Ocean Waves

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Waves breaking on the sea front in Ardrossan, Western Scotland,
as Storm Gertrude hits the UK **on January 29, 2016**.

IMAGE: DANNY LAWSON/PA WIRE/ASSOCIATED PRESS

Ocean waves:

We are dealing with wind generated waves from gentle to rough …

Porthleven Clock Tower, Cornwall, UK

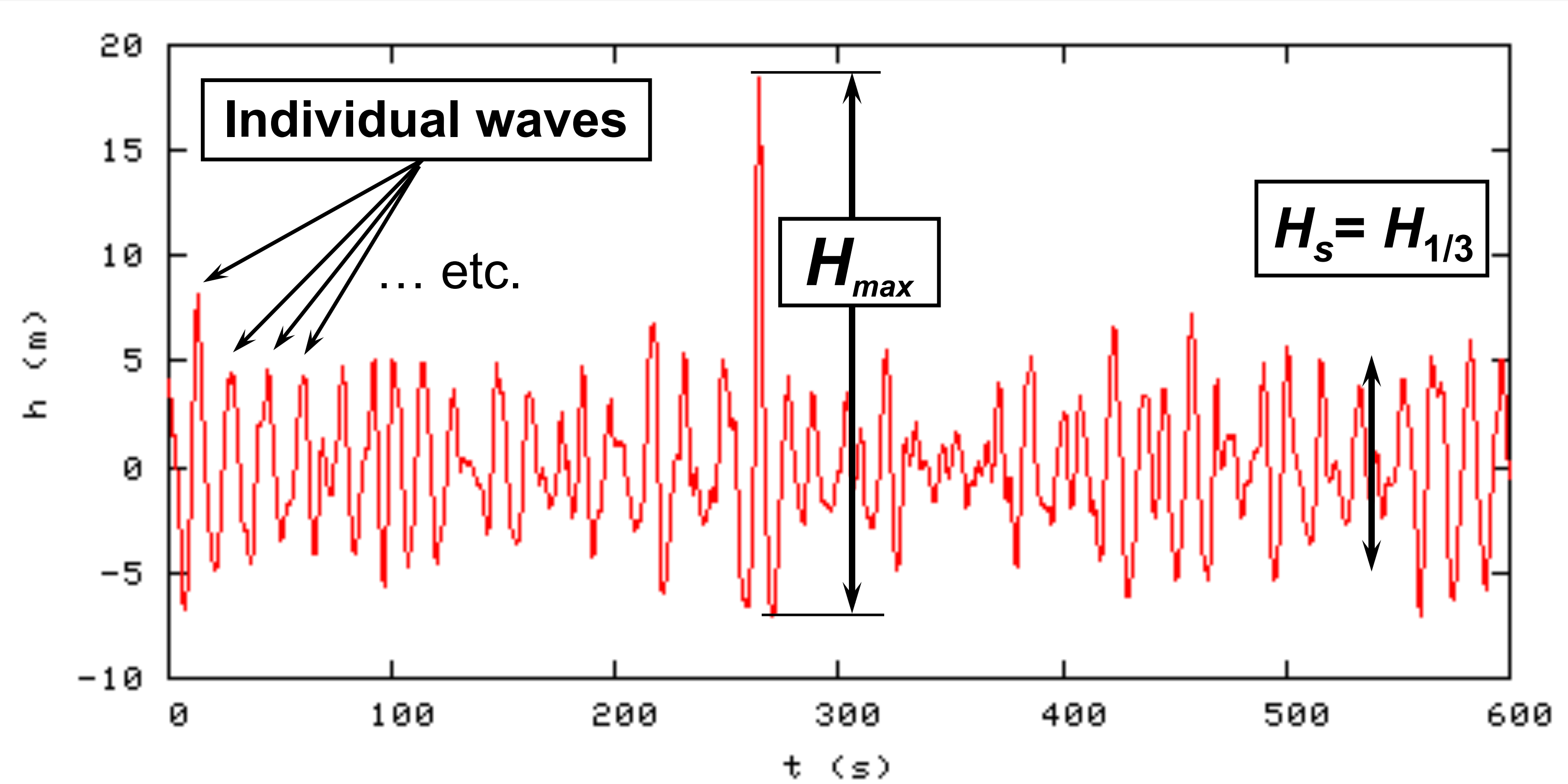
May 1, 2013

February 5, 2014

Observe Individual Waves,

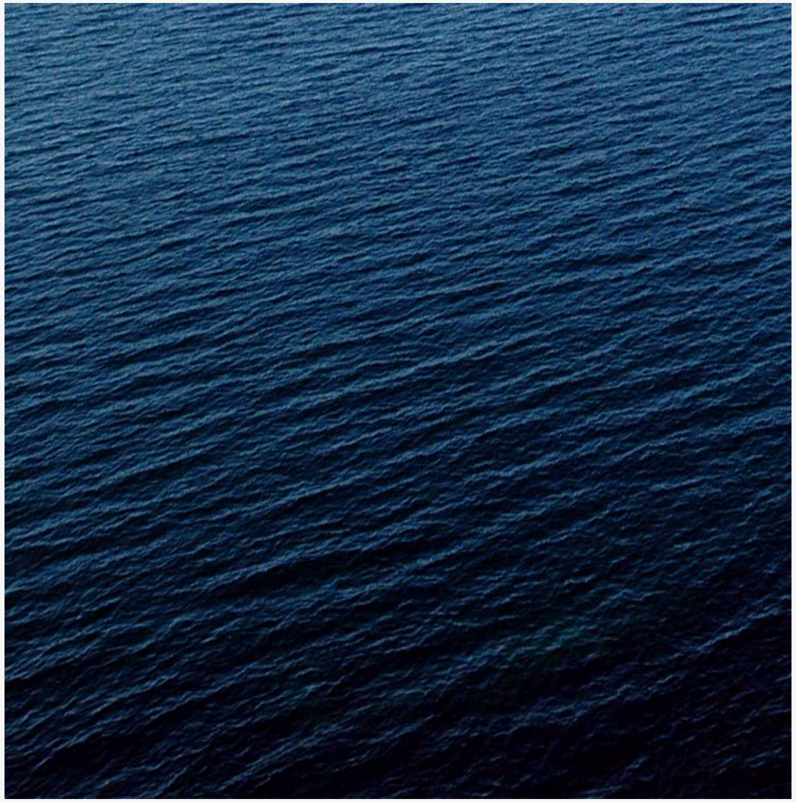
After a while, you can estimate a characteristic height the waves: the Significant Wave Height, H_s,

You might also notice that some waves are larger than the rest, characterised by the Maximum Individual Wave Height, H_{max}

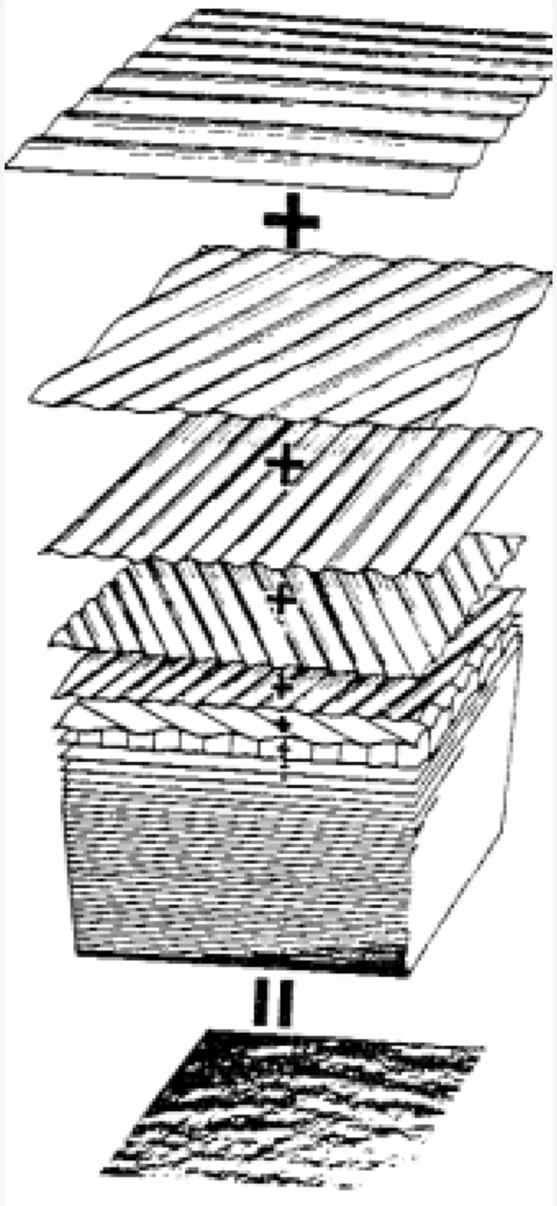


Surface elevation time series from platform Draupner in the North Sea

How do we go about making predictions on the sea state?

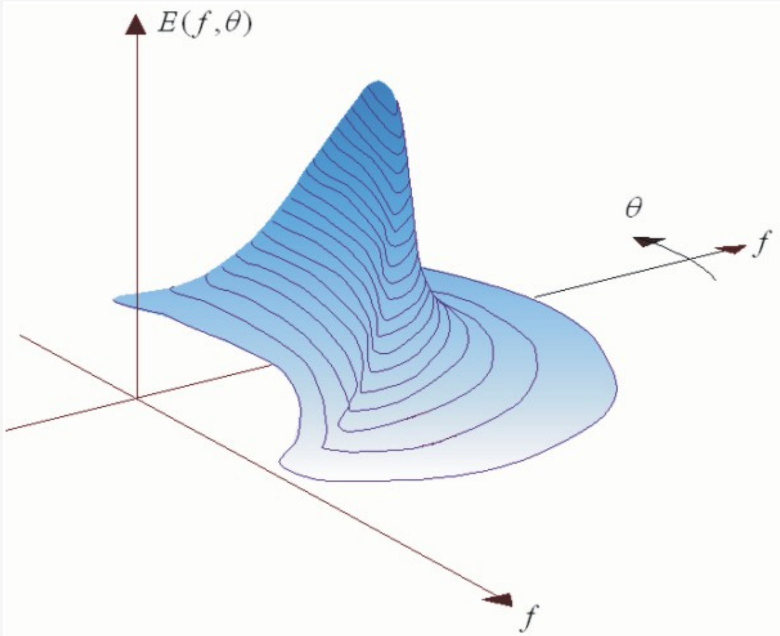


Wave Spectrum



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

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

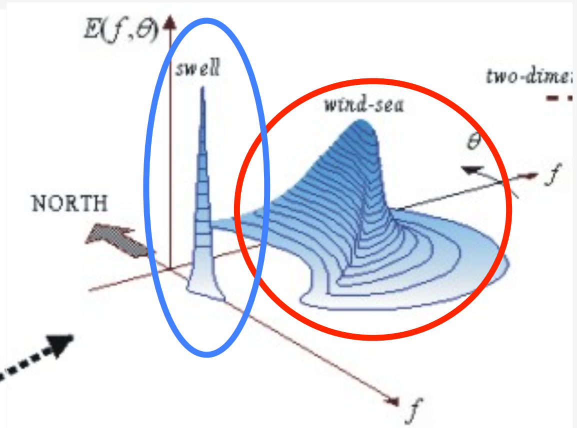


Modern ocean wave prediction systems are based on statistical description of oceans waves (i.e. ensemble average of individual waves).

The sea state is described by the two-dimensional wave spectrum F(f,θ).

For instance, the sea state off the coast of Holland might the results of a local sea breeze. These waves are generally known as windsea

Waves might have also propagated from their generation area as swell



Windsea: broad distribution of the waves around a peak

swell: well defined peak in direction and frequency.

Ocean Wave Modelling

- The 2-D spectrum follows from the energy balance equation (in its simplest form: deep water case, no surface currents):

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

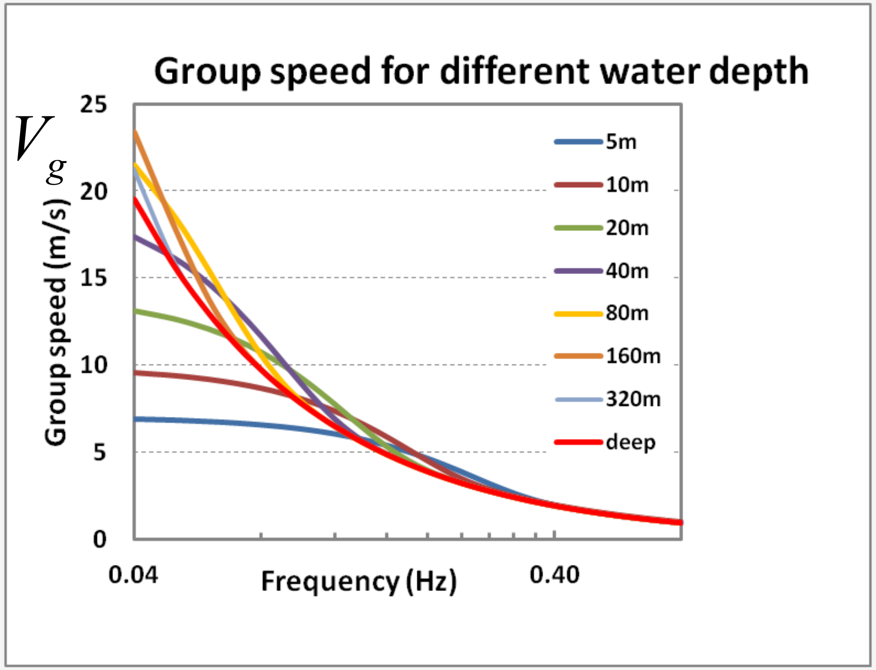
Where the group velocity $\mathbf{V_g}$ is derived from the dispersion relationship which relates frequency (***f***) and wave number (***k***) for a given water depth (D).

$$\omega^2 = g\,k\tanh(k\,D)$$

$$V_g = \frac{\partial \omega}{\partial k}$$

$$\omega = 2\pi\, f$$

D: water depth



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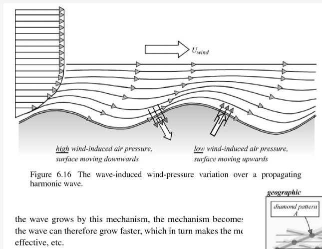
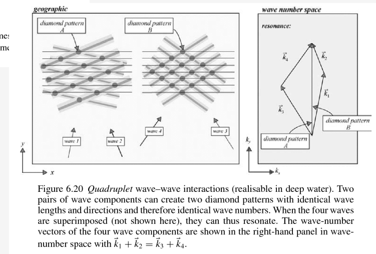


S_{in}: wind input source term (generation).



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


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

Wave Model Parameters

- Once you know the wave spectrum F, any other sea state parameters can be estimated. 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):

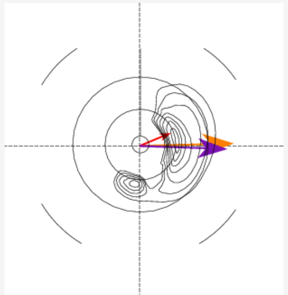
$$H_s = 4\sqrt{\langle \eta^2 \rangle}$$

The term significant wave height is historical as this value appeared to be well correlated with visual estimates of wave height from experienced observers.

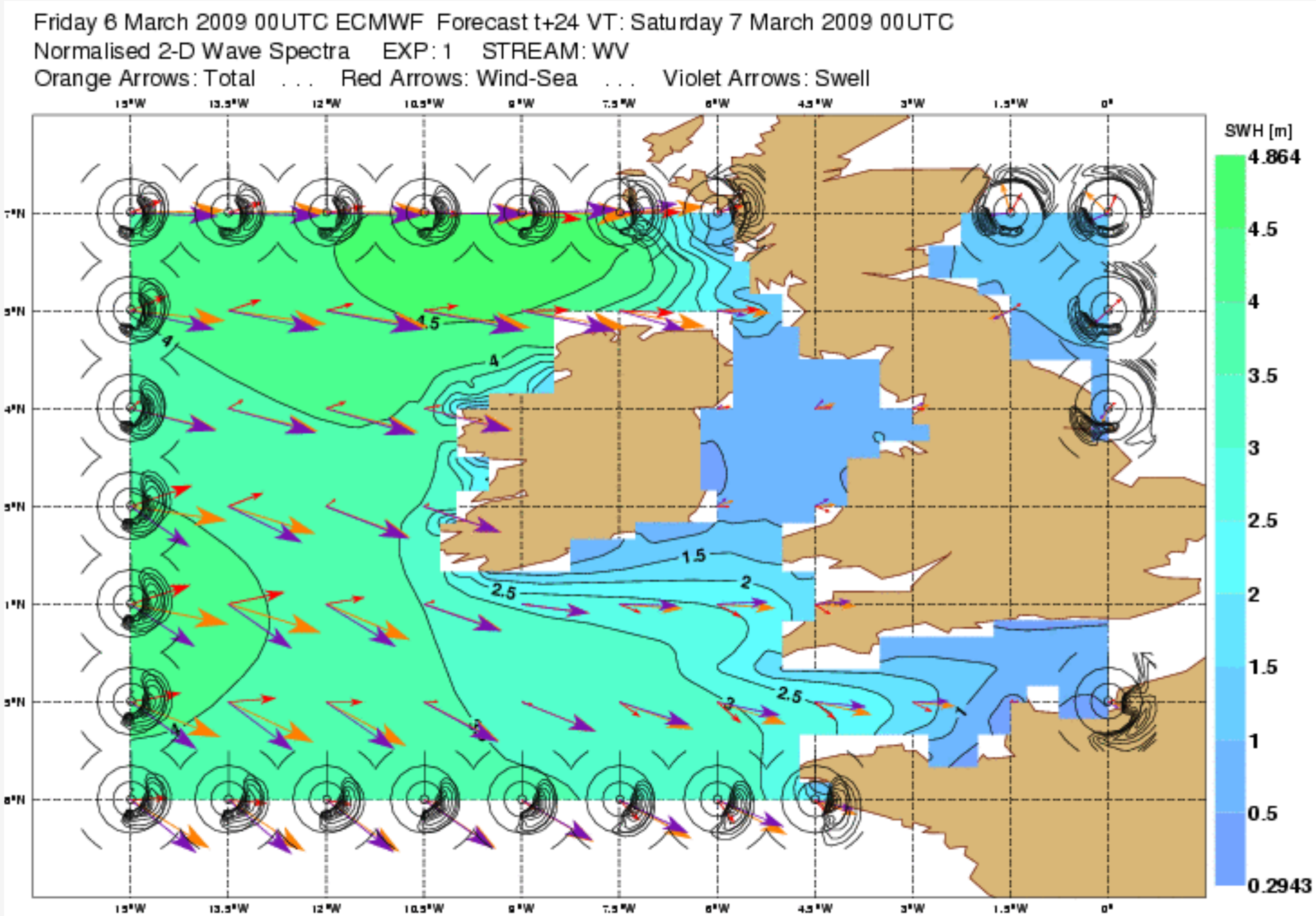
It can be shown to correspond to the average 1/3rd highest waves ($H_{1/3}$).

Wave Model Parameters

2-D spectrum can be used to specify boundary conditions for limited area wave model.



