Ocean Waves

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ECMWF

Sea State Forecasting

Porthcawl, South Wales, UK, 6 Jan 2014

European Centre for Medium-range Weather Forecasts

Ocean waves:

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

May 1, 2013

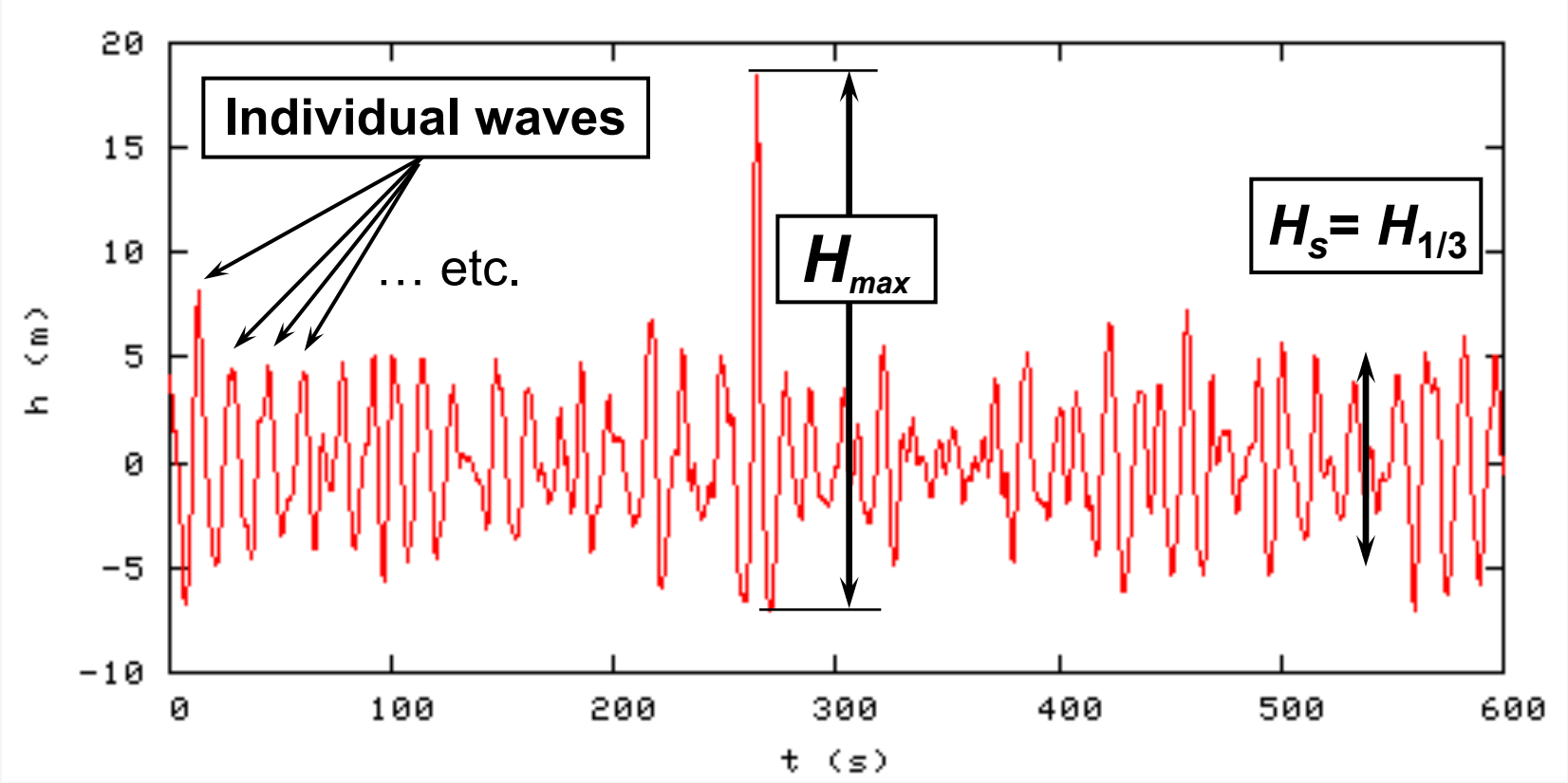
Porthleven Clock Tower, Cornwall, UK

February 5, 2014

Observe Individual Waves,

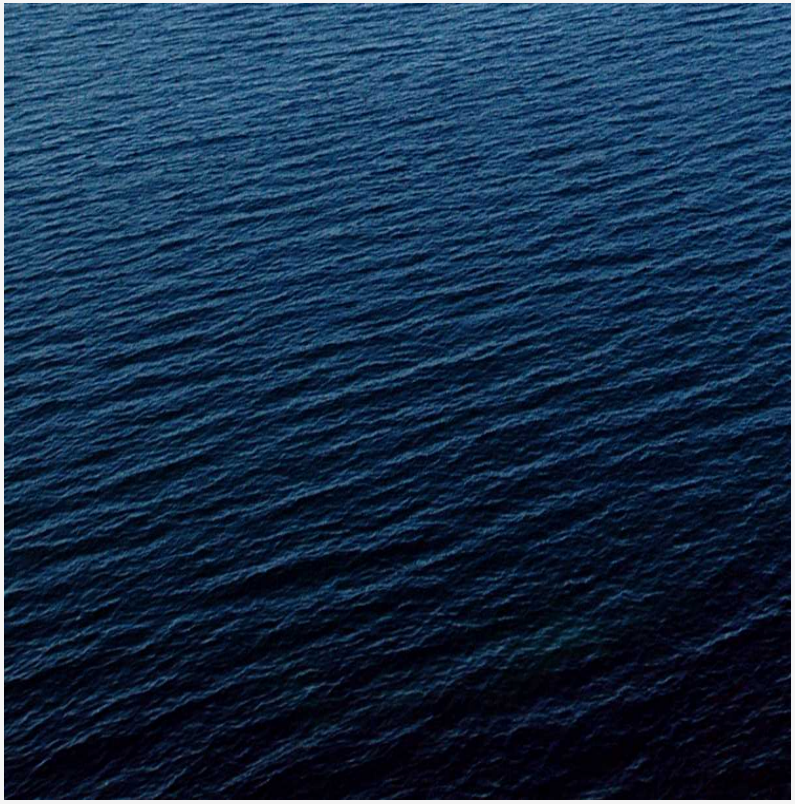
After a while, you can estimate a characteristic height the waves: the Significant Wave Height, H_s,

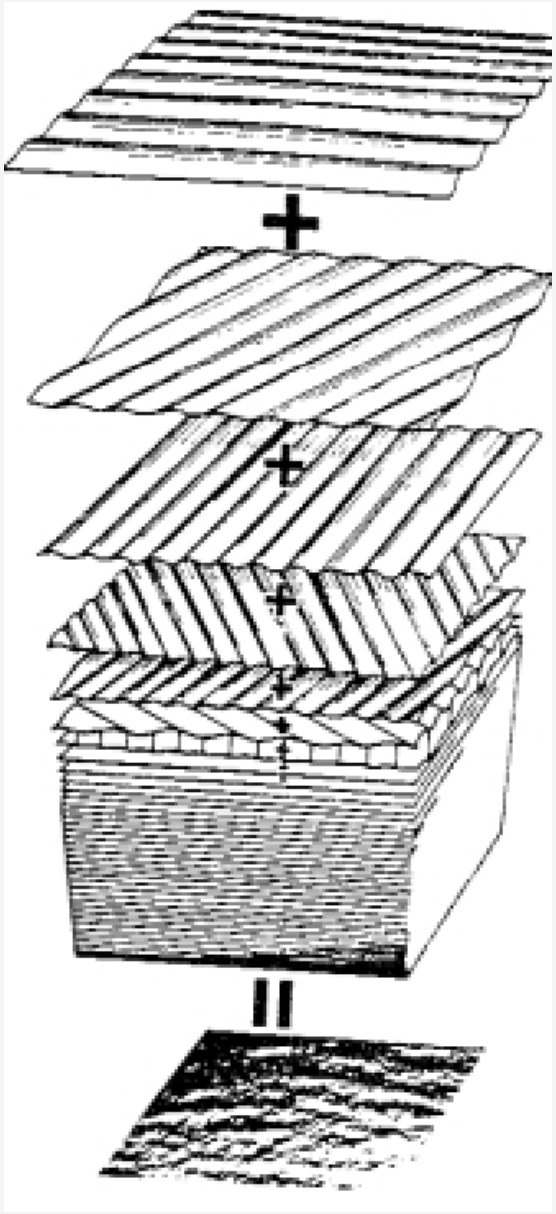
You might also notice that some waves are larger than the rest, characterised by the Maximum Individual Wave Height, H_{max}



Surface elevation time series from platform Draupner in the North Sea

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

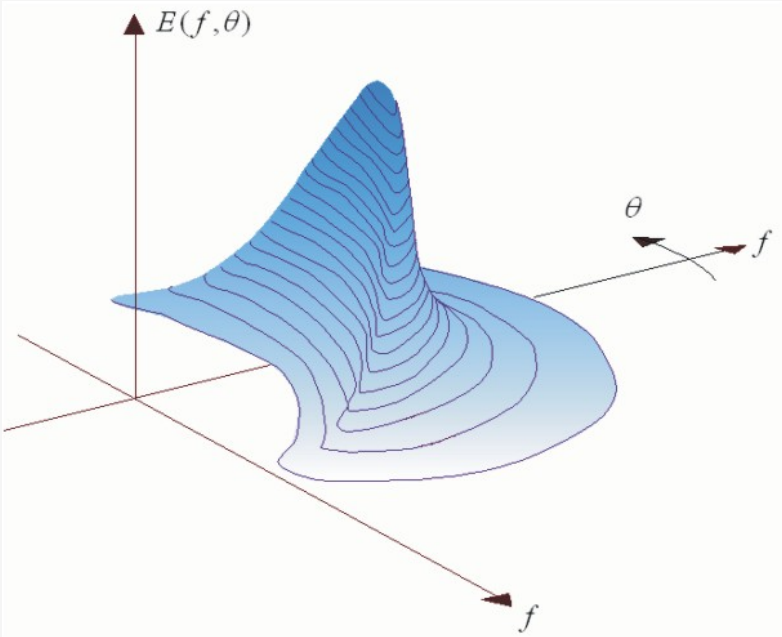




Wave Spectrum

- 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).

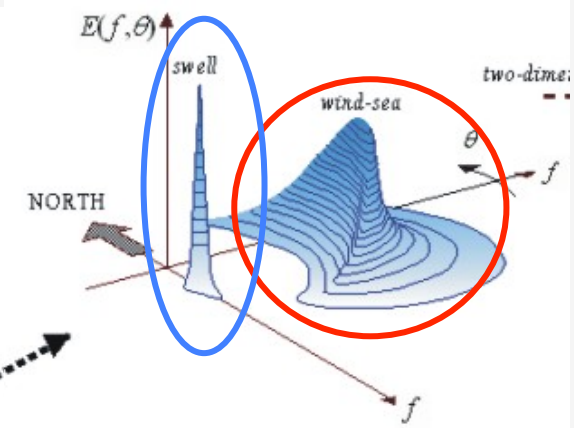


Modern ocean wave prediction systems are based on statistical description of oceans waves (i.e. ensemble average of individual waves).

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

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



swell: well defined peak in direction and frequency.

Windsea: broad distribution of the waves around a peak

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 frequency and wave number.

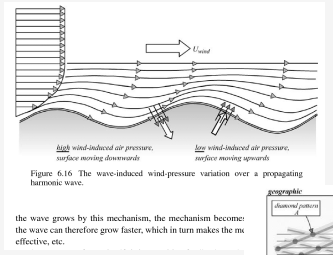


Figure 6.16 The wave-induced wind-pressure variation over a propagating harmonic wave.

the wave grows by this mechanism, the mechanism become
the wave can therefore grow faster, which in turn makes the m
effective, etc.

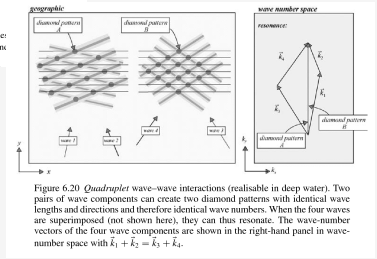
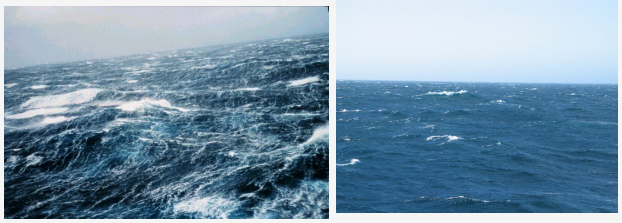


Figure 6.20 *Quadruplet* wave–wave interactions (realisable in deep water). Two pairs of wave components can create two diamond patterns with identical wave lengths and directions and therefore identical wave numbers. When the four waves are superimposed (not shown here), they can thus resonate. The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

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

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

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



Ocean Wave Modelling

- 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:

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

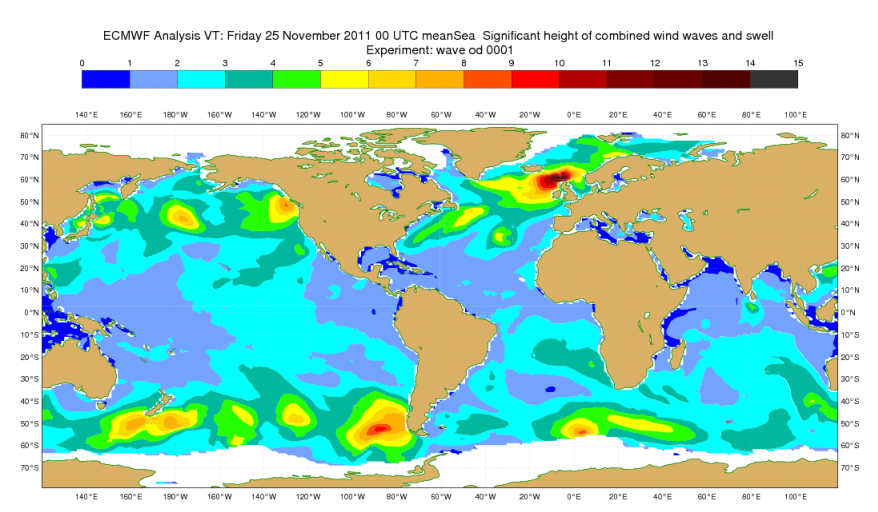
- The statistical measure for wave height, called the significant wave height (H_s):

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

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

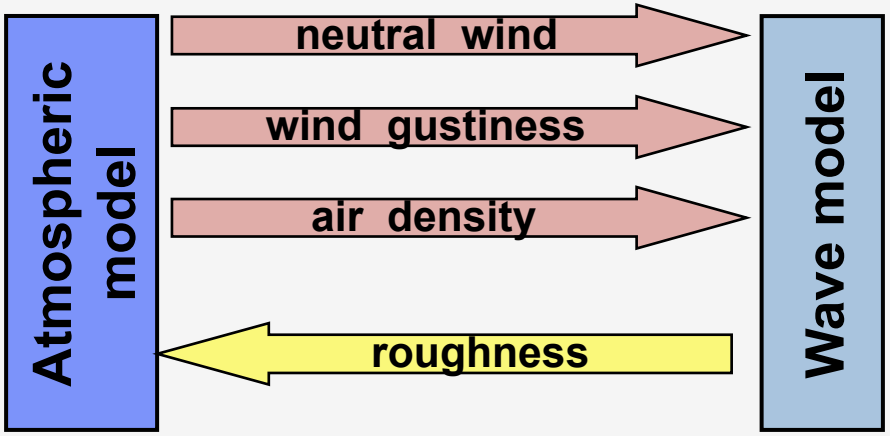
It can be shown to correspond to the average 1/3rd highest waves ($H_{1/3}$).

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.



The interface between WAM and the IFS has been generalised to include air density and gustiness effects on wave growth.

ECMWF Wave Model Configurations

High resolution

- 28 km grid spacing.
- 36 frequencies.
- 36 directions.
- Coupled to the TL1279 model.

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

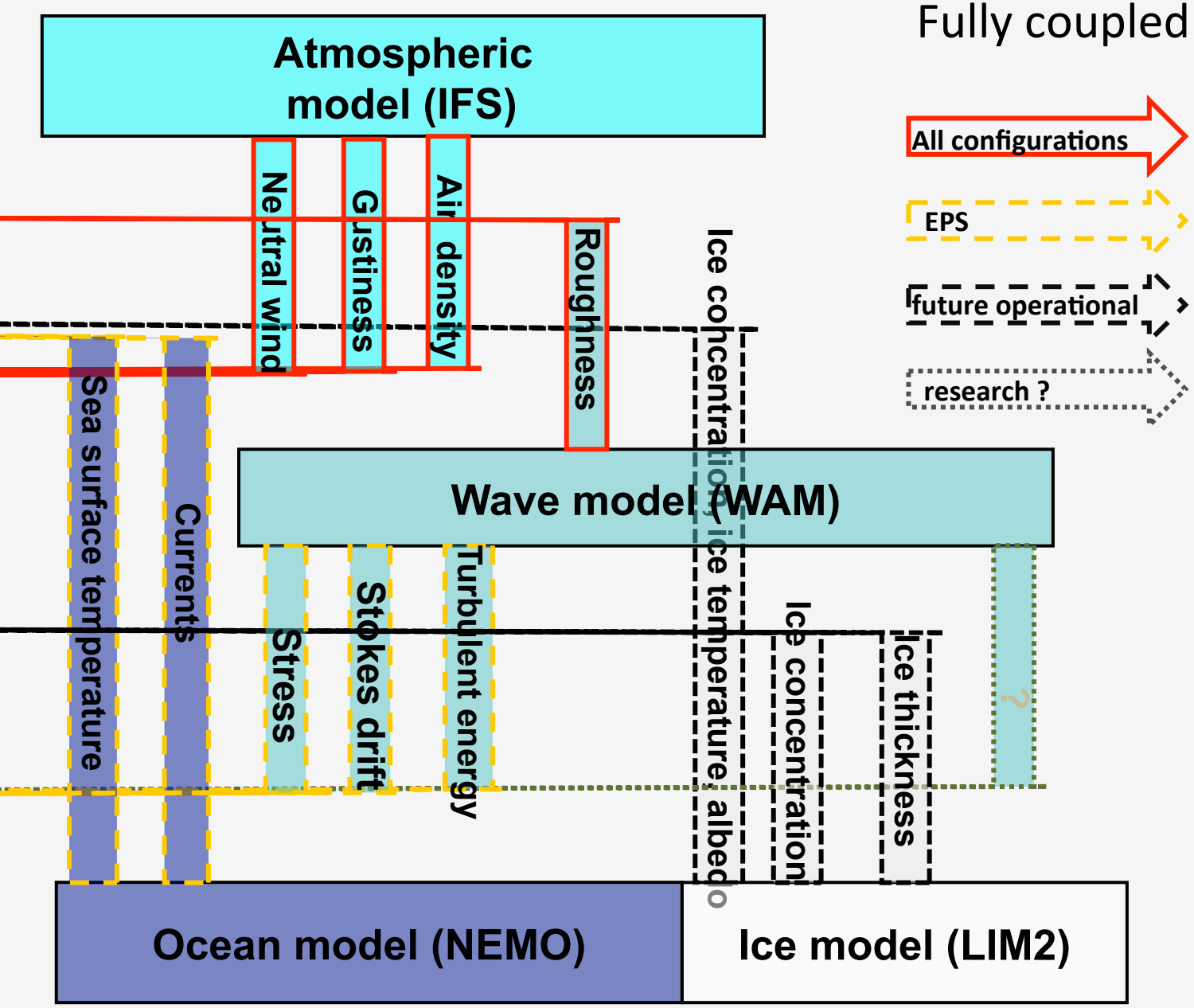
Ensemble forecasts (EPS)

- 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 twice a week).
- **Coupled to ocean model**.

* Change in resolutions after 10 days

NB: also in seasonal forecast at lower resolutions

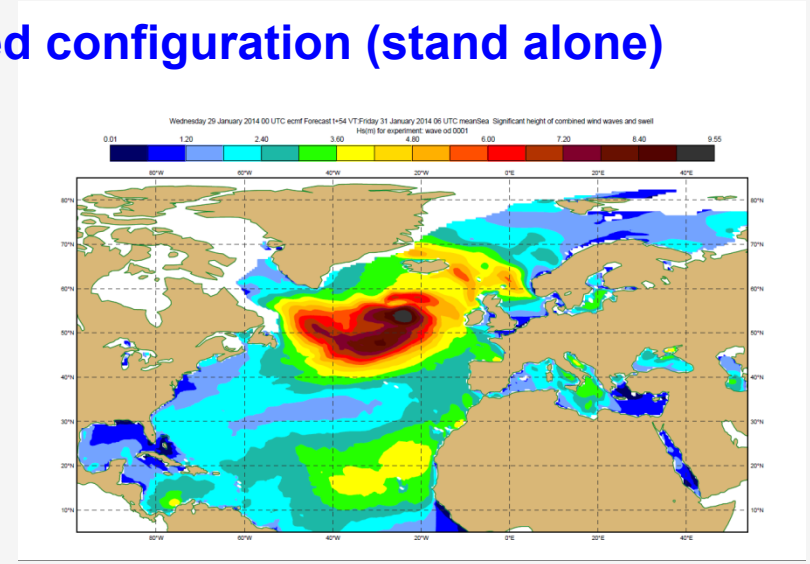
Fully coupled system?



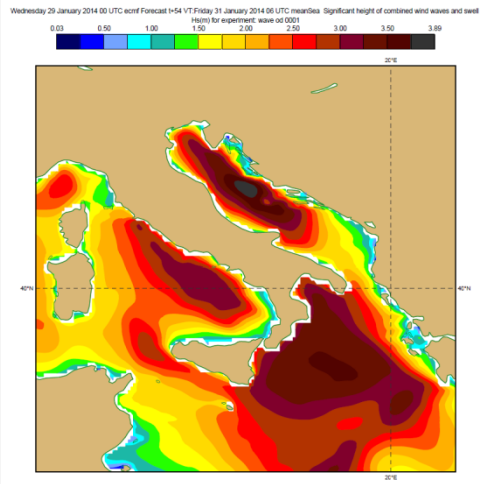
ECMWF Wave Model Configurations

We also have the uncoupled configuration (stand alone)

- From 5°N to 90°N and 98°W to 56°E.
- 11 km grid spacing.
- 36 frequencies and 36 directions
- Forced by 10m neutral wind fields from the global system.
- Data assimilation of altimeter wave heights (Jason 2).
- 2 daily forecasts (from 0 & 12 UTC) extending to day 5, output every hour.



t+54 forecast wave height
valid 31 January 2014, 6 UTC



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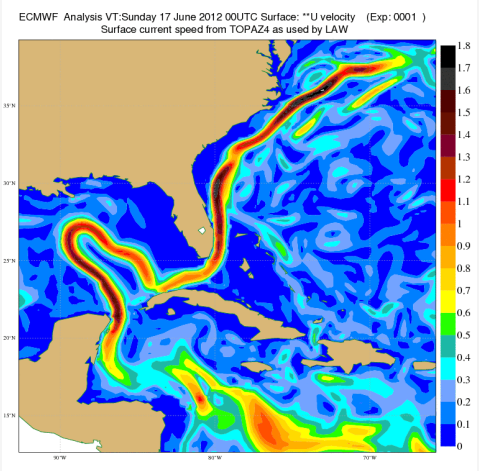
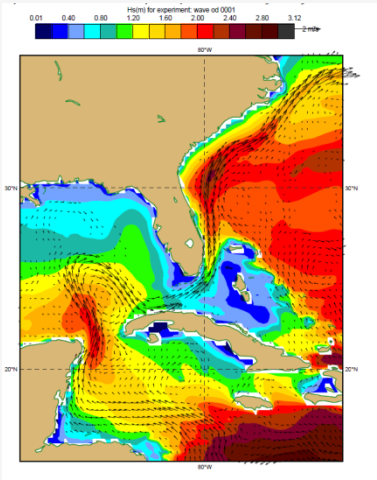
- Forced by 10m neutral wind fields from the global system.
- Data assimilation of altimeter wave heights (Jason 2).
- 2 daily forecasts (from 0 & 12 UTC) extending to day 5, output every hour.
- Imposed surface currents from TOPAZ4 system.

