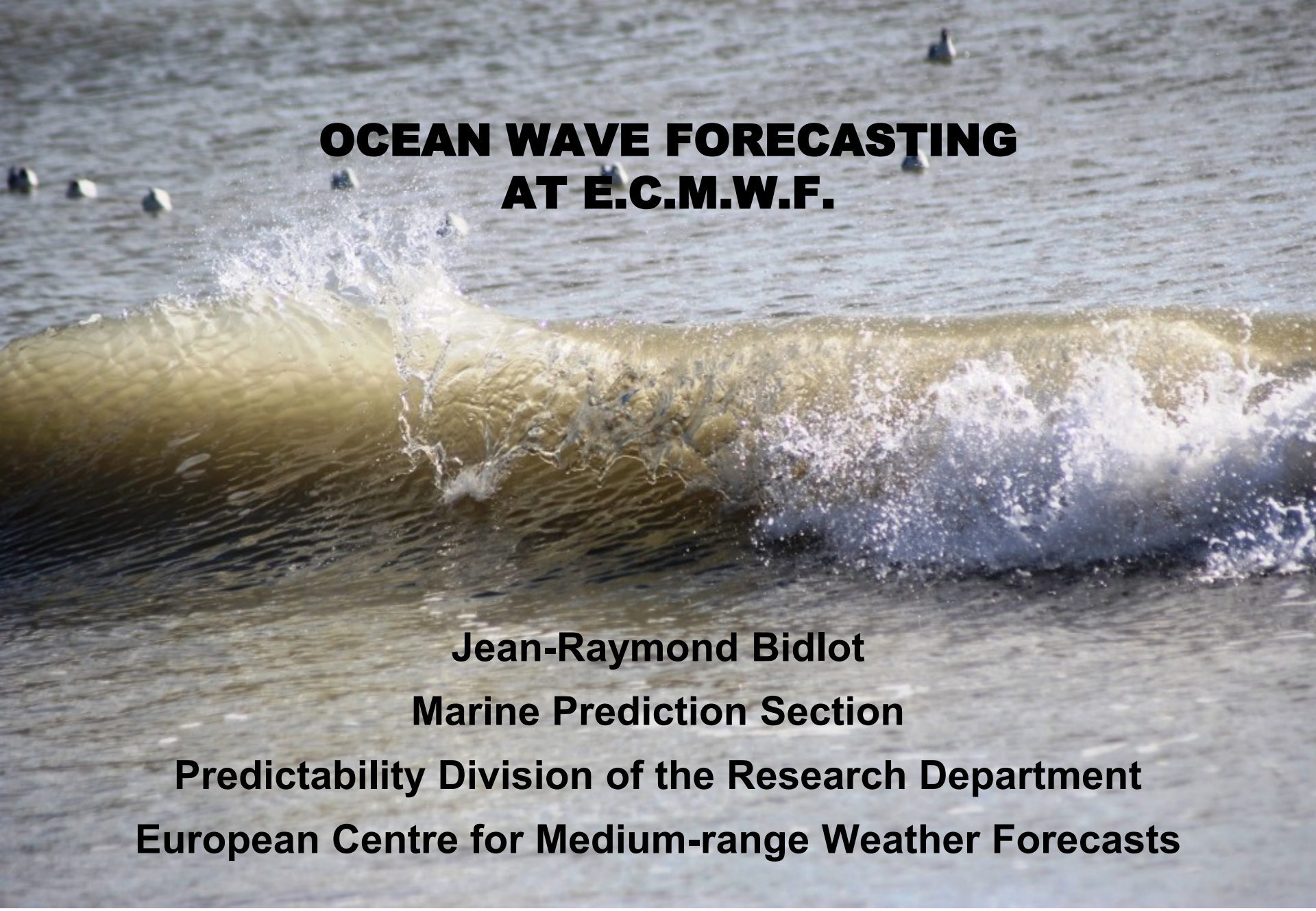


OCEAN WAVE FORECASTING AT E.C.M.W.F.

Jean-Raymond Bidlot

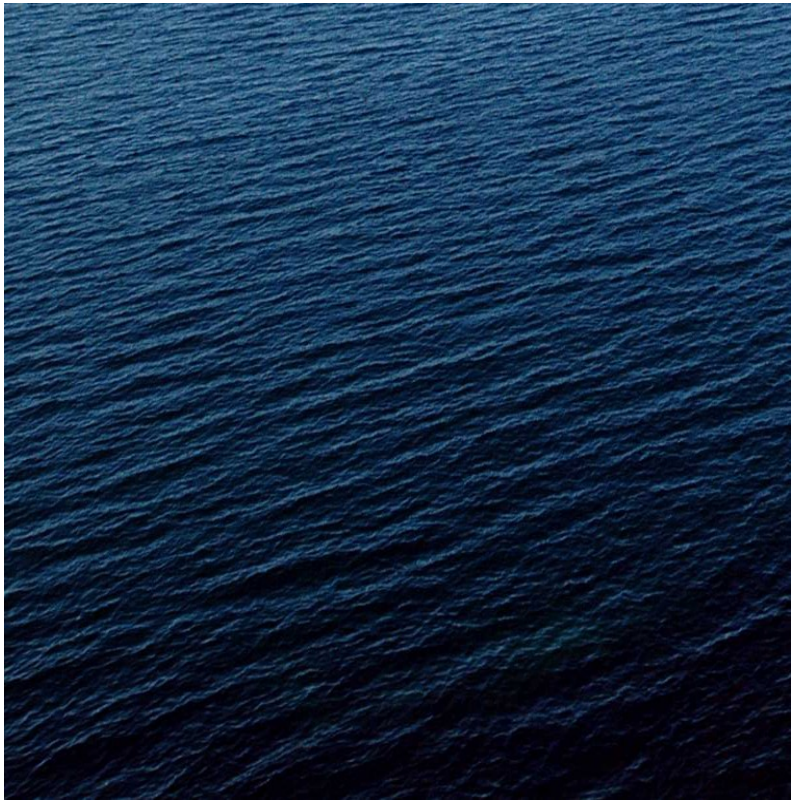
Marine Prediction Section

Predictability Division of the Research Department

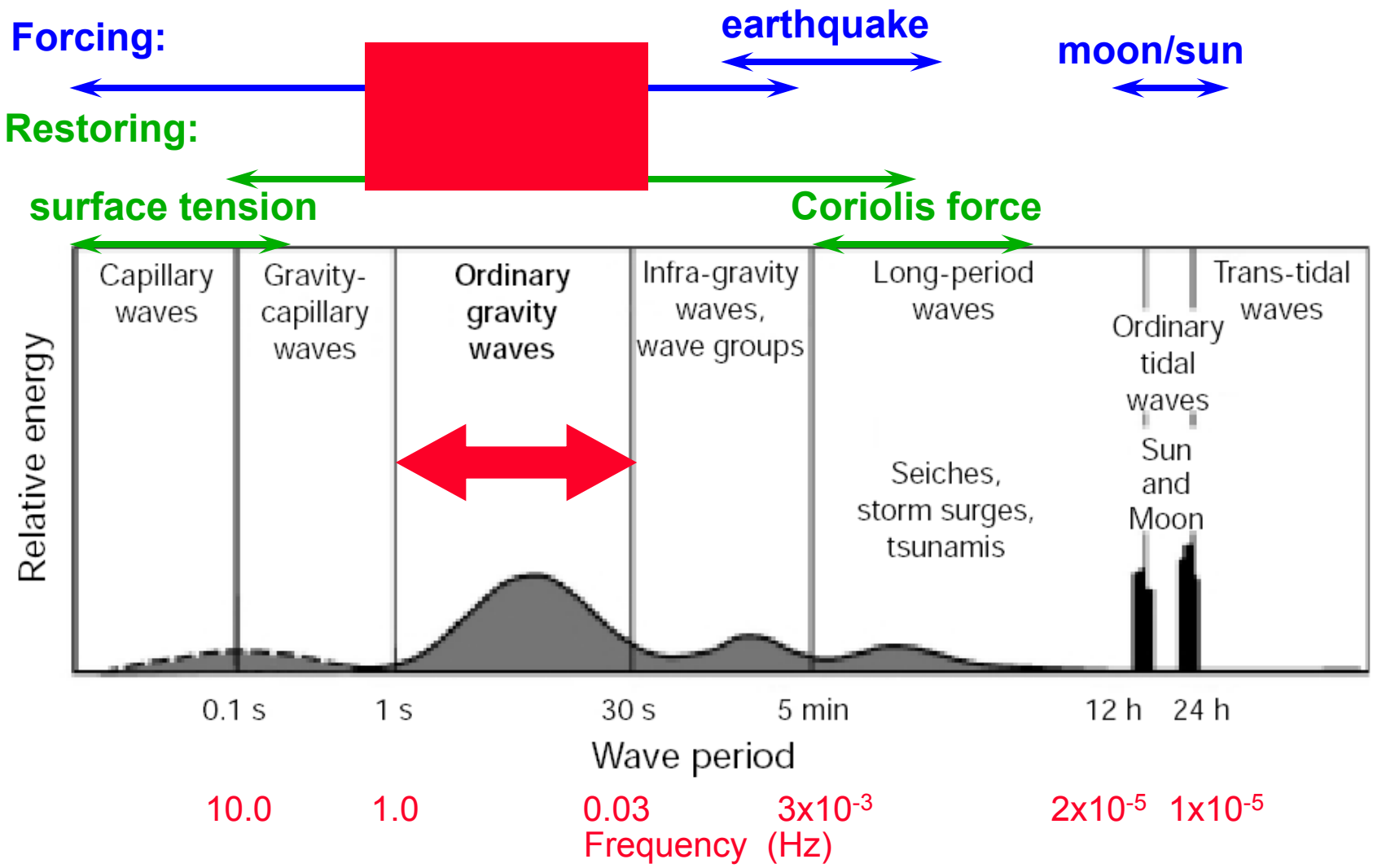
European Centre for Medium-range Weather Forecasts

Ocean waves:

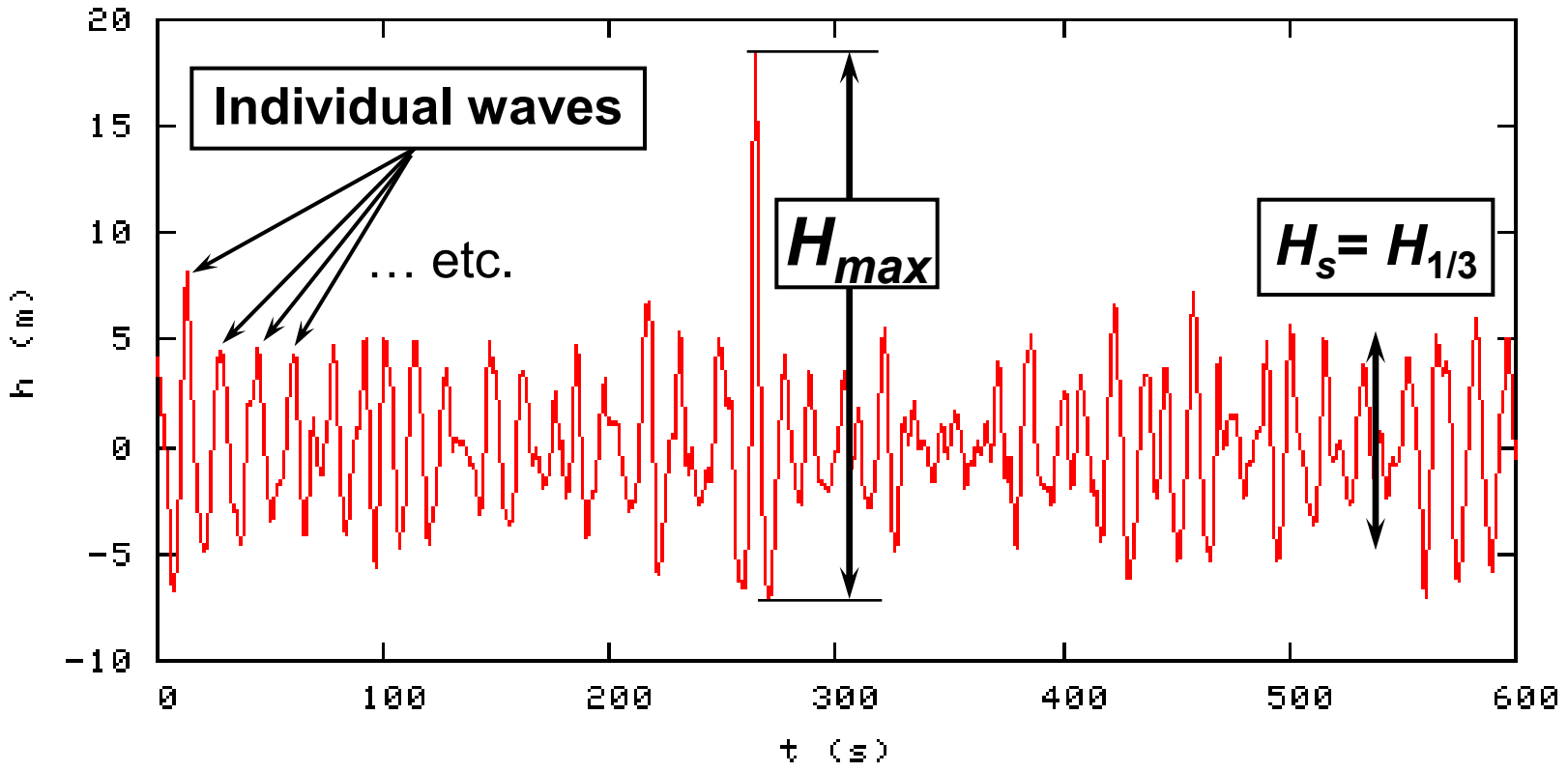
We are dealing with wind generated waves at the surface of the oceans, from gentle to rough …



Ocean Waves

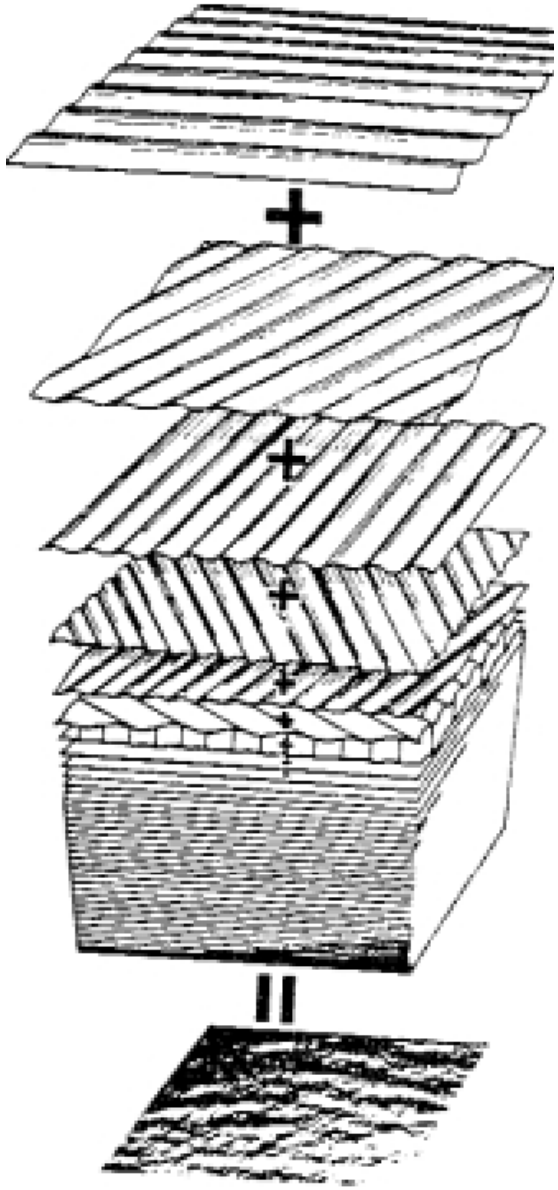

Forcing:
earthquake
moon/sun
Restoring:
surface tension
Coriolis force
Capillary waves
Gravity-capillary waves
Ordinary gravity waves
Infra-gravity waves, wave groups
Long-period waves
Ordinary tidal waves
Trans-tidal waves
Seiches, storm surges, tsunamis
Sun and Moon
Relative energy
0.1 s
1 s
30 s
5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

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



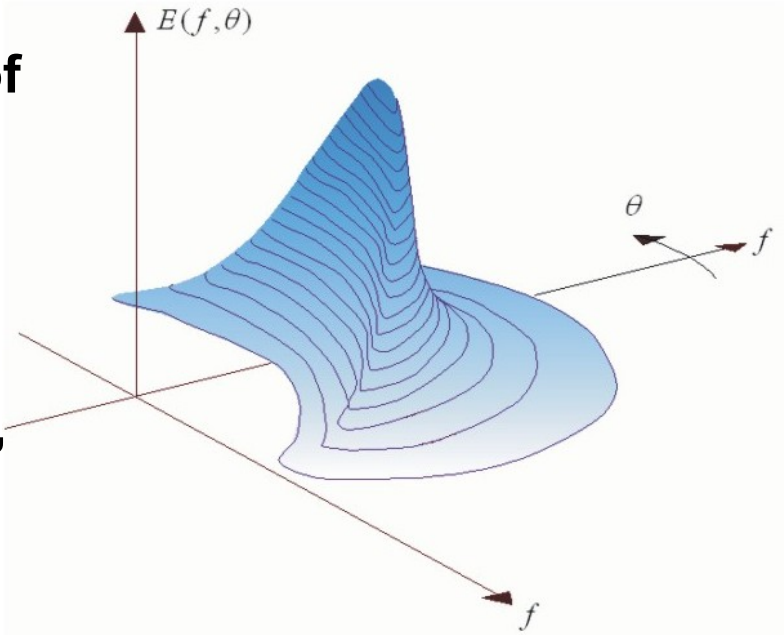
Surface elevation time series from platform Draupner in the North Sea

Wave Spectrum



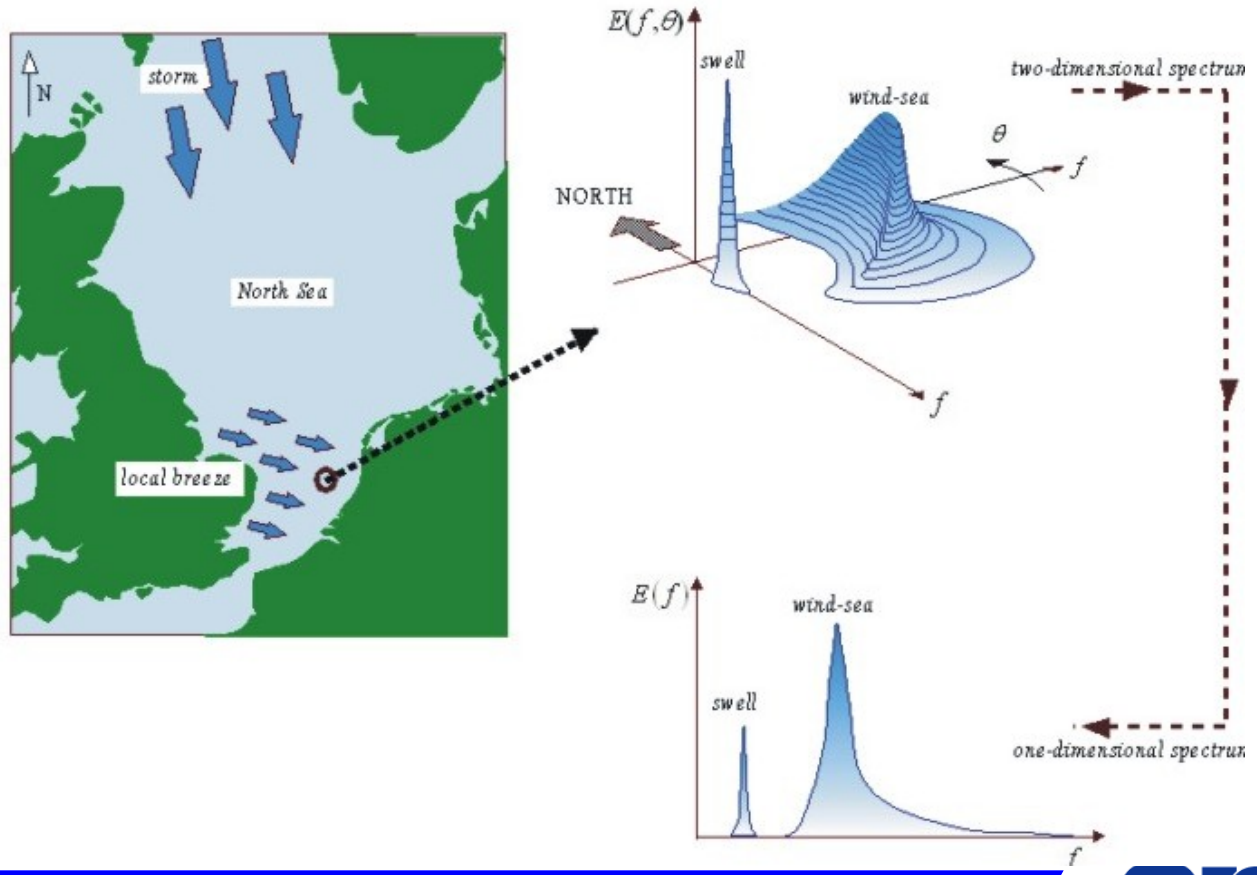
- The irregular water surface can be decomposed into (*infinite*) number of simple sinusoidal components with different frequencies (f) and propagation directions (θ).