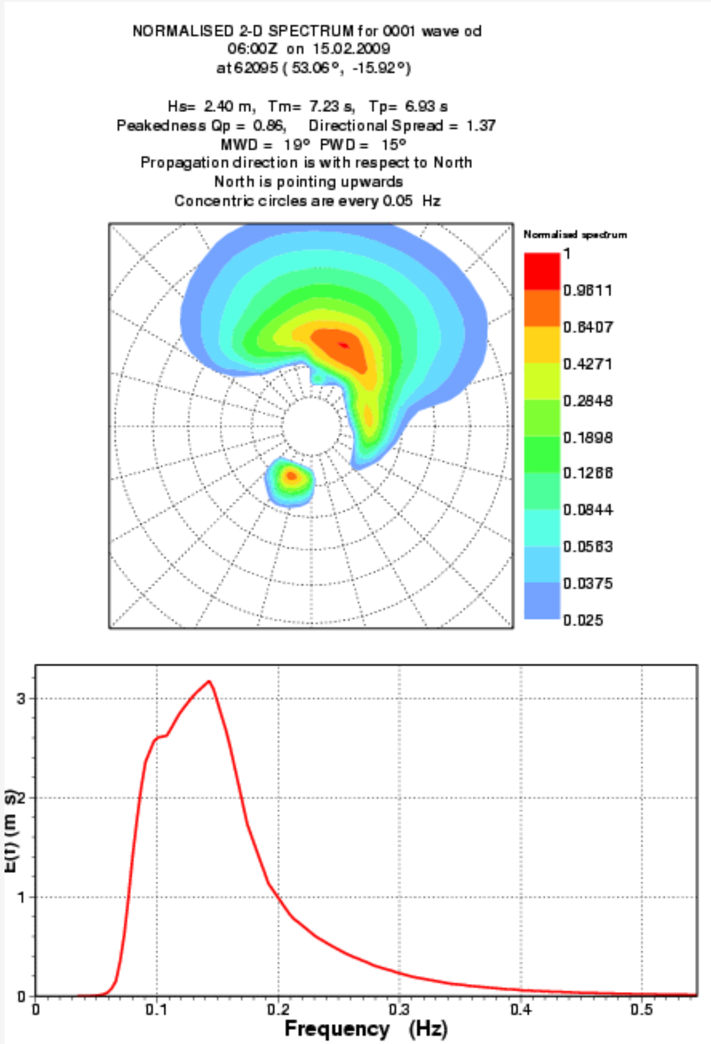
Spectra used as boundary conditions



- windsea
- swell
- total sea

Wave Model Parameters

Or if you only look at one location …

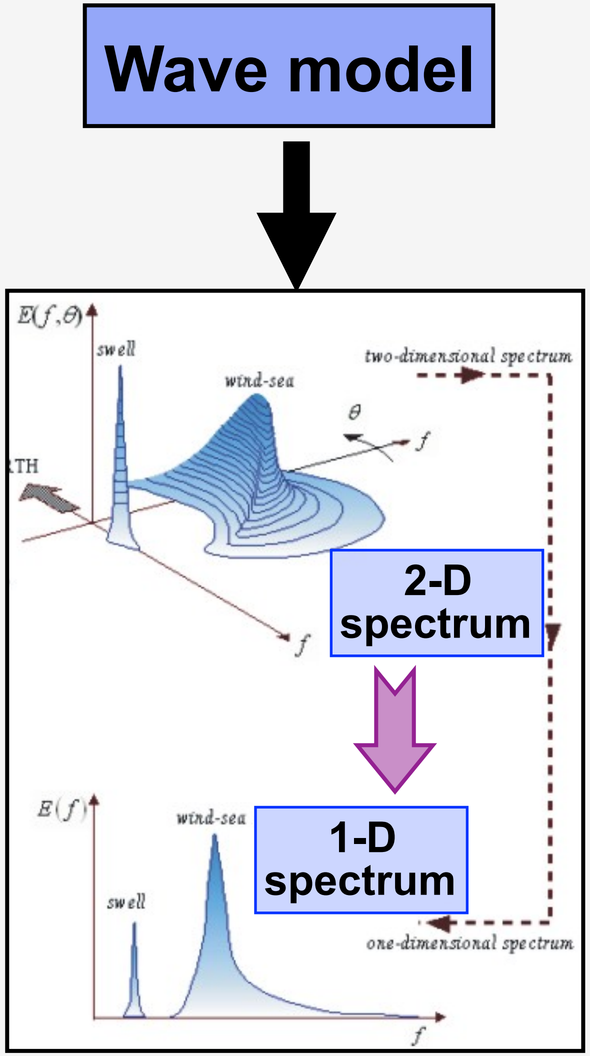


Wave Model Products

The complete description of the sea state is given by the 2-D spectrum, however, it is a fairly large amount of data.

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 Parameters

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

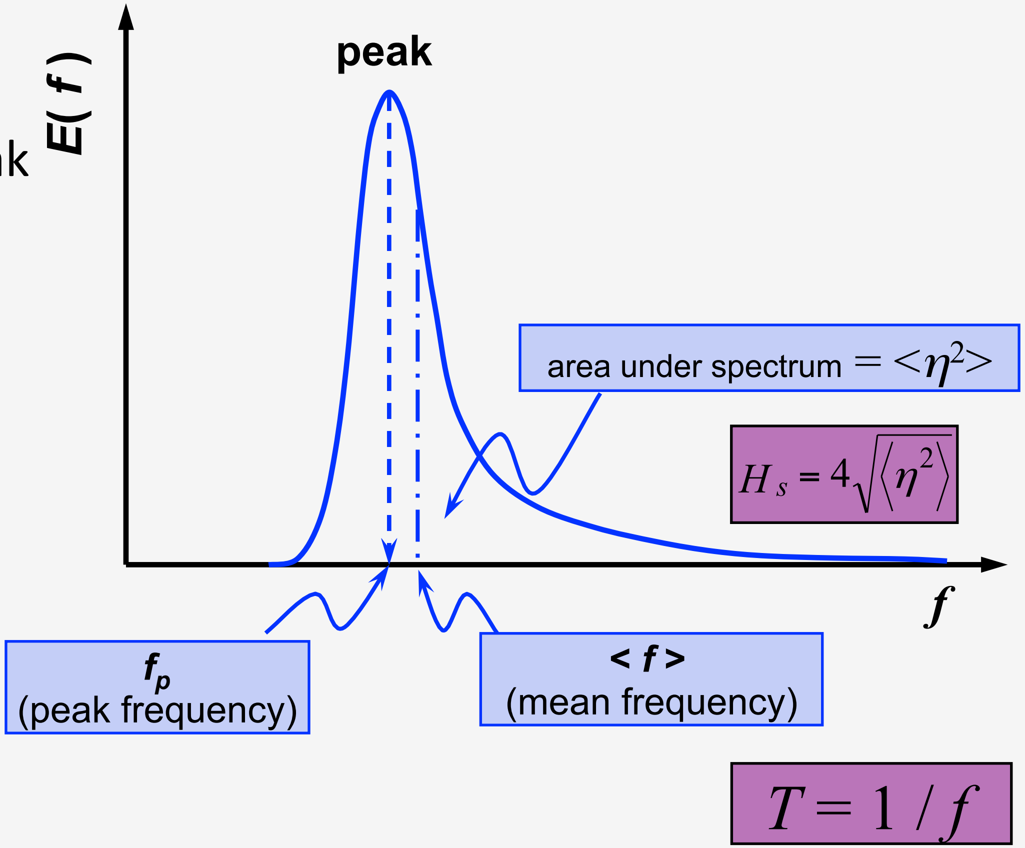
The significant wave height (H_s).

The peak period (period of the peak of the 1-D spectrum).

Mean period(s) obtained from weighted integration of the 2-D spectrum.

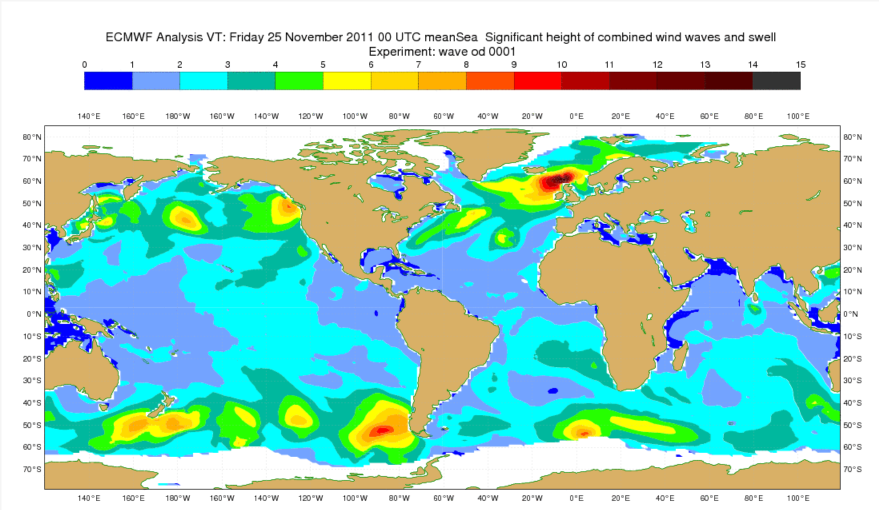
Integrated mean direction.

and many others.



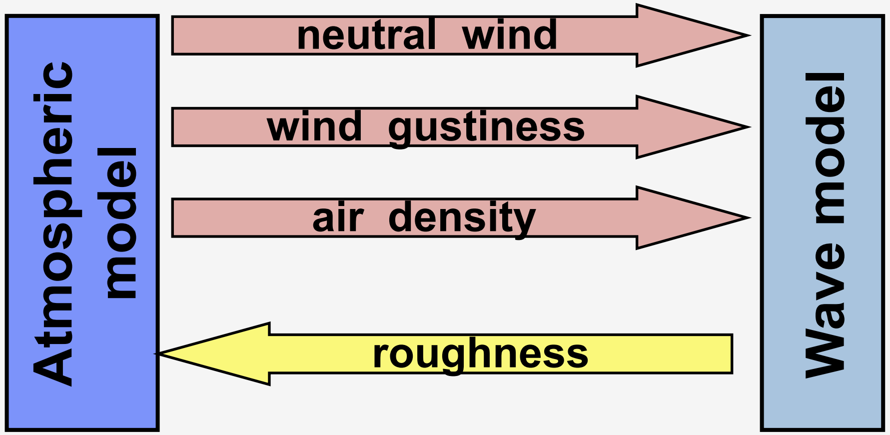
Complete list at: http://www.ecmwf.int/services/archive/d/parameters/order=/table=140/

ECMWF Wave Model Configurations



Global from 81°S to 90°N

Coupled to the atmospheric model with feedback of the sea **surface roughness** change due to waves.



ECMWF Wave Model Configurations

High resolution (HRES-WAM)

- 14 km grid spacing.
- Dissemination grid: 0.125°x0.125°
- 36 frequencies.
- 36 directions.
- Coupled to the TCo1279 model.

- Analysis every 6 hrs and 10 day forecasts from 0 and 12 UTC.

Ensemble forecasts (EPS-WAM)

- 28 km grid spacing.
- Dissemination grid: 0.25°x0.25°
- 36 frequencies.
- 36 directions .
- Coupled to TCo639 .
- (50+1) 15 day forecasts from 0 and 12UTC (monthly twice a week).
- **Coupled to ocean model**.

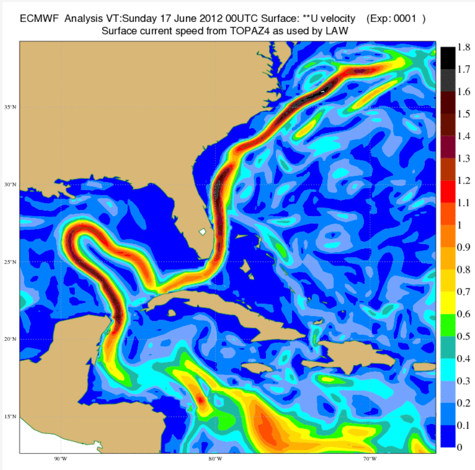
ECMWF Wave Model Configurations

We also have the uncoupled global configuration (stand alone)

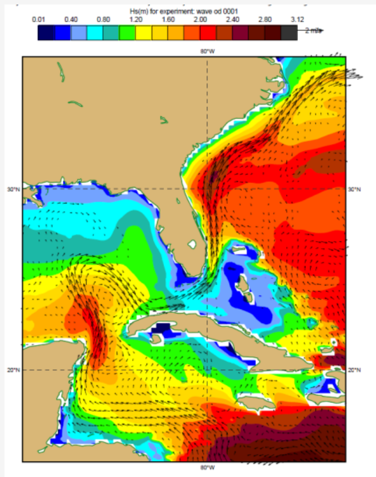
High resolution stand alone(HRES-SAW)

- **11 km** grid spacing.
- Dissemination grid: 0.1°x0.1°
- 36 frequencies.
- 36 directions.
- Forced by HRES fields.

- Analysis every 6 hrs and 10 day forecasts from 0 and 12 UTC.
- Imposed surface currents from TOPAZ4 system.



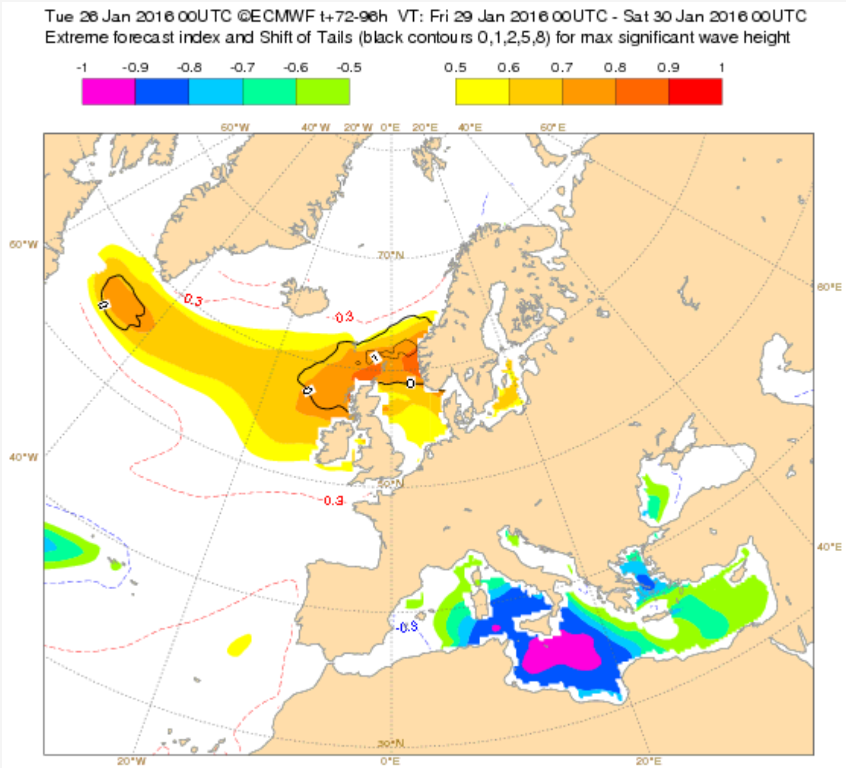
TOPAZ4 surface currents



Wave Model Products: EFI plots

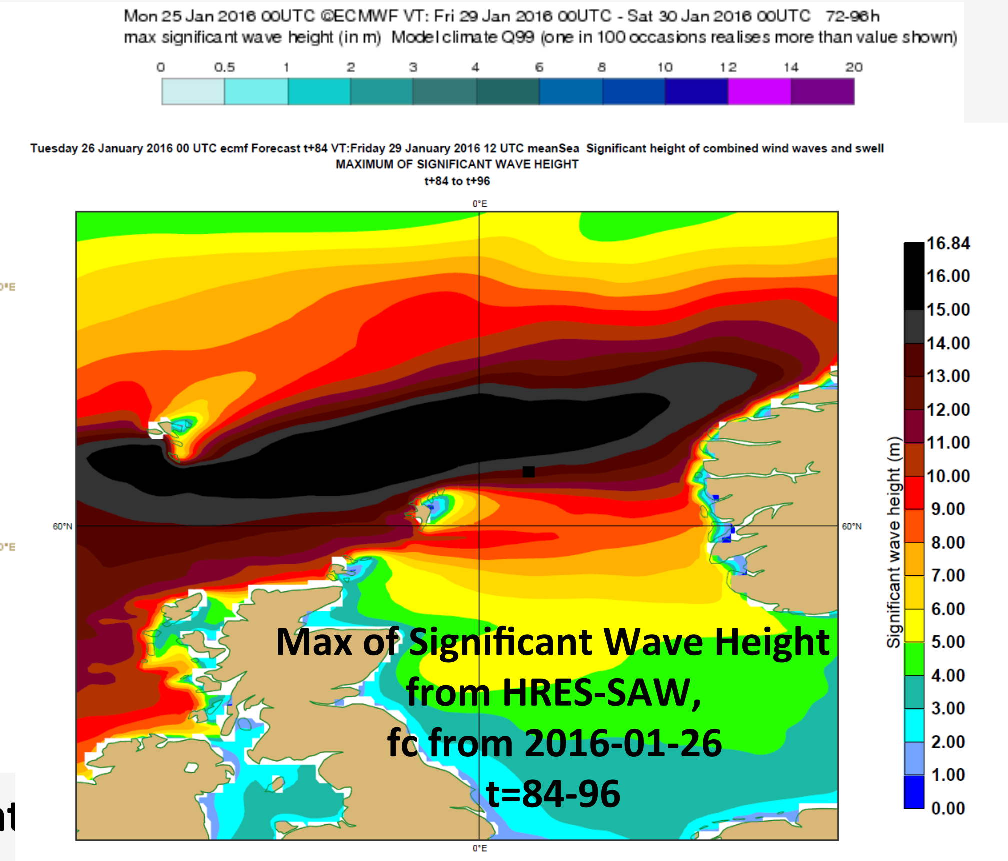
From the model climate, it is possible to derive indices that indicate deviations in probabilistic terms from what is 'expected'.