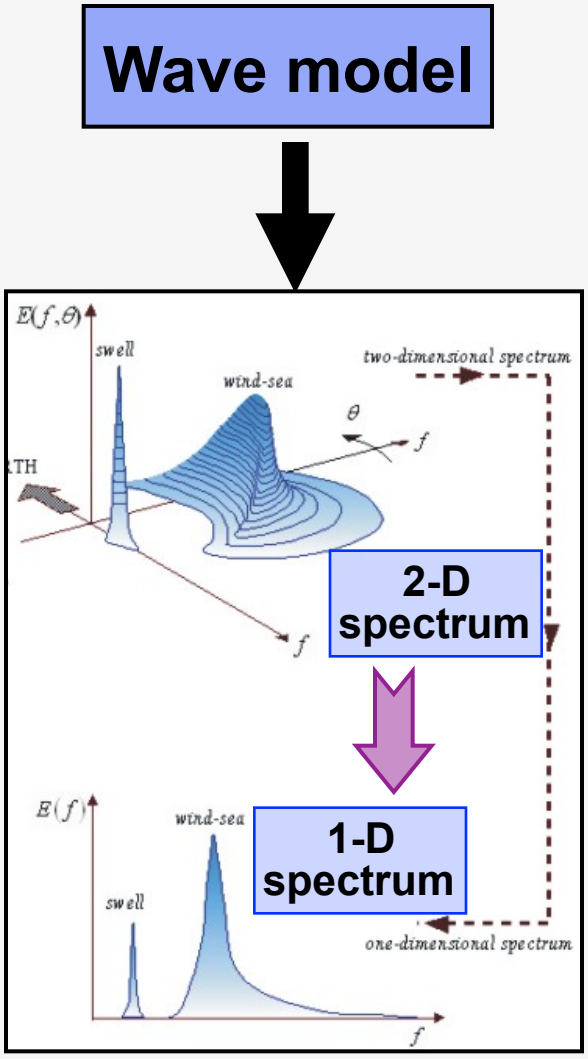


TOPAZ4 surface currents



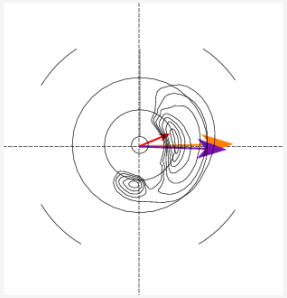
Wave Model Products

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

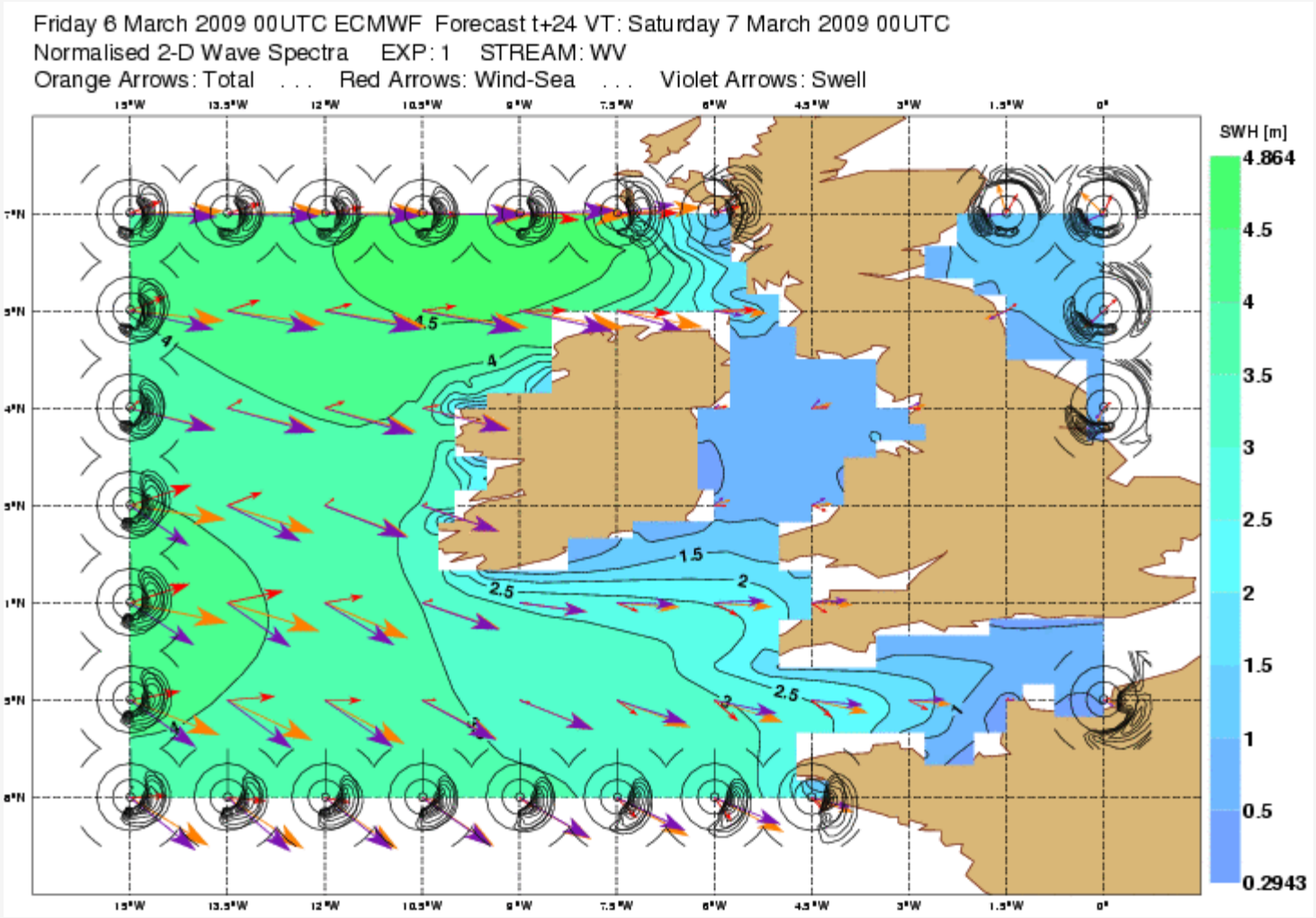


Wave Model Products

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



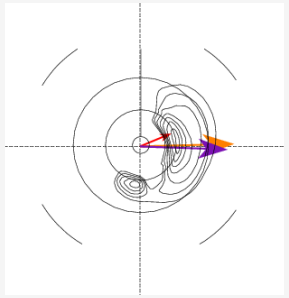
Spectra used as boundary conditions



→ windsea
→ swell
→ total sea

Wave Model Products

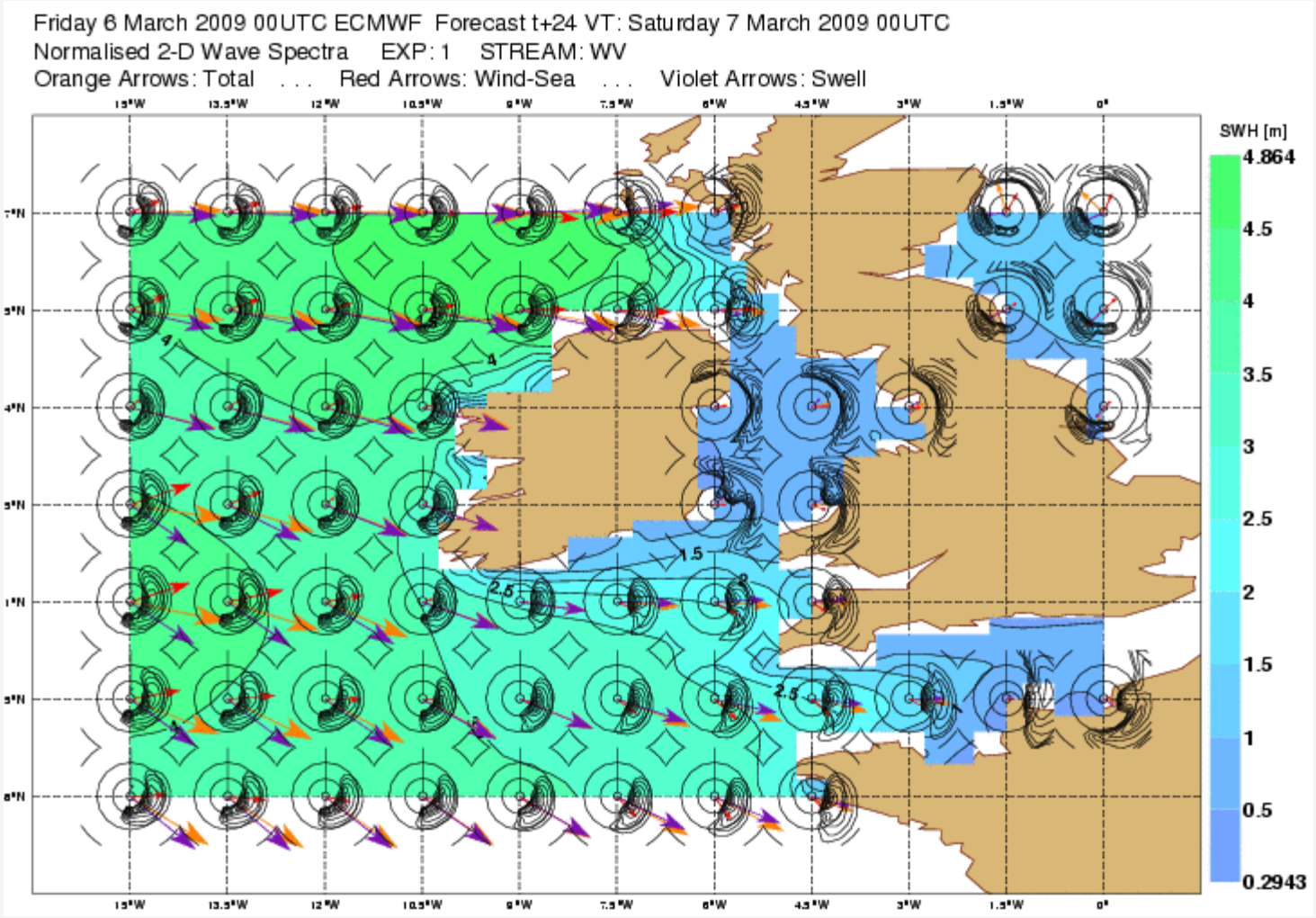
Plot of 2-D spectrum can become very busy !



windsea

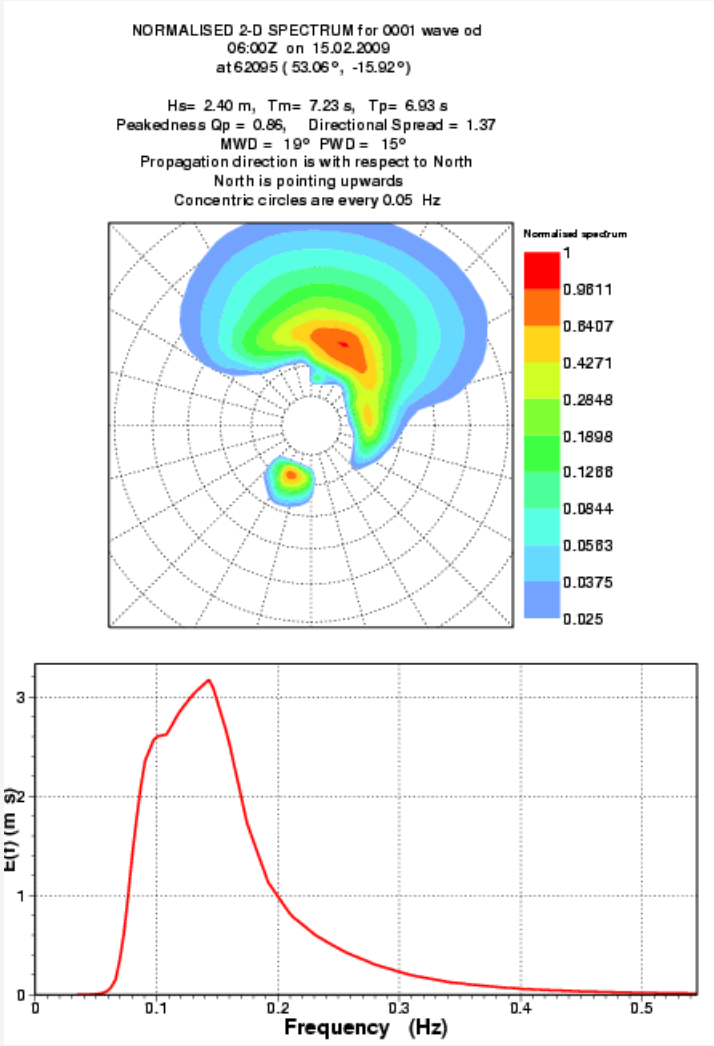
swell

total sea



Wave Model Products

Except if you only look at one location …

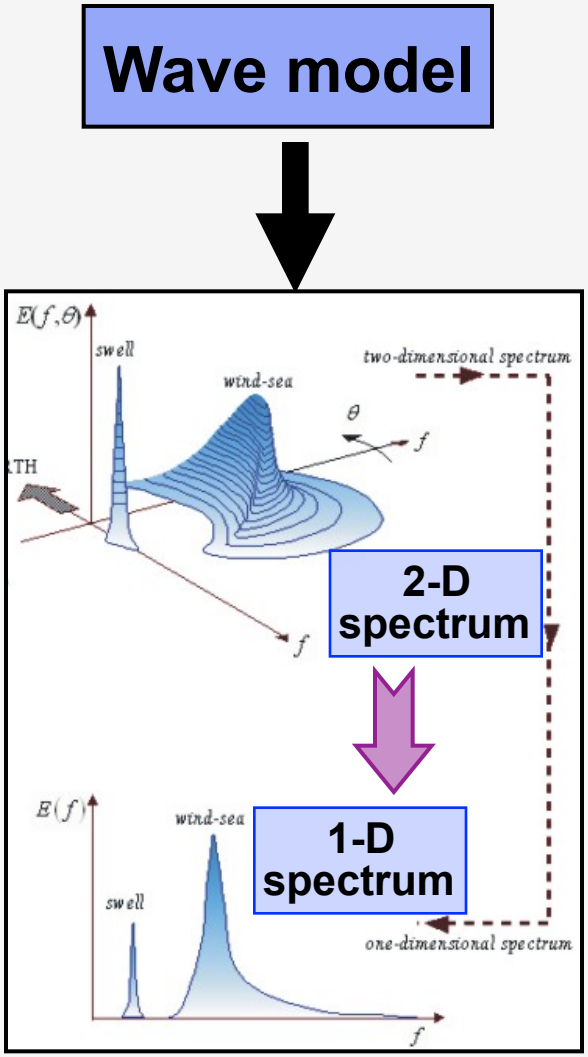


Wave Model Products

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 Products

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

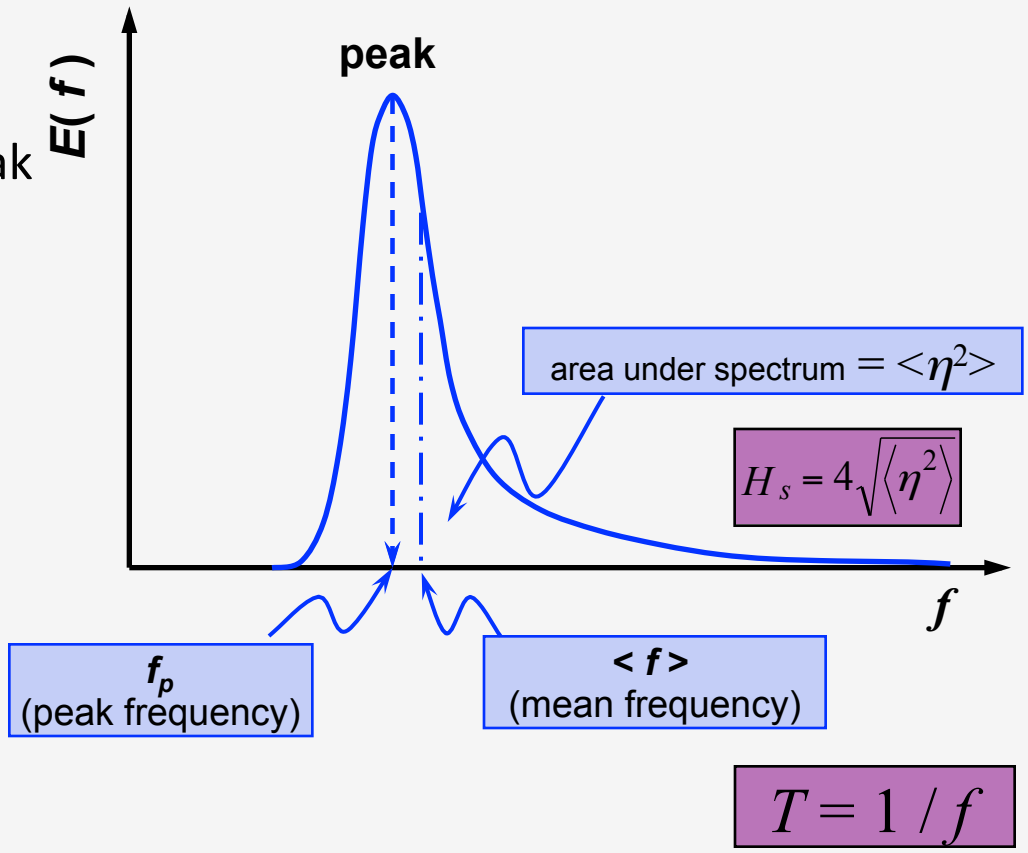
The significant wave height (H_s).

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.

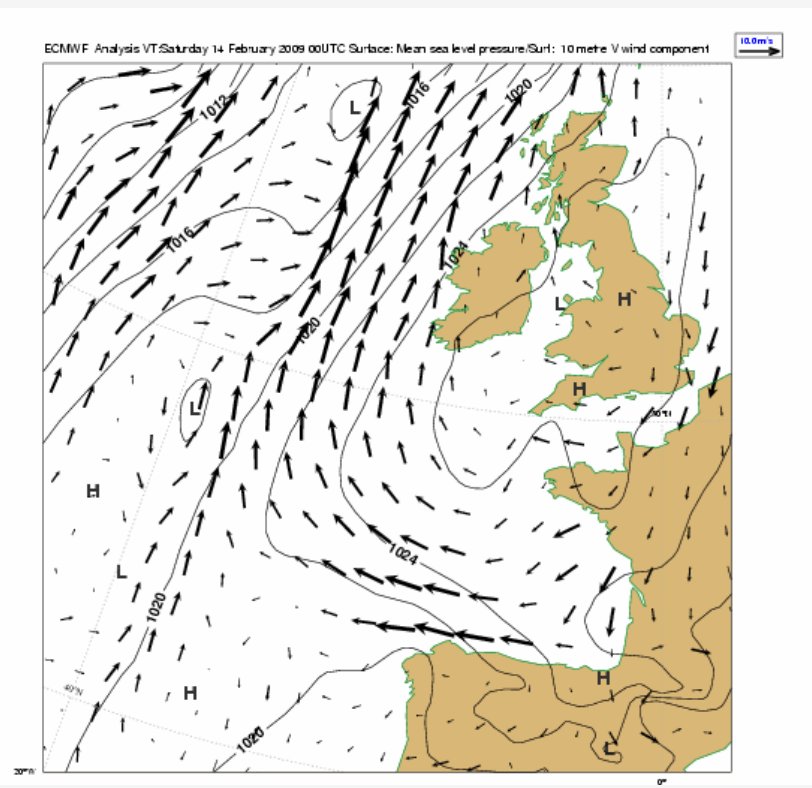
many others.