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



- 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 $F(f,\theta)$.



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.

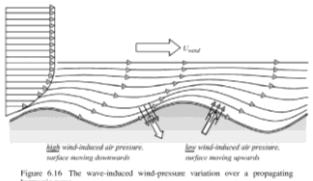


Figure 6.16 The wave-induced wind-pressure variation over a propagating harmonic wave.

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

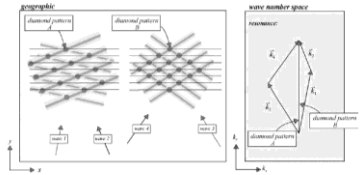
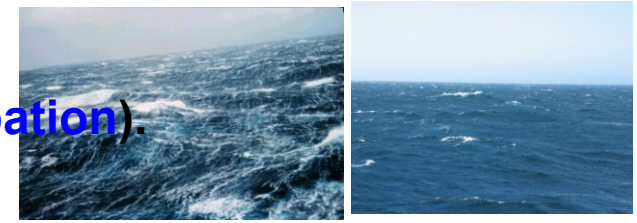


Figure 6.20 *Quadruplet* wave–wave interactions (realisable in deep water). Two pairs of wave components can create two diamond patterns with identical wave lengths and directions and therefore identical wave numbers. When the four waves are superimposed (not shown here), they can thus resonate. The 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).



ECMWF

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):

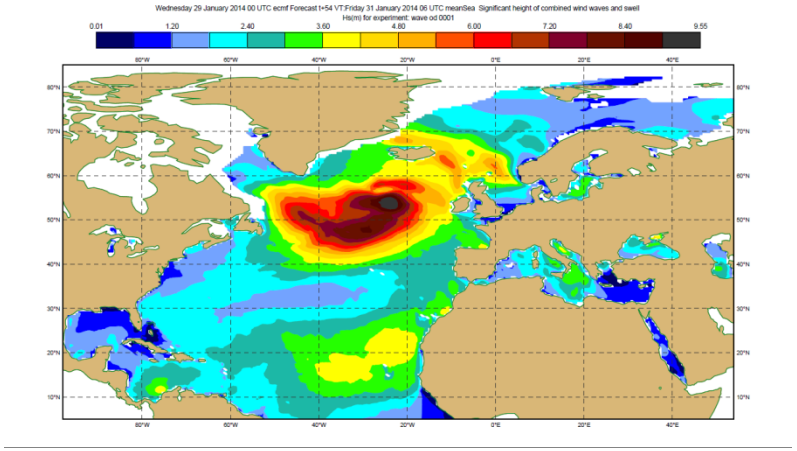
$$H_s = 4\sqrt{\langle \eta^2 \rangle}$$

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 ($H_{1/3}$).

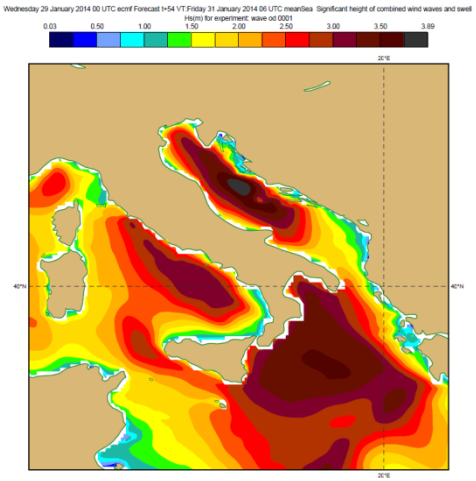
ECMWF Wave Model Configurations

1) Limited area model (LAW)

- 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



ECMWF Wave Model Configurations

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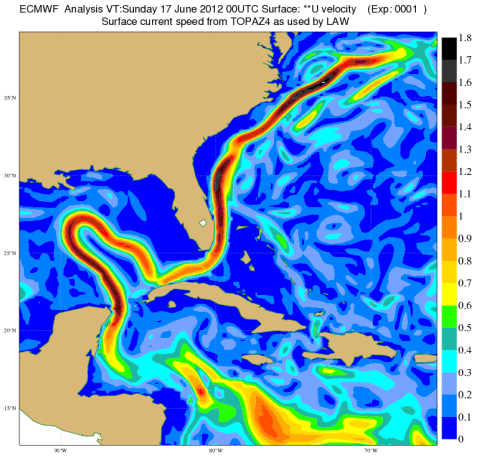
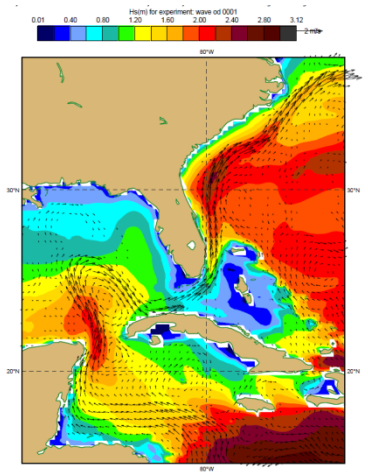
- Data assimilation of altimeter wave heights (Jason 2).
- 2 daily forecasts (from 0 & 12 UTC) extending to day 5, output every hour.
- **Imposed surface currents from TOPAZ4 system.**



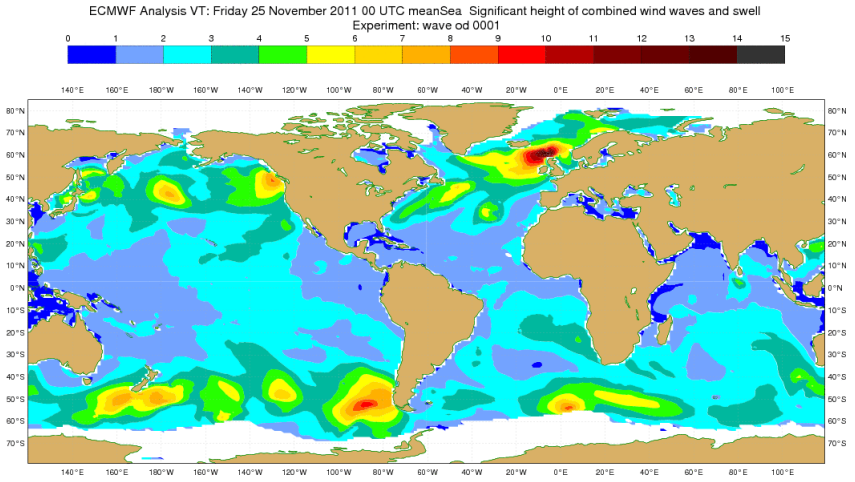
TOPAZ4 surface currents



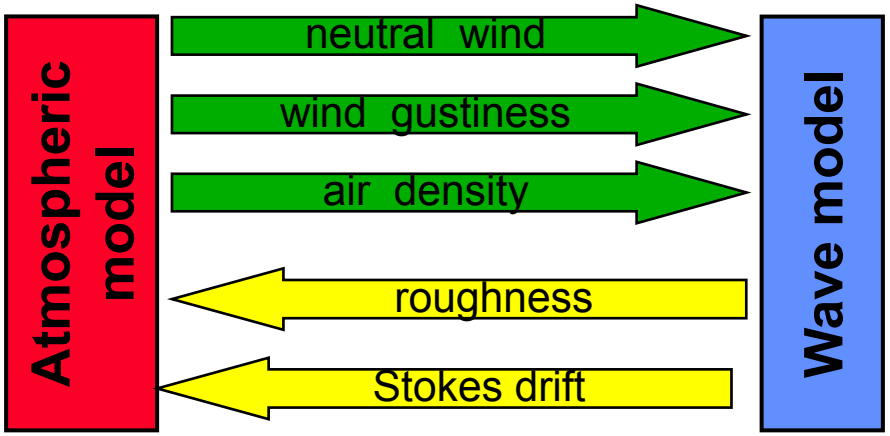
ECMWF Wave Model Configurations

2) Global models

- Global from 81 S to 90 N
- Coupled to the atmospheric model (IFS) with feedback of the sea surface roughness change due to waves. The Stokes drift is also returned for the parameterisation in the skin layer model for the daily cycle of the SST.
- 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 of Jason-2 altimeter wave heights.