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



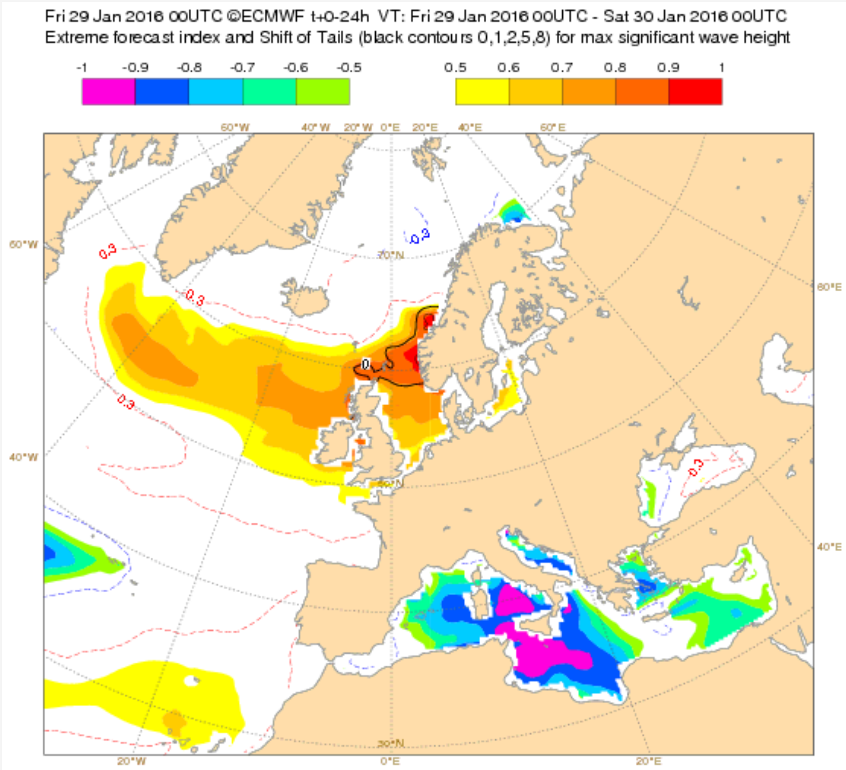
EFI and shift of tail for significant wave height

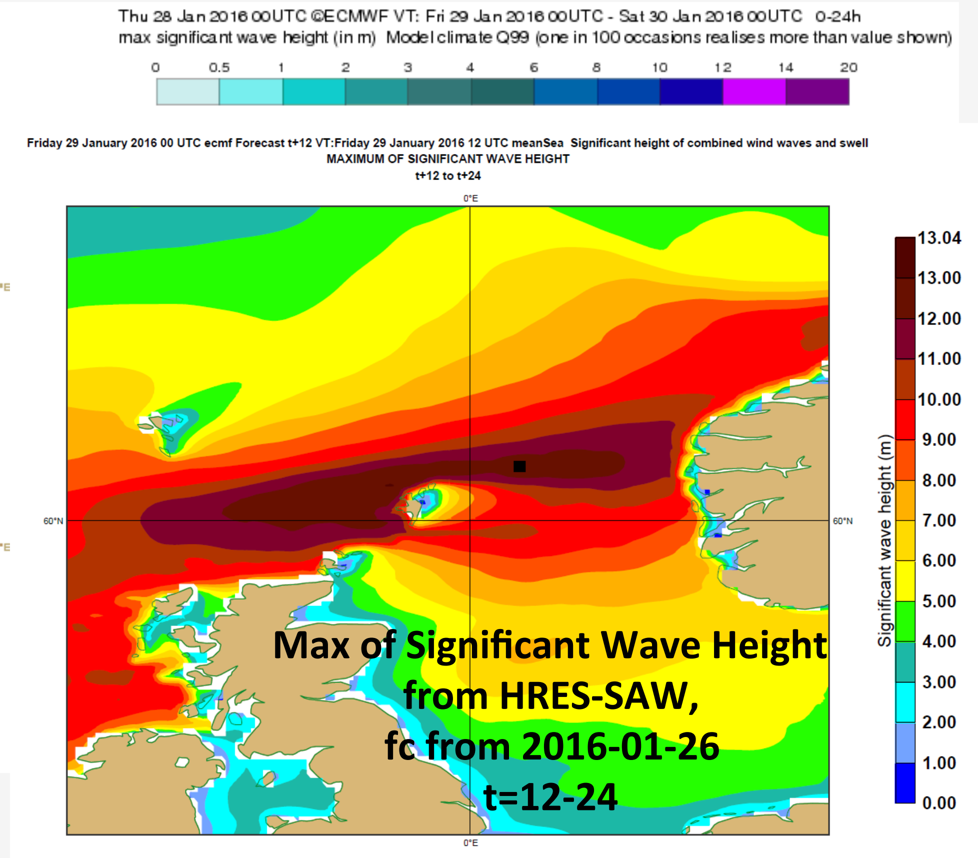
Tue 26 Jan 2016, 00 UTC, t=72-96
Gertrude (UK), Tor (Norway)



significant wave height

Wave Model Products

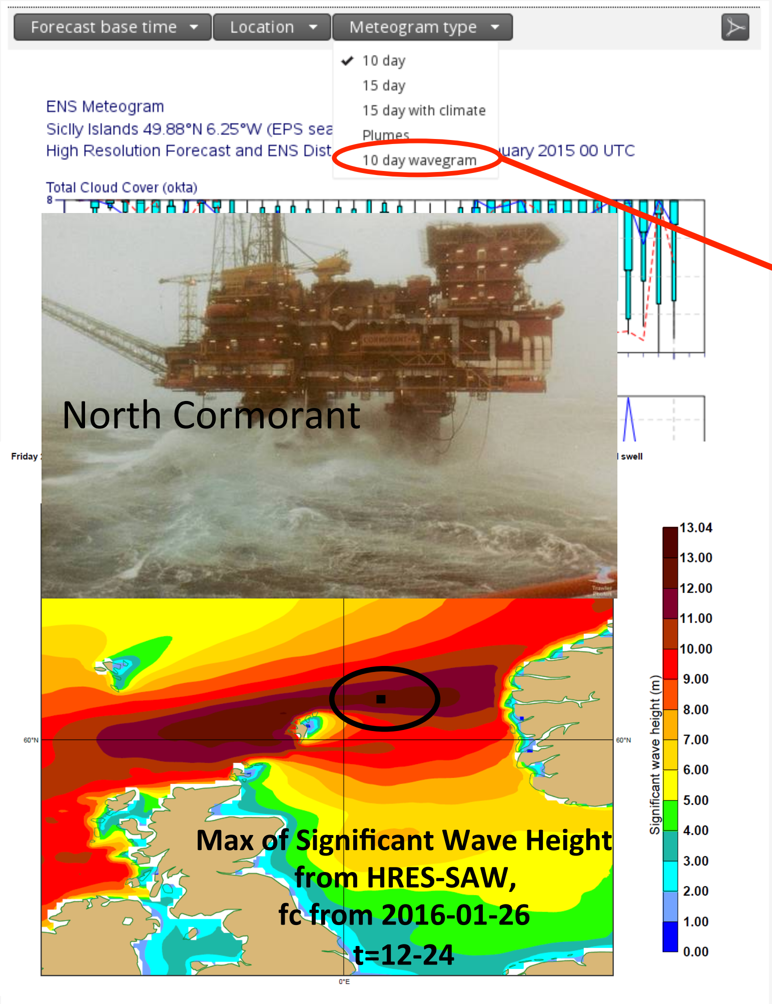


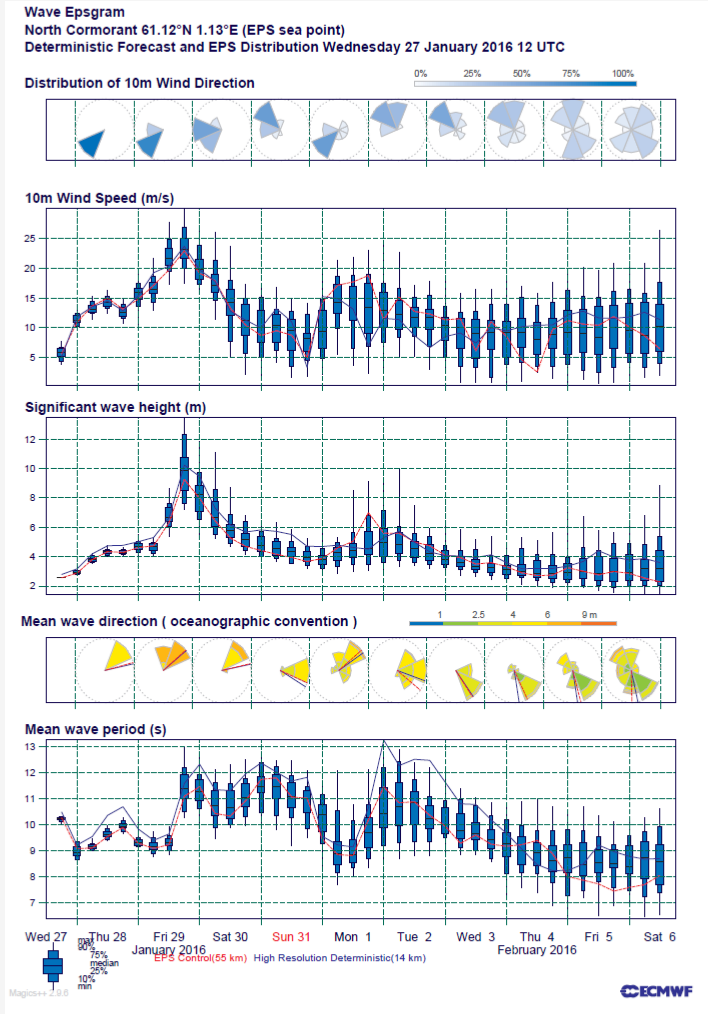


Fri 29 Jan 2016, 00 UTC, t=12-24

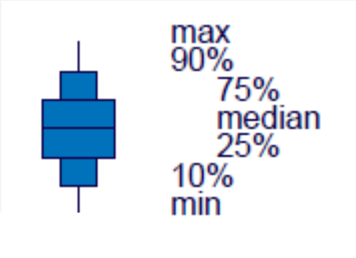
A bit more compact: Wave EPSgram:

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

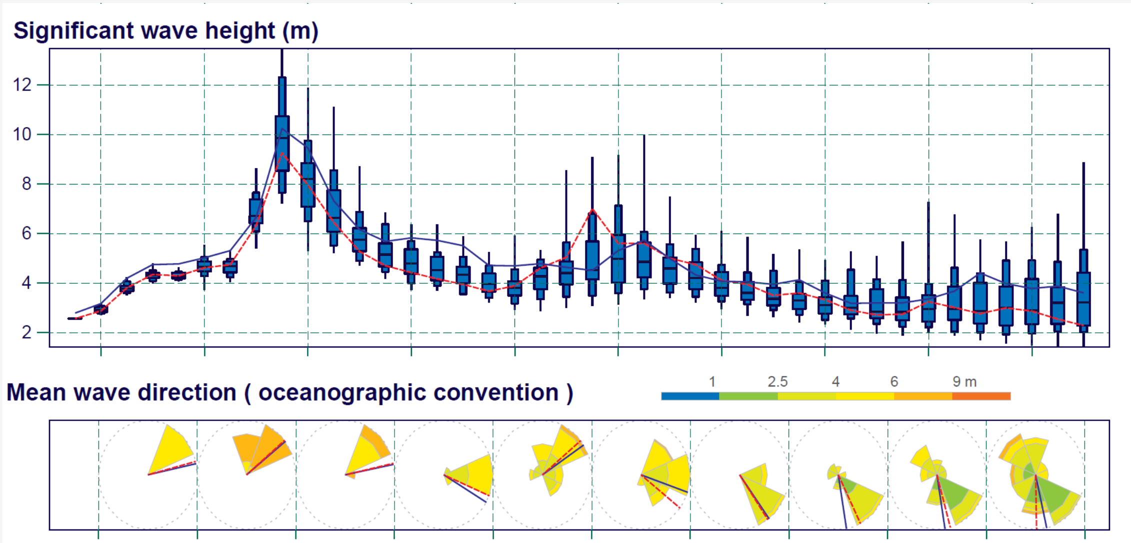


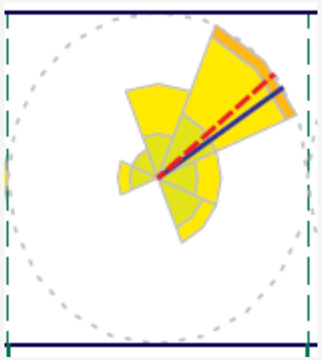


A bit more compact: Wave EPSgram:



ENS Control(55 km) High Resolution (28 km)

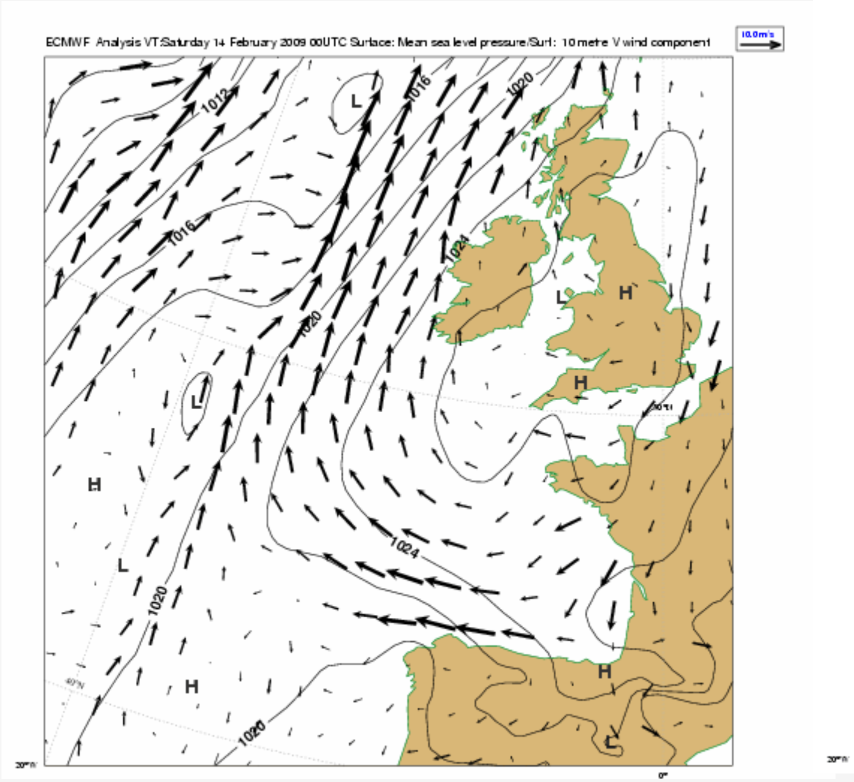




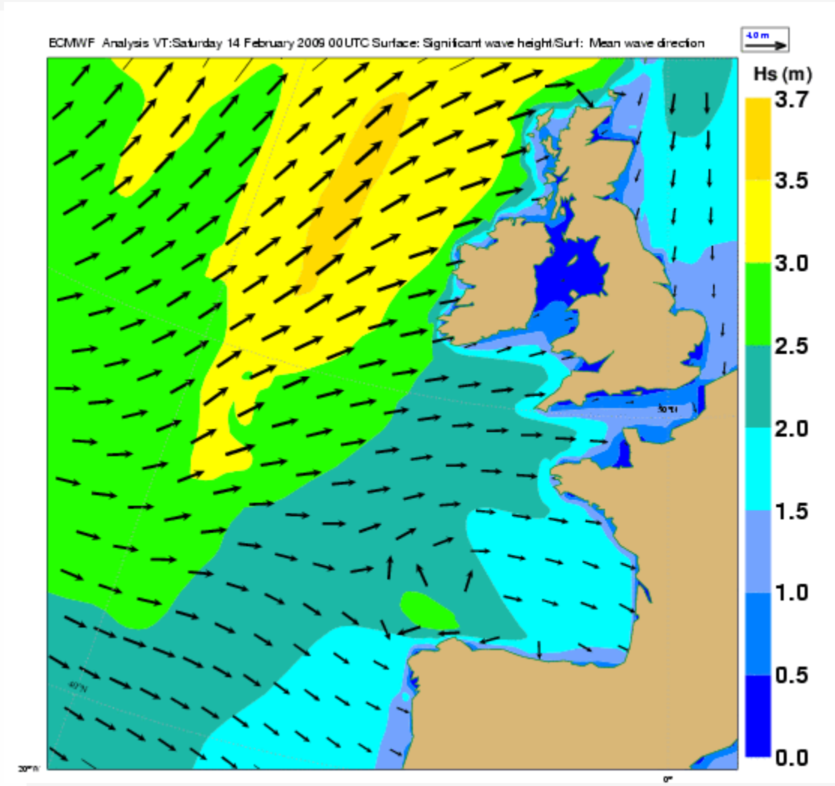
Each octant is coloured based on the distribution of the significant wave height associated with each mean direction. The coloured areas correspond to the fractional number of ensemble members with wave height in the range specified by the coloured ruler.

A bit more on Wave Model Products

Use simple parameters:
total wave height and mean propagation direction

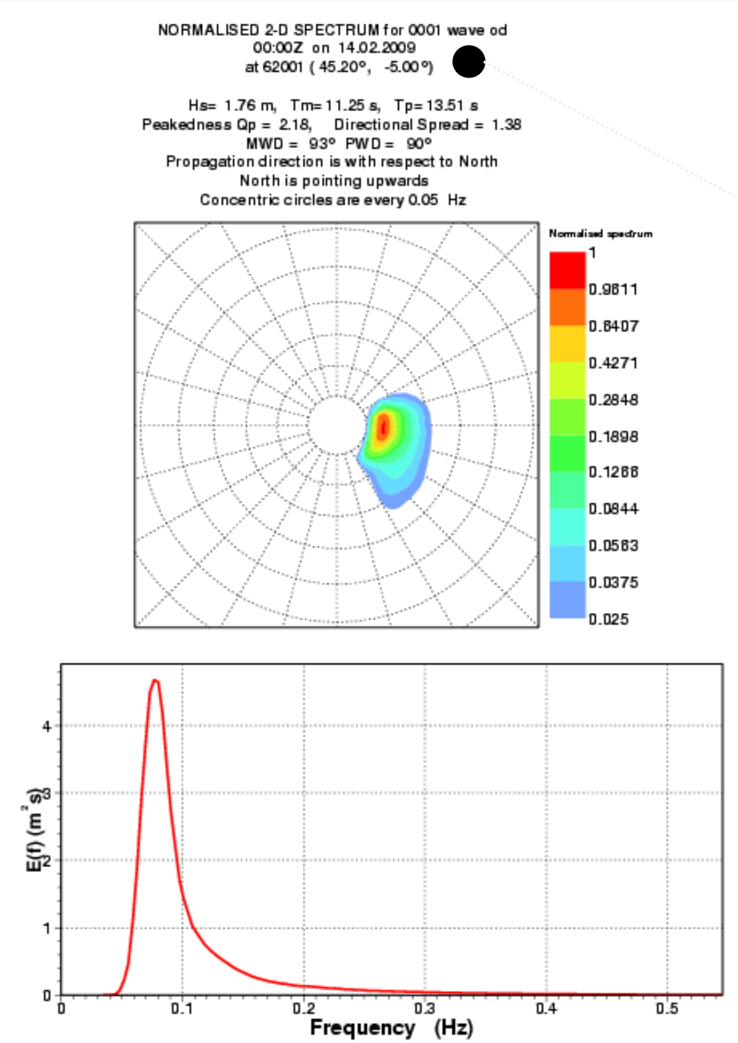


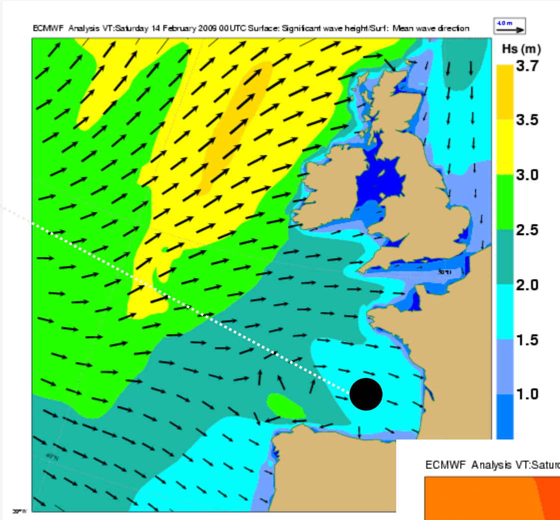
10m winds and mean sea level pressure:
Analysis : 14 February 2009, 00 UTC



