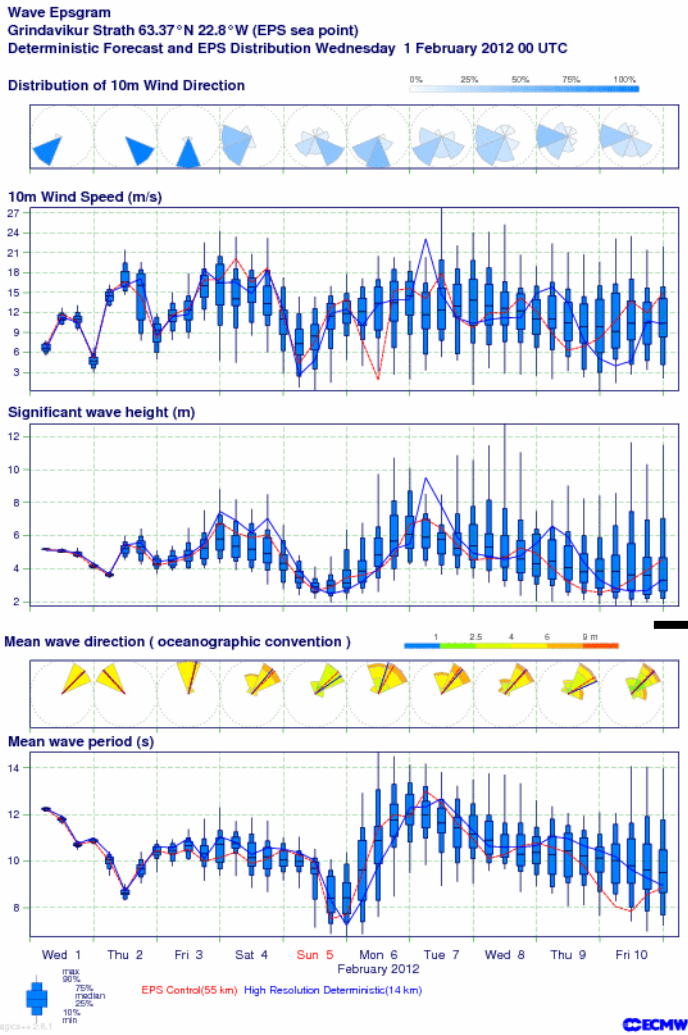


Basic EPS Wave Model Products

probability for set thresholds (8m)

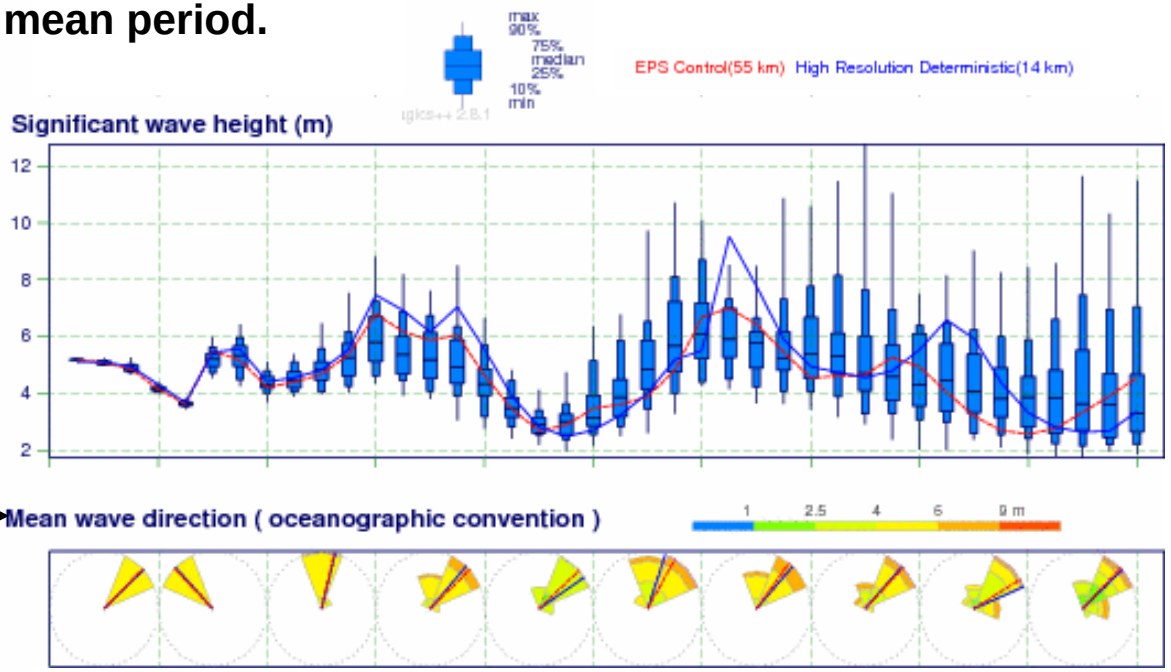


A bit more compact: Wave EPSgram:



South of Grindavik, Iceland

Like normal EPSgram but for wind direction, wind speed, significant wave height, mean wave direction and mean period.

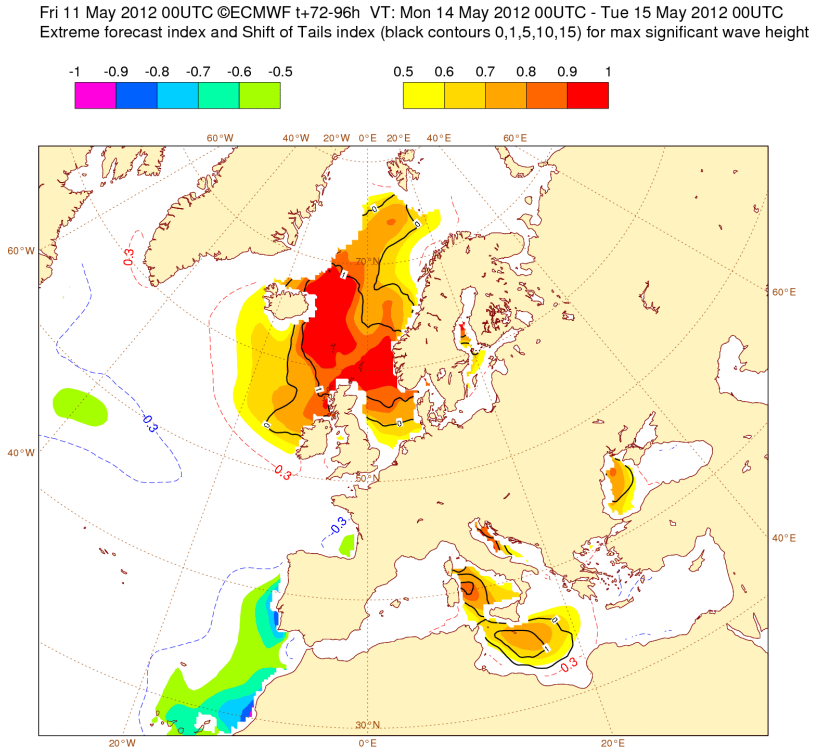


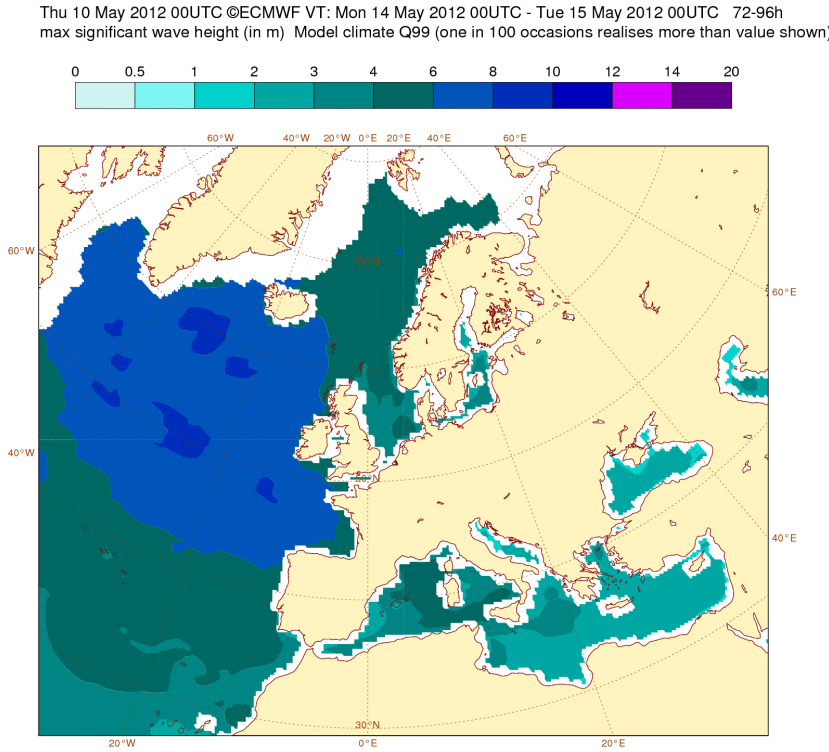
Each octant is coloured based on the distribution of the significant wave height associated with each mean direction. The coloured areas correspond to the fractional number of ensemble members with wave height in the range specified by the coloured ruler.