Global from 81 S to 90 N



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)

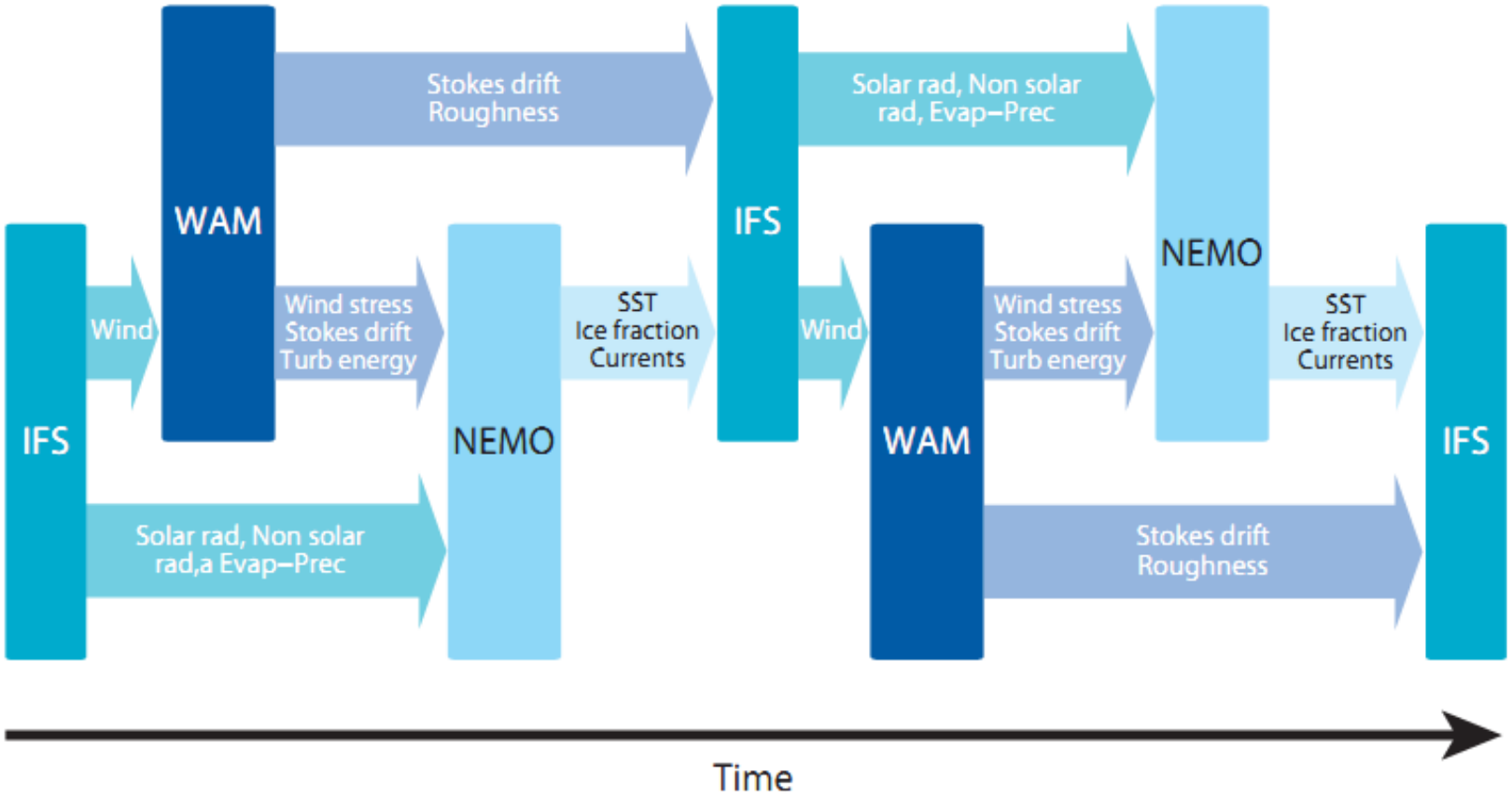
- 55 km grid spacing.
- 30→ 25 frequencies *.
- 24 → 12 directions *.
- Coupled to TL639 → TL319 model *.
- (50+1) (10+5) day forecasts from 0 and 12Z (monthly once a week).
- Coupling to ocean model.

* Change in resolutions after 10 days

NB: also in seasonal forecast at lower resolutions

IFS-WAM-NEMO coupled system. atmosphere – waves - oceans

The single executable coupled forecast model



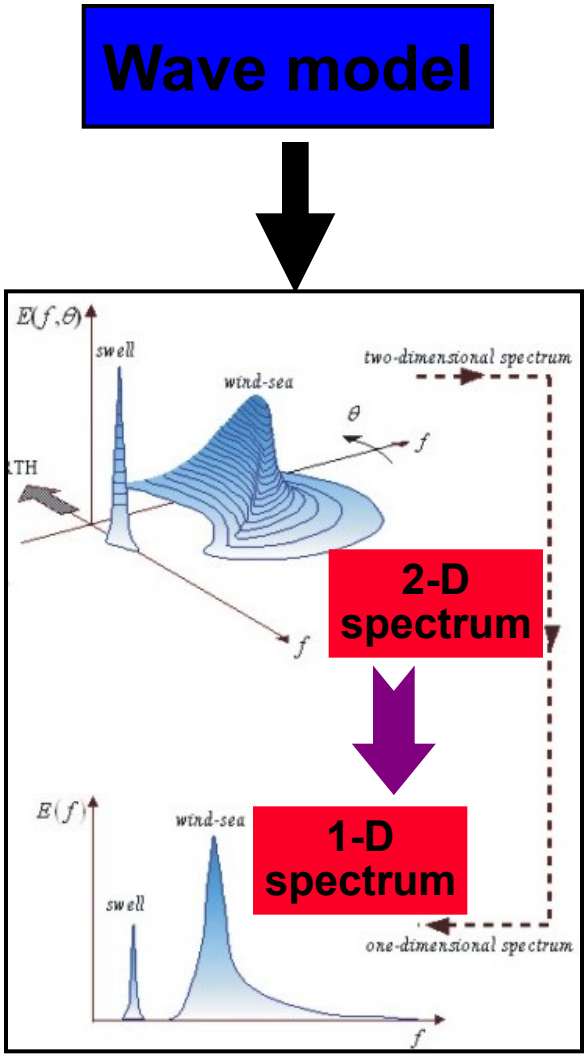
ECMWF

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:

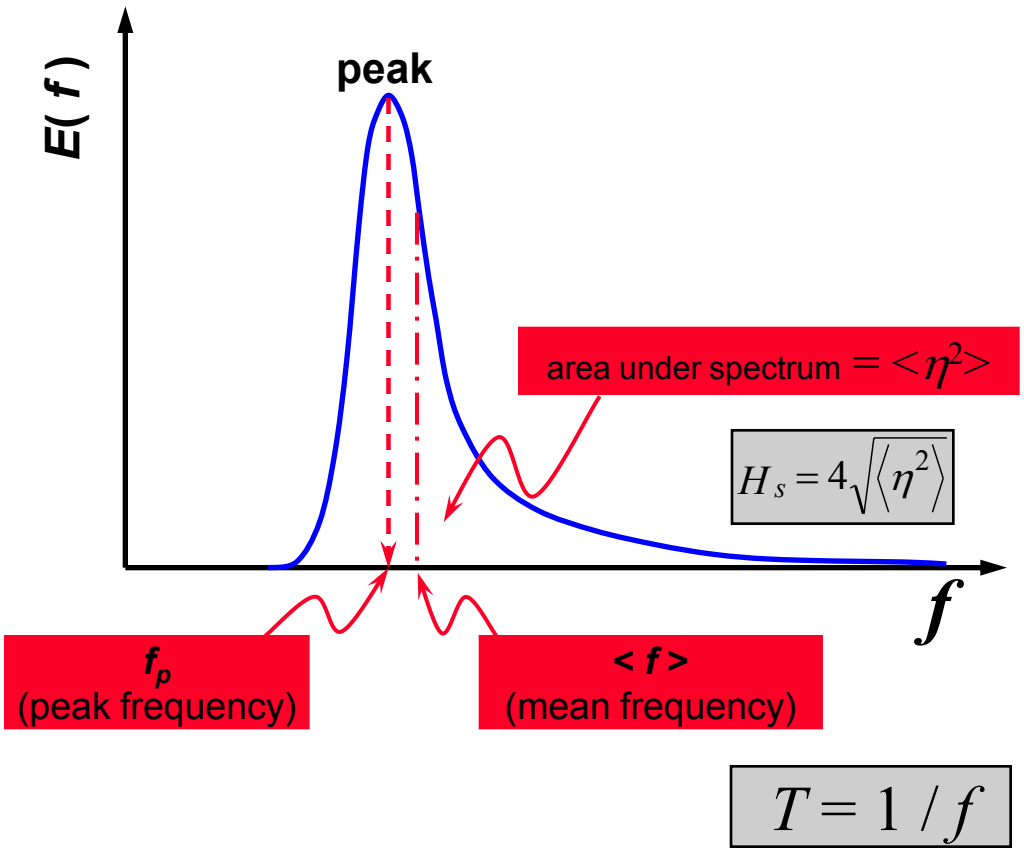
- **1-D spectrum obtained by integrating the 2-D spectrum over all directions and/or over a frequency range.**



Wave Model Products

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

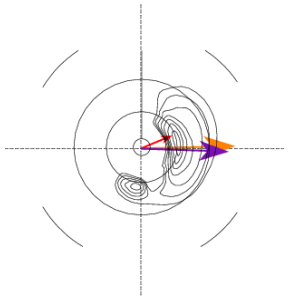
- **The significant wave height (H_s).**
- **The peak period (period of the peak of the 1-D spectrum).**
- **Mean period(s) obtained from weighted integration of the 2-D spectrum.**
- **Integrated mean direction.**
- ***Few others.***