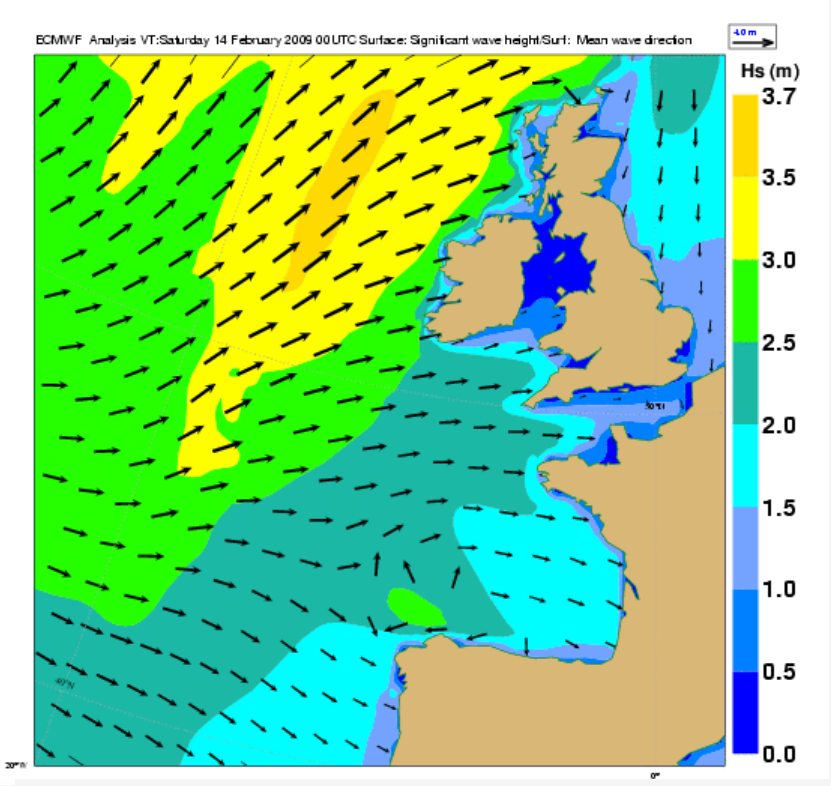
Complete list at: http://www.ecmwf.int/services/archive/d/parameters/order=/table=140/

Wave Model Products

Use simple parameters:
total wave height and mean propagation direction

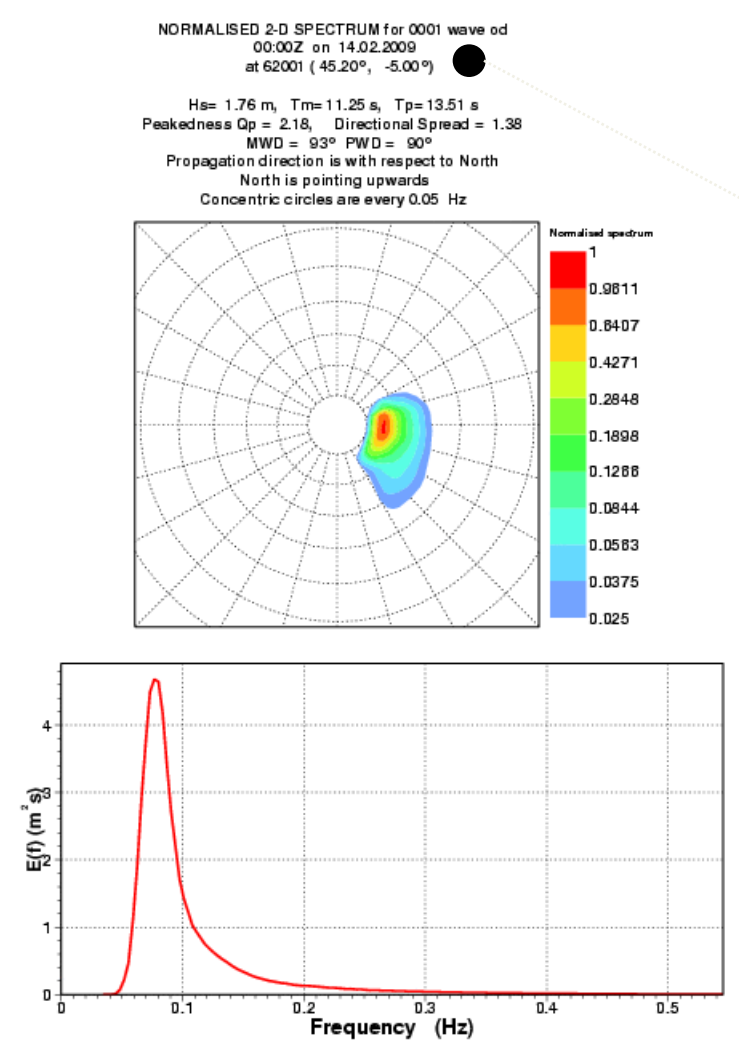


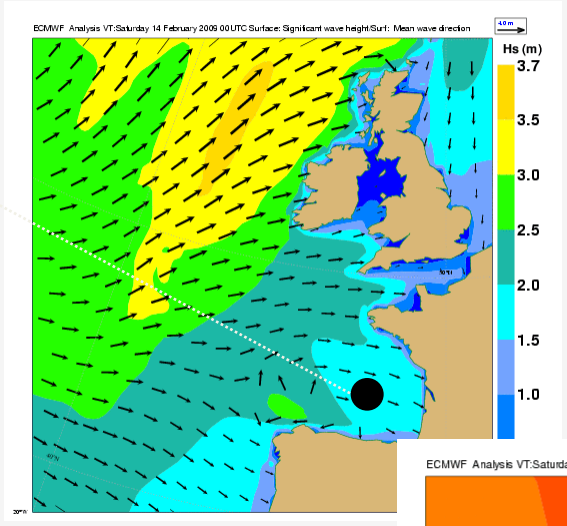
10m winds and mean sea level pressure:
Analysis : 14 February 2009, 00 UTC



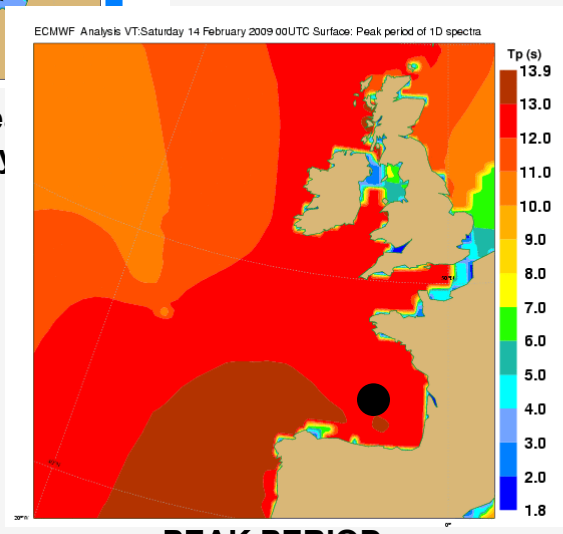
Wave height and mean direction:
Analysis : 14 February 2009, 00 UTC

Wave Model Products





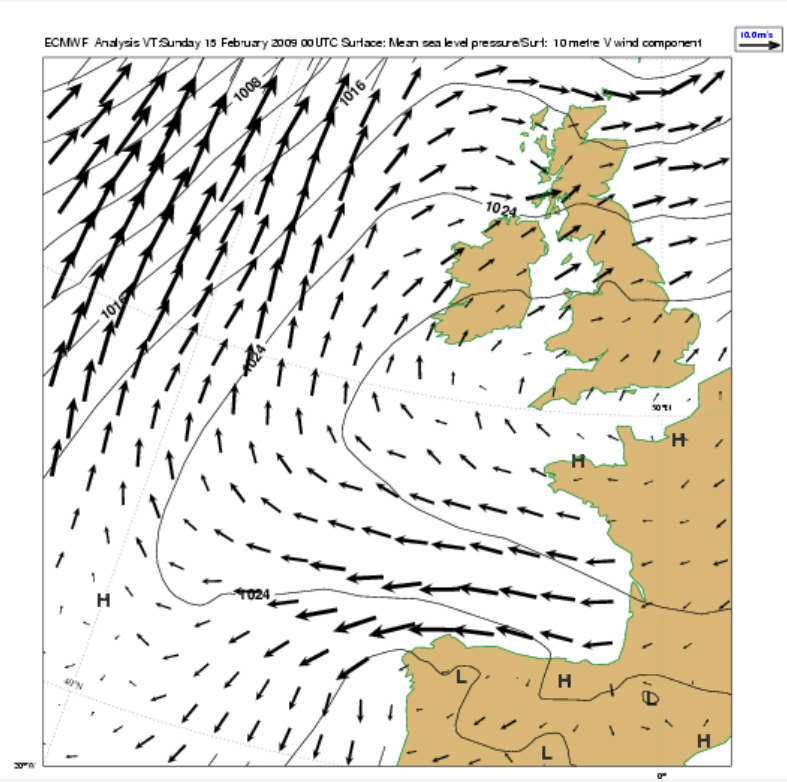
Wave height and me
Analysis : 14 February



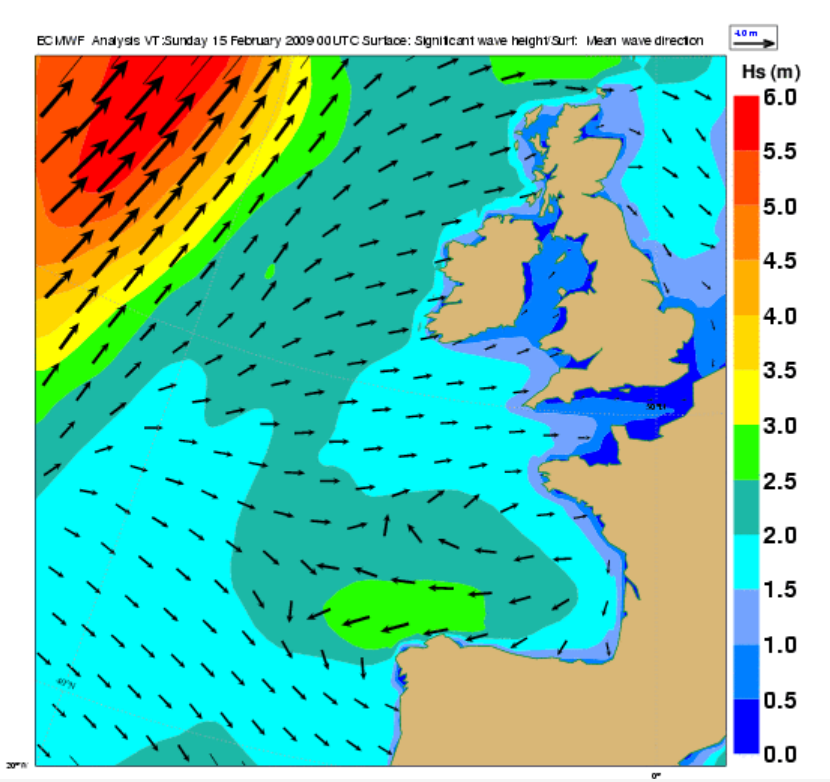
PEAK PERIOD:
Analysis : 14 February 2009, 00 UTC

Wave Model Products

Situation might be more complicated !



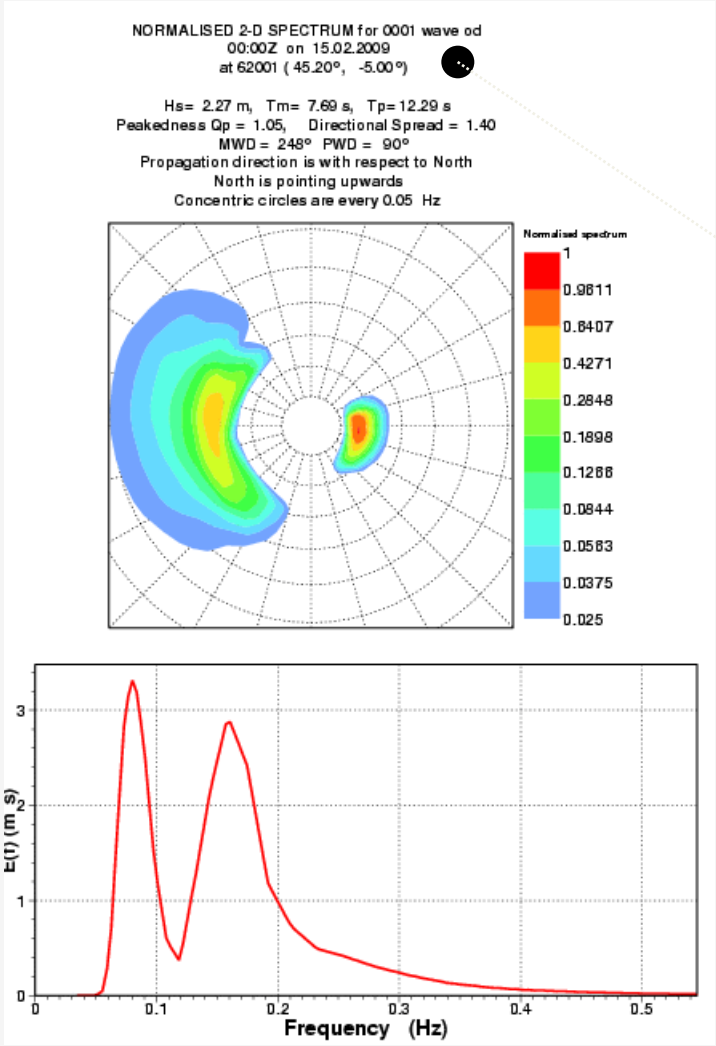
10m winds and mean sea level pressure:
Analysis : 15 February 2009, 00 UTC

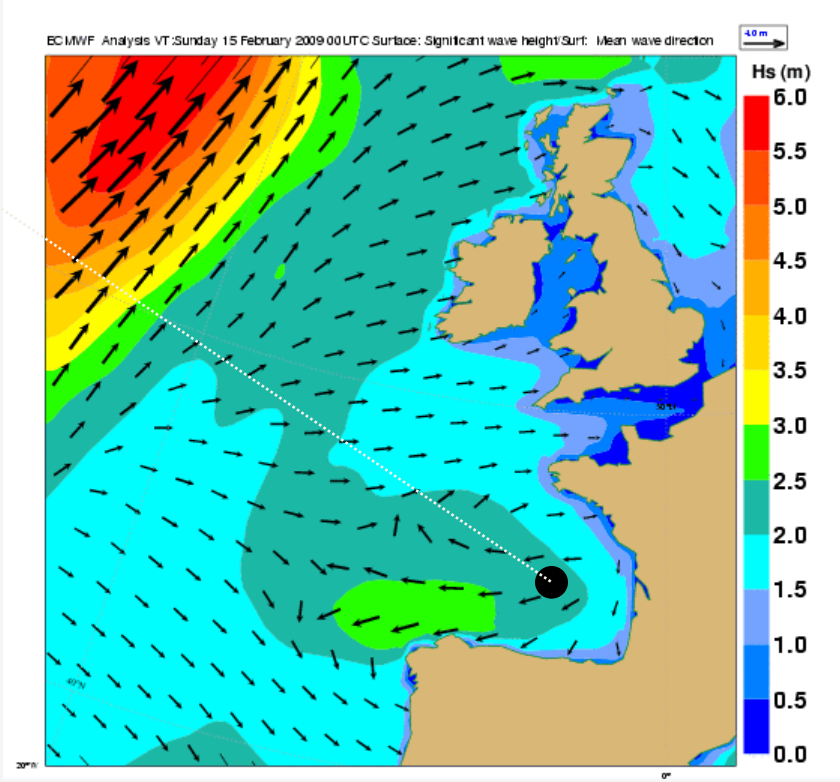


Wave height and mean direction:
Analysis : 15 February 2009, 00 UTC

Wave Model Products

Situation might be more complicated:

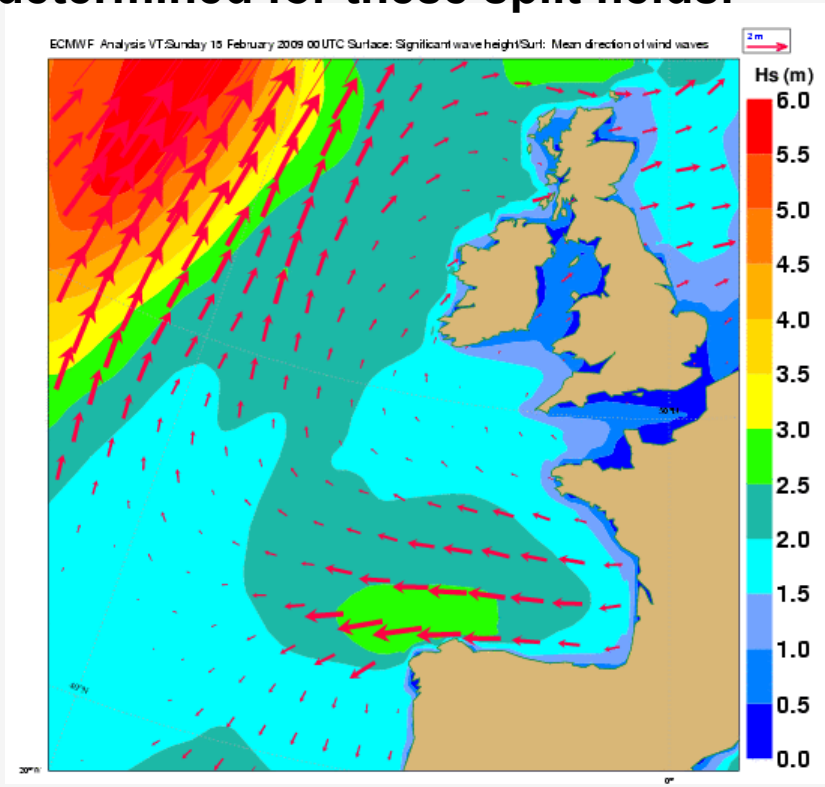




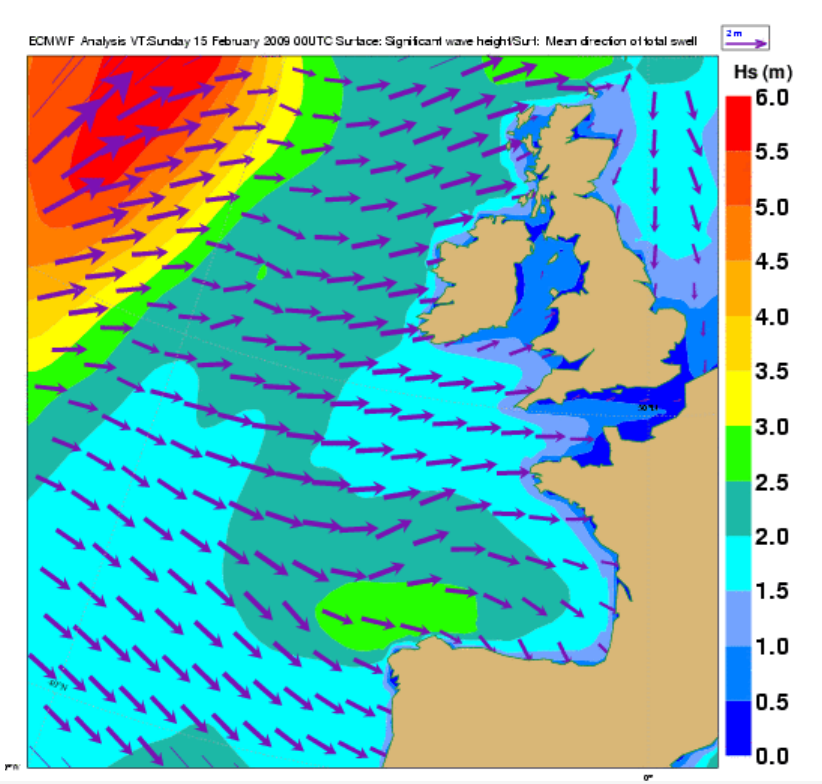
Wave height and mean direction:
Analysis : 15 February 2009, 00 UTC

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.



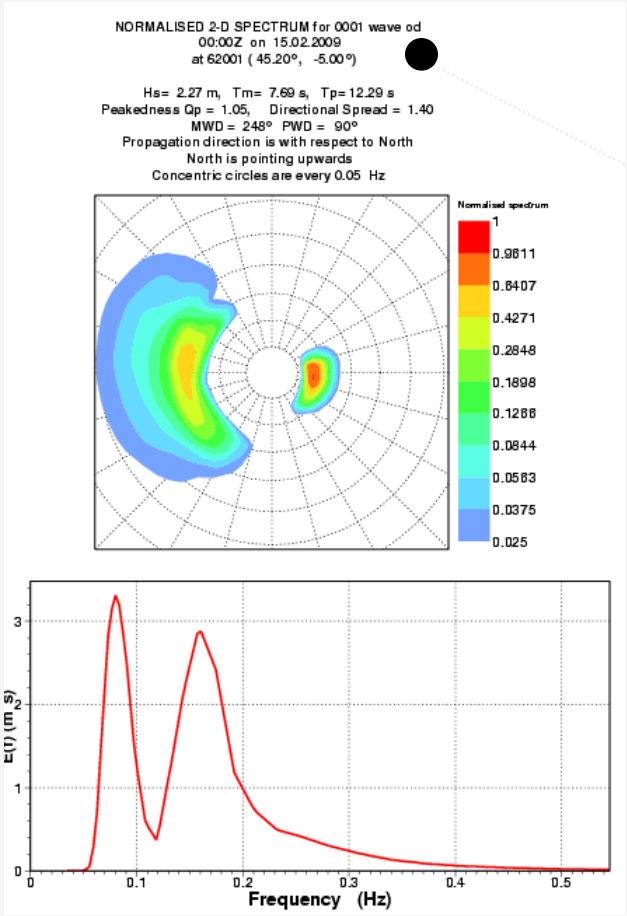
Wave height and windsea mean direction:
Analysis : 15 February 2009, 00 UTC