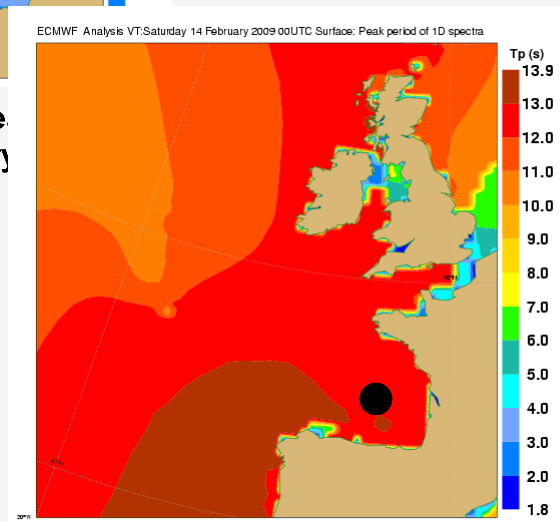
Wave height and mean direction:
Analysis : 14 February 2009, 00 UTC

Wave Model Products





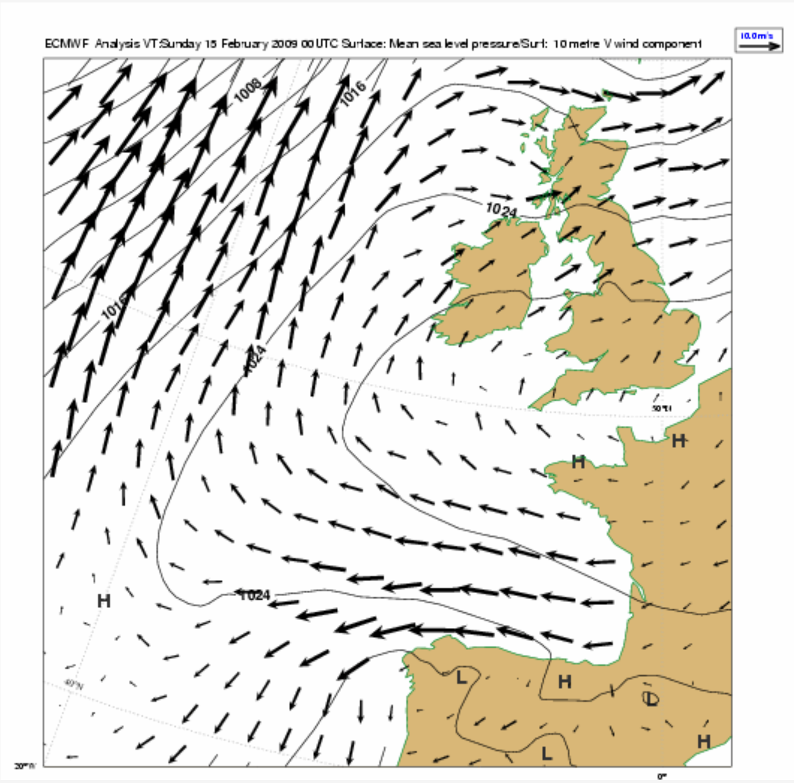
Wave height and me
Analysis : 14 February



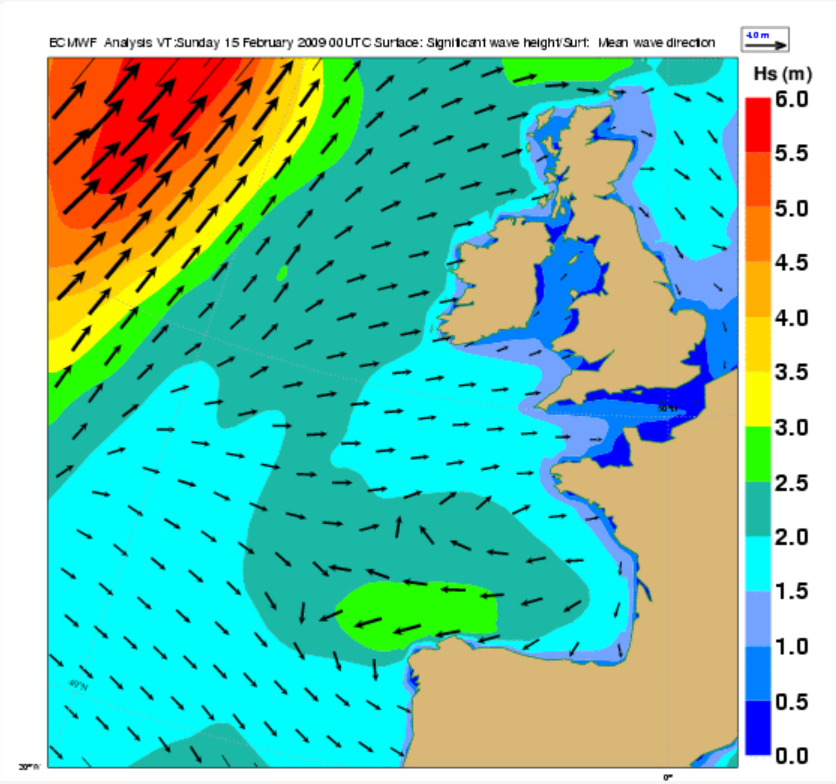
PEAK PERIOD:
Analysis : 14 February 2009, 00 UTC

Wave Model Products

Situation might be more complicated !



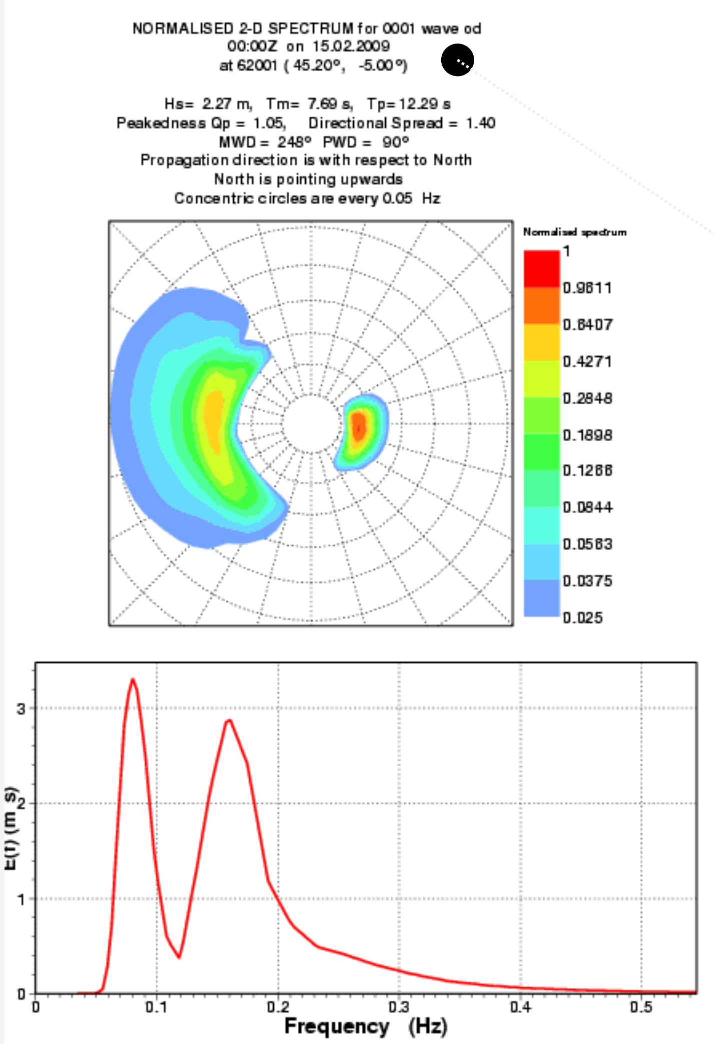
10m winds and mean sea level pressure:
Analysis : 15 February 2009, 00 UTC

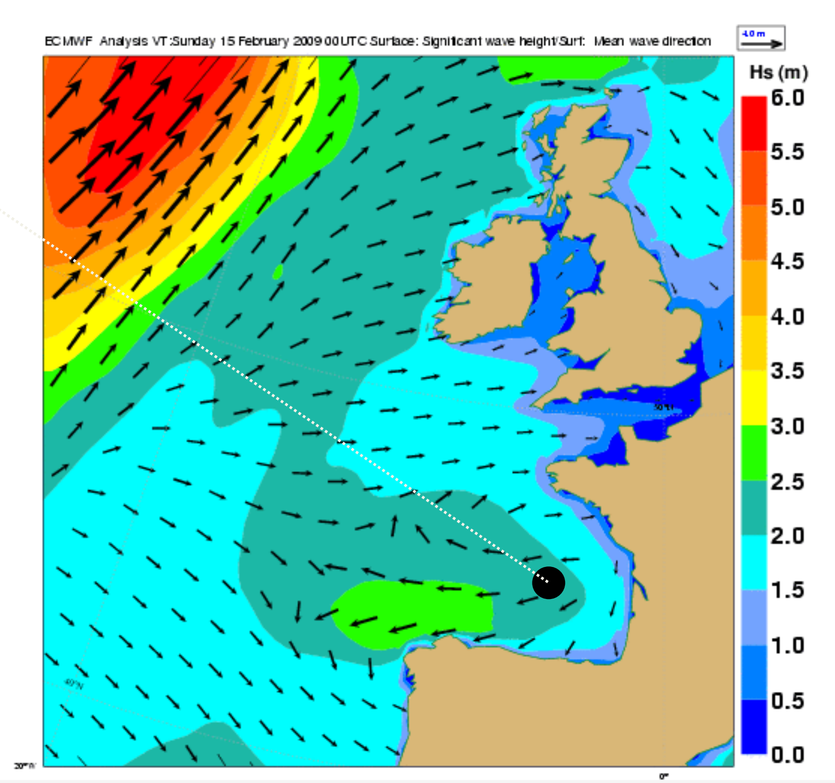


Wave height and mean direction:
Analysis : 15 February 2009, 00 UTC

Wave Model Products

Situation might be more complicated:

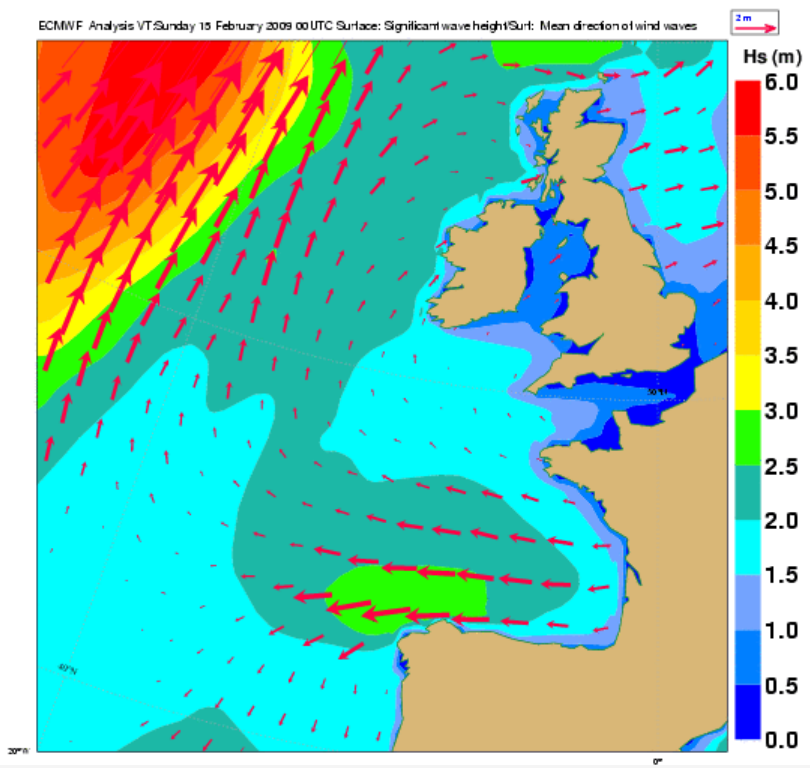




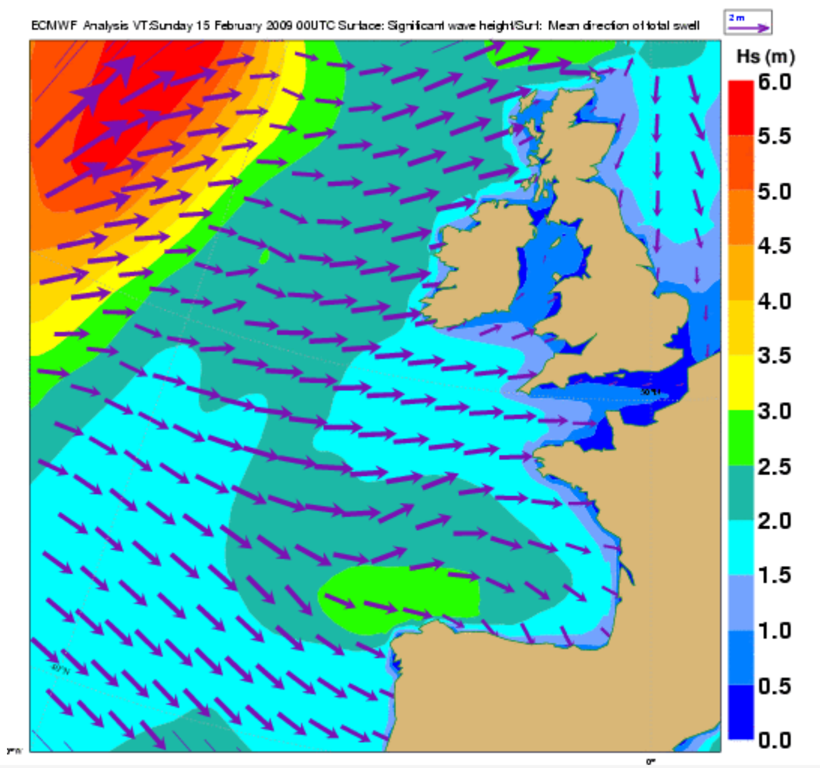
Wave height and mean direction:
Analysis : 15 February 2009, 00 UTC

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.



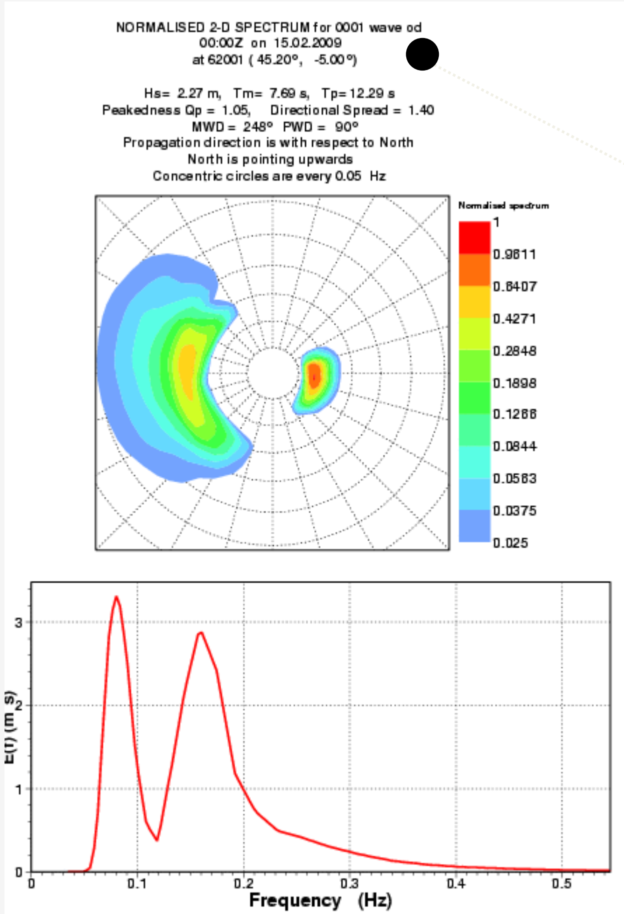
Wave height and windsea mean direction:
Analysis : 15 February 2009, 00 UTC