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

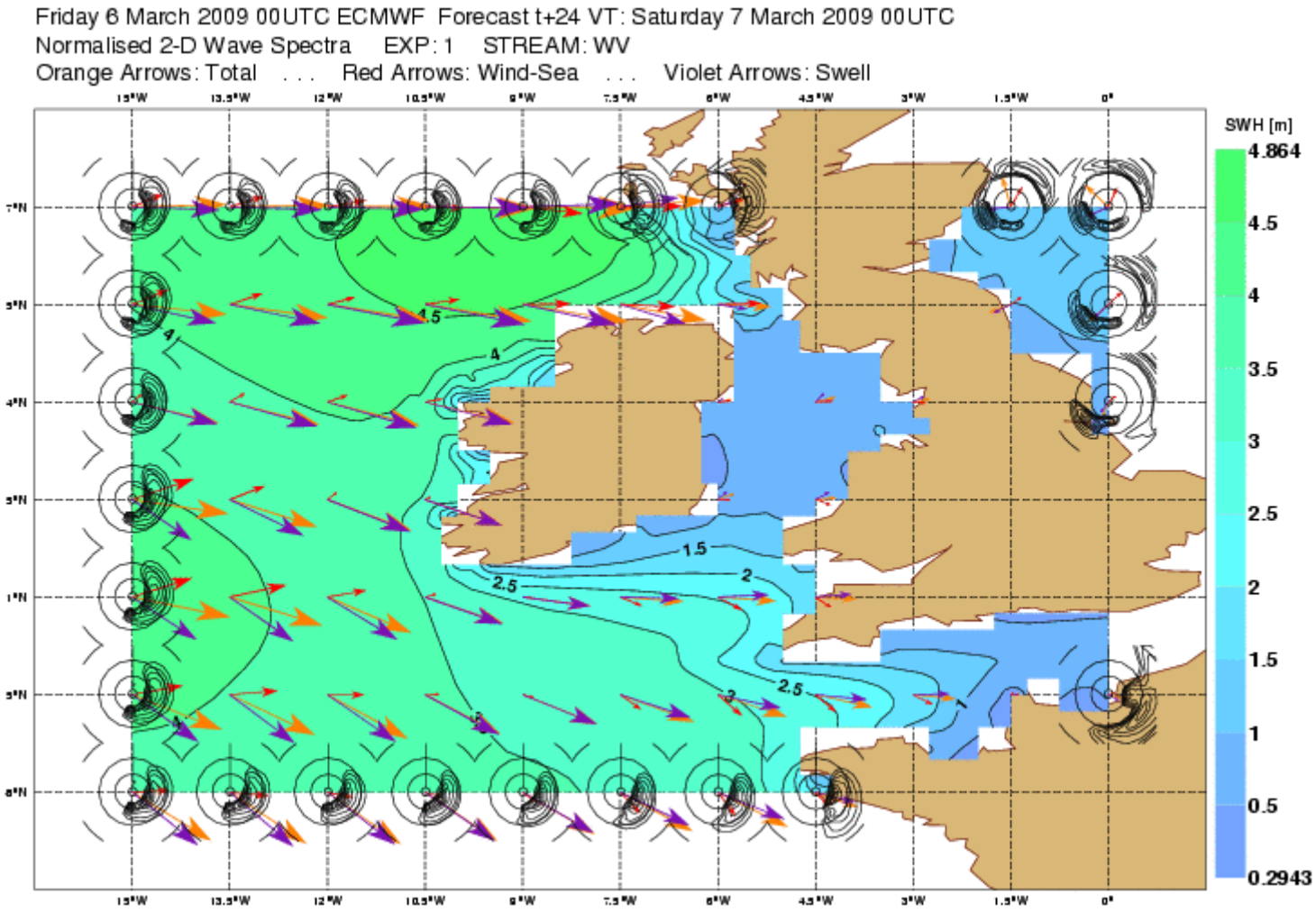
Wave Model Products

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



Spectra used as boundary conditions by Met Éireann

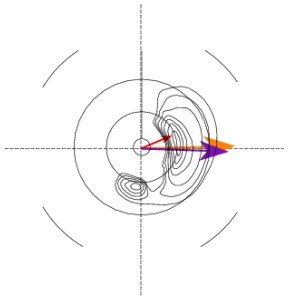
→ windsea
→ swell
→ total sea



ECMWF

Wave Model Products

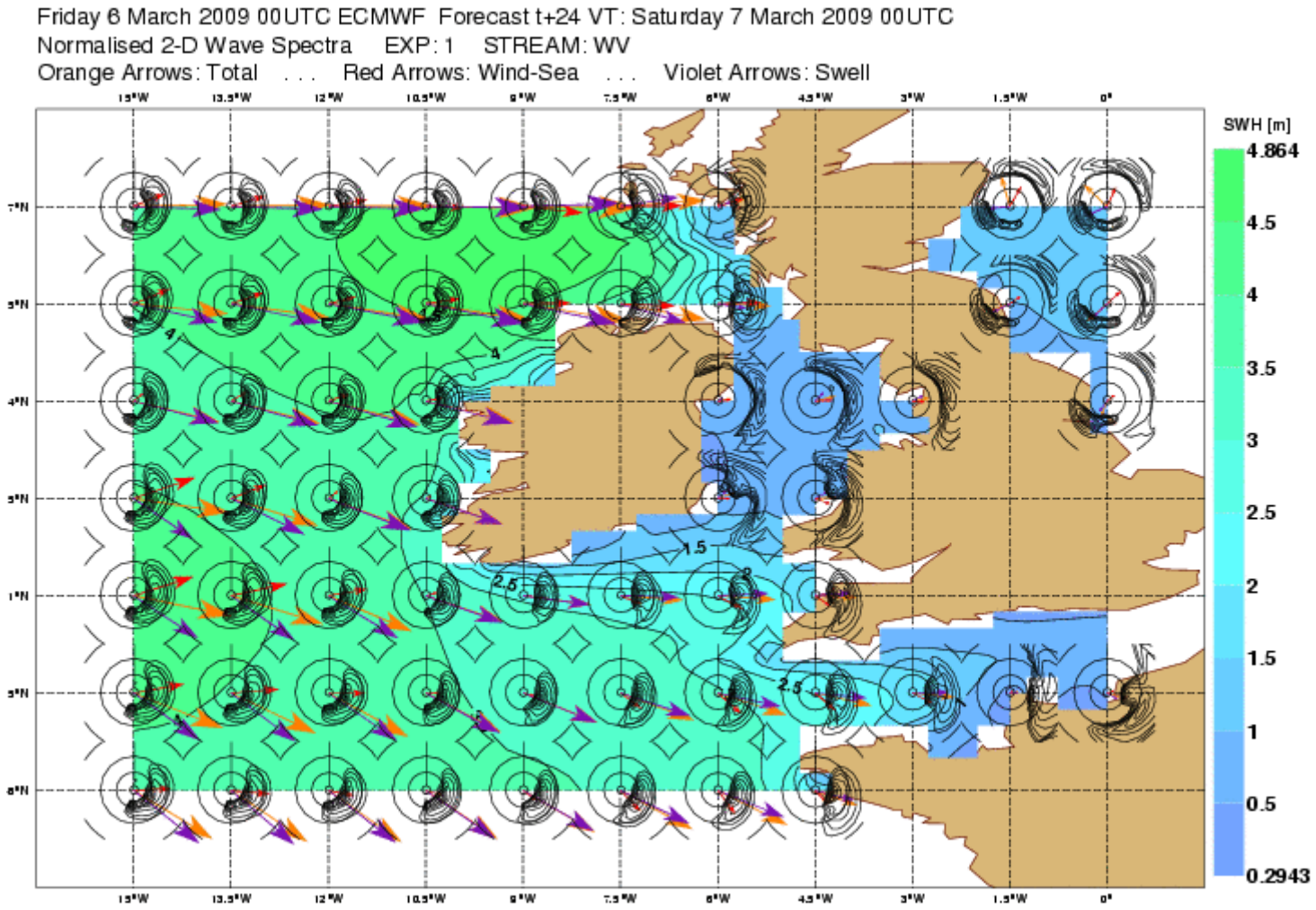
Plot of 2-D spectrum can become very busy !