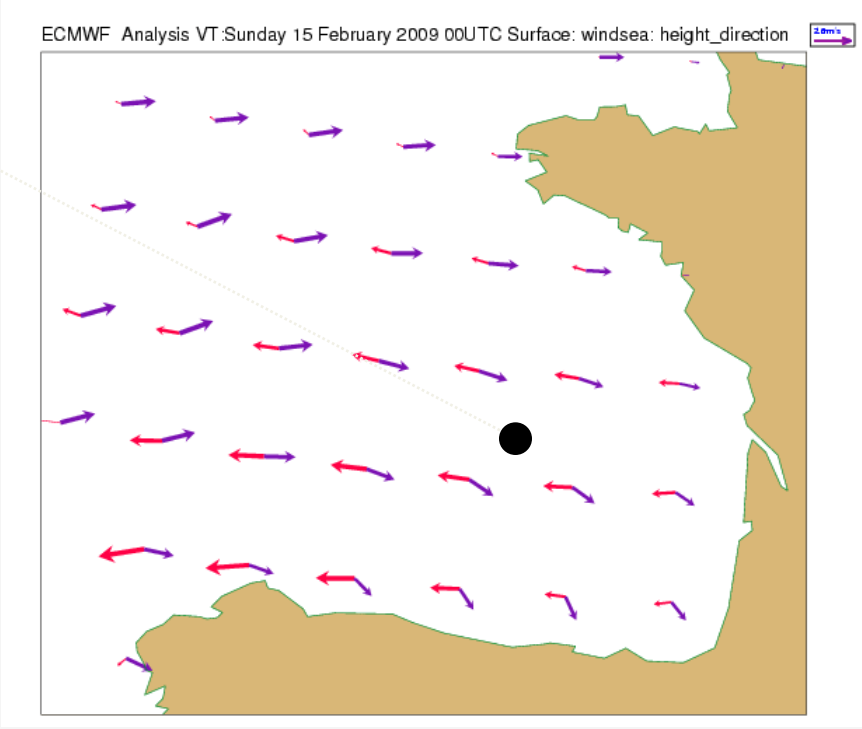


Wave height and swell mean direction:
Analysis : 15 February 2009, 00 UTC

Wave Model Products

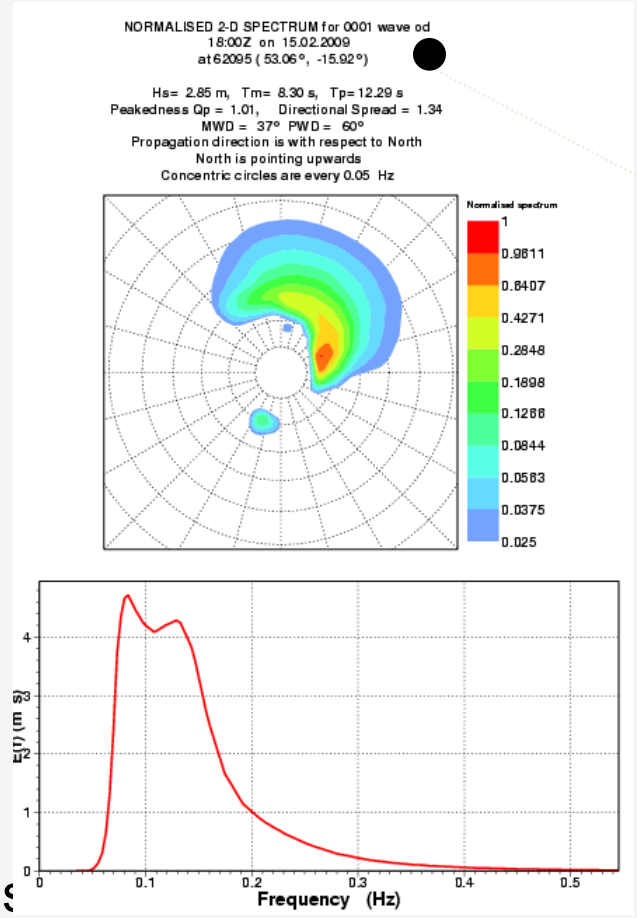
Windsea and swell: opposing sea

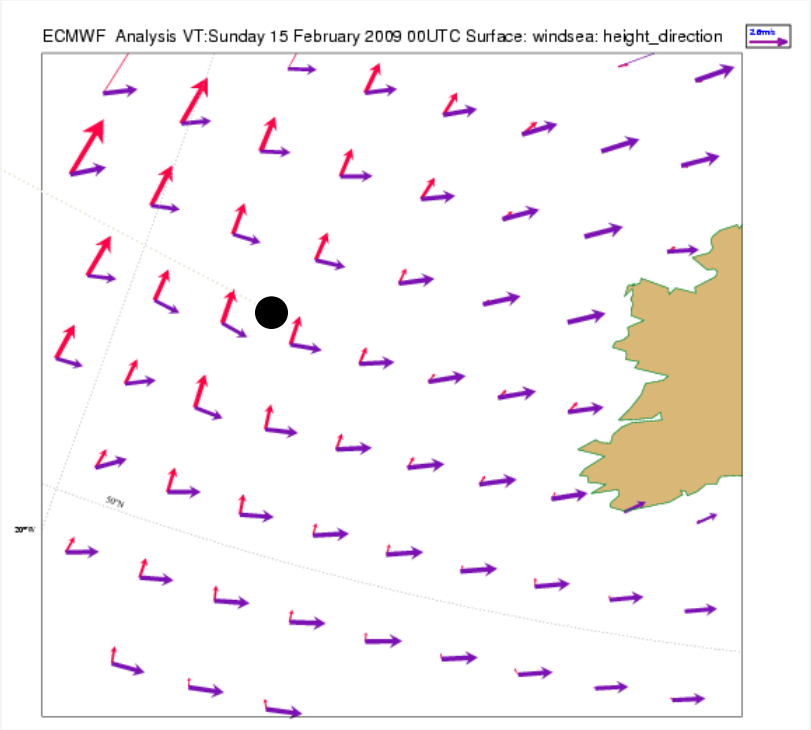




Wave Model Products

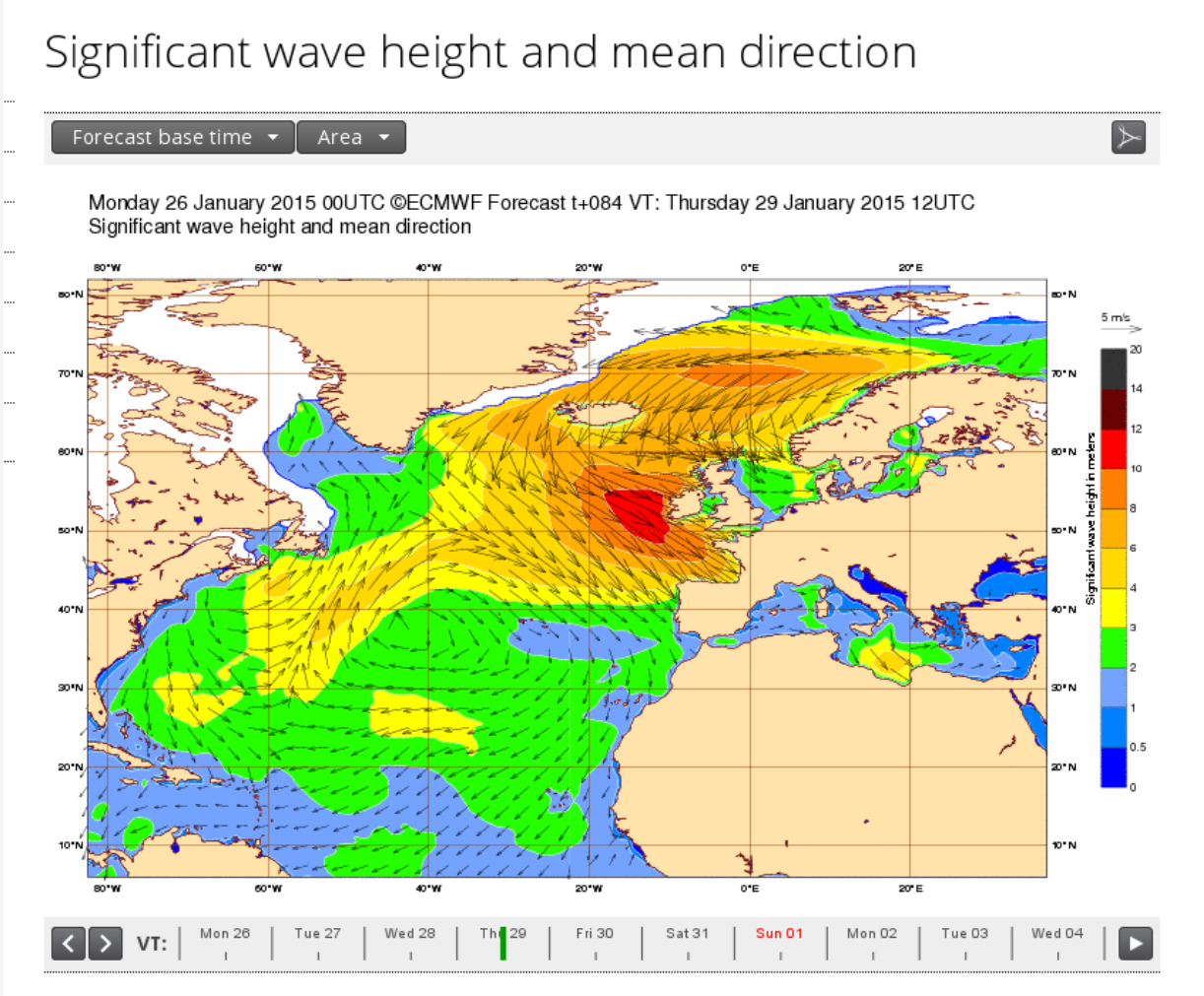
Windsea and swell: cross sea





Wave model deterministic products on the web

Wave products available <u>by default</u> on the centre's web pages:
(Home -> Forecasts -> Charts -> Ocean Waves :
http://www.ecmwf.int/en/forecasts/charts/catalogue?f[0]=im_field_chart_type%3A481&f[1]=im_field_parameters%3A539



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:

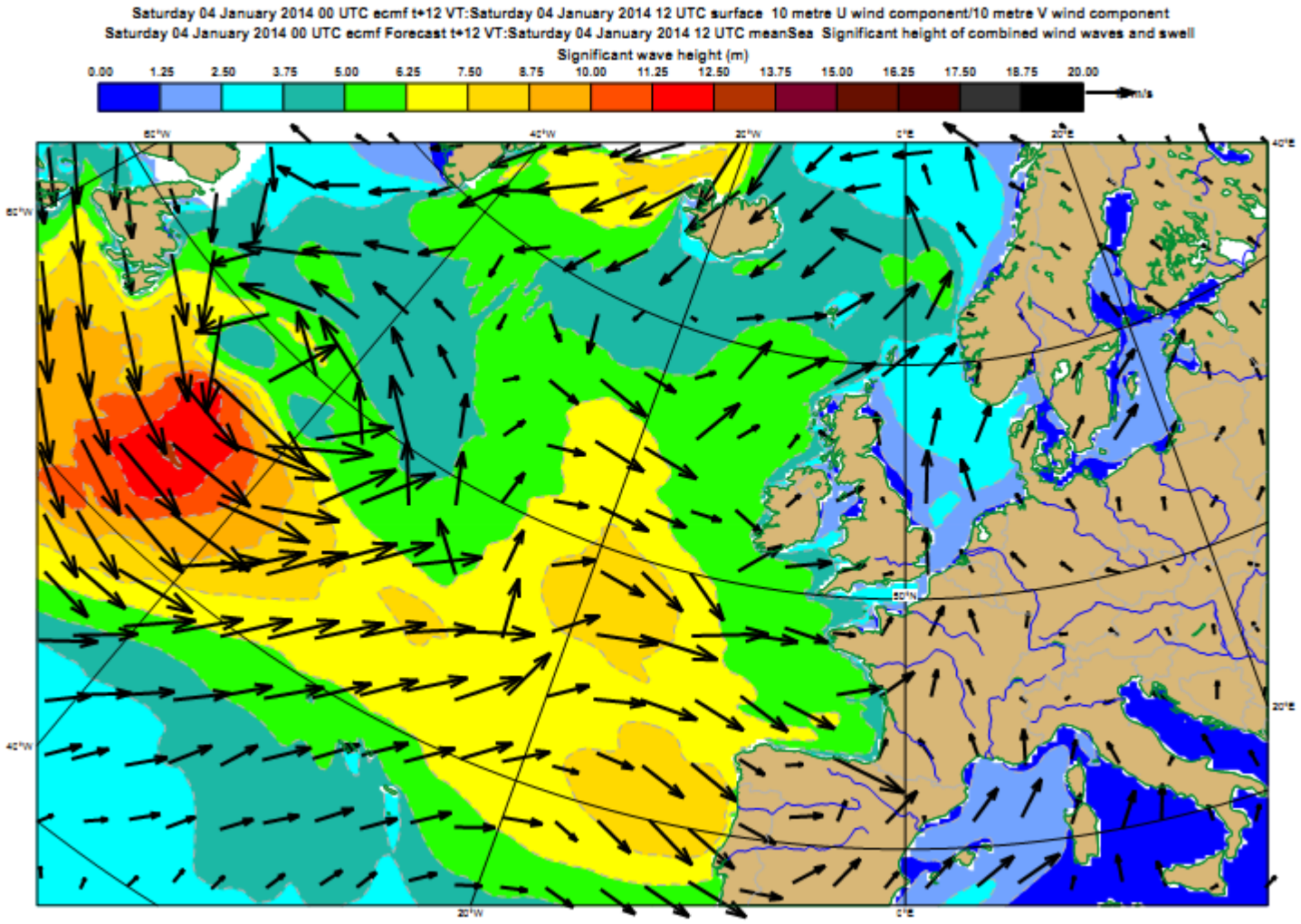
May 1, 2013

Porthleven Clock Tower, Cornwall

February 5, 2014

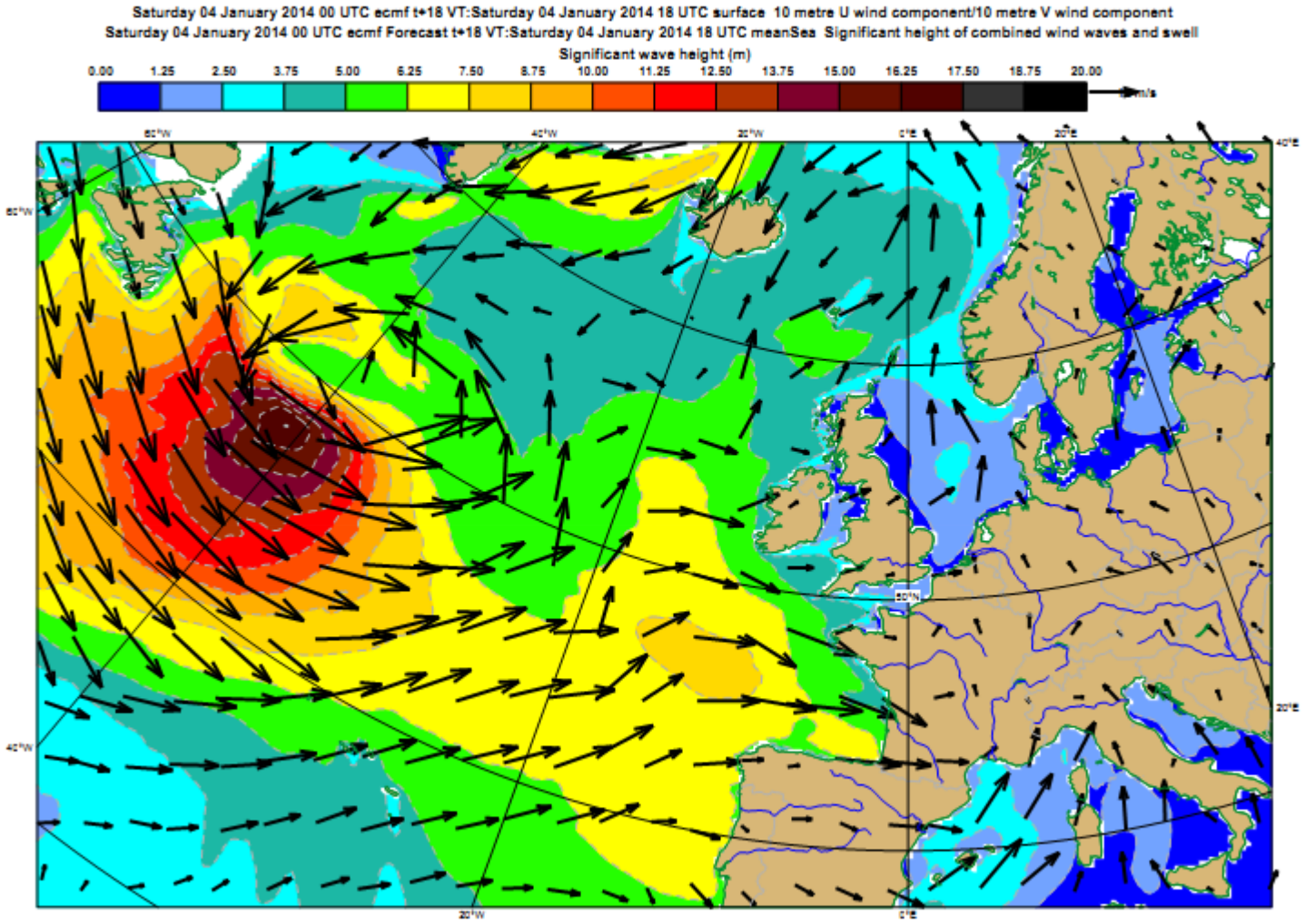
Ocean wave forecasts

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



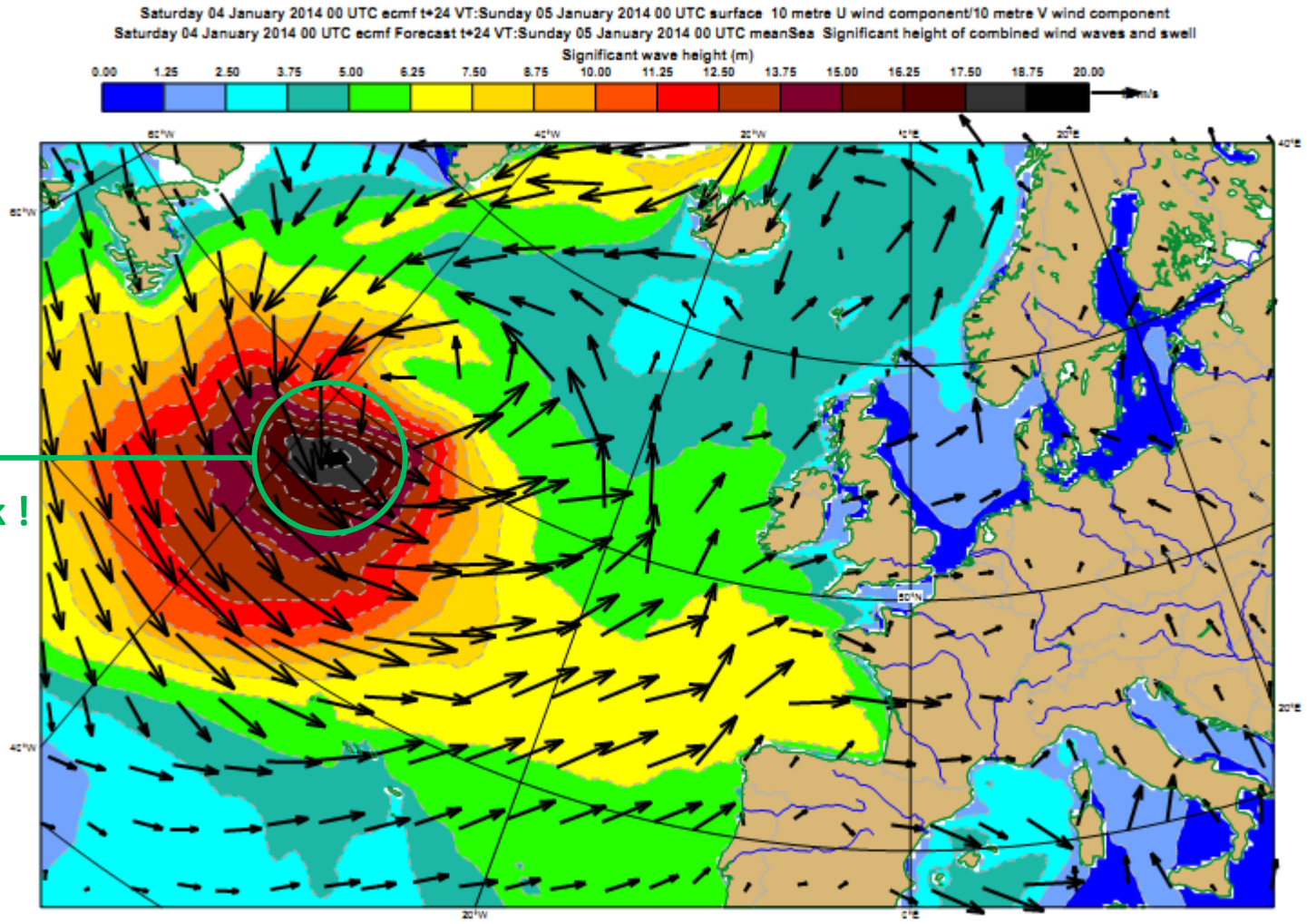
Ocean wave forecasts

Wave height forecast and wind from 4 January 2014, step 18 hours



Ocean wave forecasts

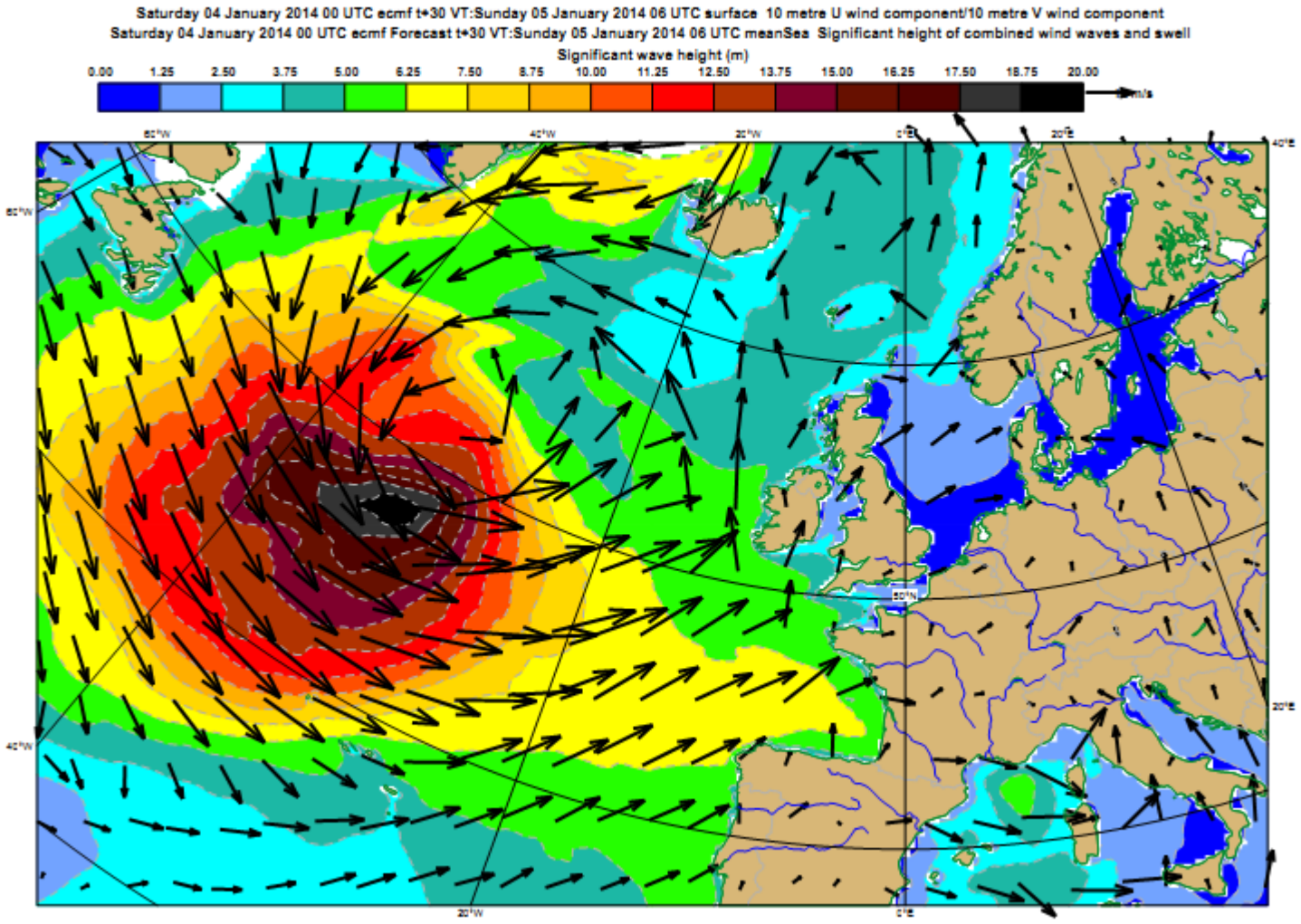
Wave height forecast and wind from 4 January 2014, step 24 hours



Nearing 20m at its peak !