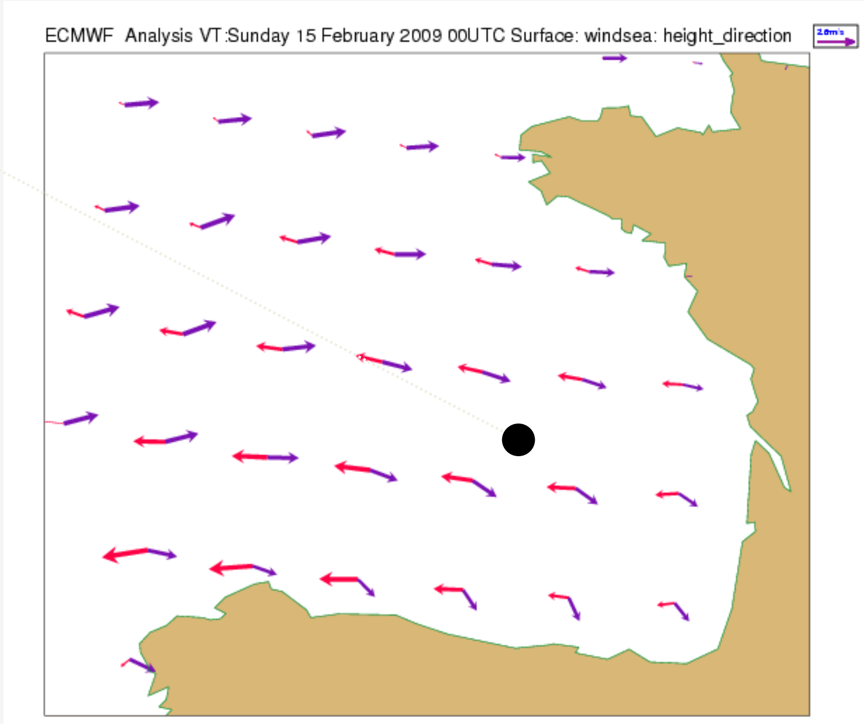


Wave height and swell mean direction:
Analysis : 15 February 2009, 00 UTC

Wave Model Products

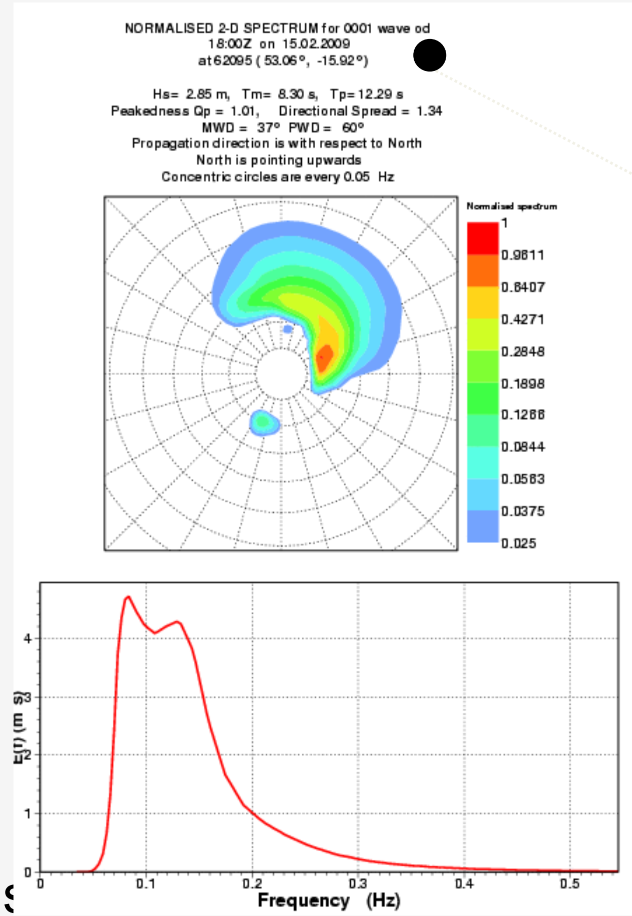
Windsea and swell: opposing sea

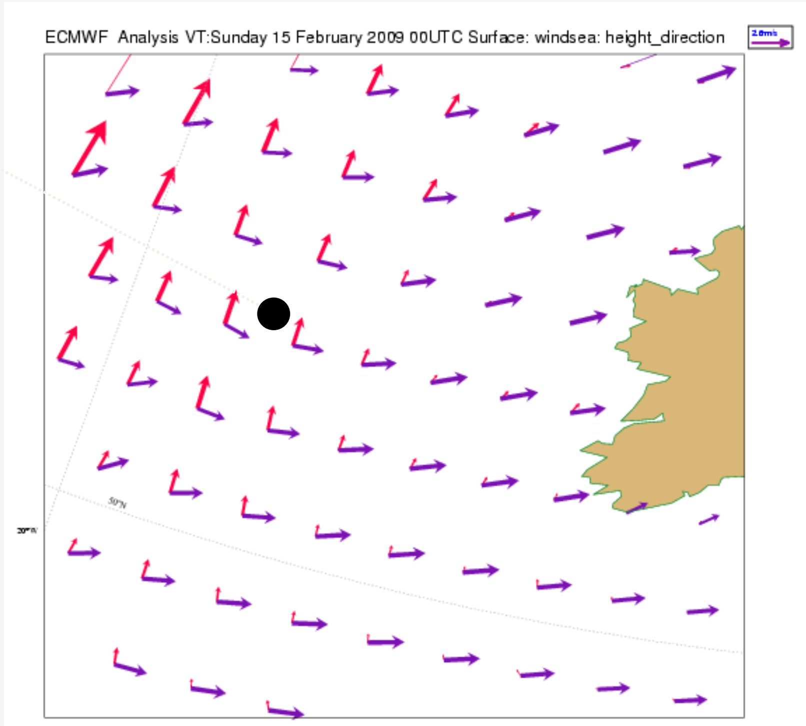




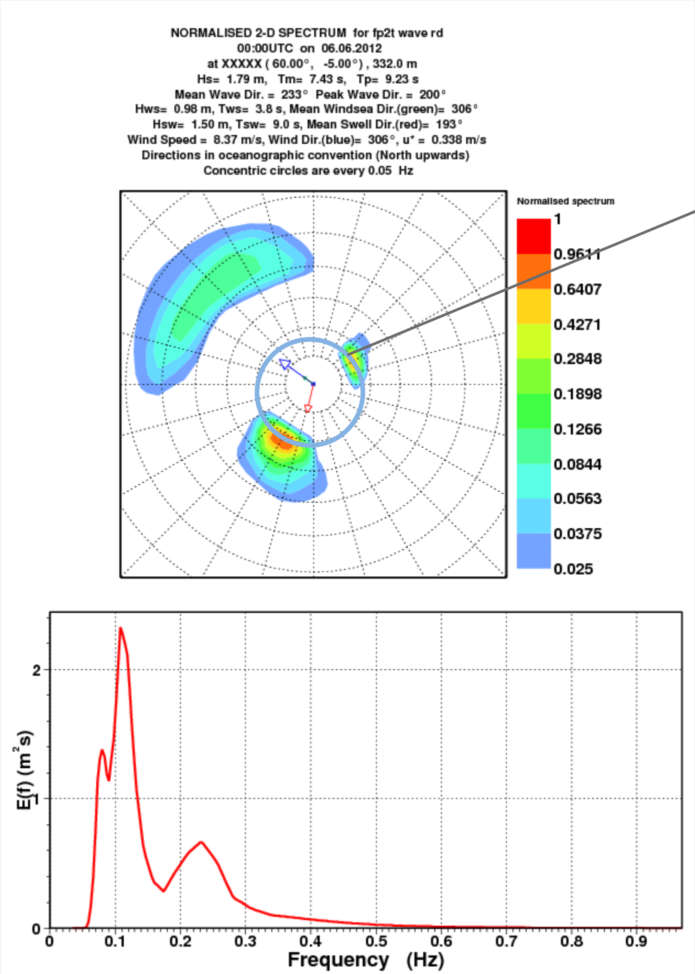
Wave Model Products

Windsea and swell: cross sea

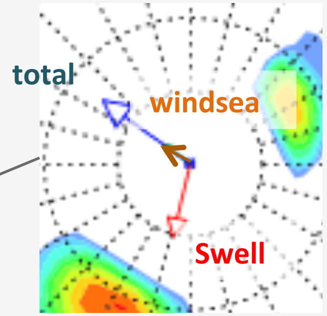


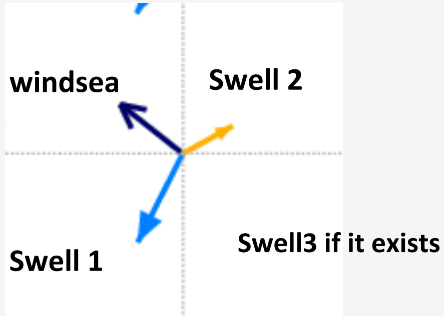


Since May 2015: spectral partitioning

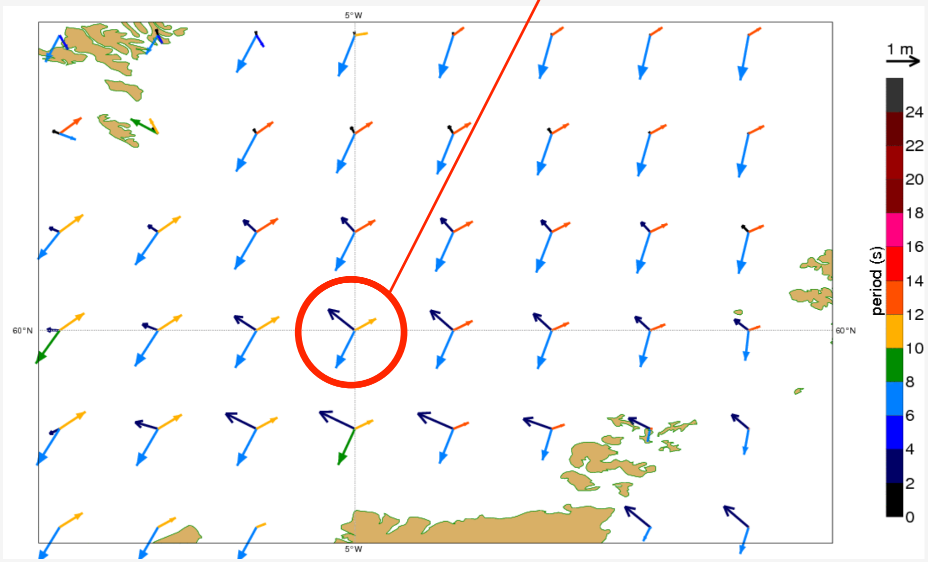


Operational:





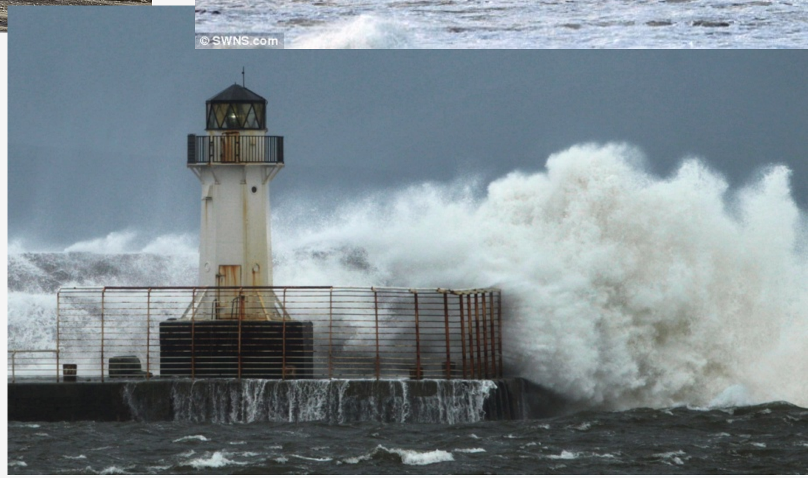
New decomposition (set of vectors):



arrow length: wave height,
arrow colour: corresponding mean wave period

Ocean wave forecasts

At the end of December 2013 and beginning of January 2014, the UK and western Europe were battered by large waves:



Ocean wave forecasts

Then again in February and early March:

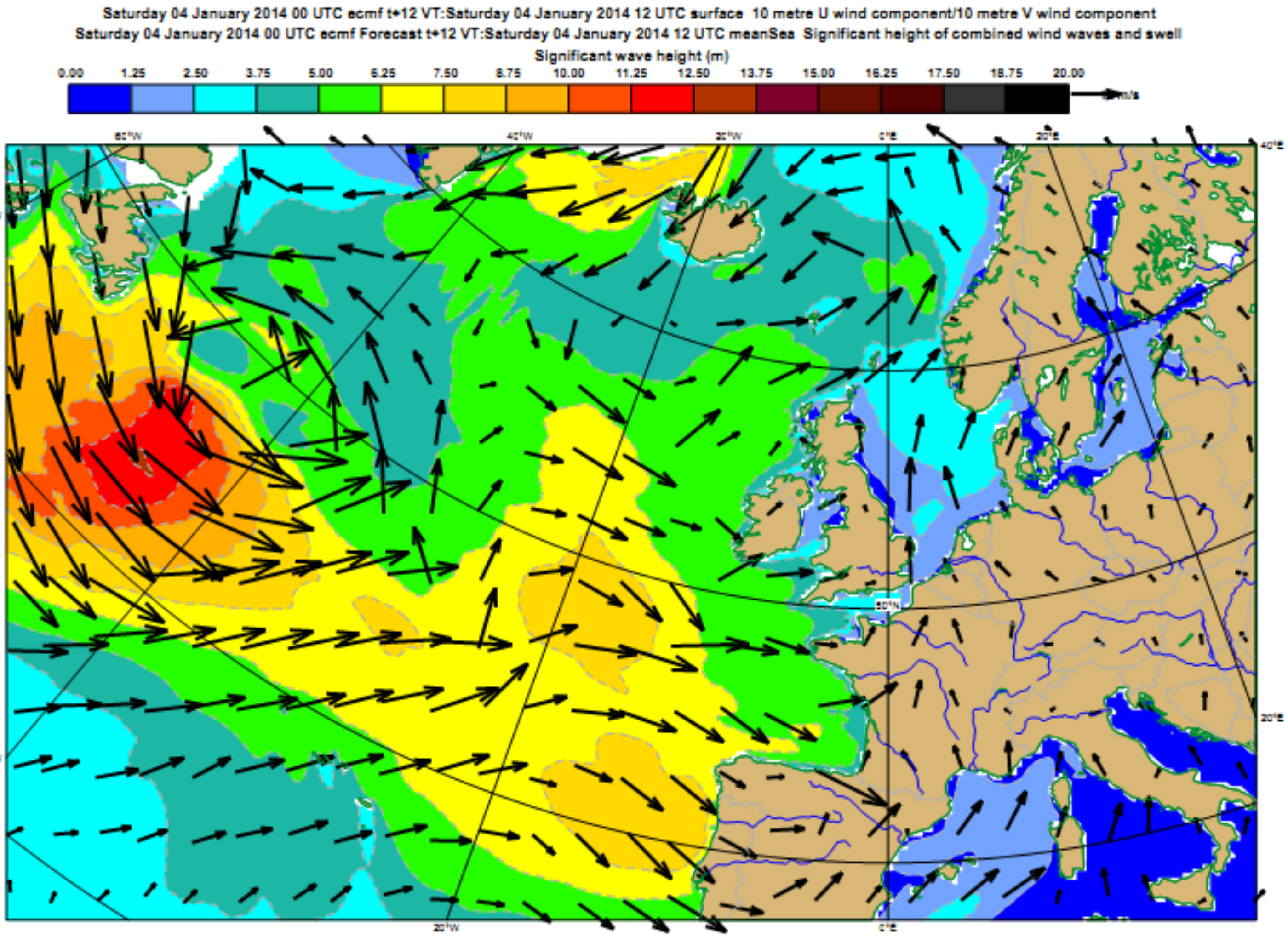
Porthleven Clock Tower, Cornwall

May 1, 2013

February 5, 2014

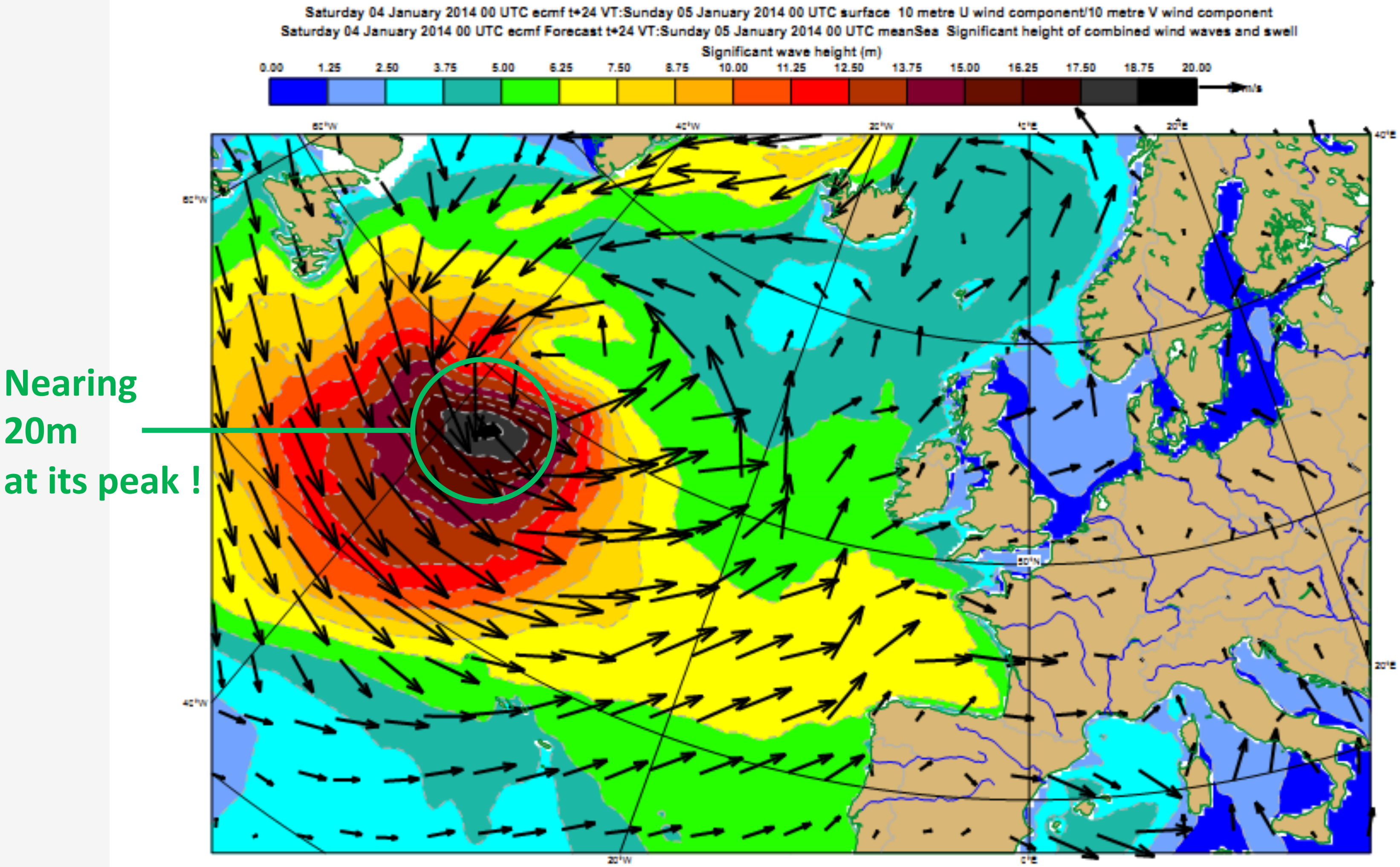
Ocean wave forecasts

Wave height forecast and wind from 4 January 2014, step 12 hours



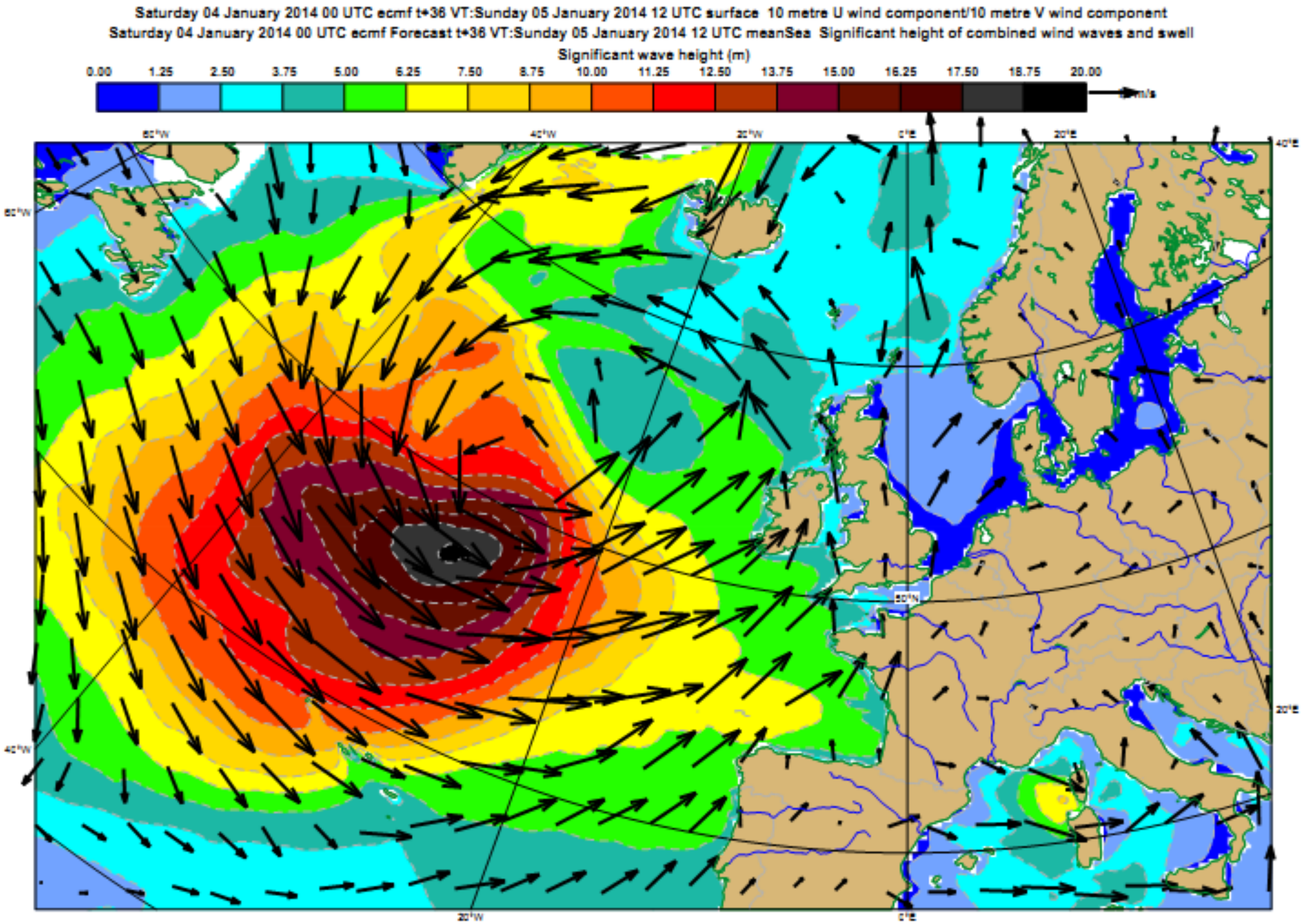
Ocean wave forecasts

Wave height forecast and wind from 4 January 2014, step 24 hours



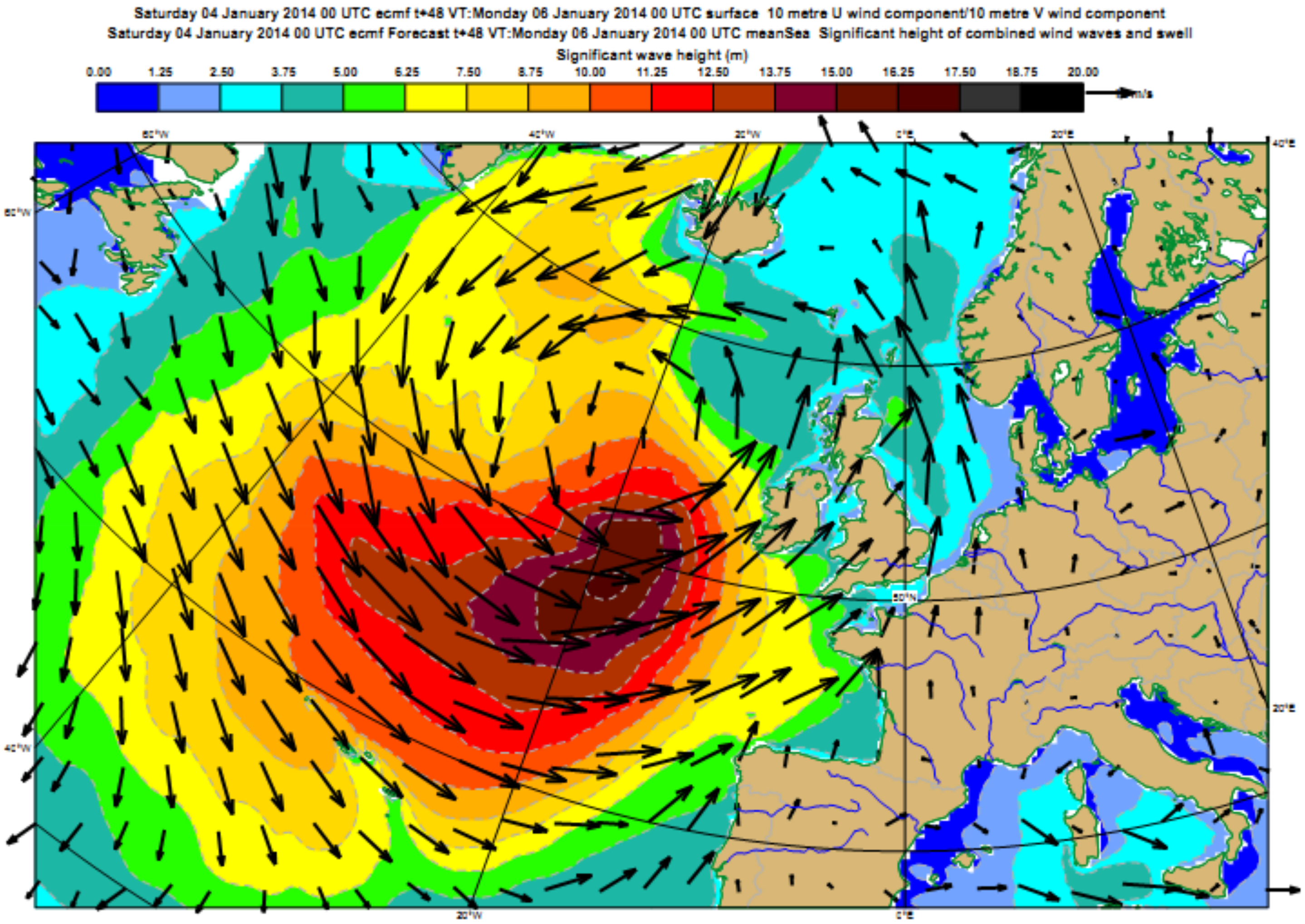
Ocean wave forecasts

Wave height forecast and wind from 4 January 2014, step 36 hours



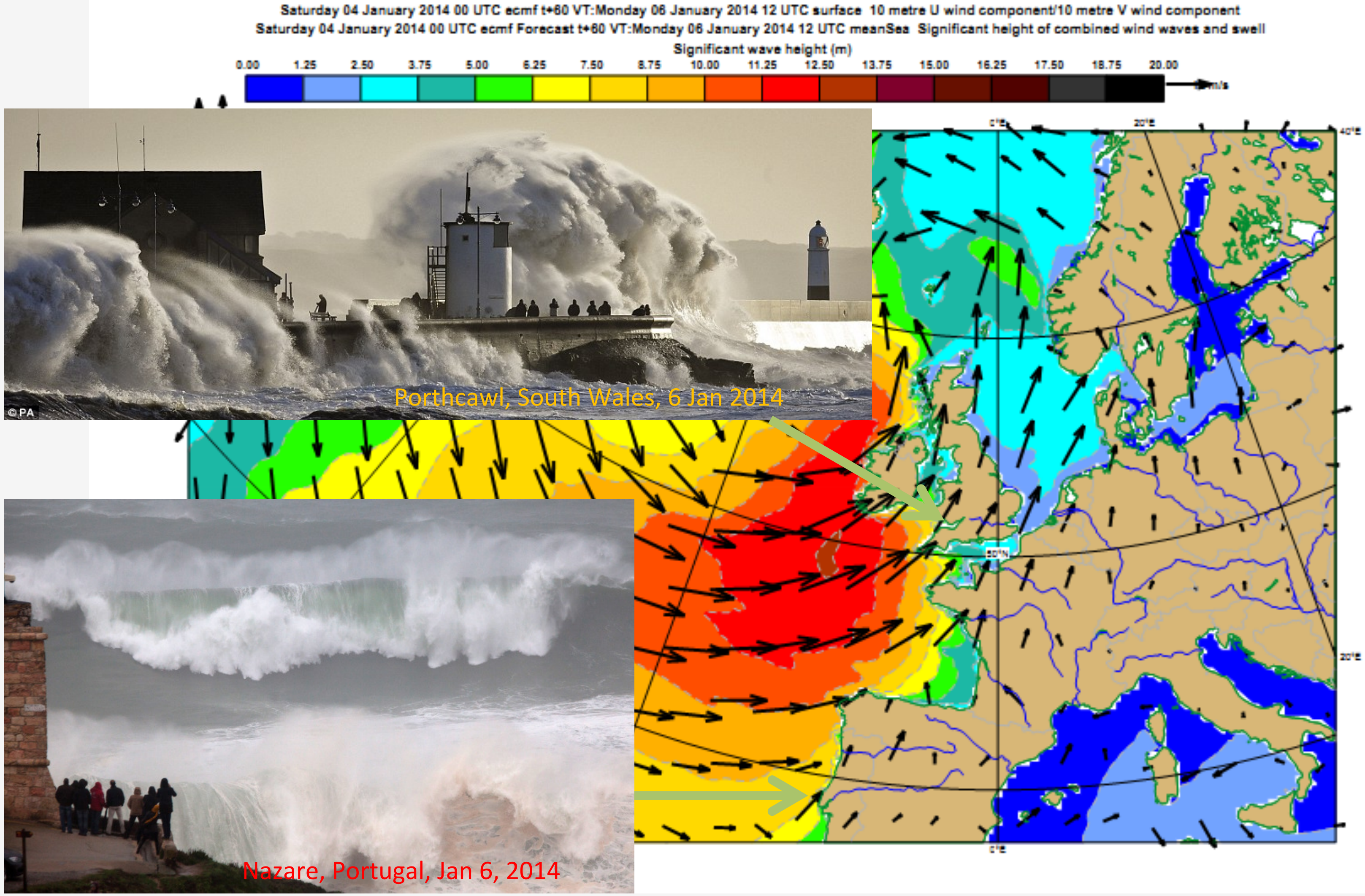
Ocean wave forecasts

Wave height forecast and wind from 4 January 2014, step 48 hours



Ocean wave forecasts

Wave height forecast and wind from 4 January 2014, step 60 hours



Porthcawl, South Wales, 6 Jan 2014

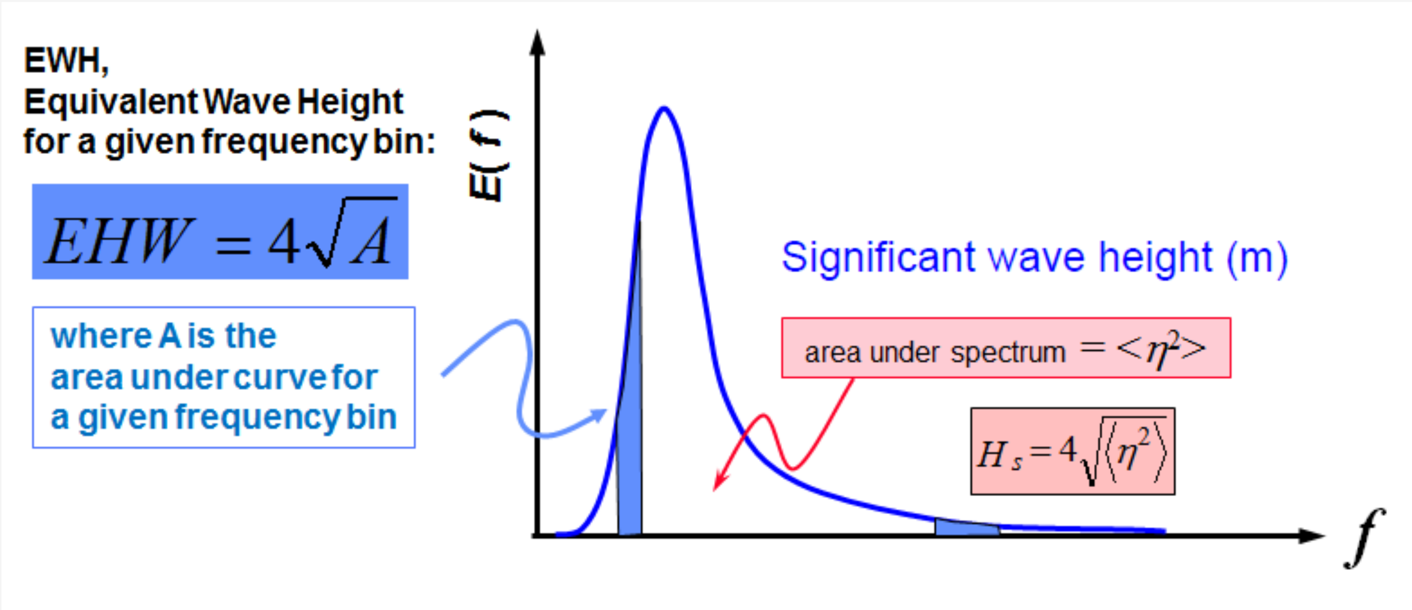
Nazare, Portugal, Jan 6, 2014

Long swell forecasts

Swell are long waves propagating away from storms.

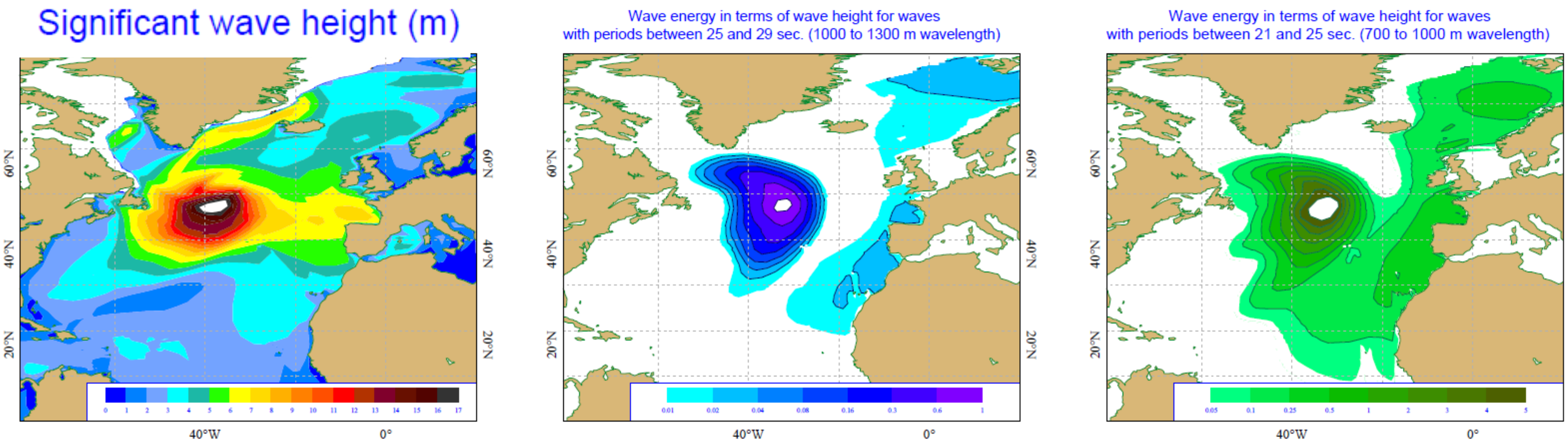
It is possible to follow the evolution of the swell.

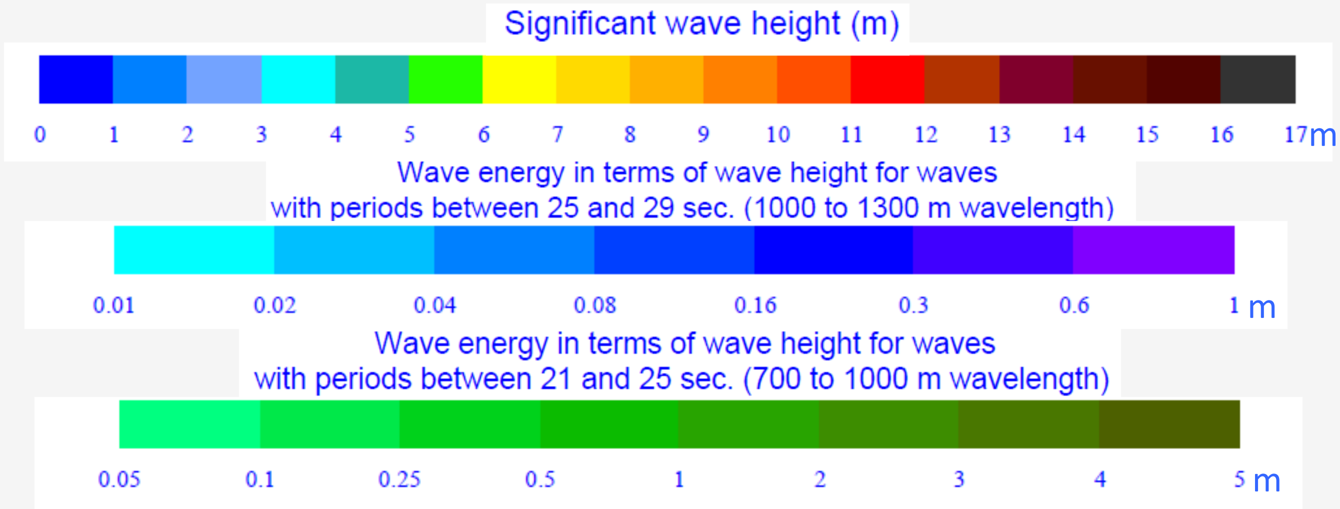
Define the Equivalent Wave Height:



Long swell forecasts

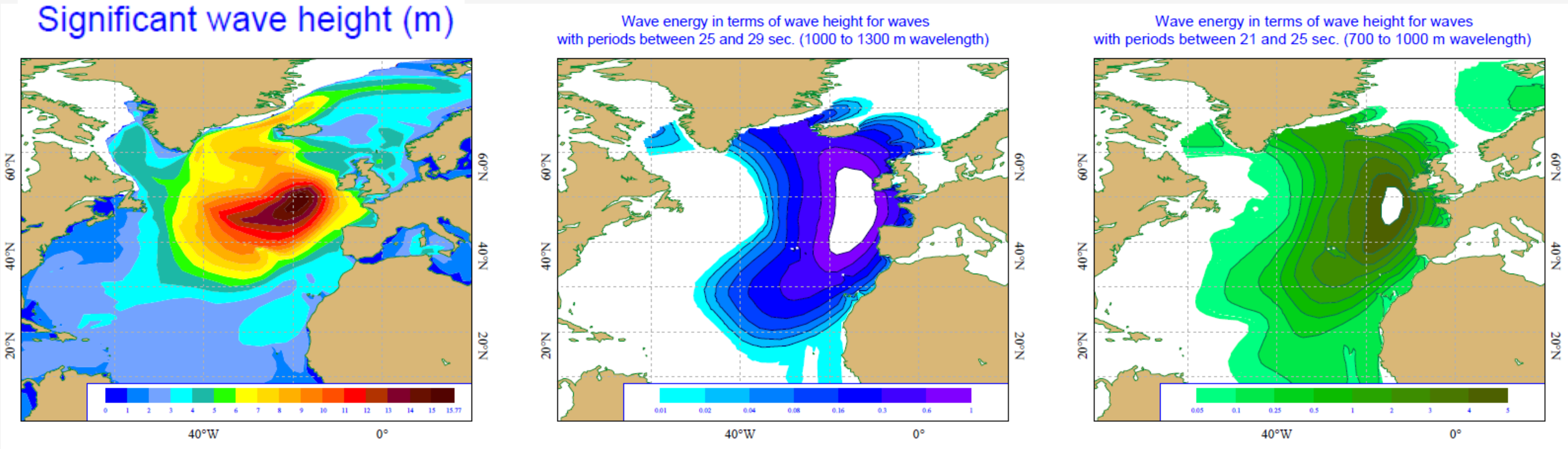
Wave height and long swell forecast from 4 January 2014, step 24