windsea

swell

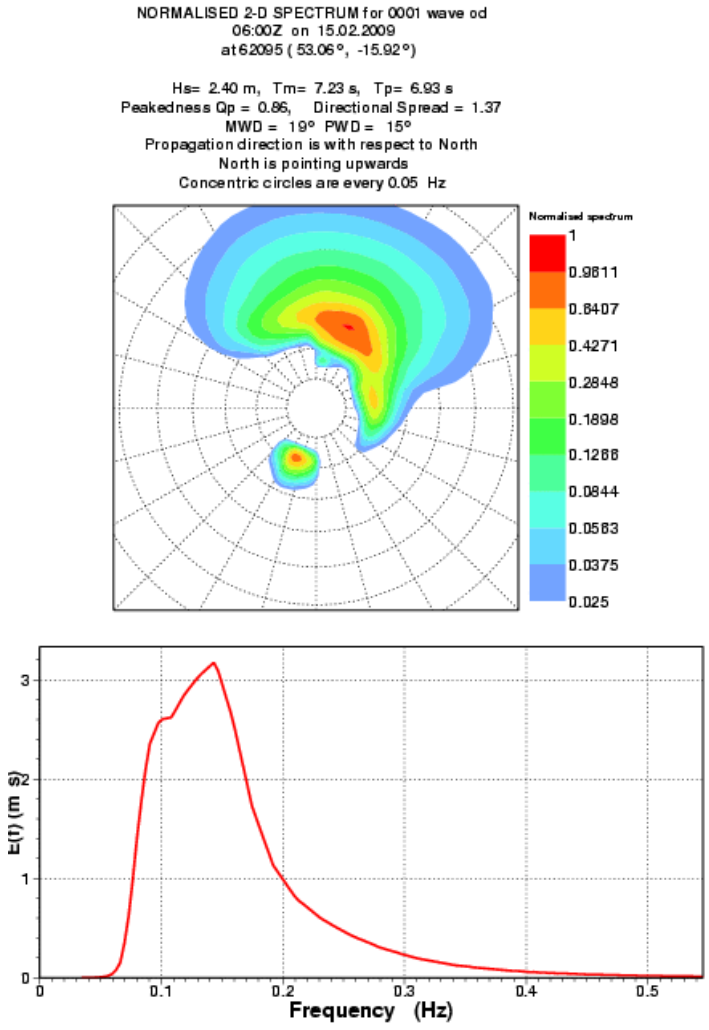
total sea



ECMWF

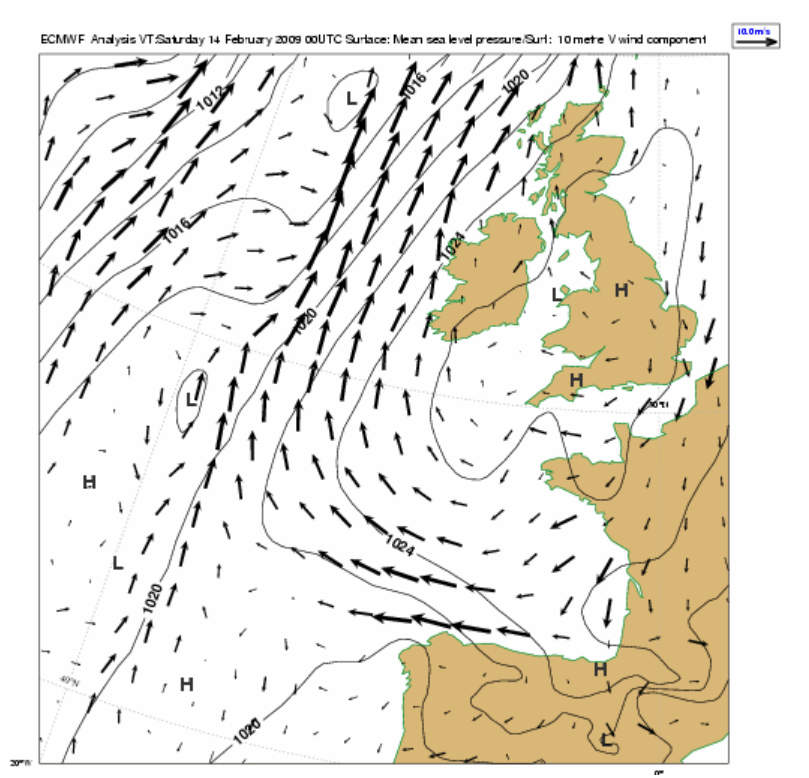
Wave Model Products

Except if you only look at one location …

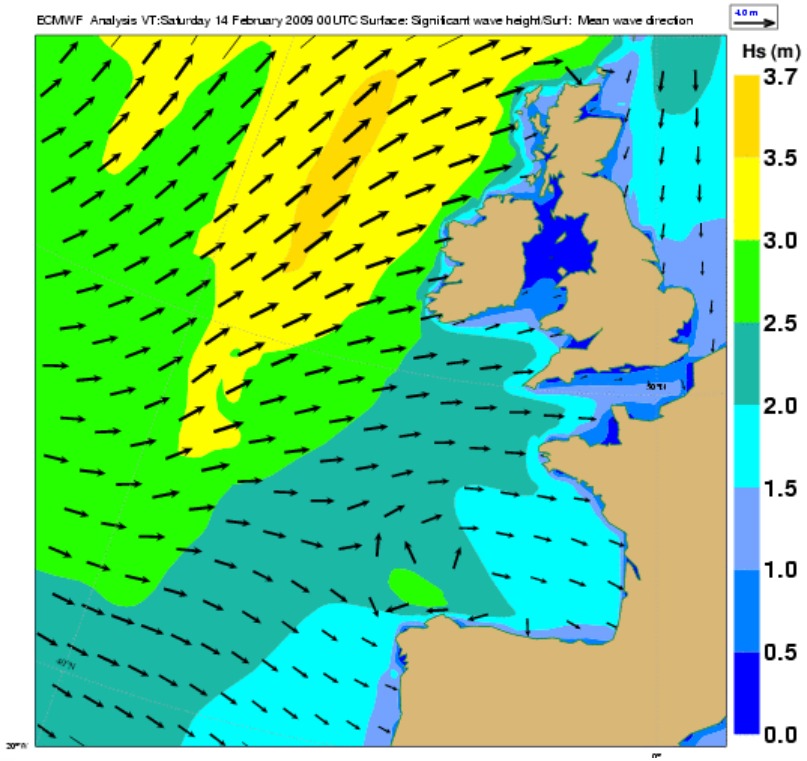


Wave Model Products

Use simple parameters:
total wave height and mean propagation direction

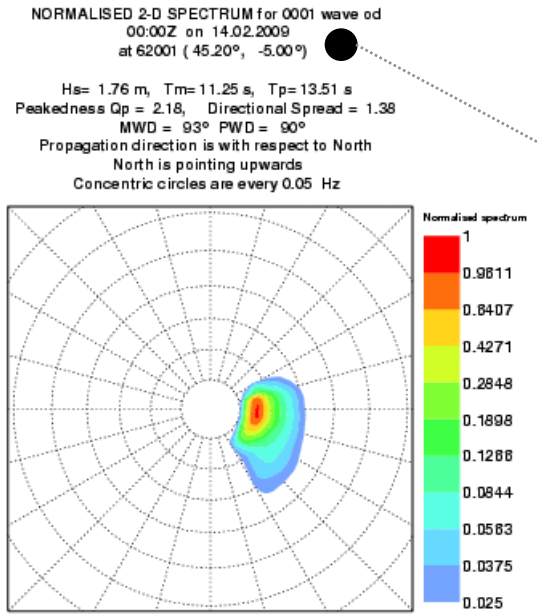


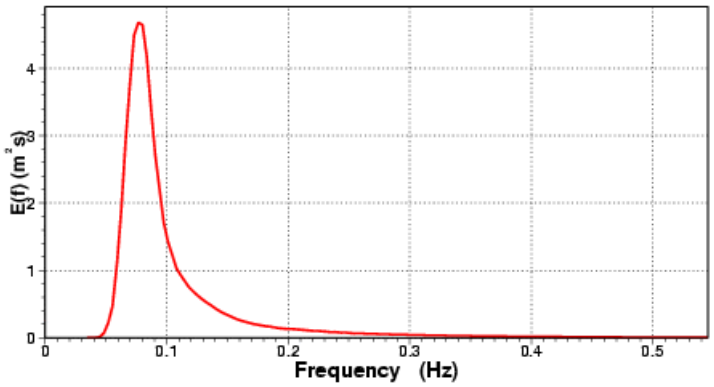
10m winds and mean sea level pressure:
Analysis : 14 February 2009, 00 UTC

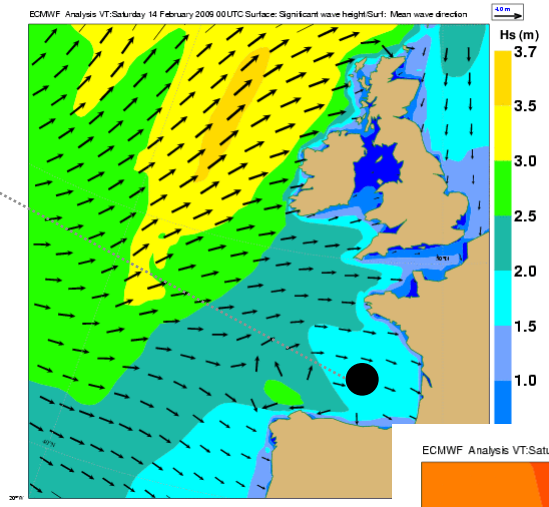


Wave height and mean direction:
Analysis : 14 February 2009, 00 UTC

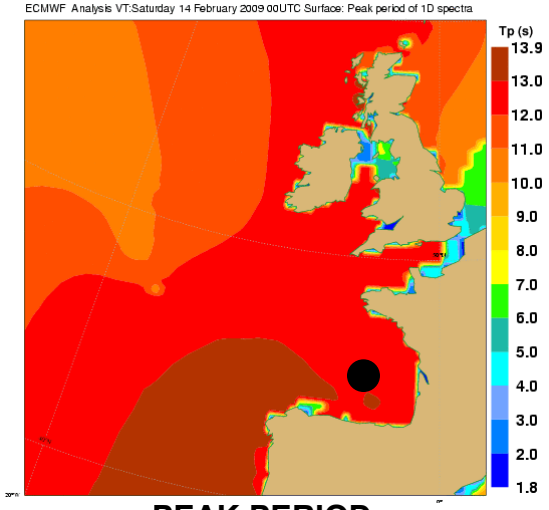
Wave Model Products







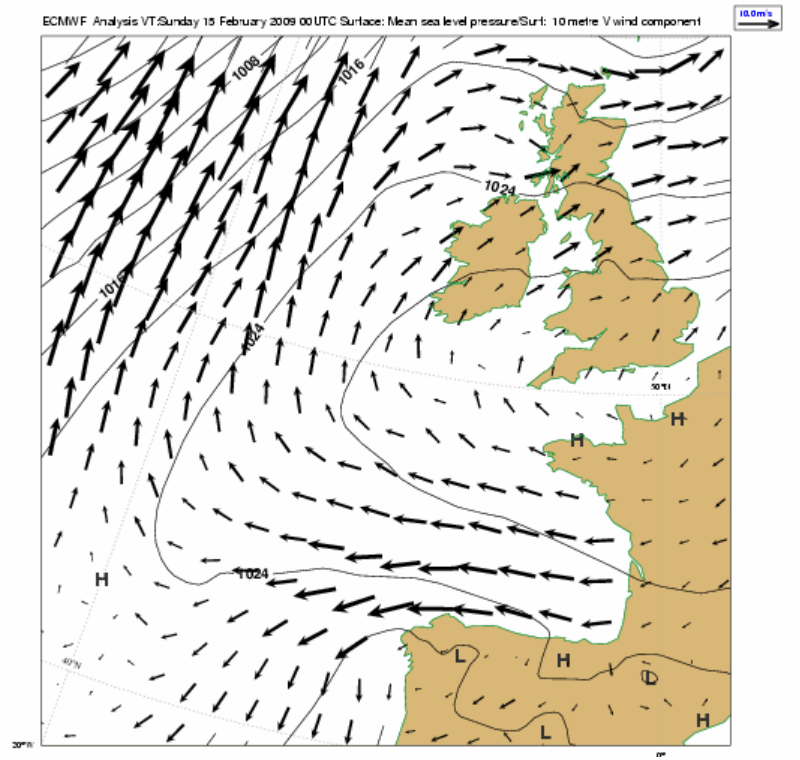
Wave height and me
Analysis : 14 February



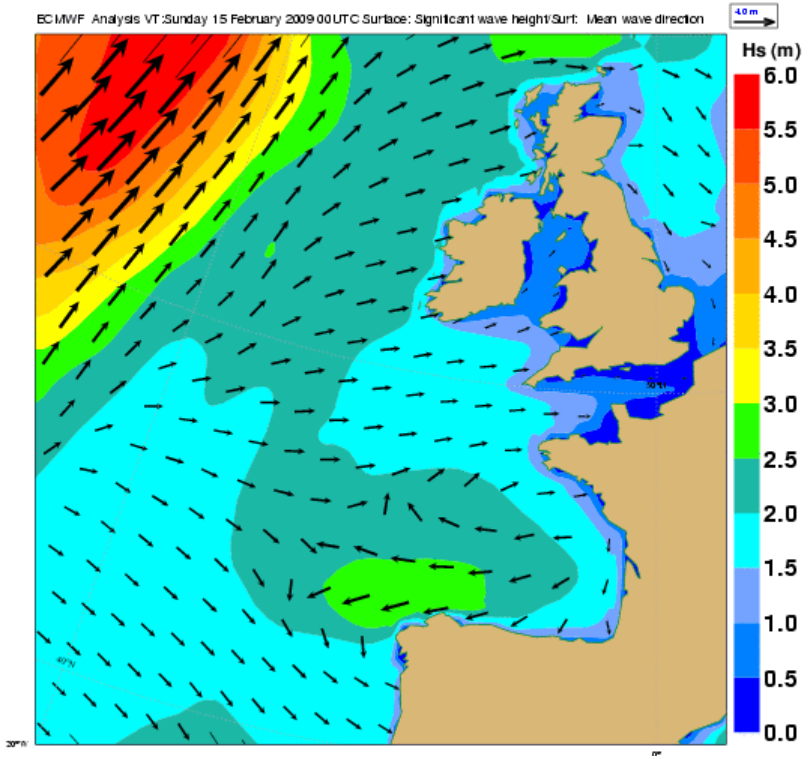
PEAK PERIOD:
Analysis : 14 February 2009, 00 UTC

Wave Model Products

Situation might be more complicated !