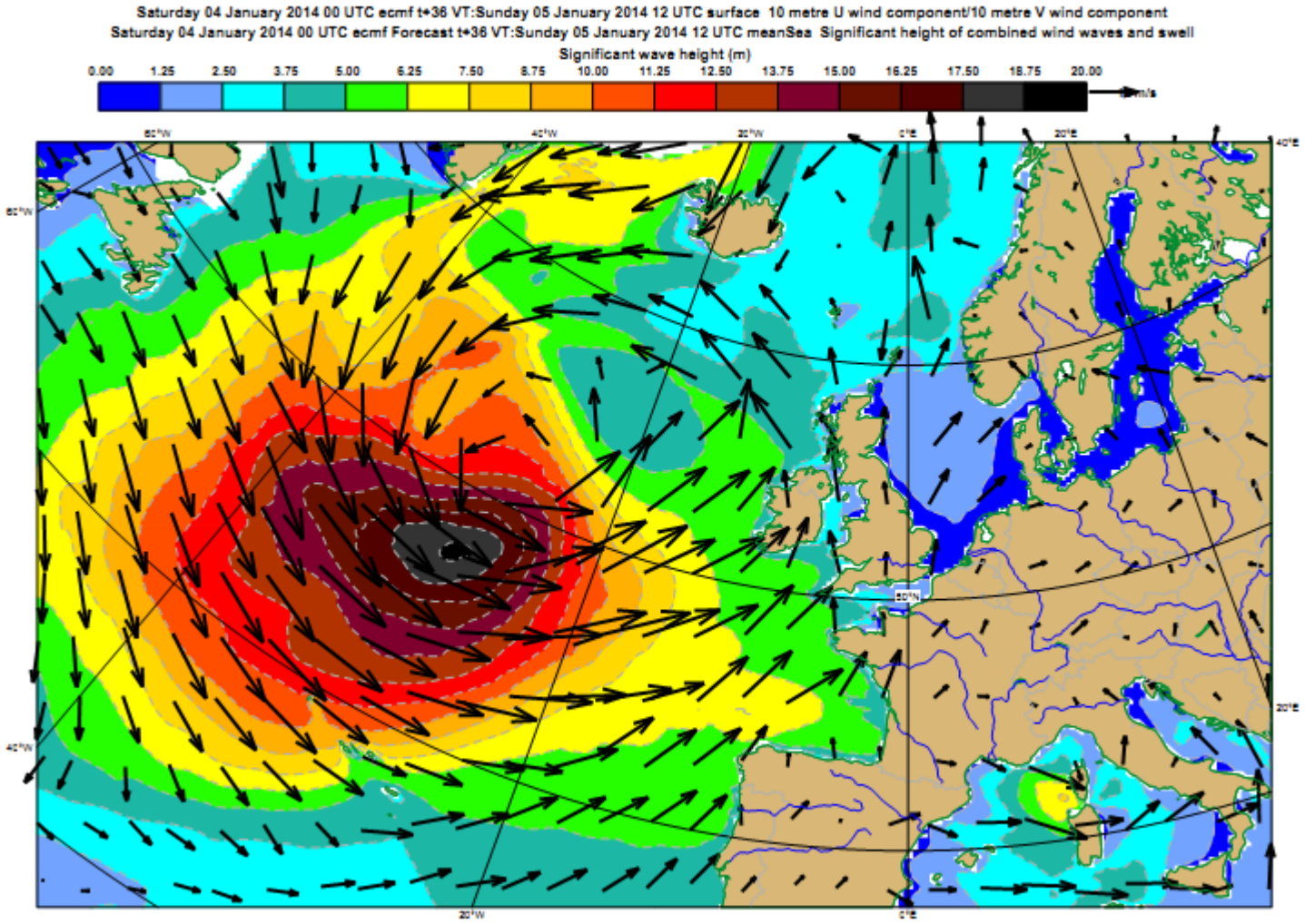
Ocean wave forecasts

Wave height forecast and wind from 4 January 2014, step 30 hours



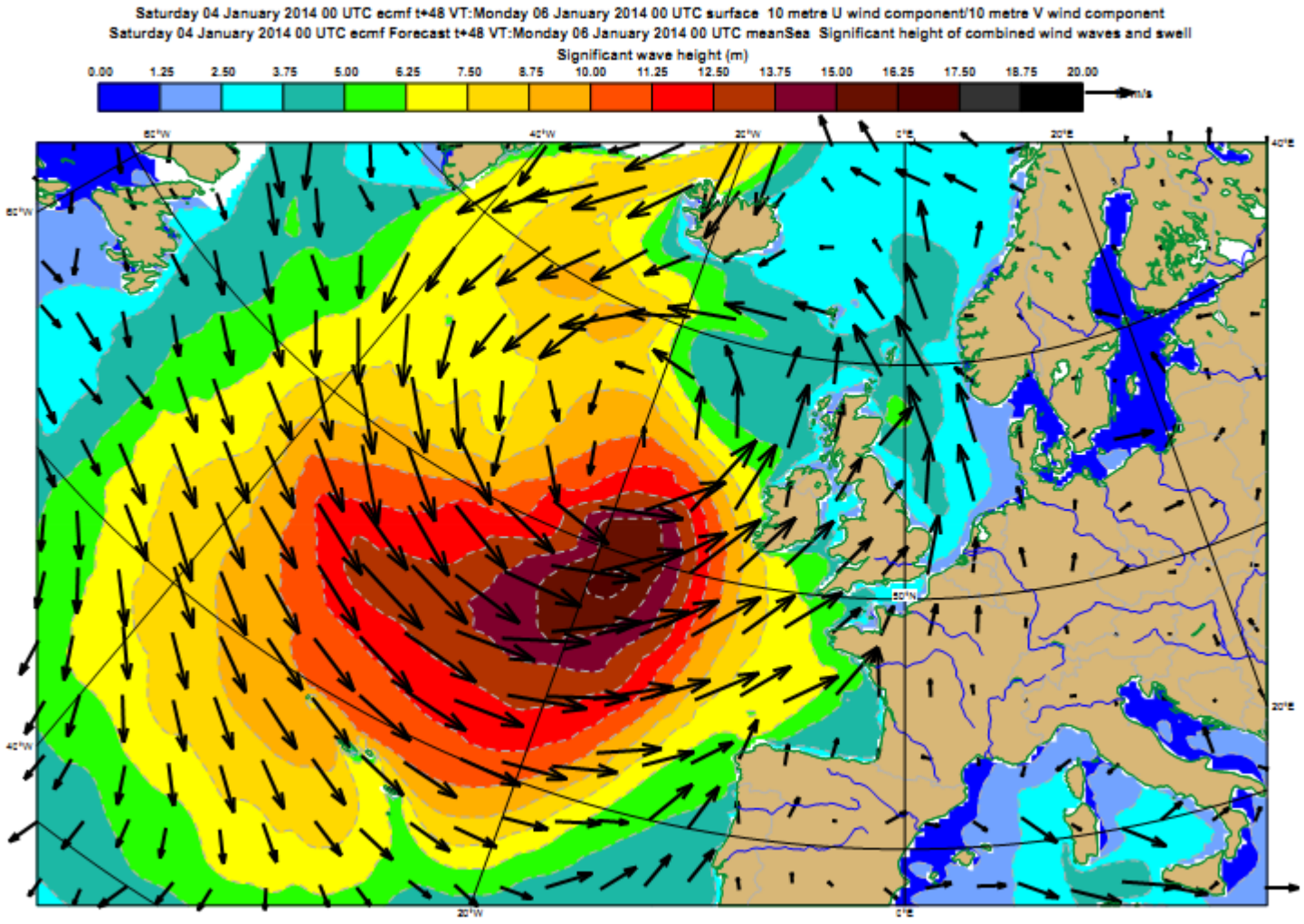
Ocean wave forecasts

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



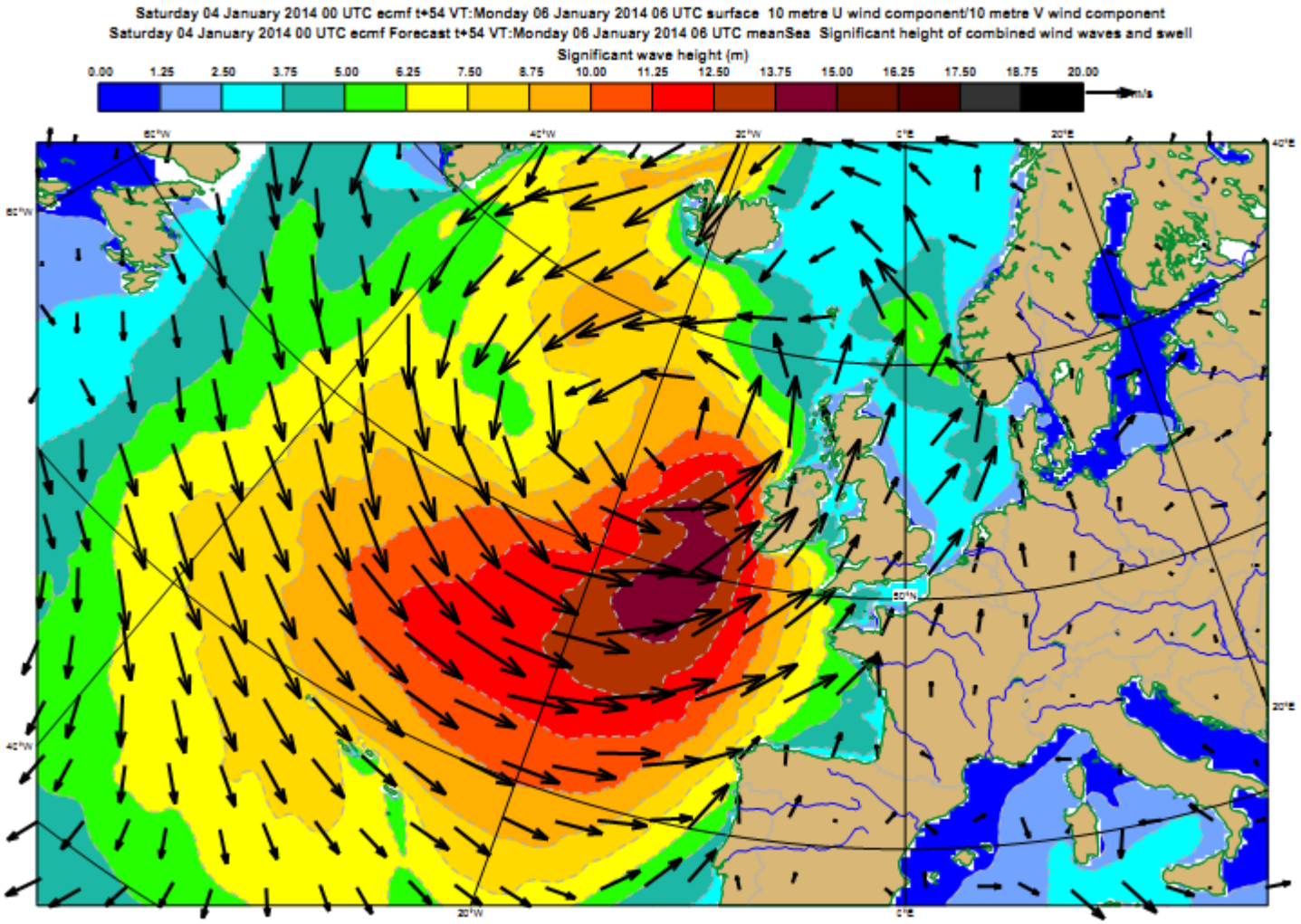
Ocean wave forecasts

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



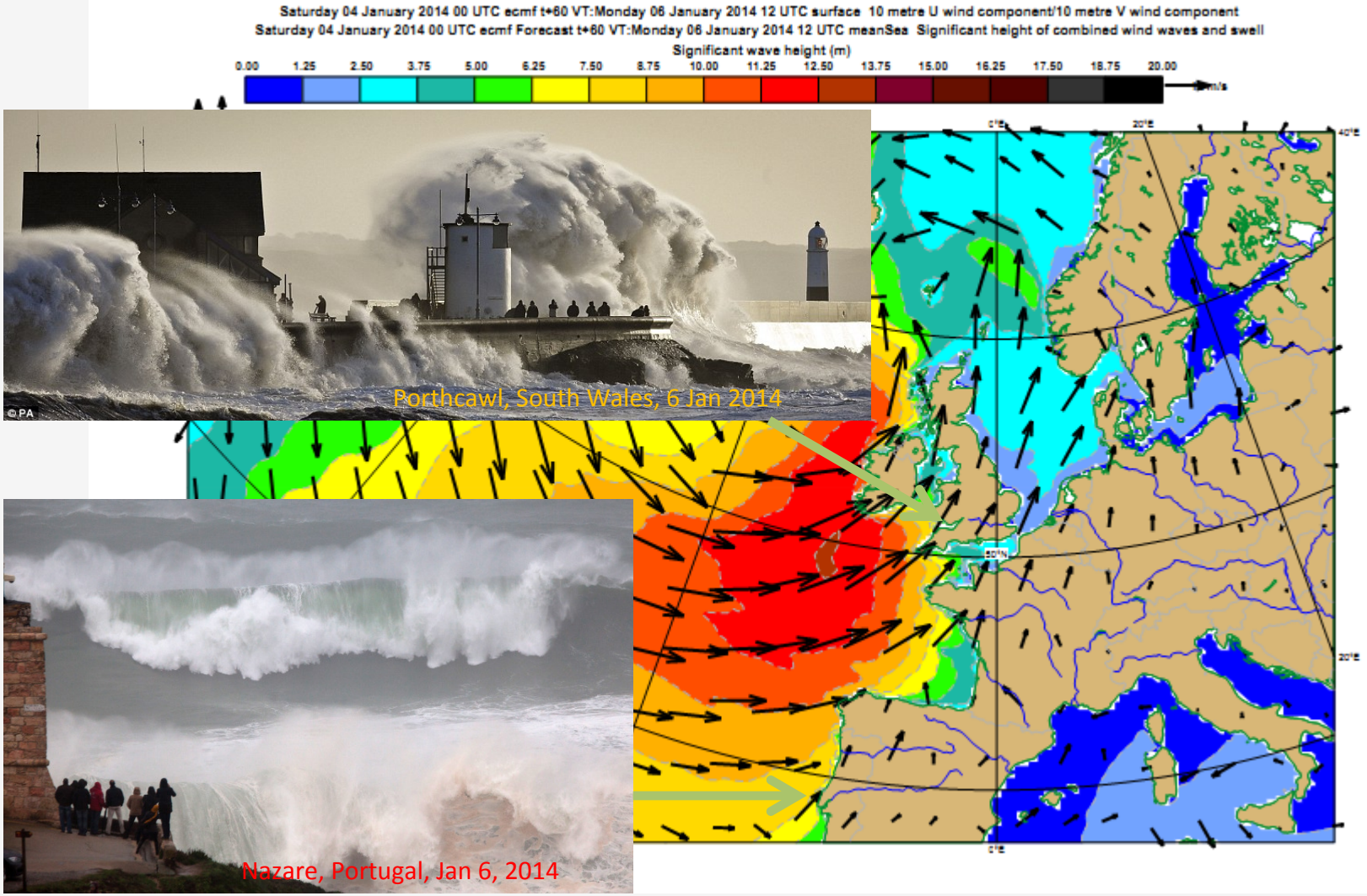
Ocean wave forecasts

Wave height forecast and wind from 4 January 2014, step 54 hours



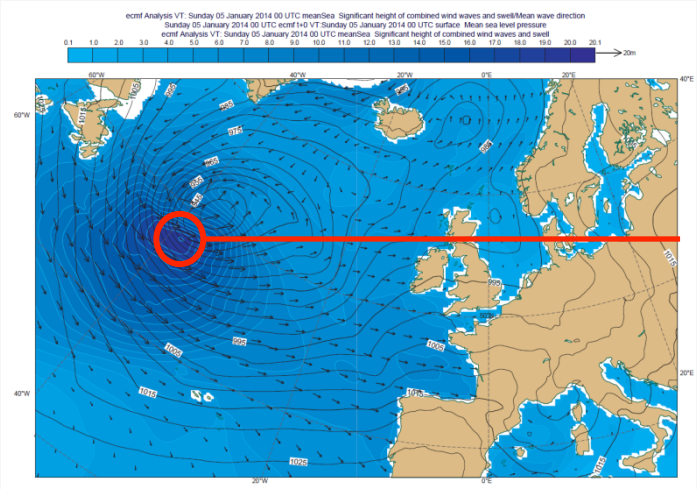
Ocean wave forecasts

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

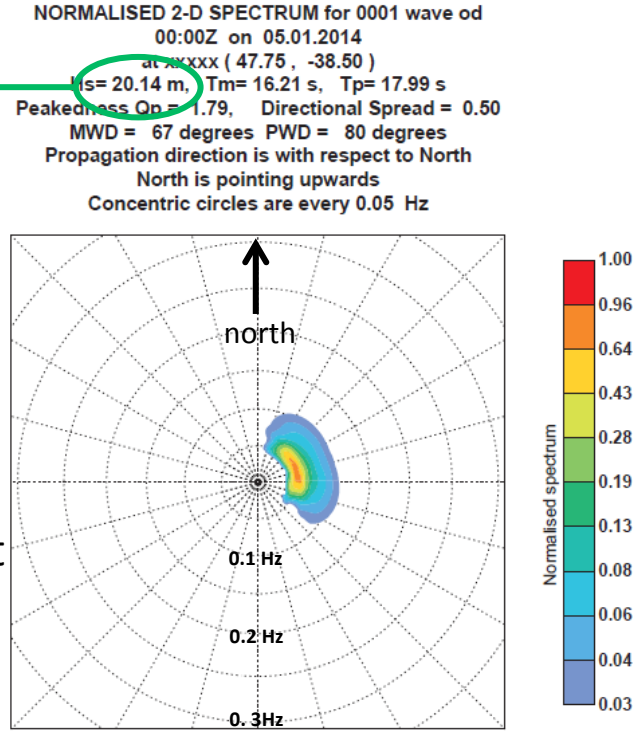


Spectral shape:

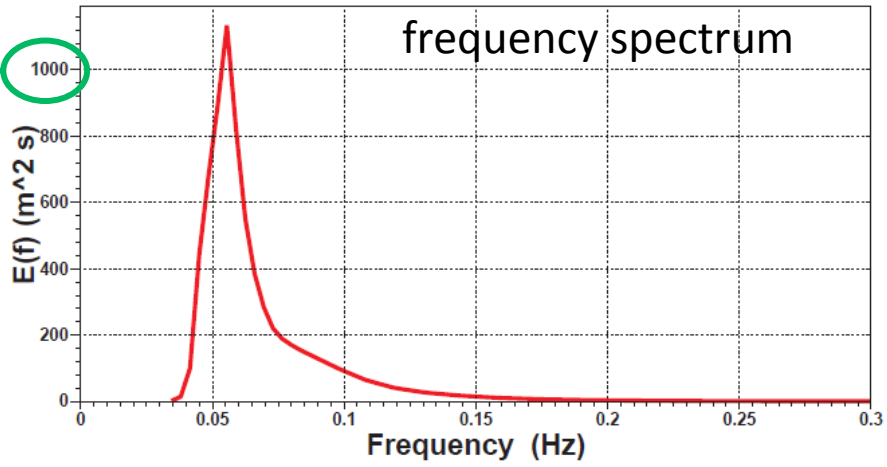
In excess of 20m



Analysis
at location of
highest wave height



In excess of
1000 m^2 s

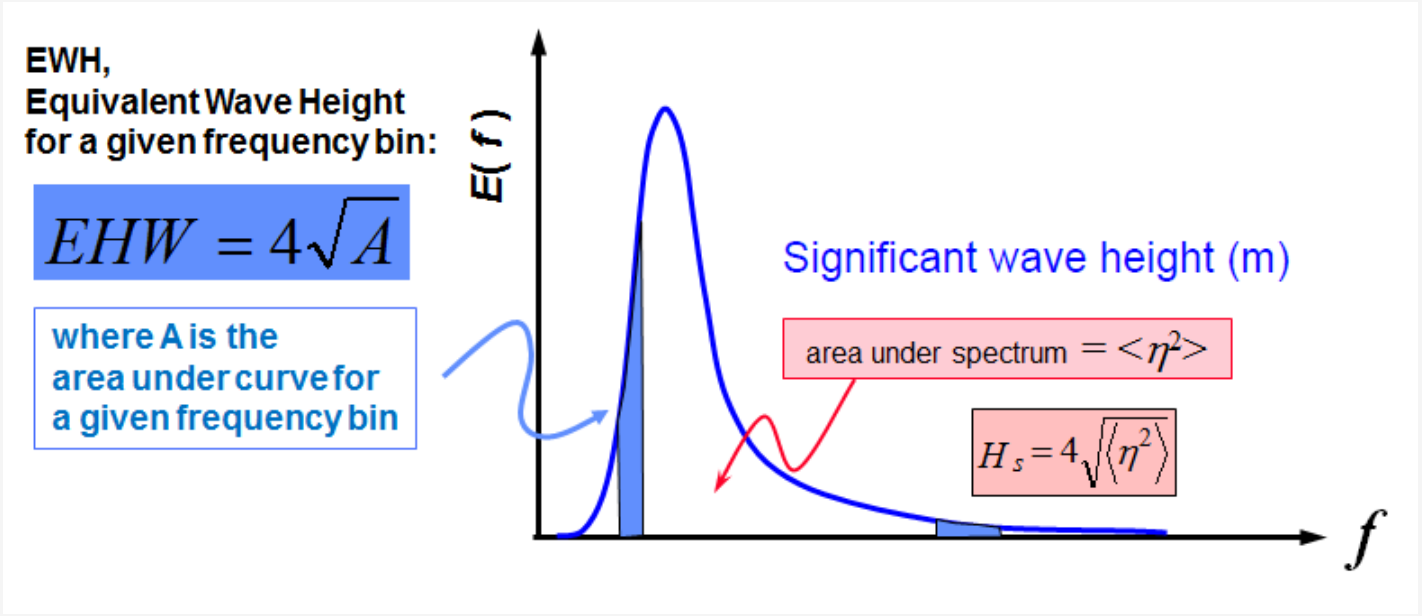


Long swell forecasts

Swell are long waves propagating away from storms.

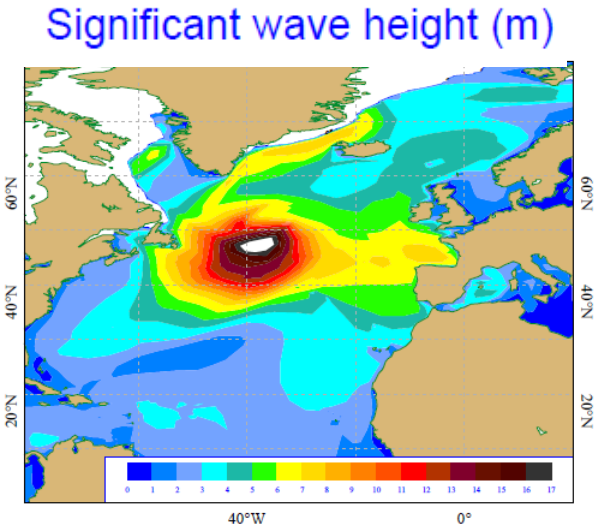
It is possible to follow the evolution of the swell.