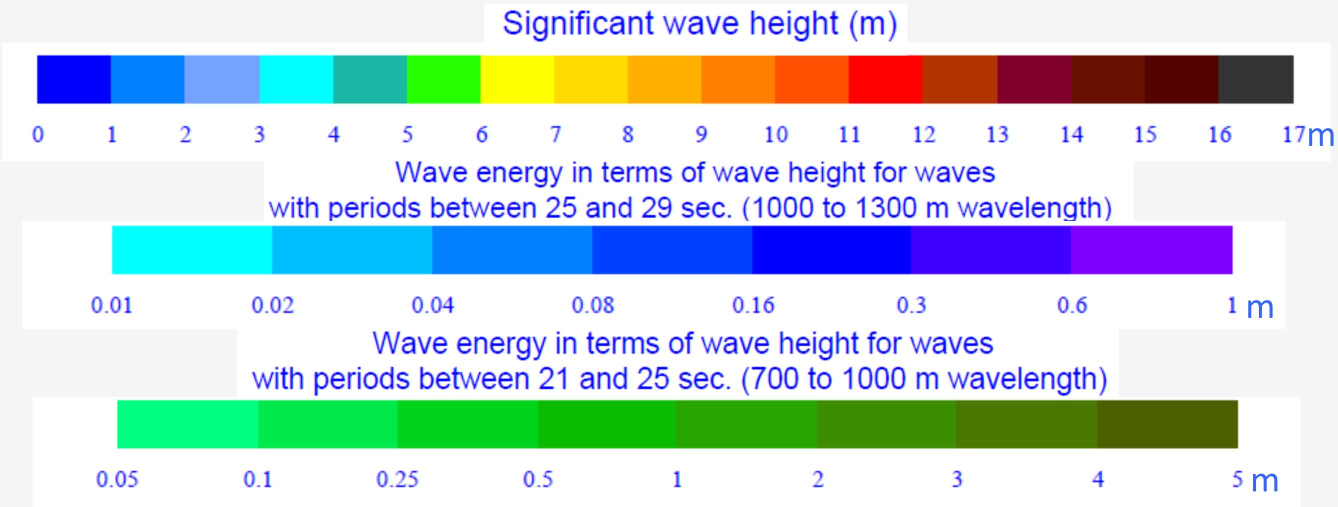




Long swell forecasts

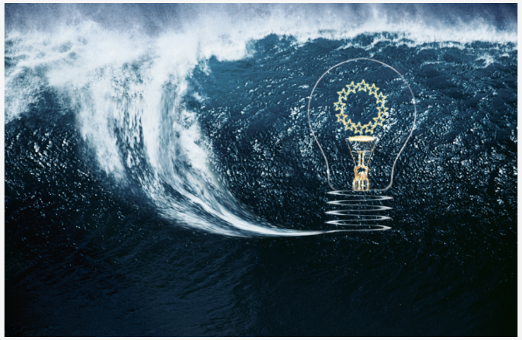
Wave height and long swell forecast from 4 January 2014, step 48

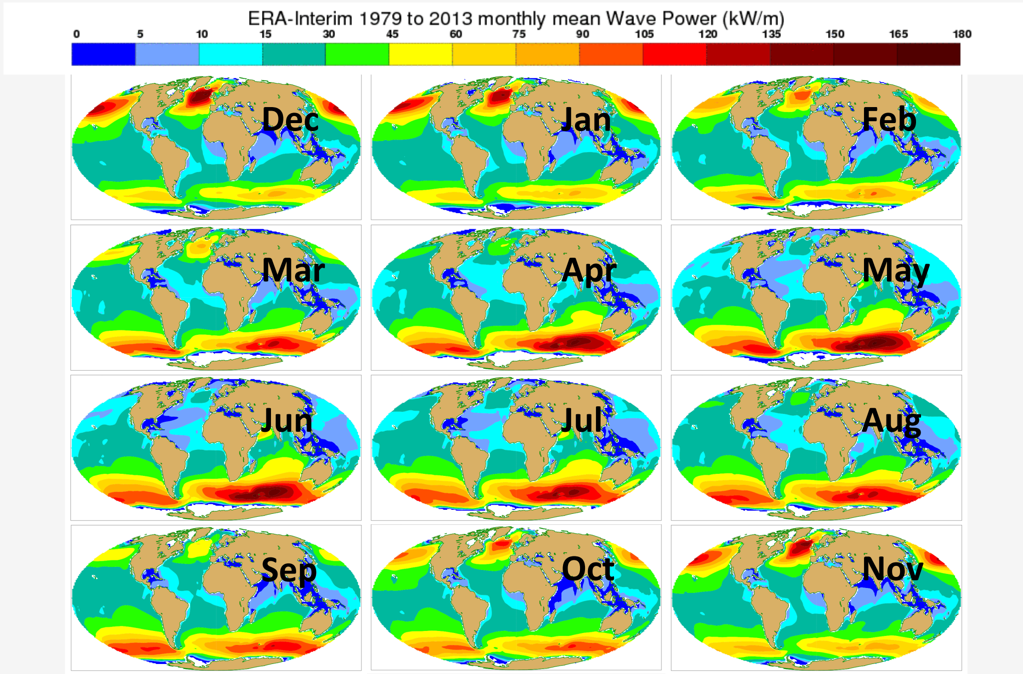




These long swell parameters have been introduced in operation in November 2016

Wave energy:




ERA-Interim 1979 to 2013 monthly mean Wave Power (kW/m)
0 5 10 15 30 45 60 75 90 105 120 135 150 165 180
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov

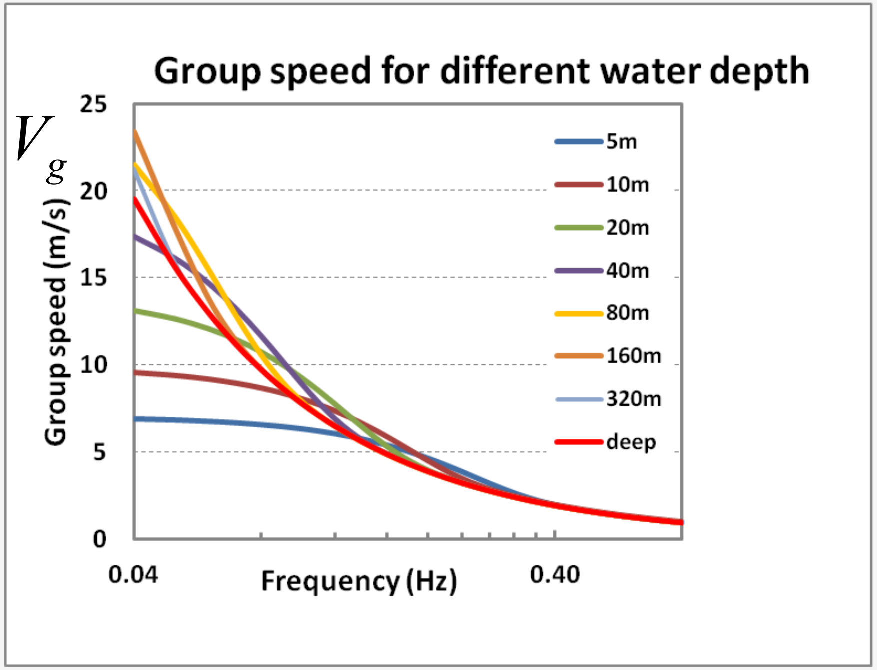
Wave energy flux:

General definition

$$\Phi = \rho_w g \iint V_g F(f,\theta) df d\theta$$

Its calculation would require integrating the spectra. But in deep water:

$$V_g = \frac{g}{4\pi f}$$



Define the spectral moments:

$$m_i = \iint f^i F(f,\theta) df d\theta$$

$$H_s = 4\sqrt{m_0} \qquad T_m = \frac{m_{-1}}{m_0}$$

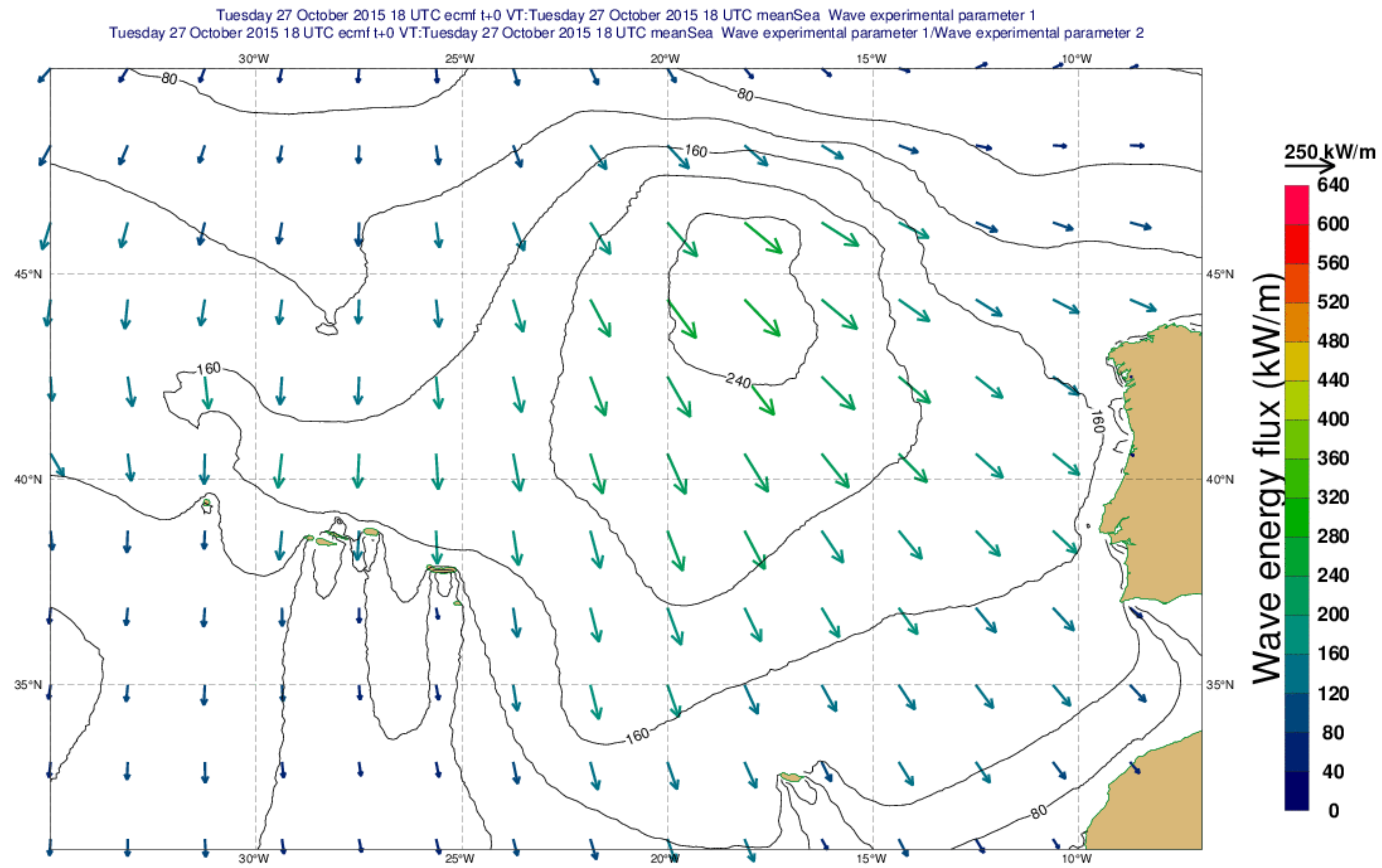
Note that mean period T_m is based on the moment -1 !

$$\Phi = \frac{\rho_w g^2}{64\pi} T_m H_s^2 \qquad \Phi \approx 0.478\, T_m H_s^2 \text{ kW/m}$$

H_s and T_m are standard output of ECWAM

Wave energy flux: using archived 2d spectra

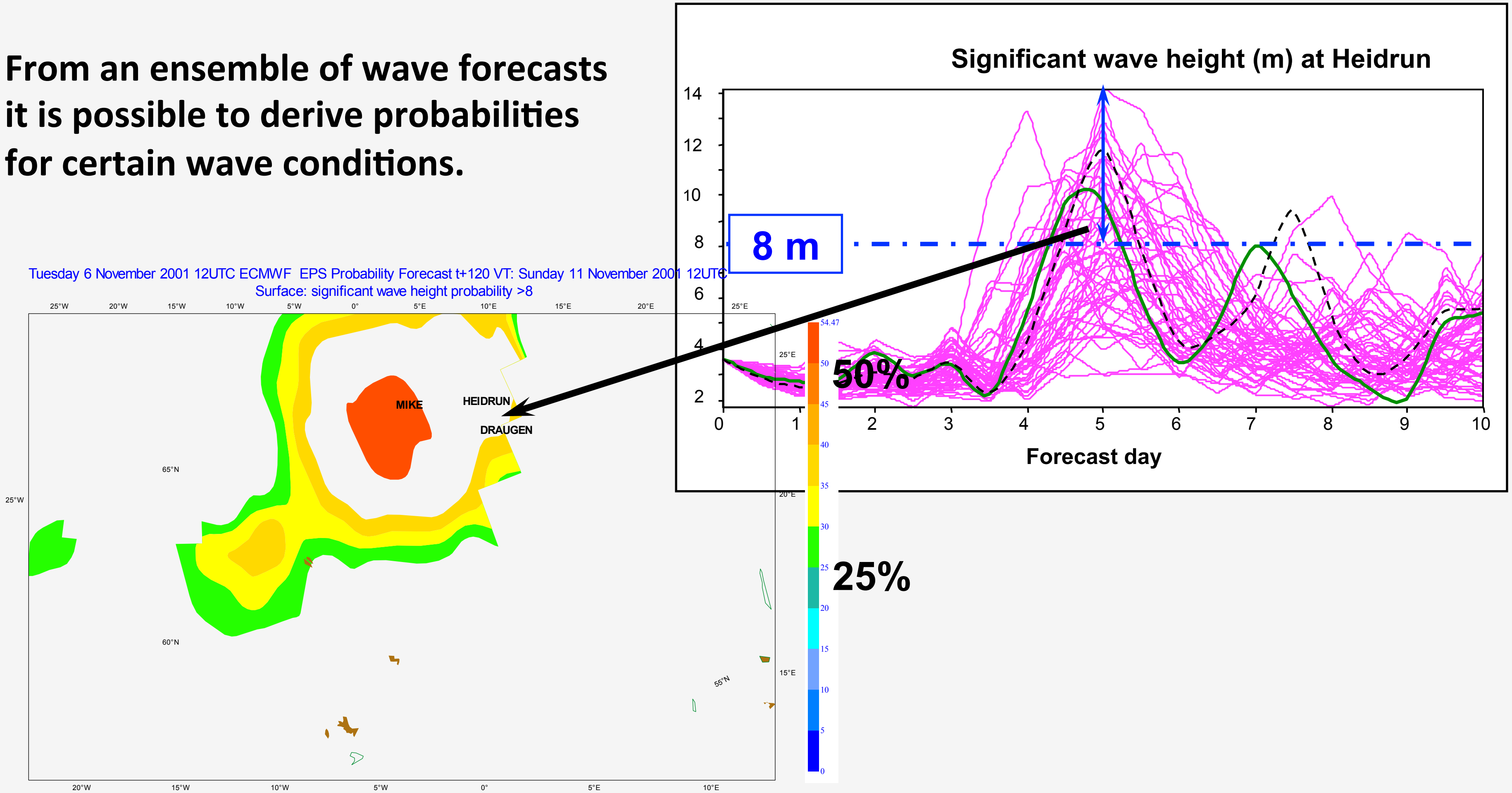
$$\vec{\Phi} = \rho_w g \iint \vec{V}_g F(f,\theta)\, df\, d\theta$$



The magnitude and direction of the wave energy flux have been introduced in operation in November 2016

A more ‘classic’ use of the EPS:

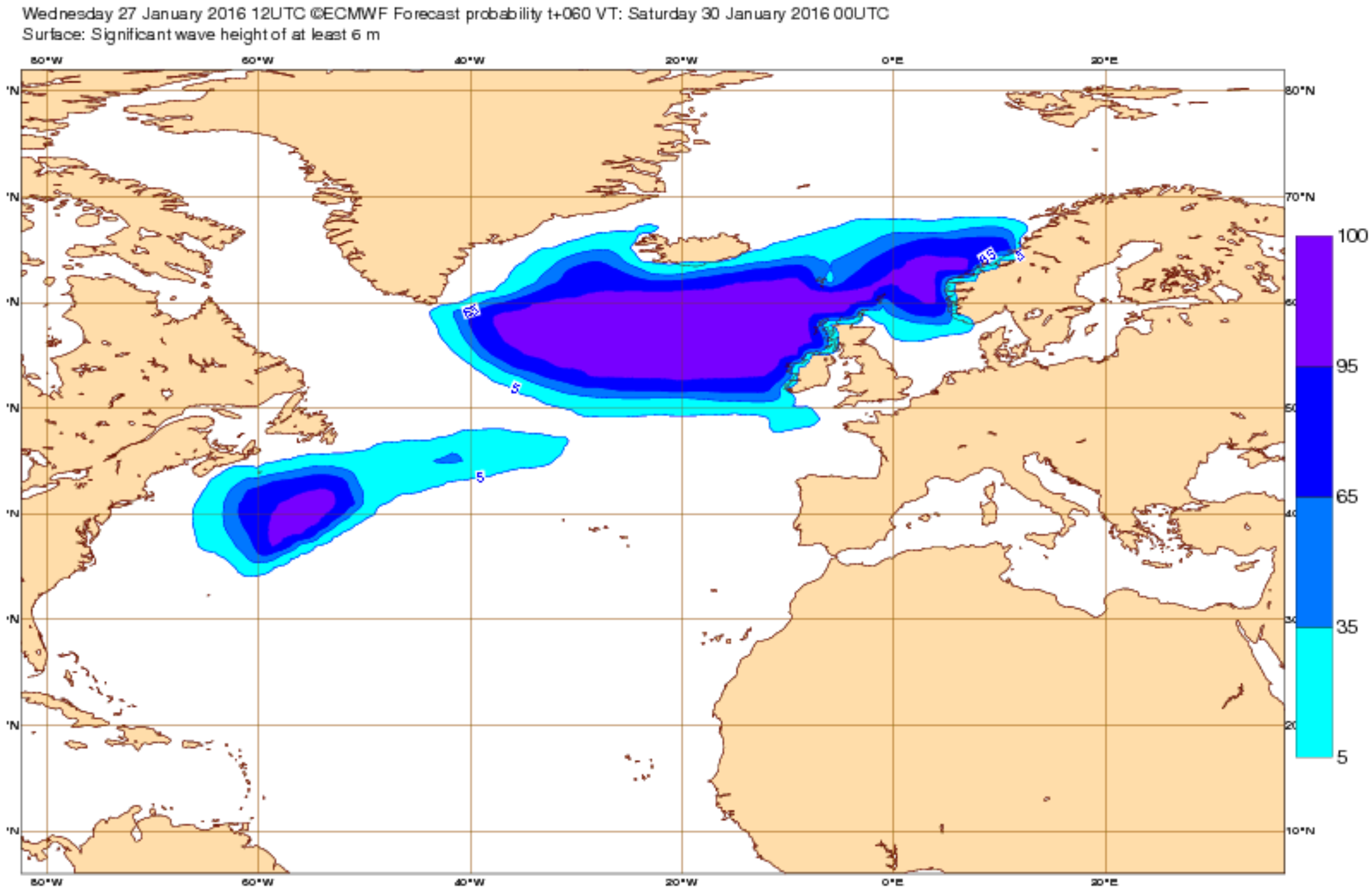
From an ensemble of wave forecasts it is possible to derive probabilities for certain wave conditions.