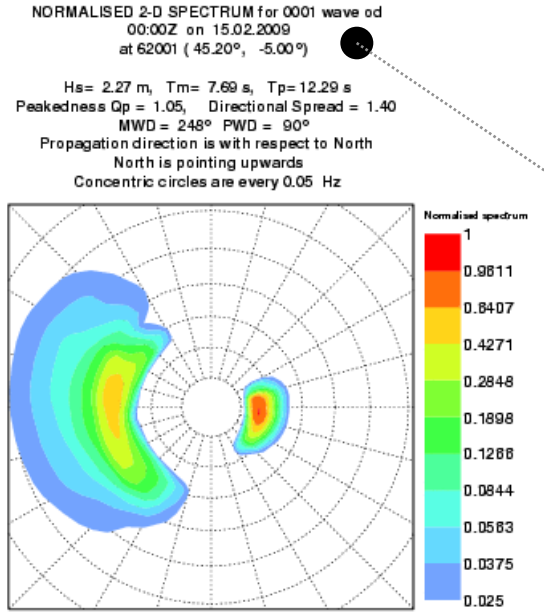
10m winds and mean sea level pressure:
Analysis : 15 February 2009, 00 UTC

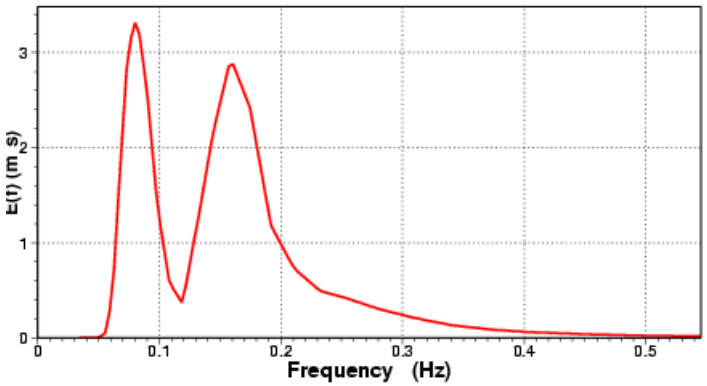


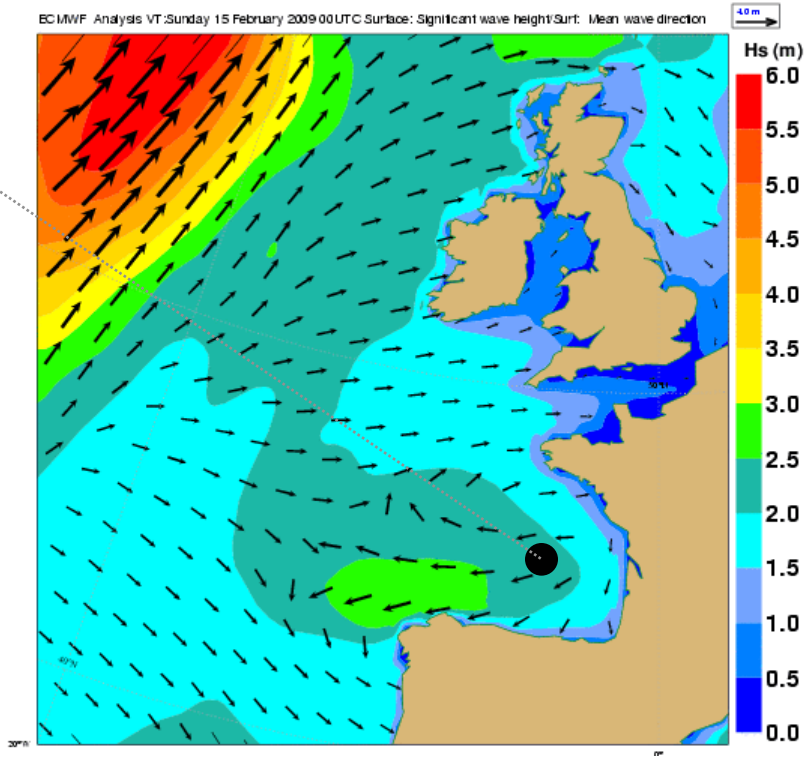
Wave height and mean direction:
Analysis : 15 February 2009, 00 UTC

Wave Model Products

Situation might be more complicated:



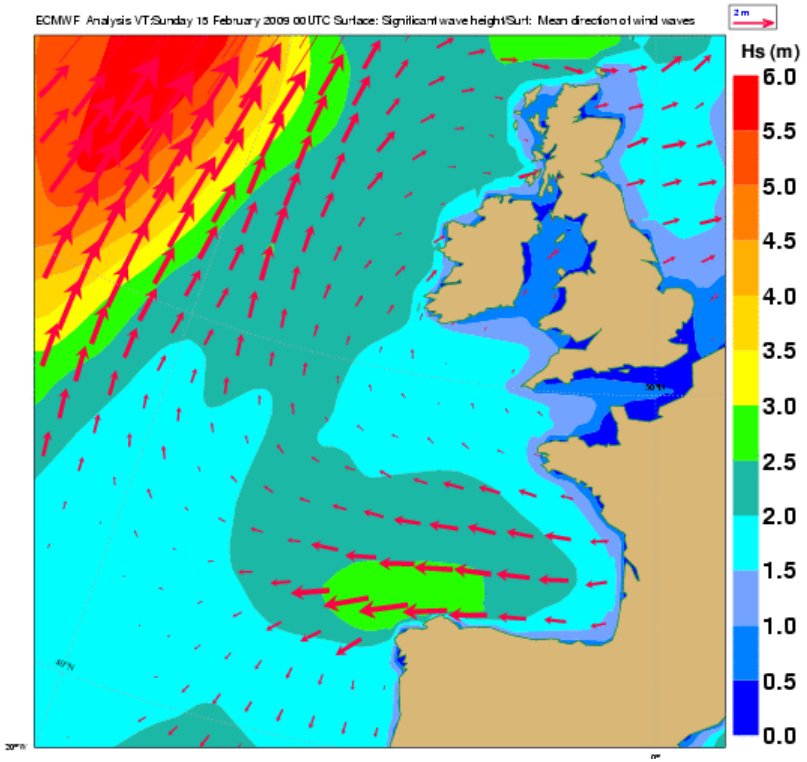




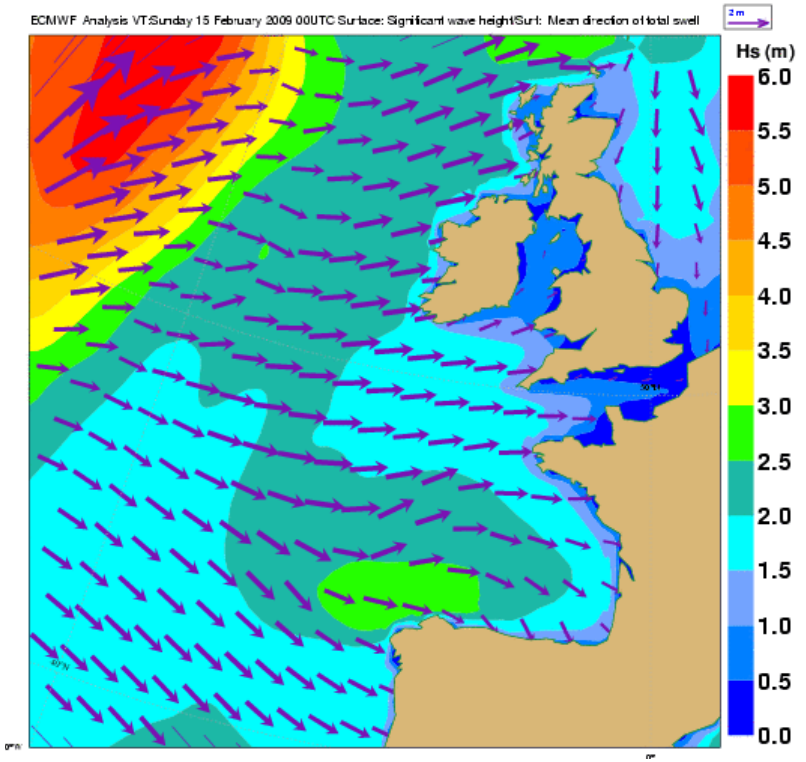
Wave height and mean direction:
Analysis : 15 February 2009, 00 UTC

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.