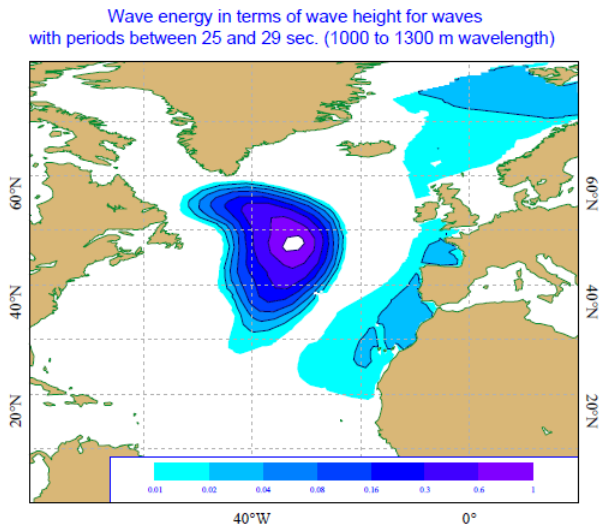
Define the Equivalent Wave Height:

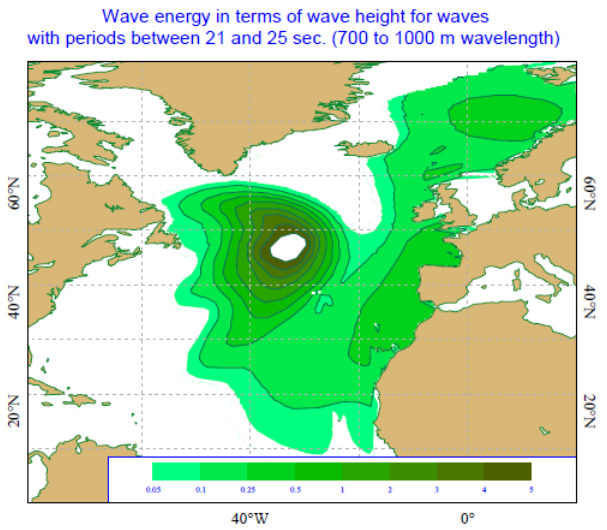


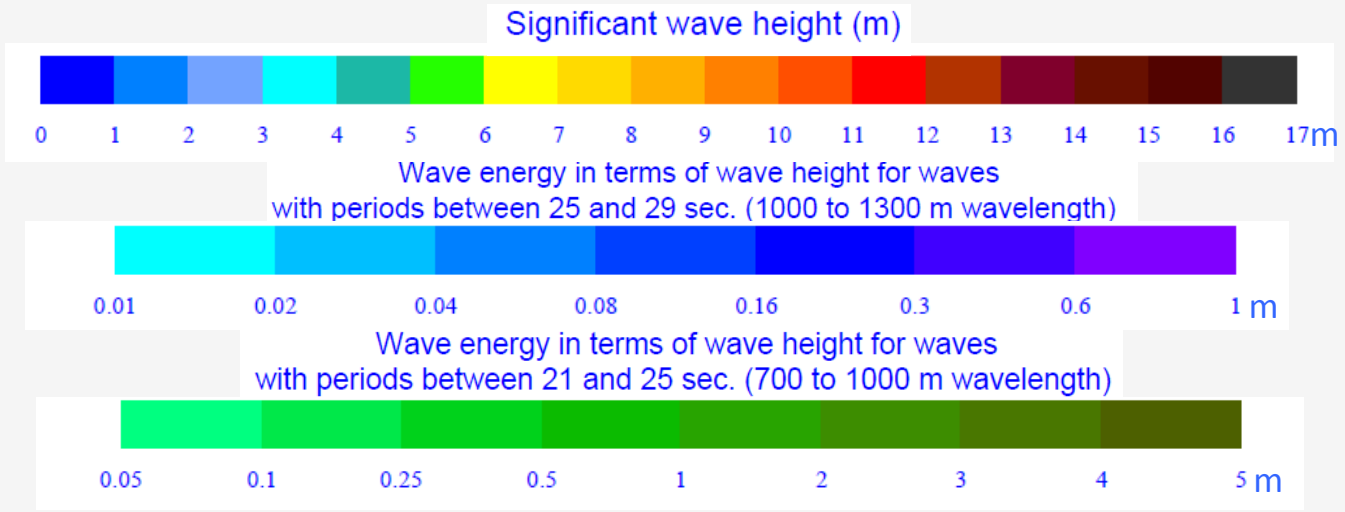
Long swell forecasts

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



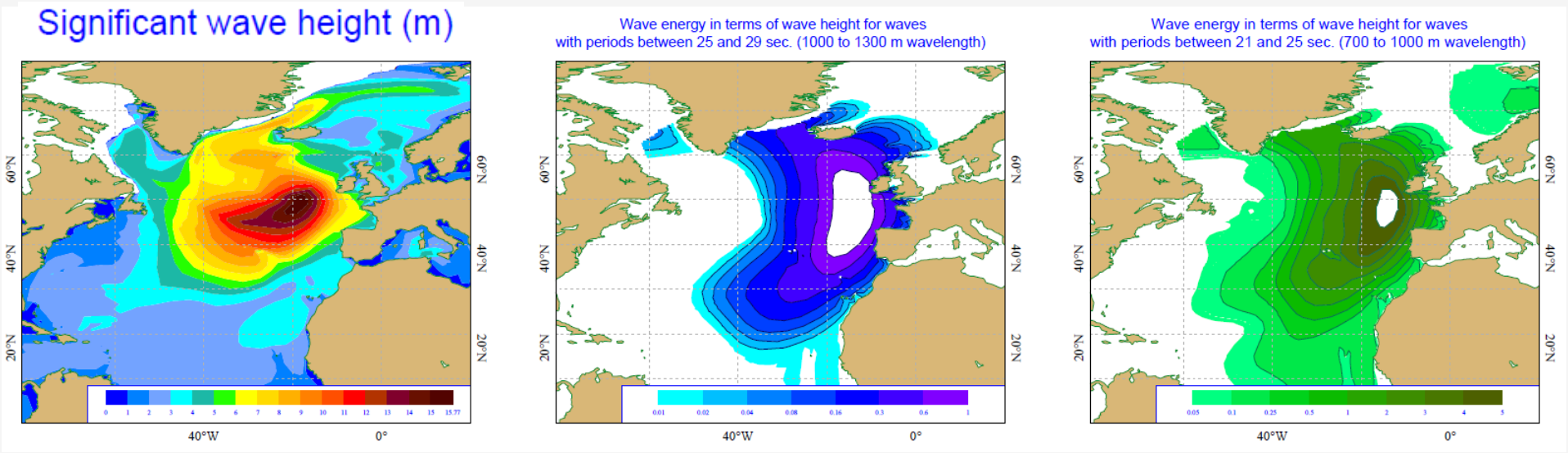


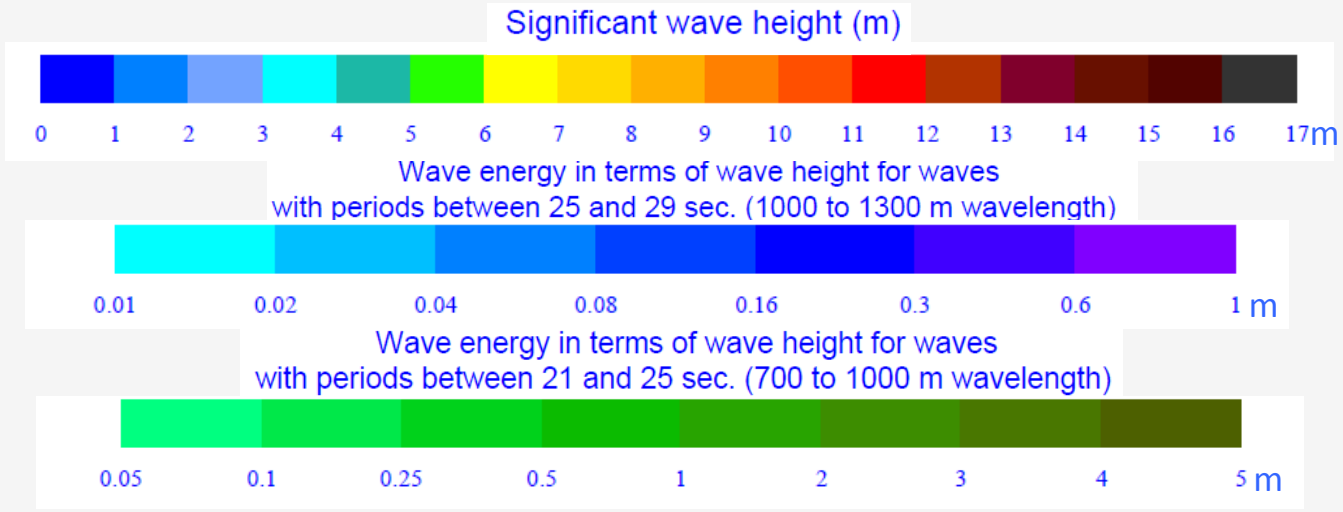




Long swell forecasts

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

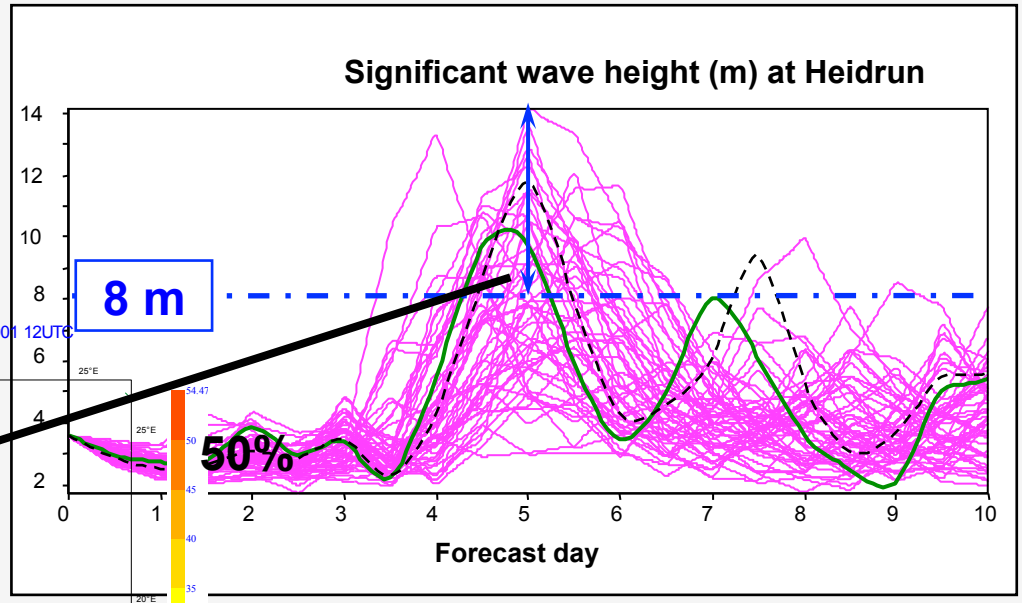


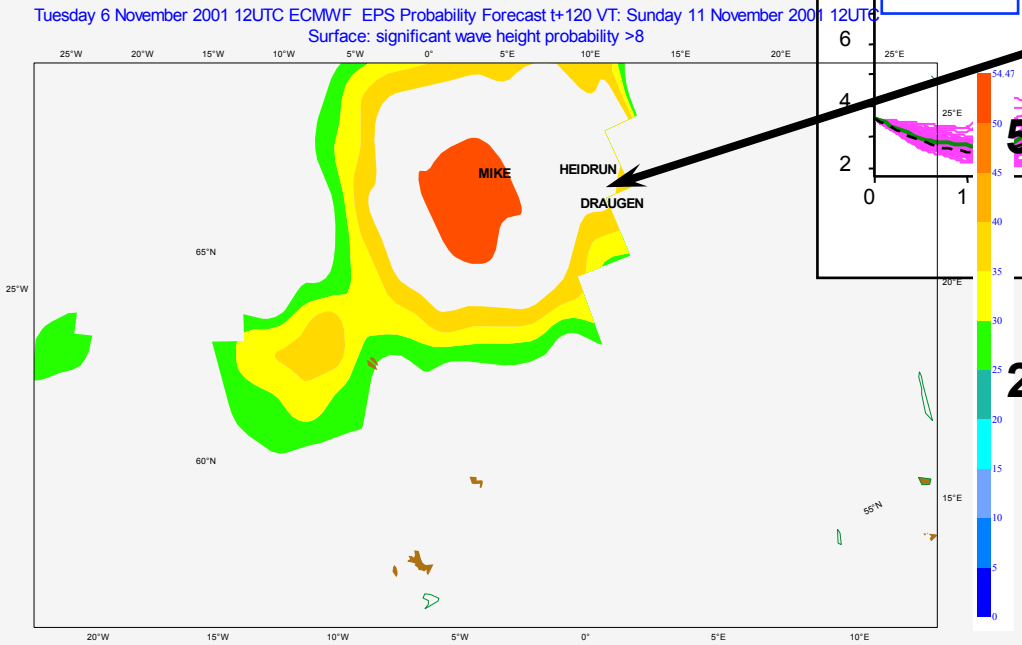


So far, everything has been presented as output from the deterministic forecast system.

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.



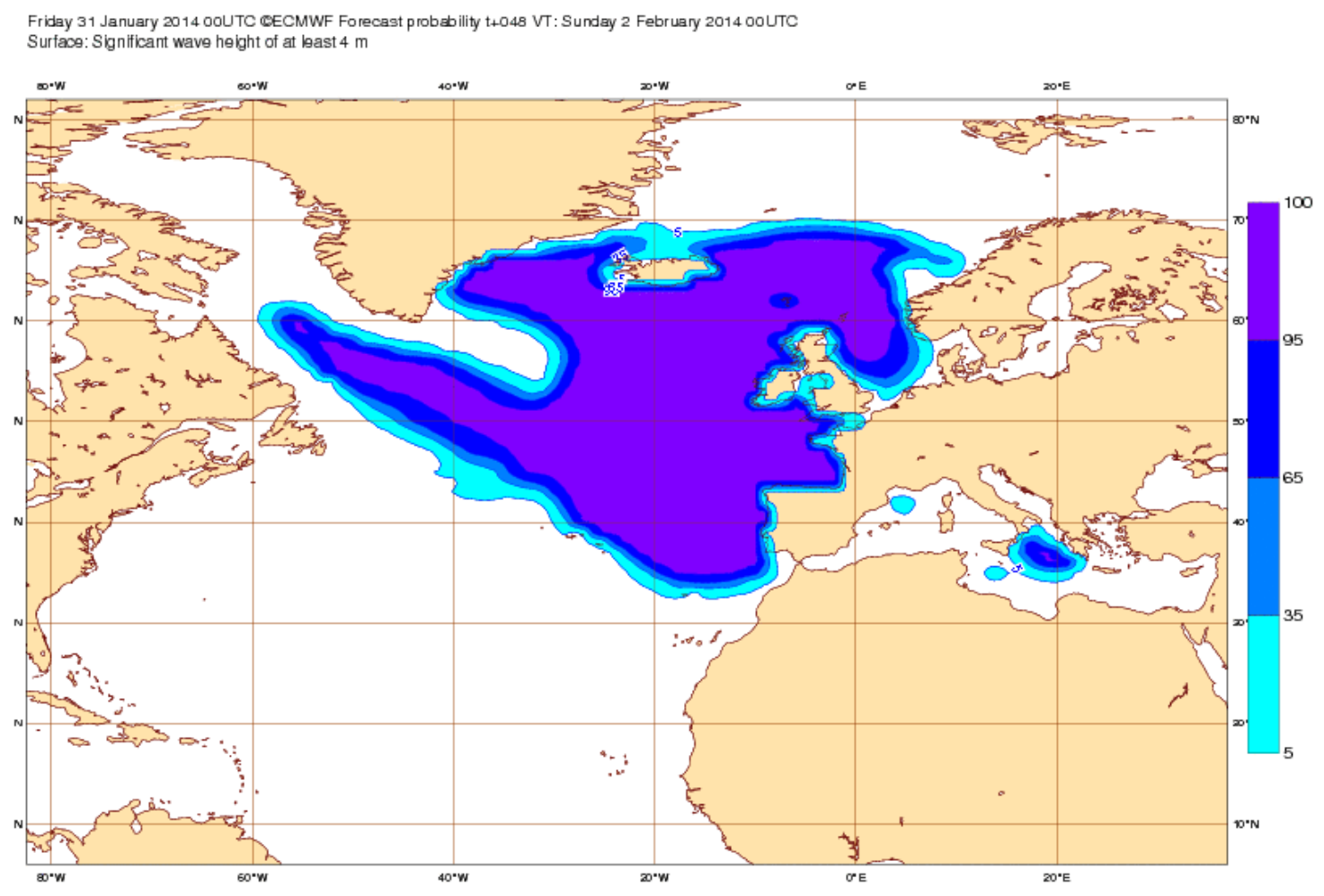


06 Nov. 2001 12 UTC ECMWF EPS probability forecast t+120

Significant wave height above 8 m

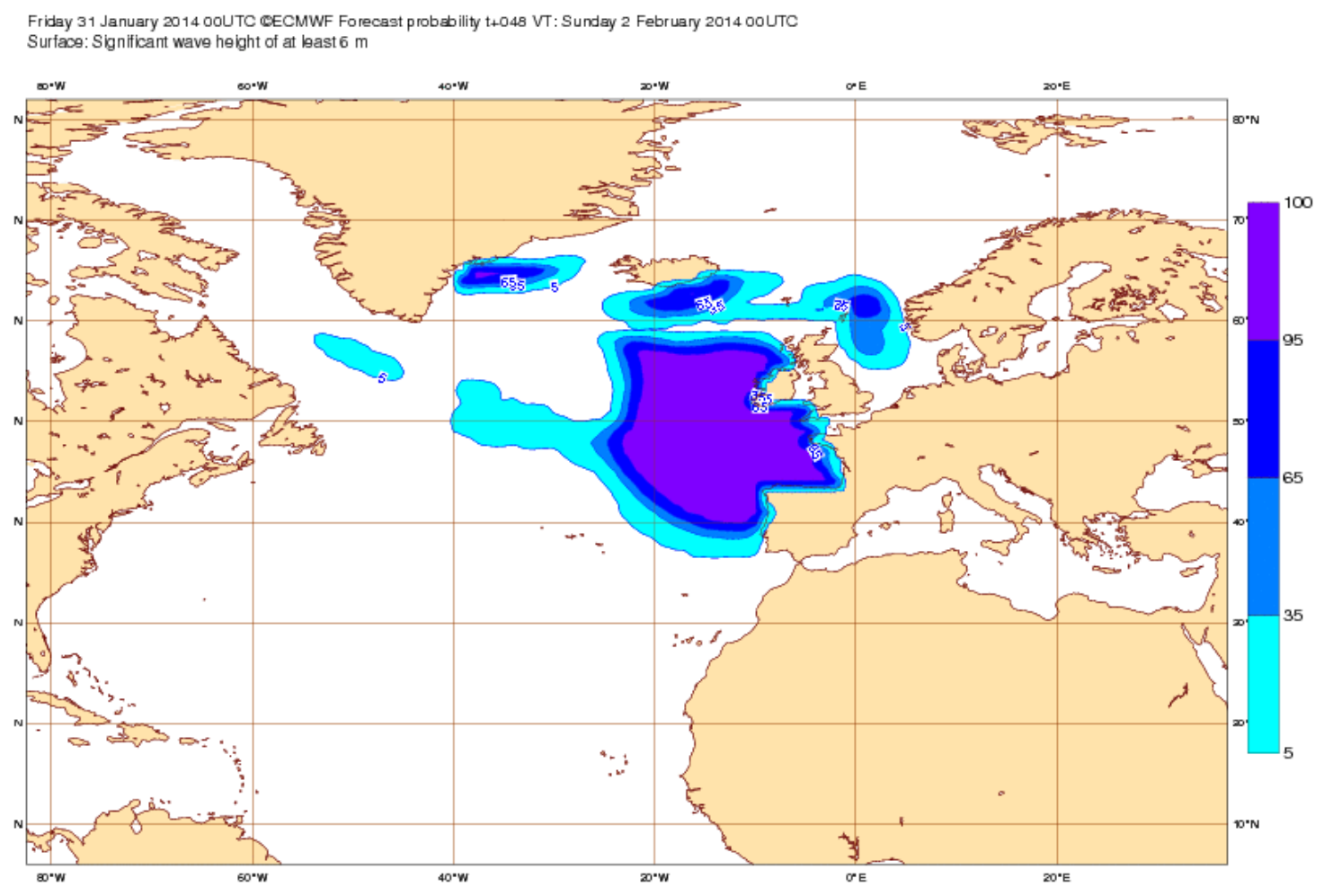
Basic EPS Wave Model Products

probability for set thresholds (4m)



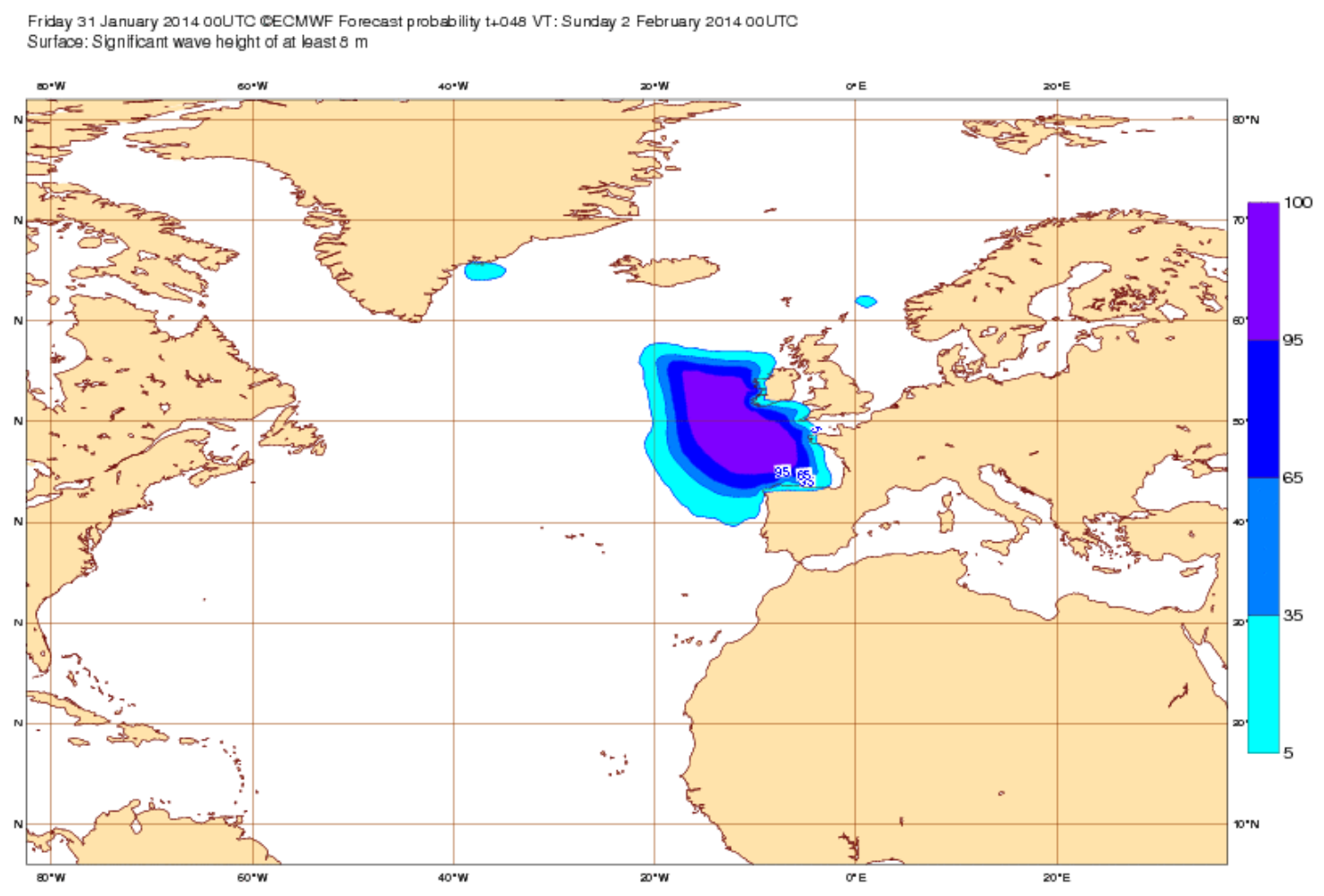
Basic EPS Wave Model Products

probability for set thresholds (6m)