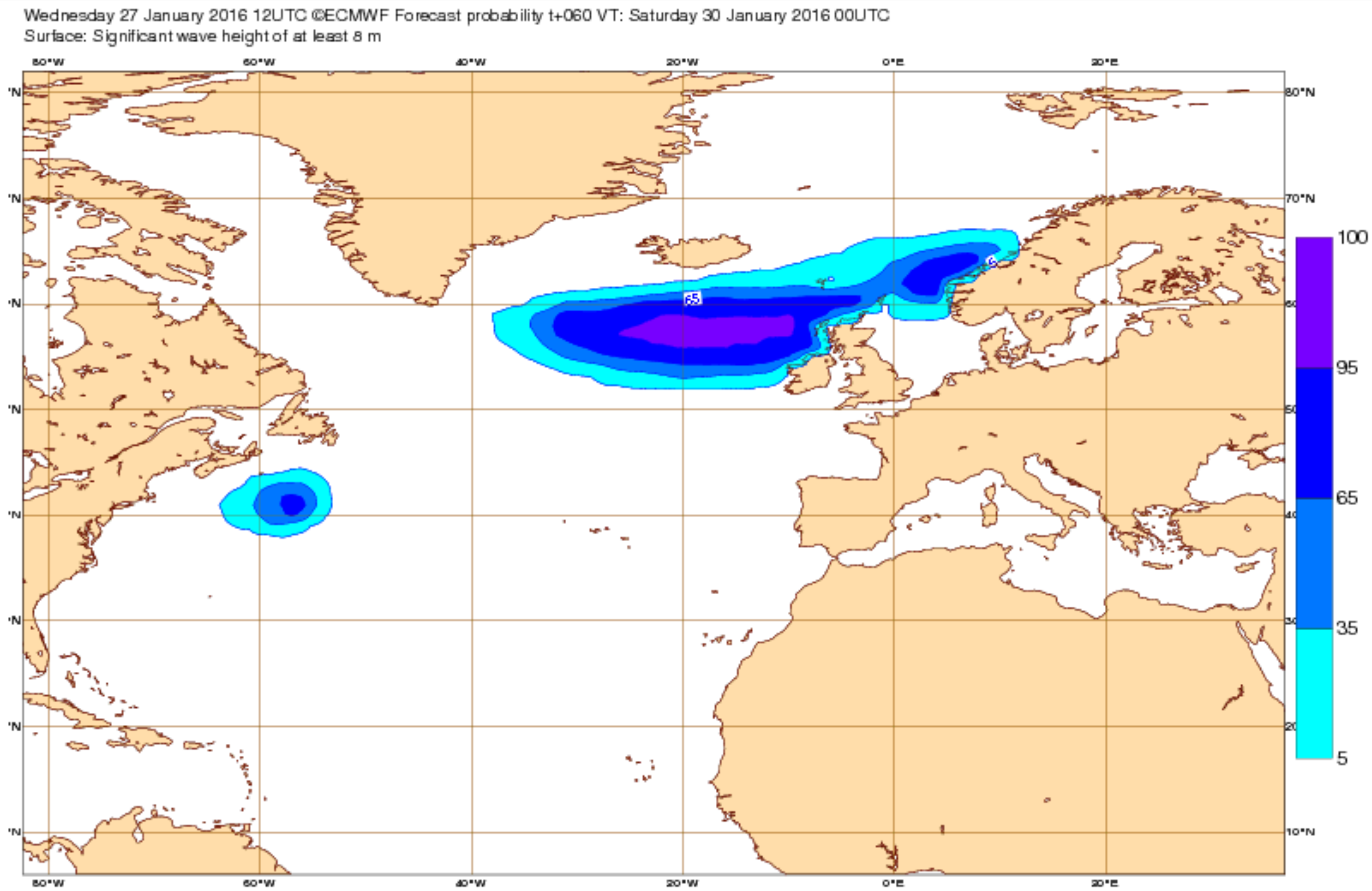
06 Nov. 2001 12 UTC ECMWF EPS probability forecast t+120

Significant wave height above 8 m

Basic EPS Wave Model Products



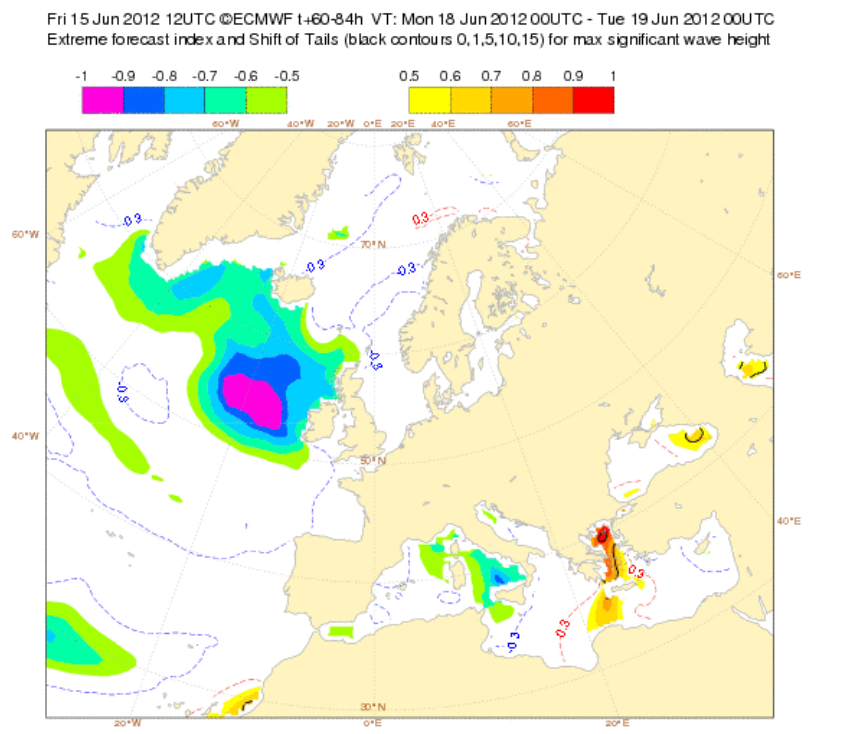
Basic EPS Wave Model Products



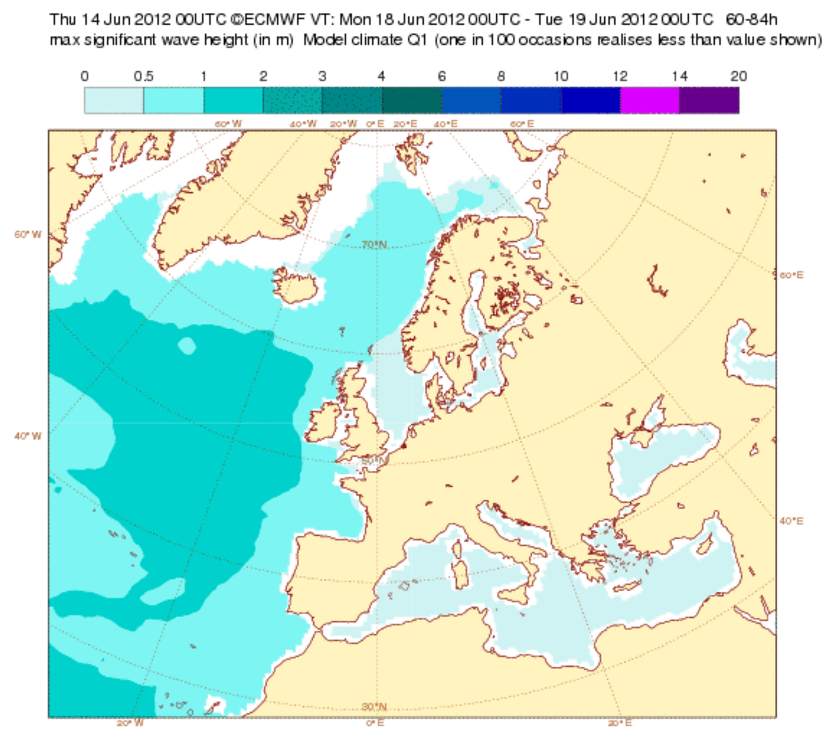
EFI plots

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 <u>below</u> climate.



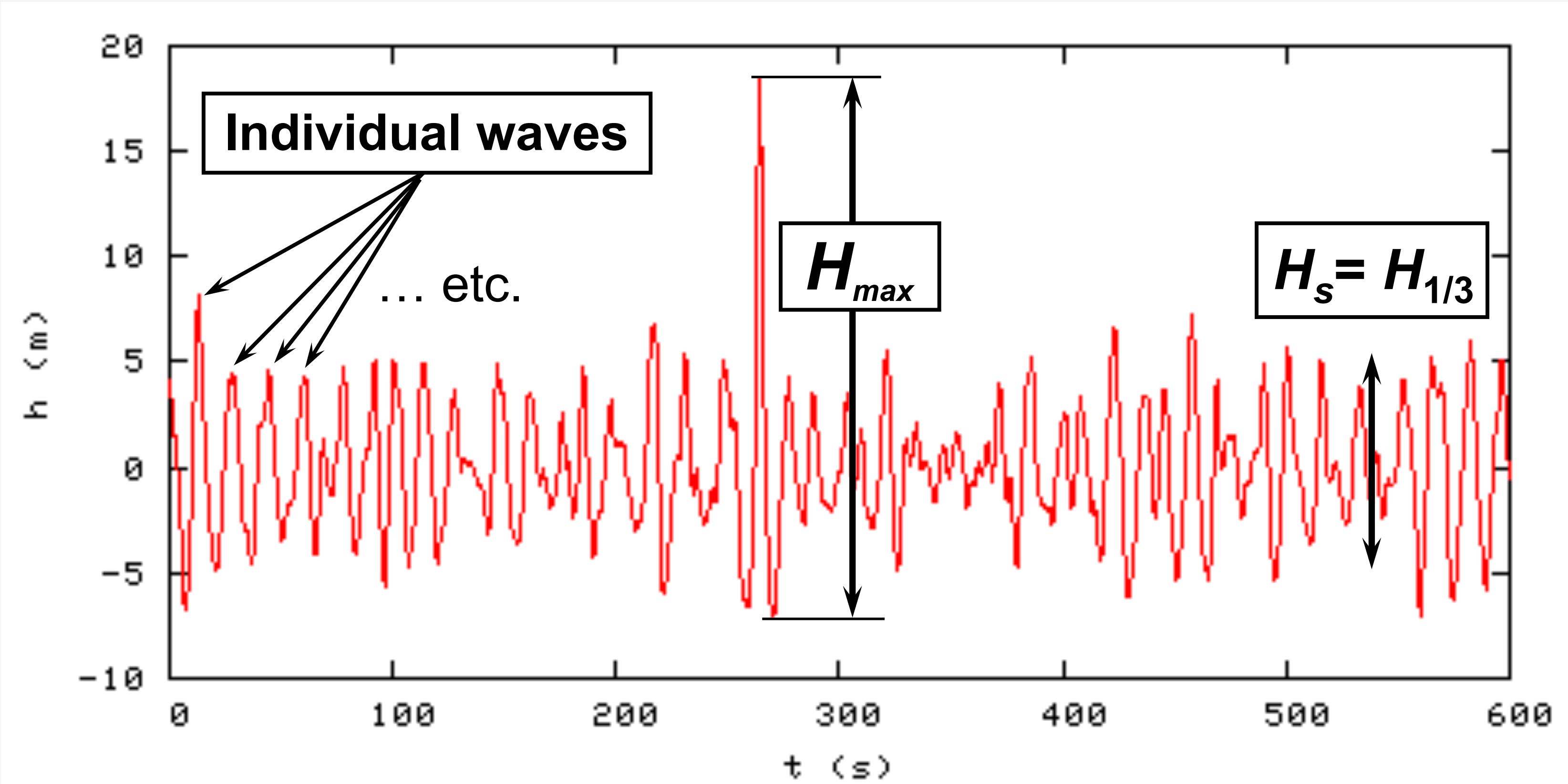
EFI for significant wave height



01 percentile of the distribution for significant wave height

We are not always dealing with nice 'predictable' waves:

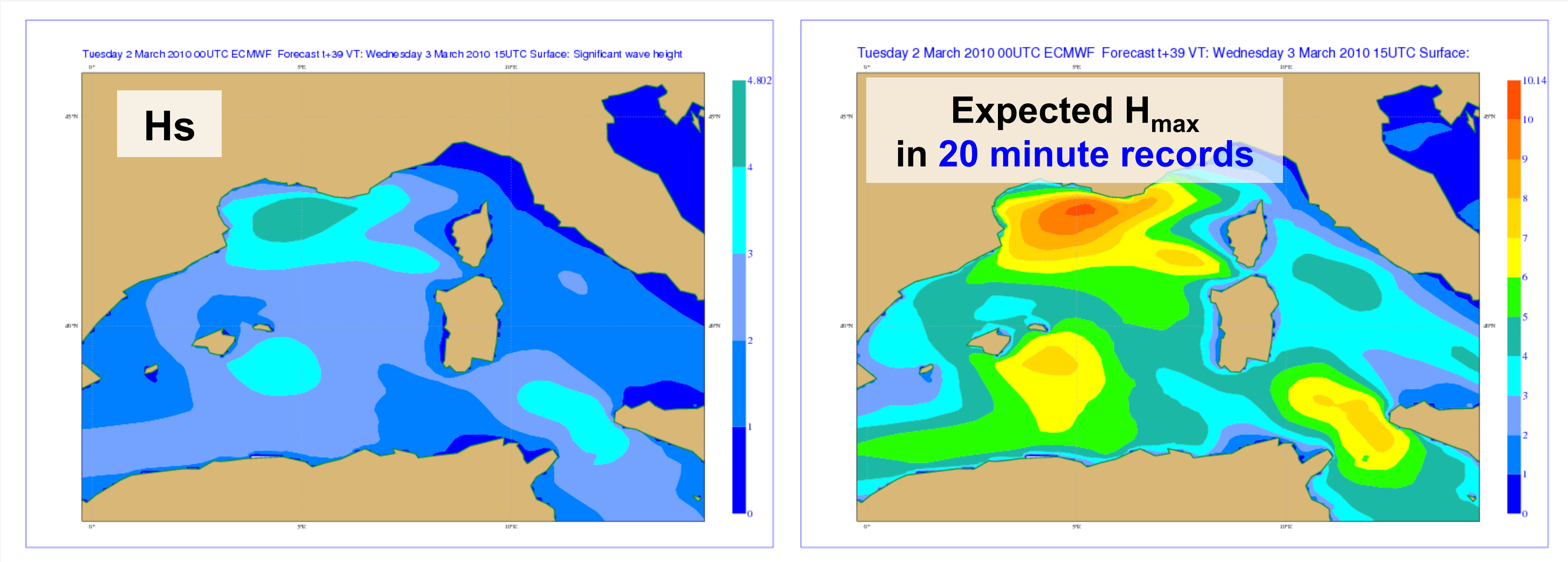
Individual Waves,
Significant Wave Height, H_s,
Maximum Individual Wave Height, H_{max}, and
Freak Wave



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

Wave Model Products: Extreme Waves

We have a parameter to estimate the height of the highest *individual* wave (H_{max}) one can expect. Its value can be derived from the 2d wave spectrum:

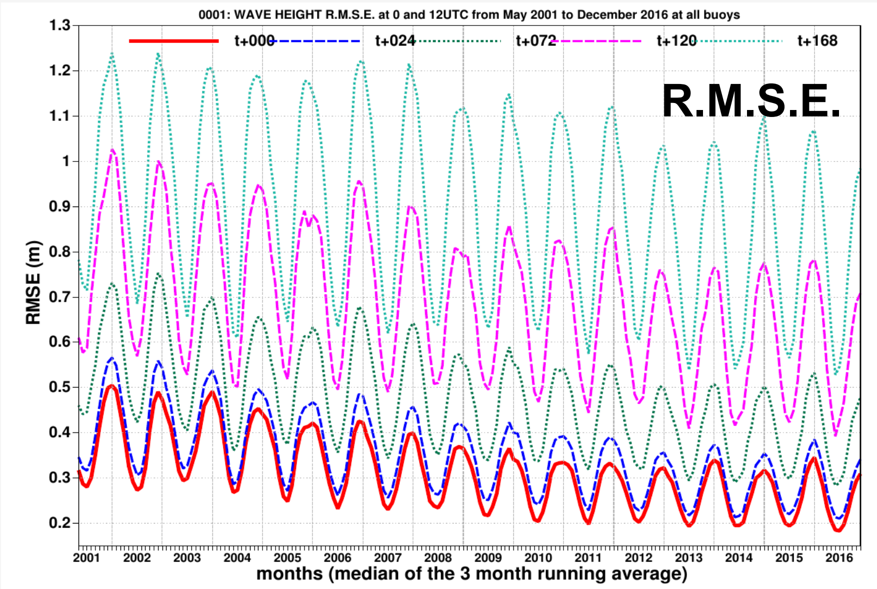


March 3, 2010, 15UTC
Forecasts fields from Friday 2 March, 2010, 0 UTC

Continued general improvement of model forecasts

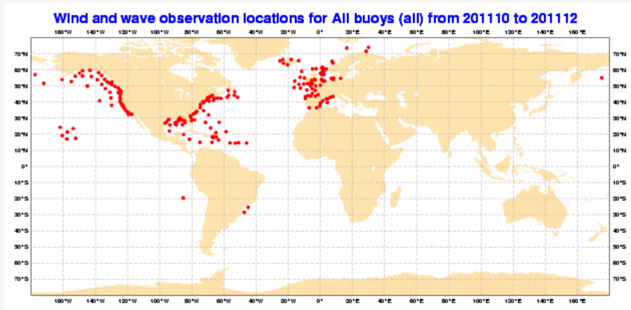
For example: ECMWF forecast wave height against buoy measurements:

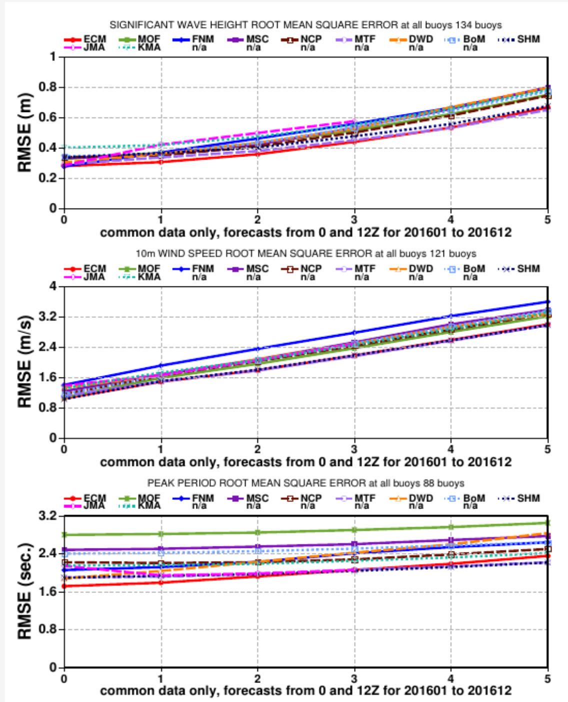
Home -> Forecasts -> Charts -> Verifications -> Wave Products Comparison



7 day FC
5 day FC
3 day FC
1 day FC
analysis

2001 2016





See also the Wave Forecast Verification Project maintained on behalf of the Expert Team on Waves and Storm Surges of the WMO-IOC Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM)

http://www.jcomm.info/index.php?option=com_content&task=view&id=131&Itemid=37


Questions ?
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