Since June 2012 : new set of EFI plots

From the new model climate, it is possible to derive indices that indicate deviations in probabilistic terms from what is 'expected'.

Extreme Forecast Index (EFI): 1 means that all EPS are above climate.

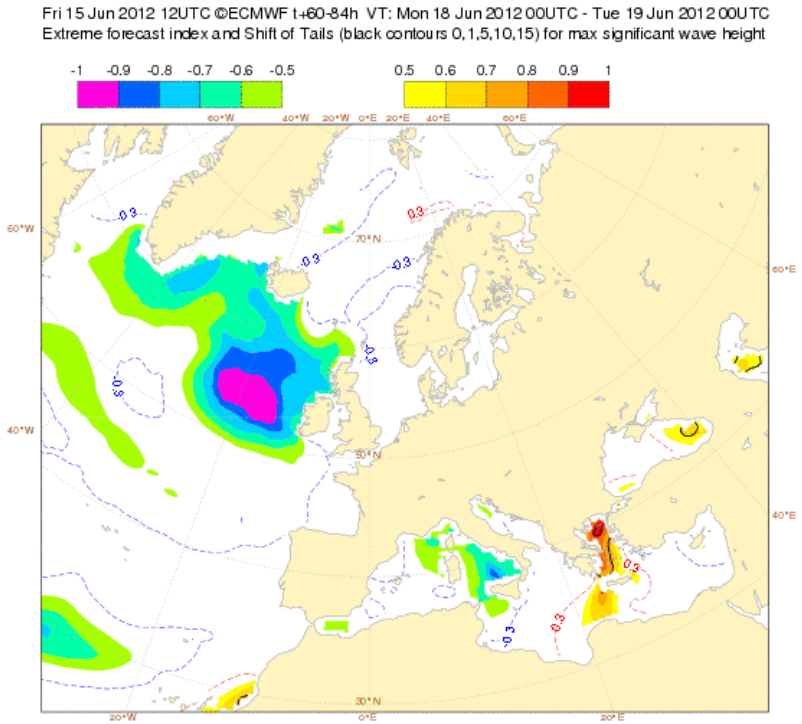


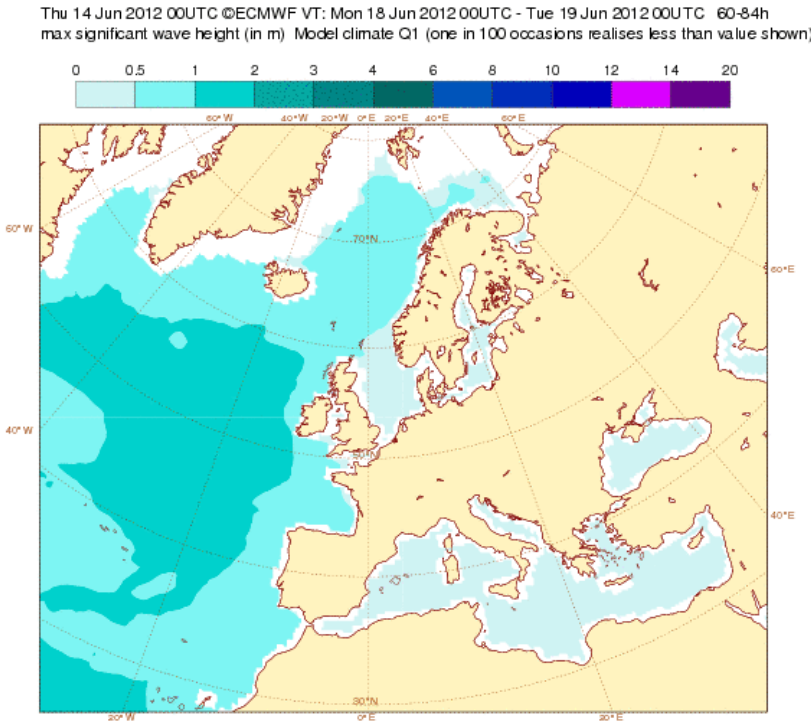


Since June 2012 : new set of EFI plots

From the new model climate, it is possible to derive indices that indicate deviations in probabilistic terms from what is 'expected'.