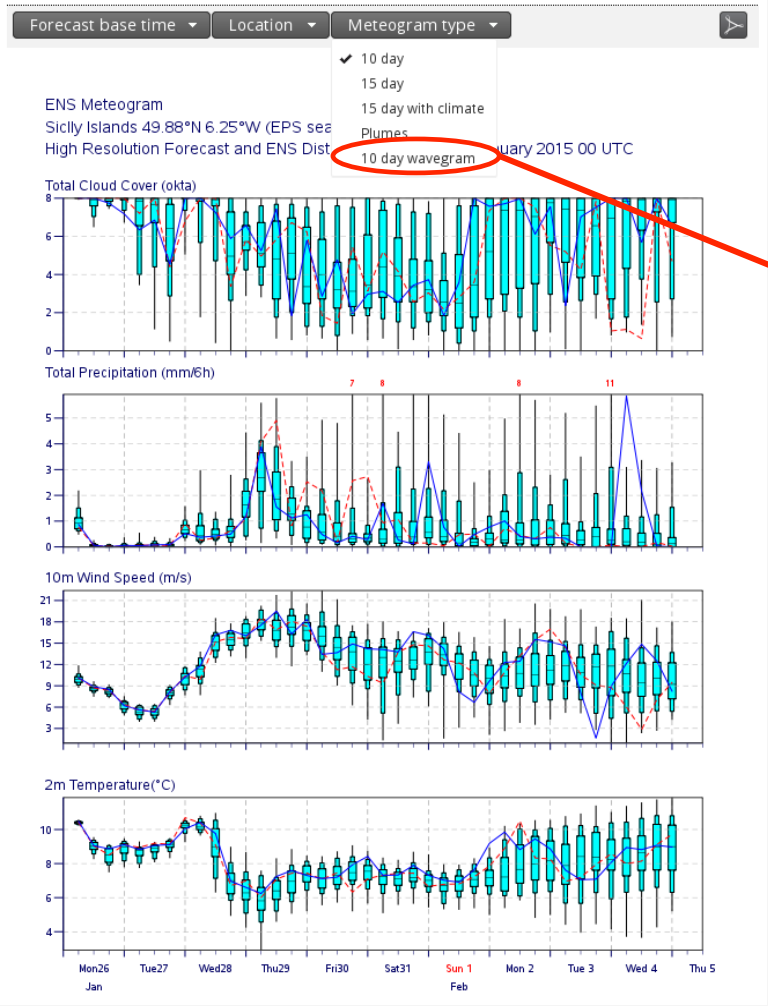
Basic EPS Wave Model Products

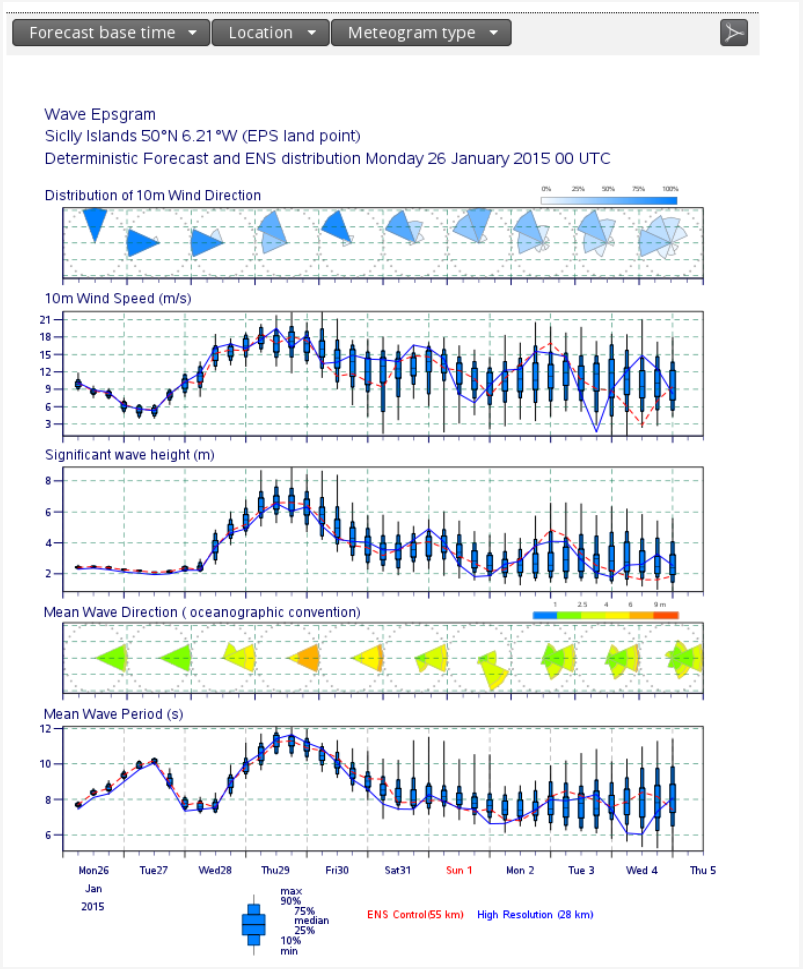
probability for set thresholds (8m)



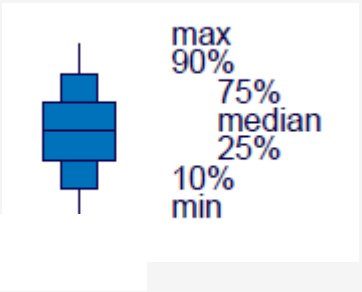
A bit more compact: Wave EPSgram:

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



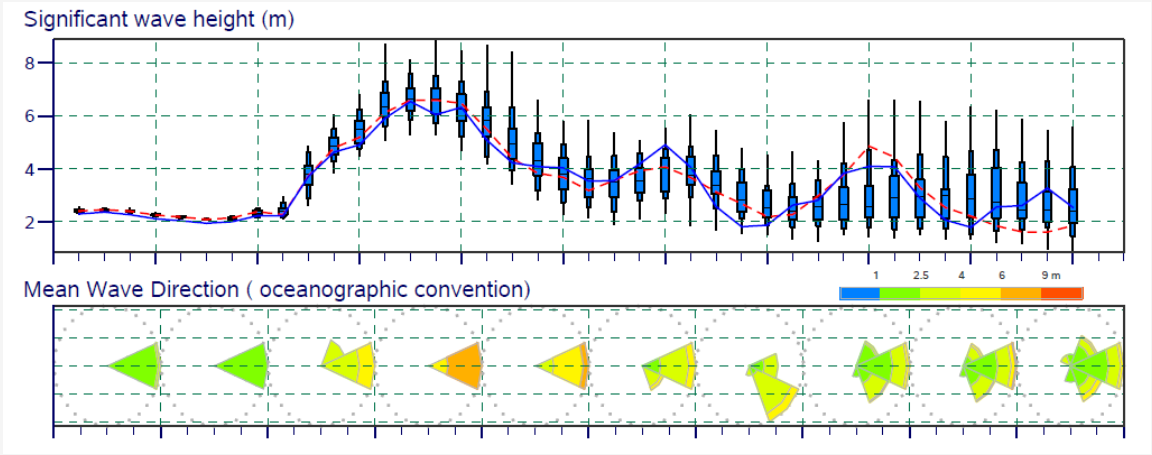


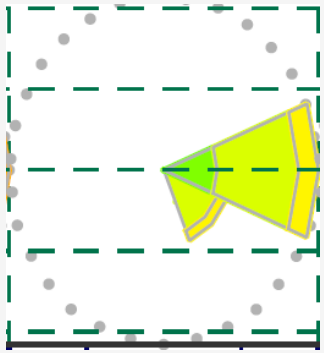
A bit more compact: Wave EPSgram:



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

Hs 1 2.5 4 6 9 m



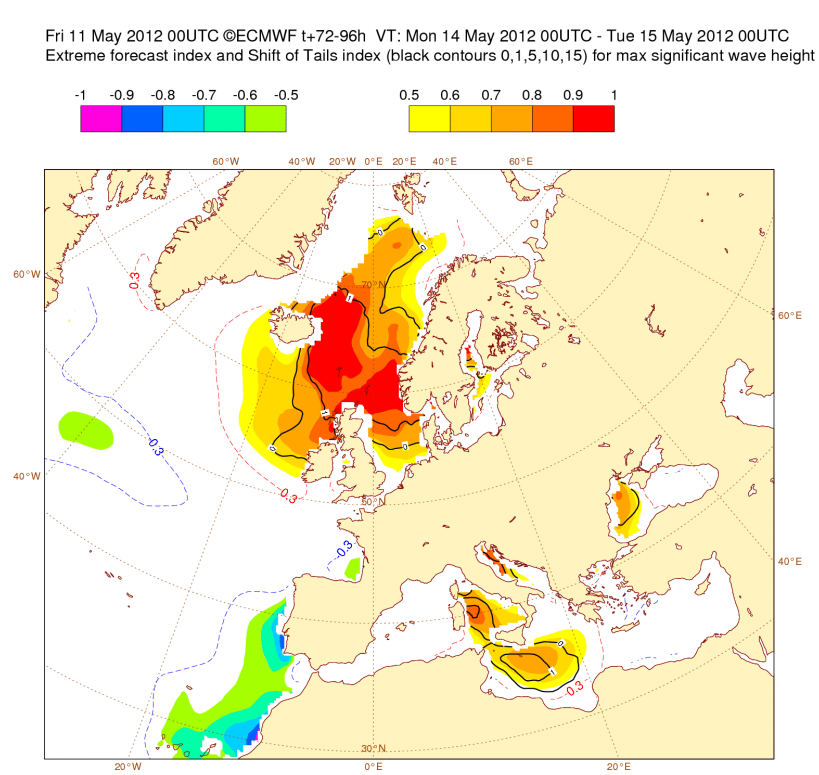


Each octant is coloured based on the distribution of the significant wave height associated with each mean direction. The coloured areas correspond to the fractional number of ensemble members with wave height in the range specified by the coloured ruler.

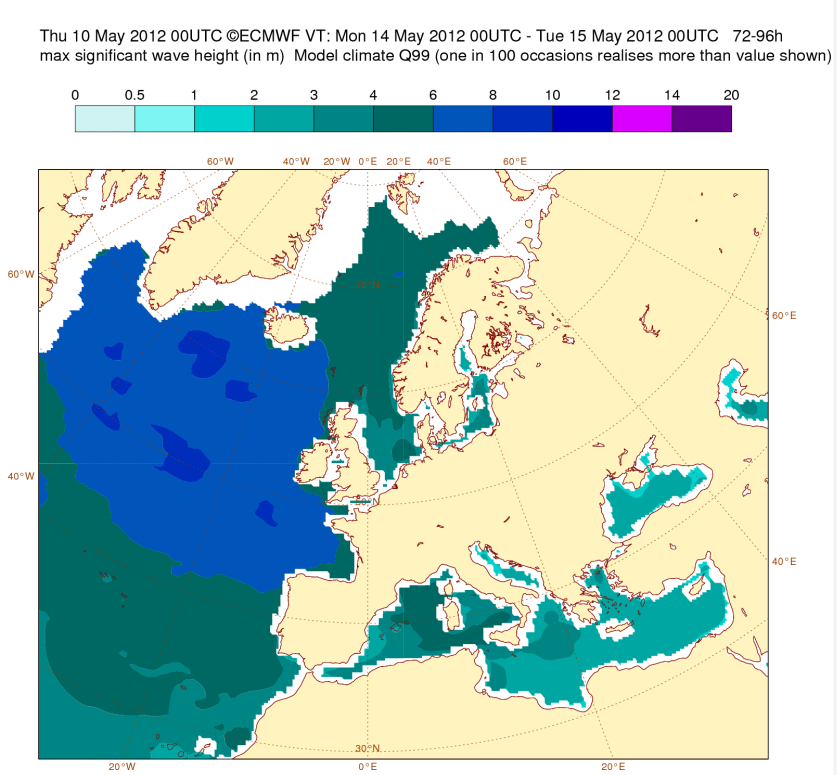
EFI plots

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>above</u> climate.



EFI for significant wave height

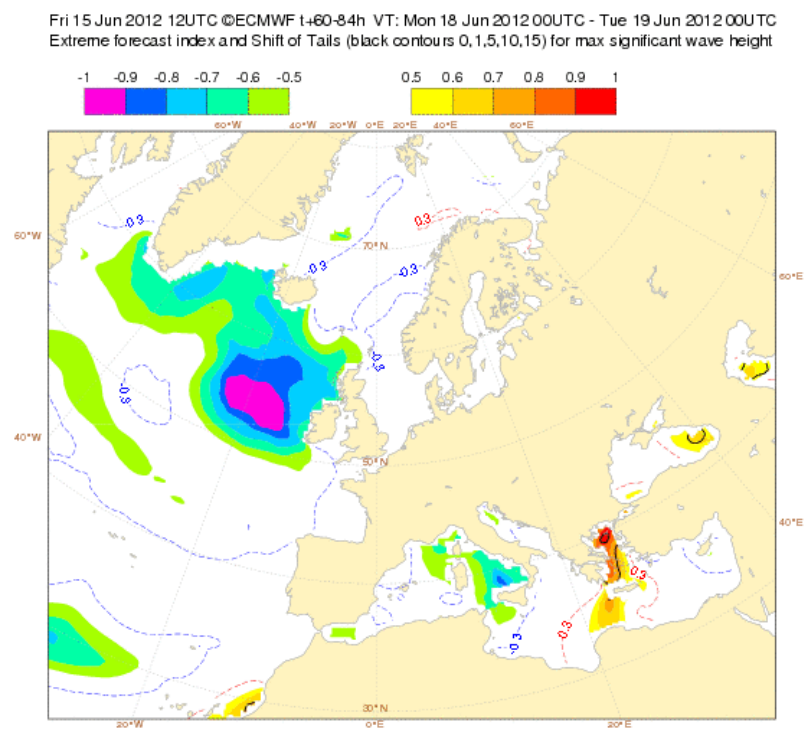


99 percentile of the distribution for significant wave height

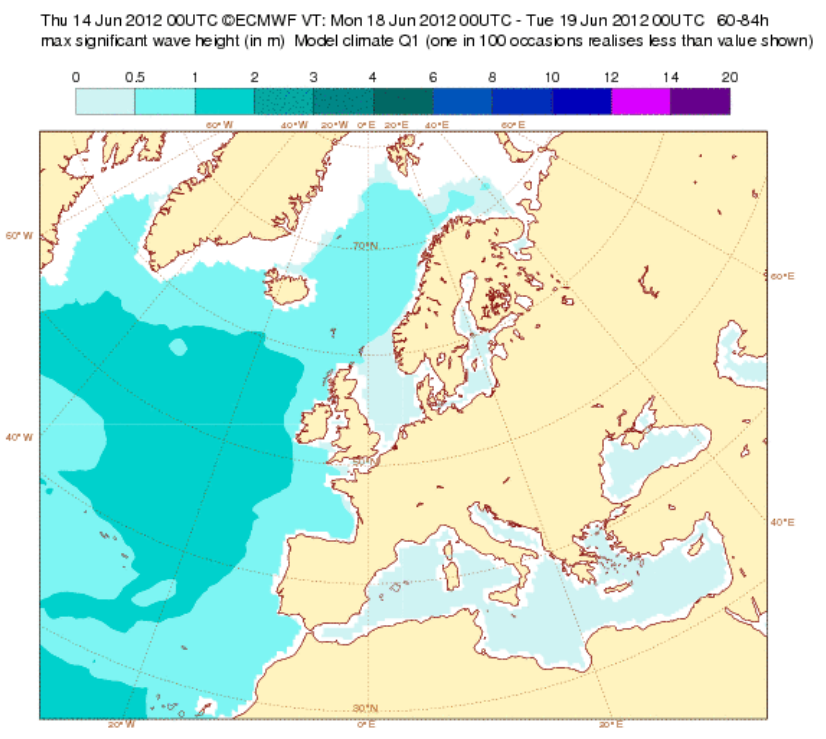
EFI plots

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.



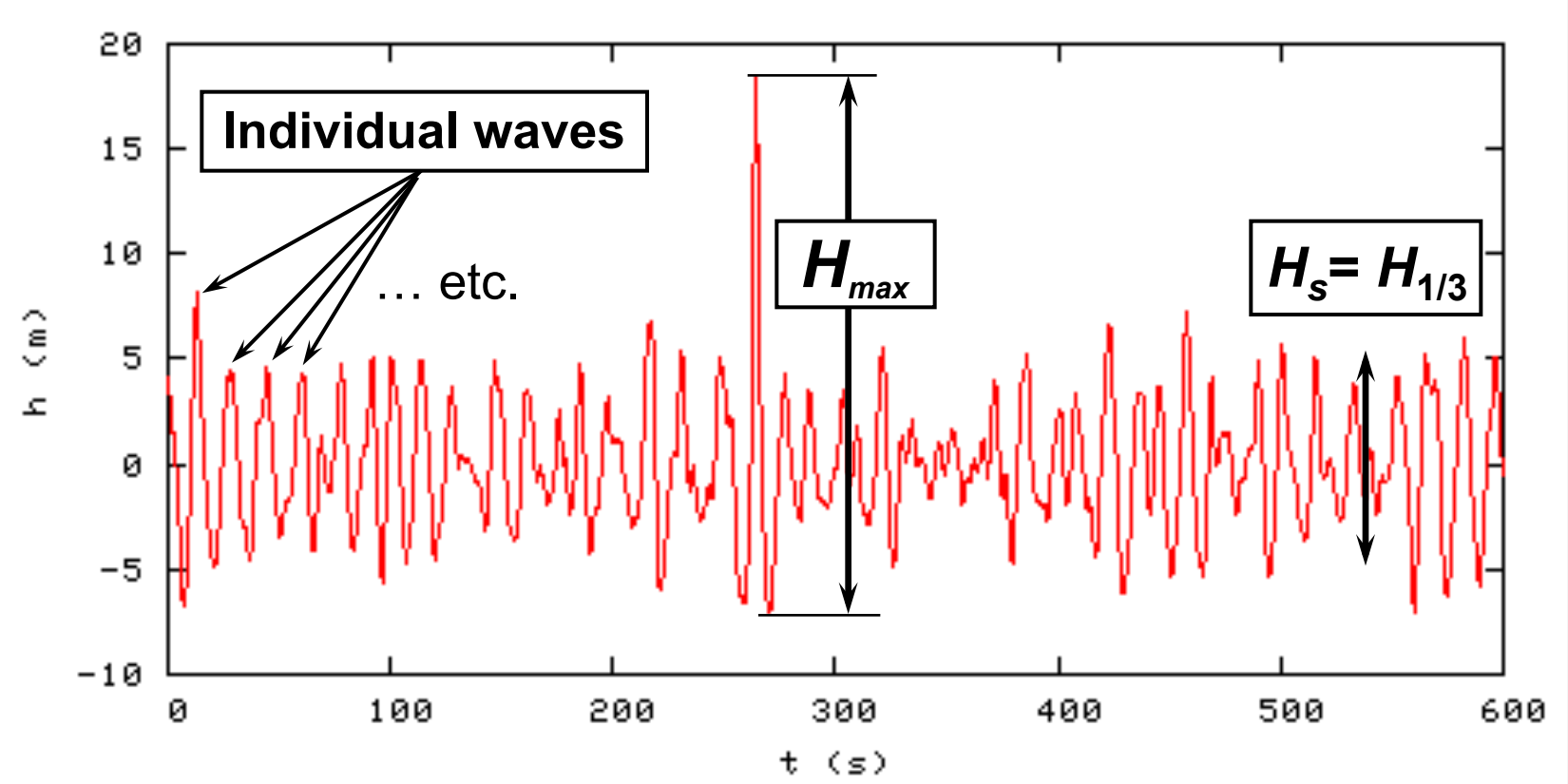
EFI for significant wave height



01 percentile of the distribution for significant wave height

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

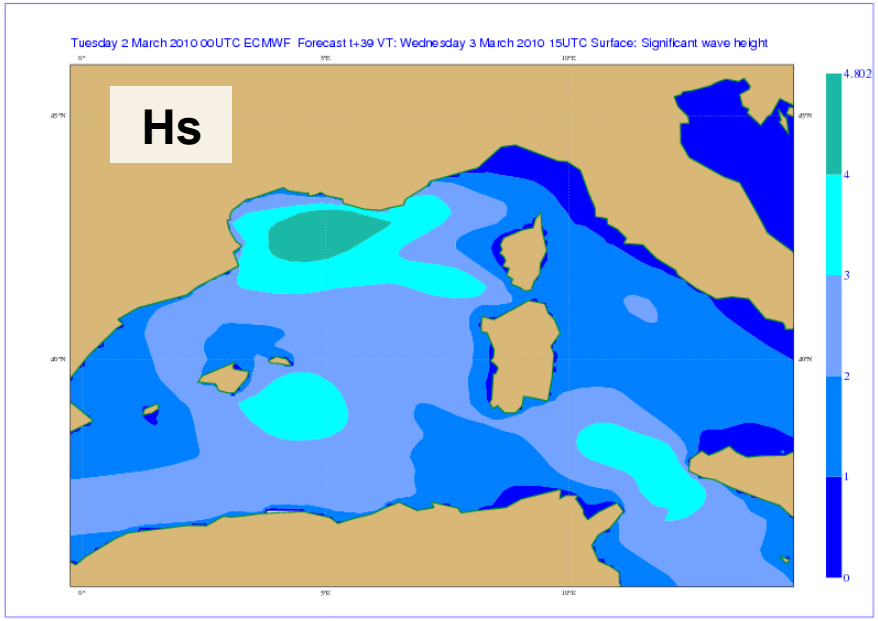
Individual Waves,
Significant Wave Height, H_s,
Maximum Individual Wave Height, H_{max}, and
Freak Wave