Extreme Forecast Index (EFI): -1 means that all EPS are below climate.

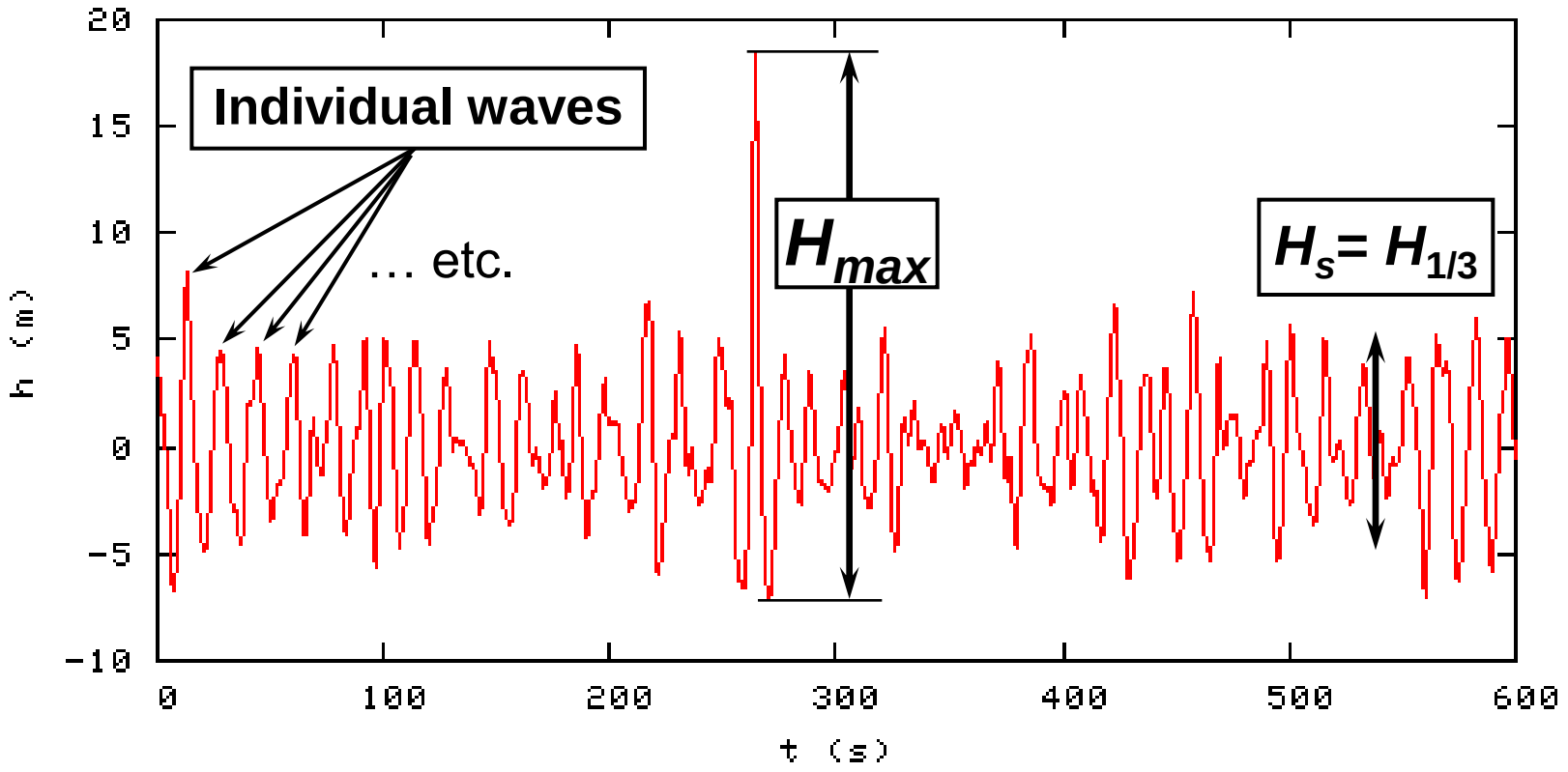




We are not always dealing with nice ‘predictable’ waves:

Click here if you have ever experienced such a freak wave:

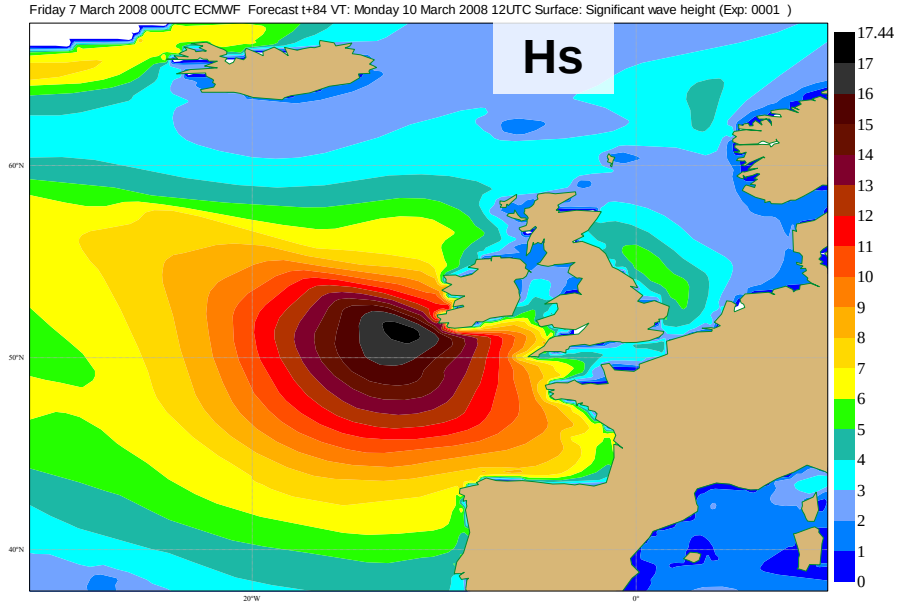
Individual Waves, Significant Wave Height, H_s, Maximum Individual Wave Height, H_{max}, and Freak Wave

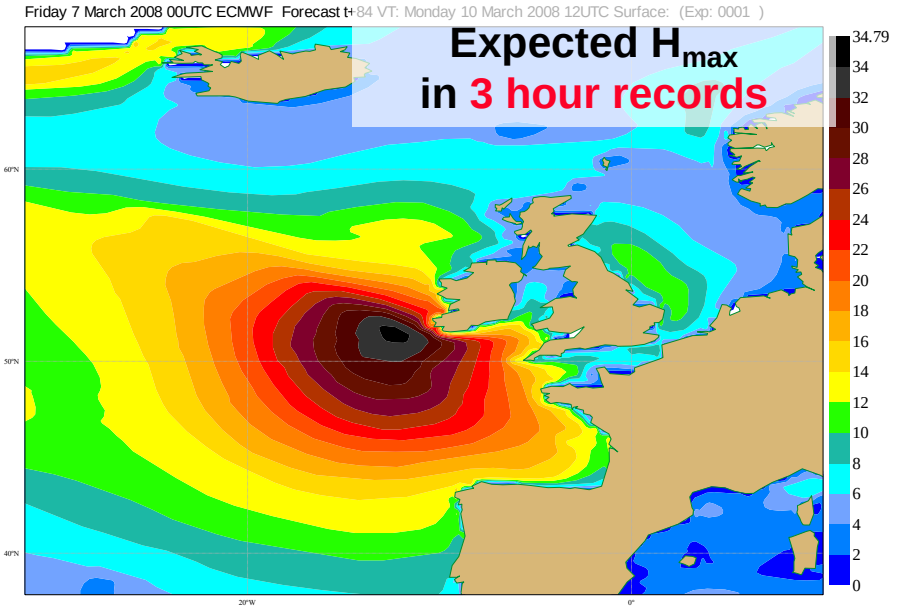


If $H_{max} > 2.2\ H_s$ ➔ freak wave event

Wave Model Products: Extreme Waves

We have recently introduced a new parameter to estimate the height of the highest individual wave (H_{max}) one can expect:





March 10th, 2008, 12UTC
Forecasts fields from
Friday 7th March, 2008, 0 UTC

See ECMWF Tech Memo 288 for derivation and discussion
http://www.ecmwf.int/publications/library/do/references/list/14


Questions/comments ?