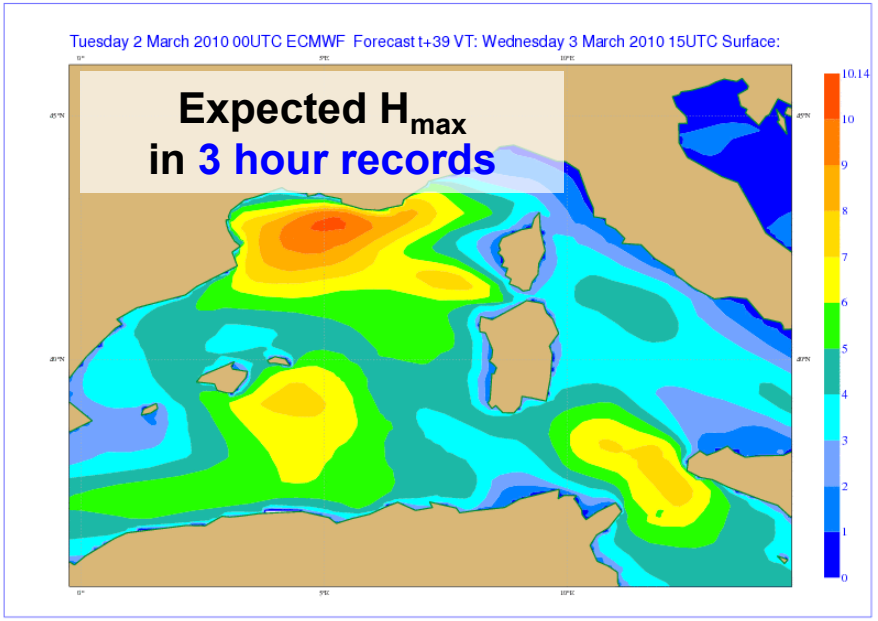


If $H_{max} > 2.2\ H_s$ ➔ freak wave event

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

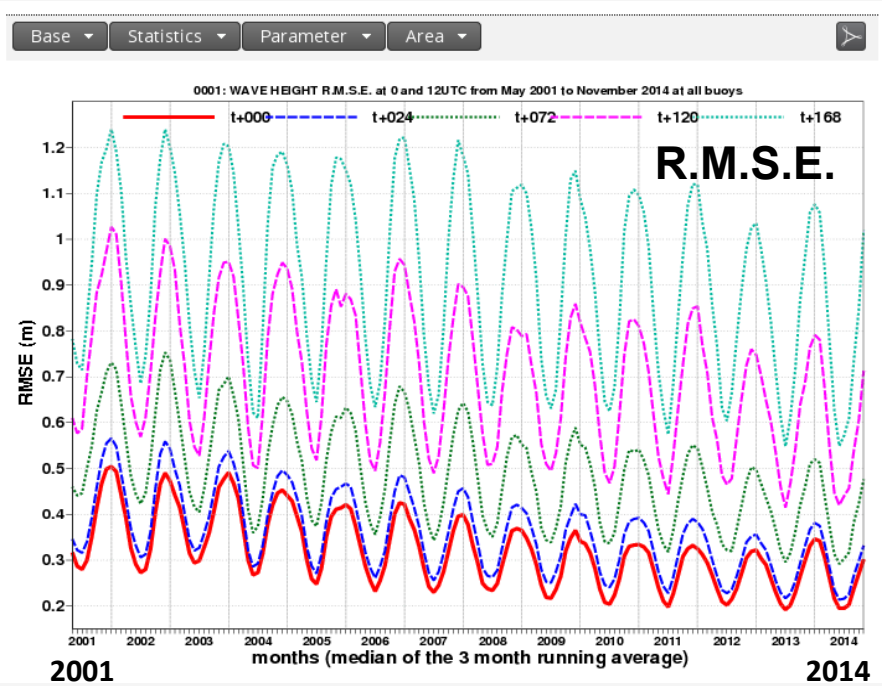
Verification:
What Do You Compare Against ?

- Using in-situ data (from buoys and platforms).
  Scarce, only few hundreds worldwide
- Using satellite data (altimeters, SAR).
  Assimilated in the model
- Using the model analysis.
  For forecast verification only
- Comparison to other centres.

Continued general improvement of model forecasts

For example: ECMWF forecast wave height against buoy measurements:

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



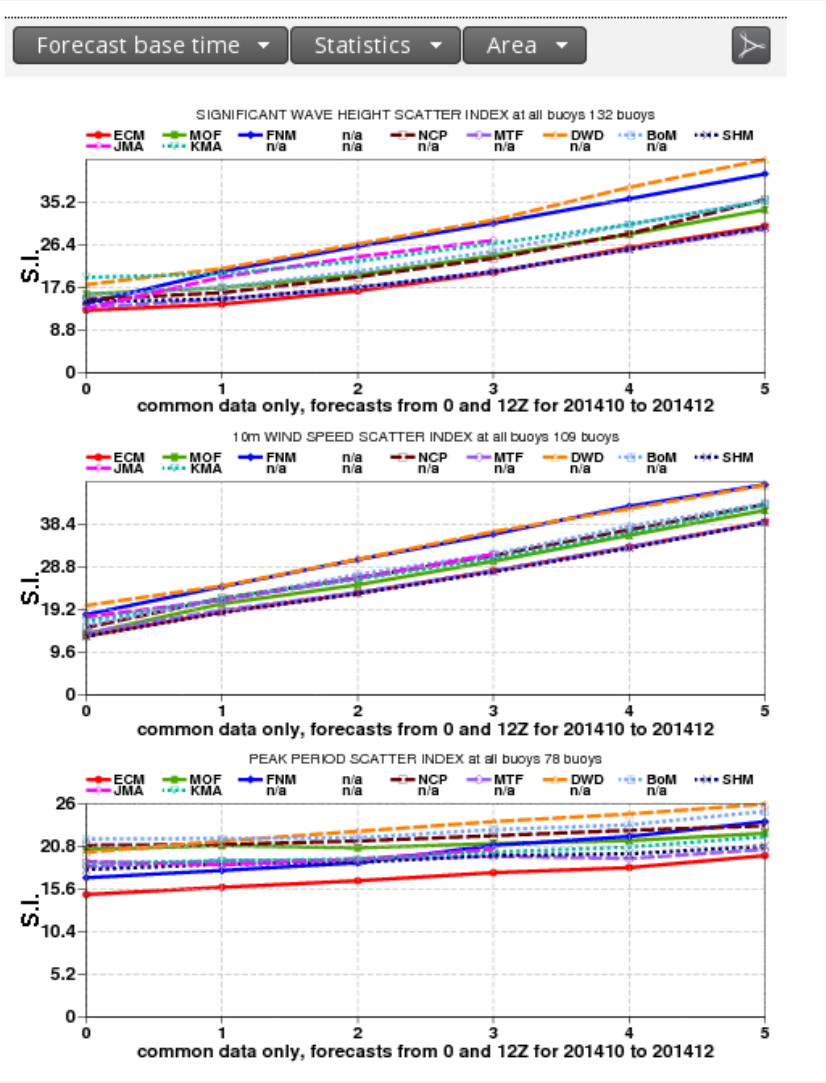
7 day FC

5 day FC

3 day FC

1 day FC

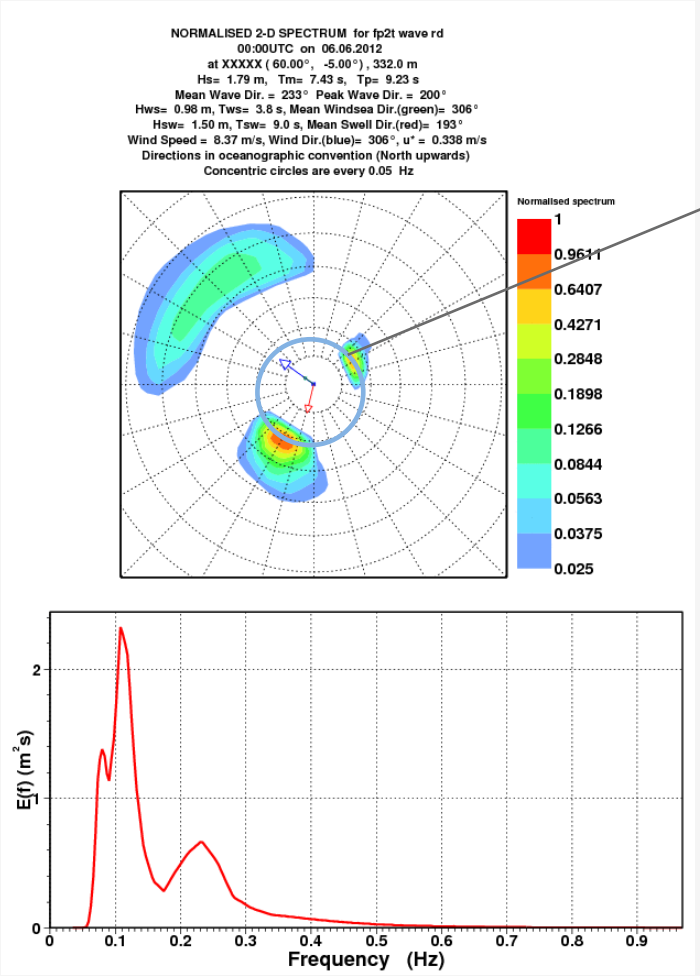
analysis



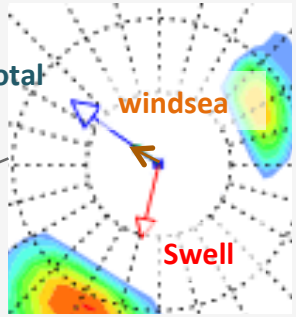
See also the Wave Forecast Verification Project maintained on behalf of the Expert Team on Waves and Storm Surges of the WMO-IOC Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM)

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

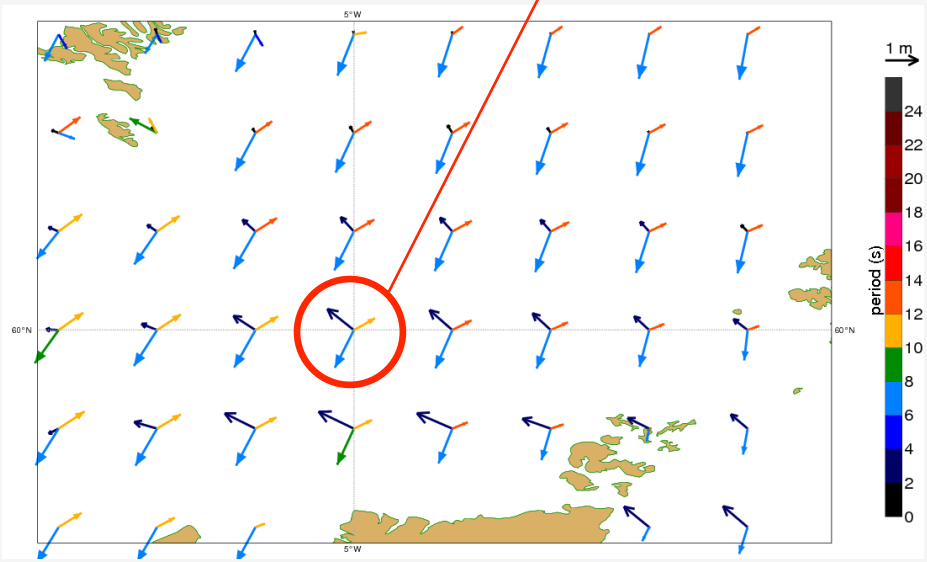
With next cycle (41R1): spectral partitioning



Operational:

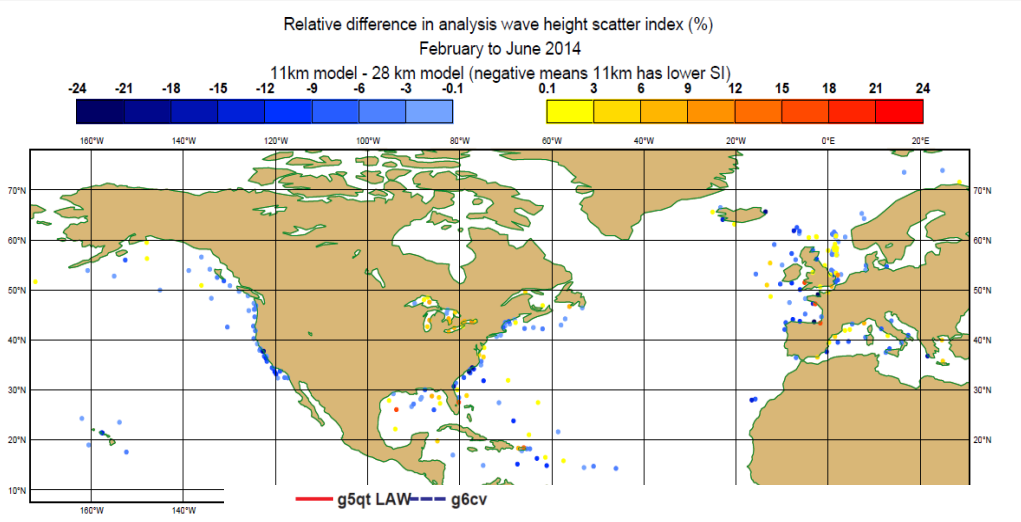


New decomposition:

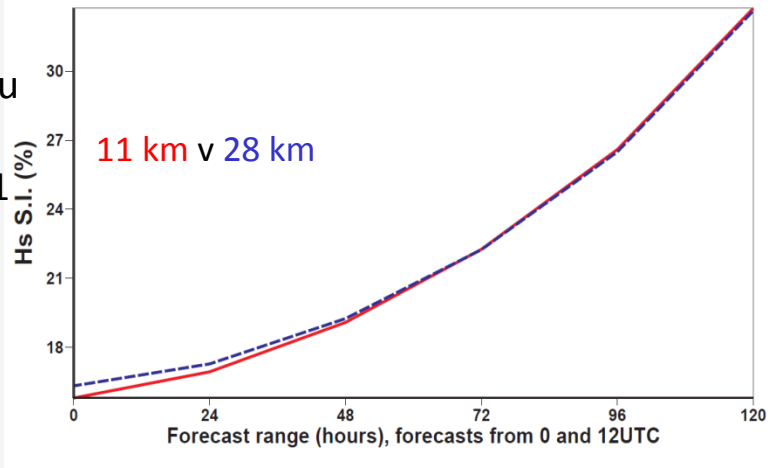


‘higher resolution’ wave model configuration

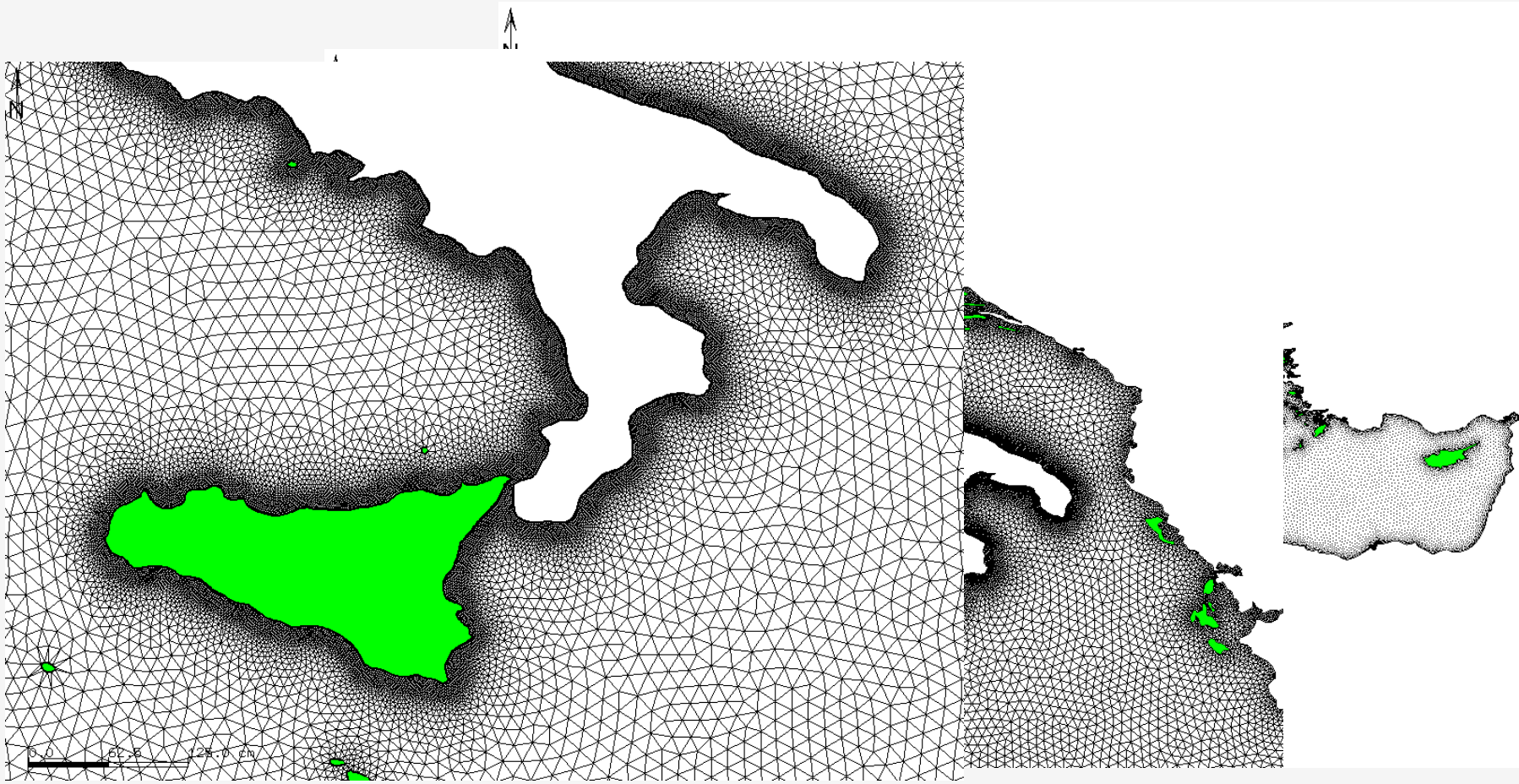
- **With CY41R1,**
- **Limited Area Wave (LAW) model (11km) to become global**
- **and**
- **extends to day 10**



Comparison to in-situ observations of stand alone WAM 11 km v 28 km.

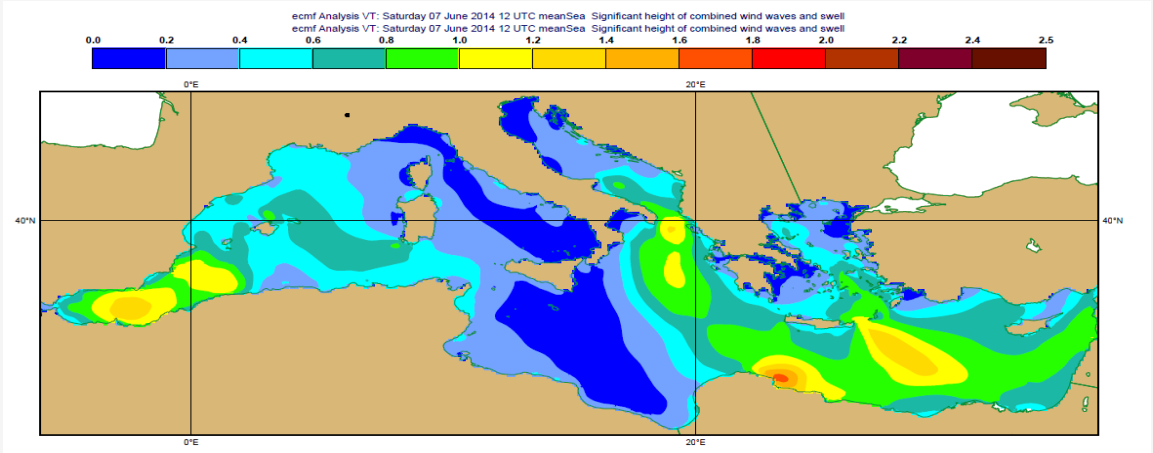


Wave modelling with unstructured grid (ongoing)

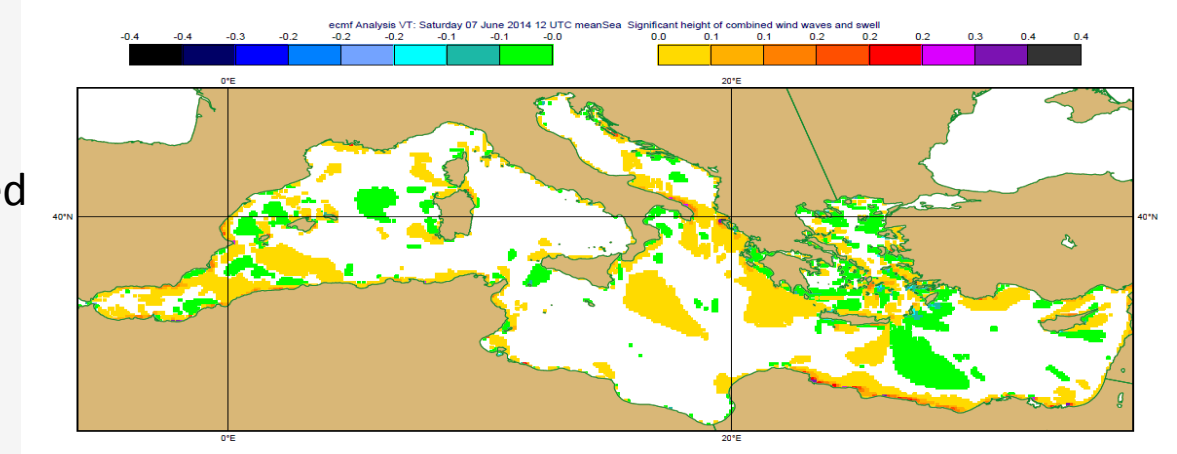


Wave modelling with unstructured grid (ongoing)

Hs (m)
from unstructured
output on a 0.1°x0.1° grid



Hs difference (m)
Unstructured - structured
output 0.1°x0.1° grid



Work is ongoing to extend the unstructured grid to global stand alone system


Questions ?
© Mike Thomas

Ocean Wave Modelling: references

- The ocean wave modelling at ECMWF is based on the wave mode WAM cycle 4 (Komen et al. 1994), albeit with frequent improvements (Janssen 2007: ECMWF Tech. Memo 529, Bidlot 2012, proceeding of the ECMWF Workshop on Ocean Waves, 25-27 June 2012).
- Products from different configurations of WAM are currently available at ECMWF.

http://www.ecmwf.int/publications/manuals/d/gribapi/param/filter=grib1/order=paramId/order_type=asc/p=1/table=140/

- Wave model page on the Centre's web site:
  http://www.ecmwf.int/products/forecasts/wavecharts/index.html#forecasts
- General documentation:
  http://www.ecmwf.int/research/ifsdocs/CY40r1/index.html

ECMWF