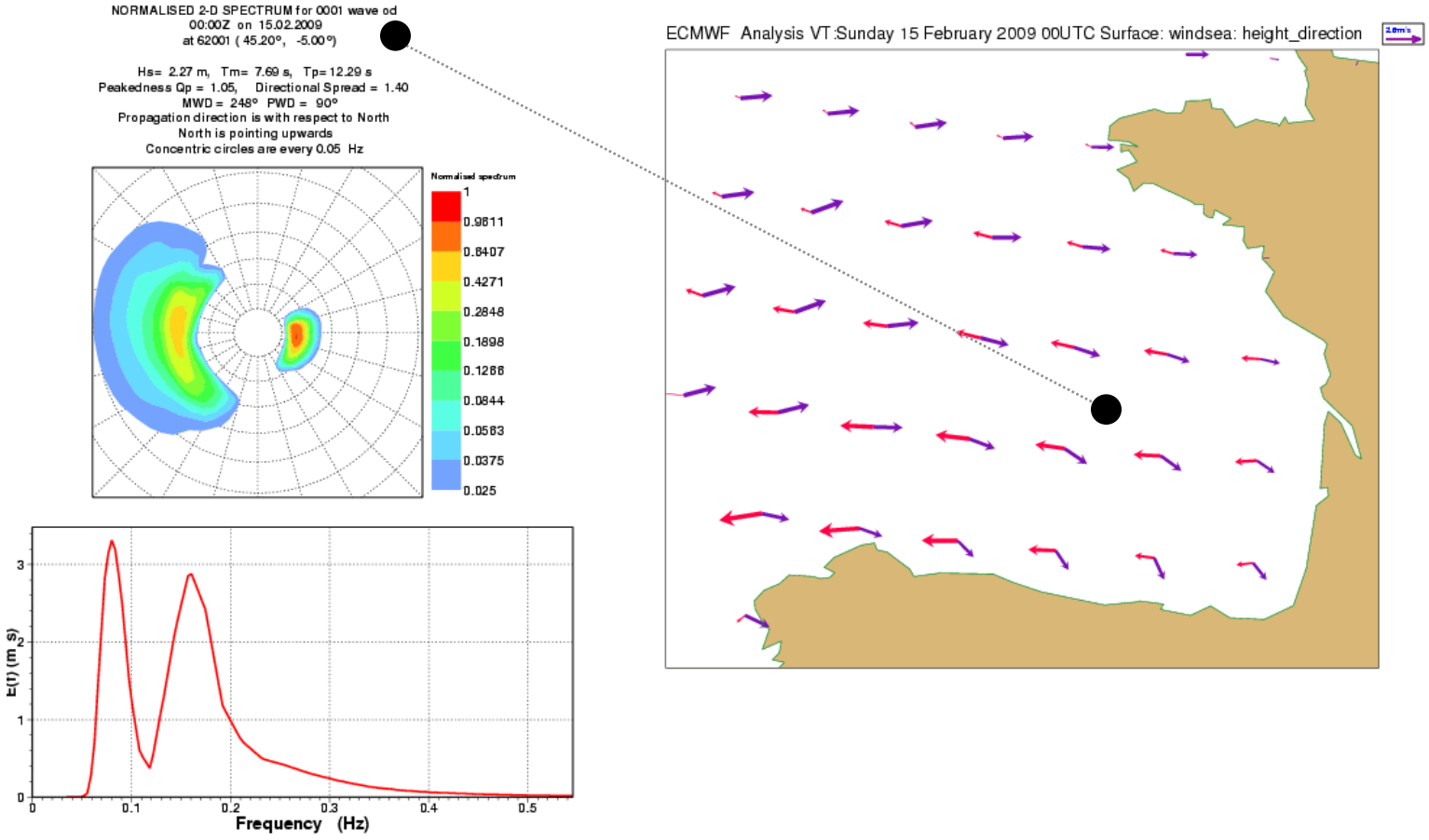
Wave height and windsea mean direction:
Analysis : 15 February 2009, 00 UTC



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

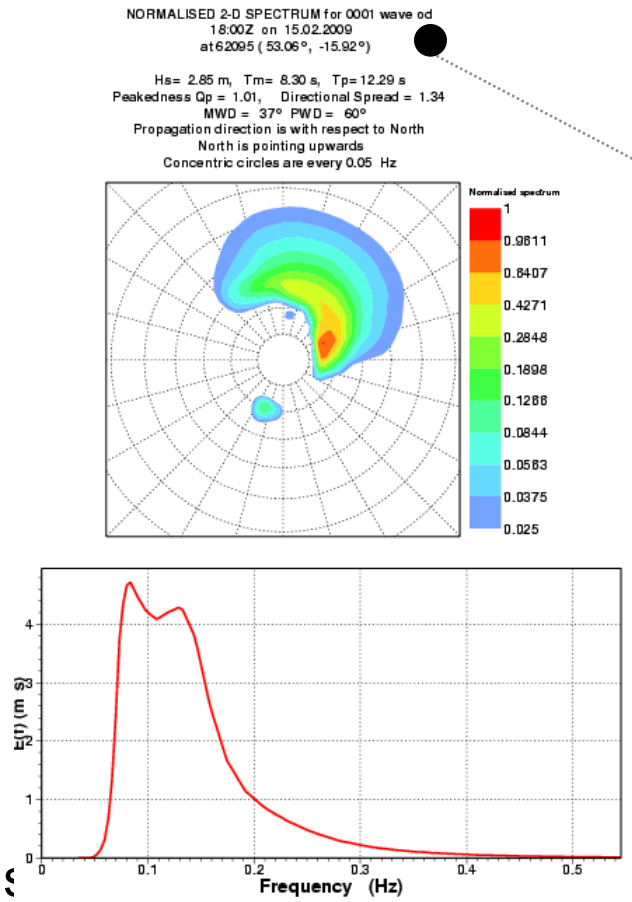
Wave Model Products

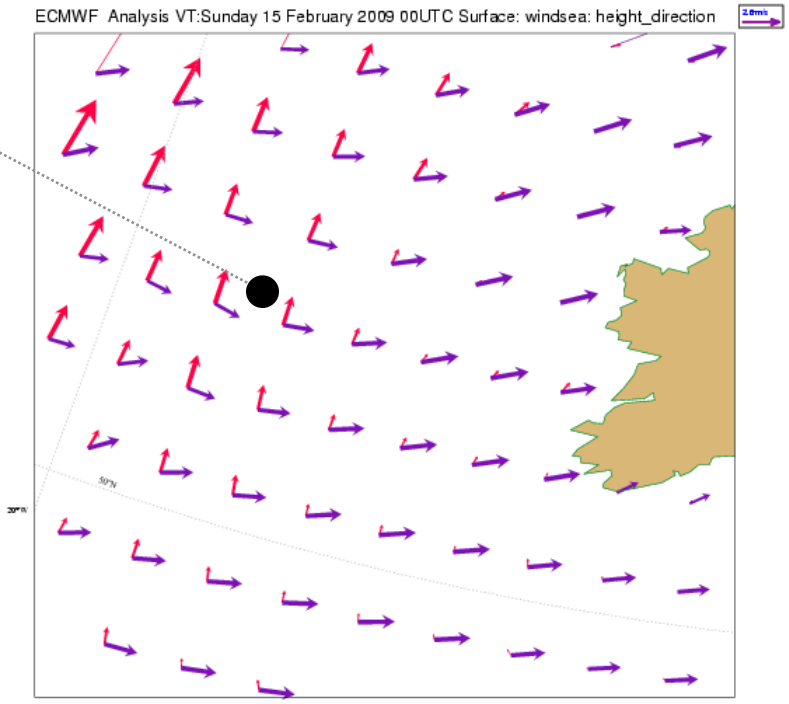
Windsea and swell: opposing sea



Wave Model Products

Windsea and swell: cross sea

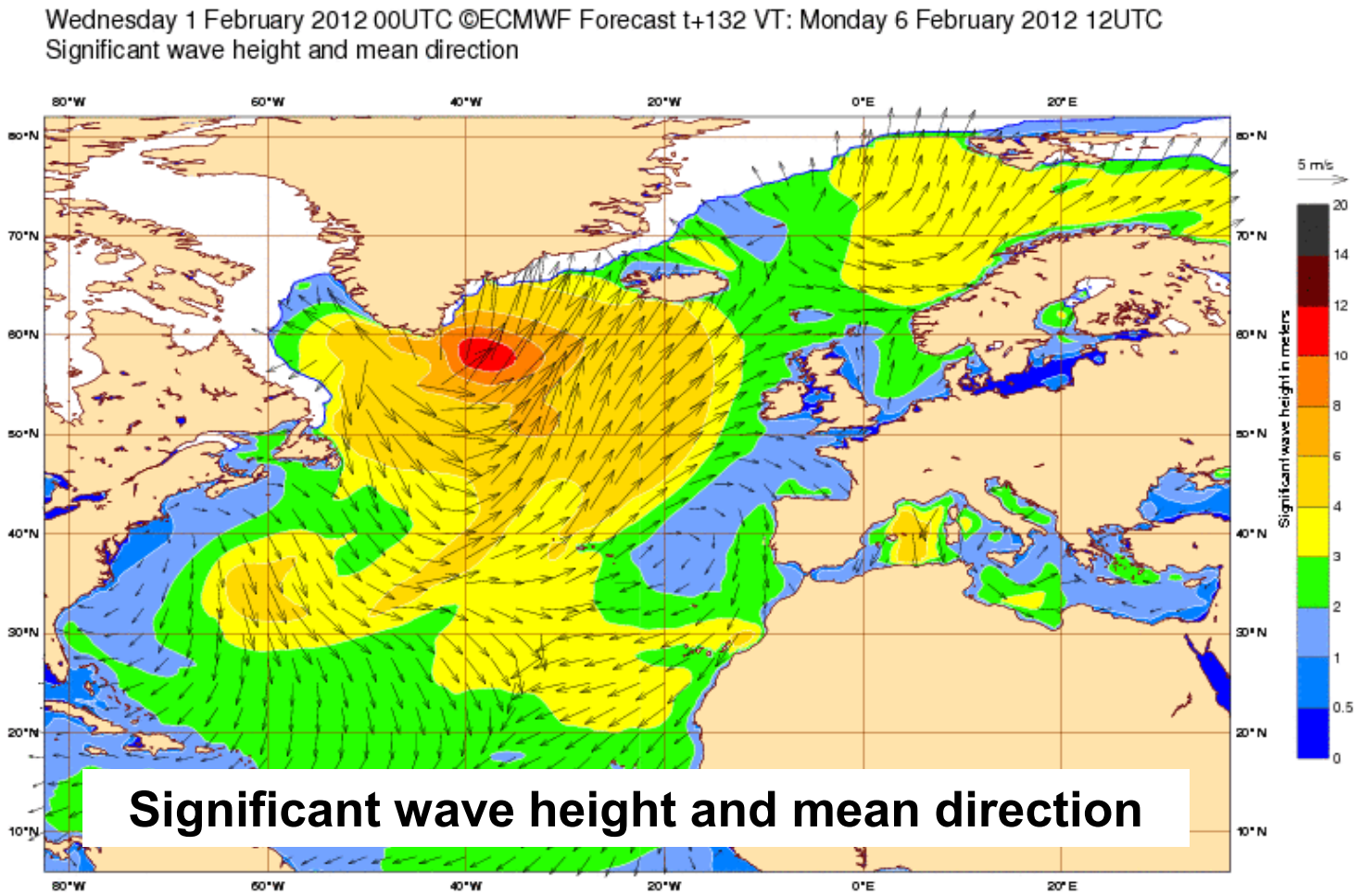




Wave model deterministic products on the web

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



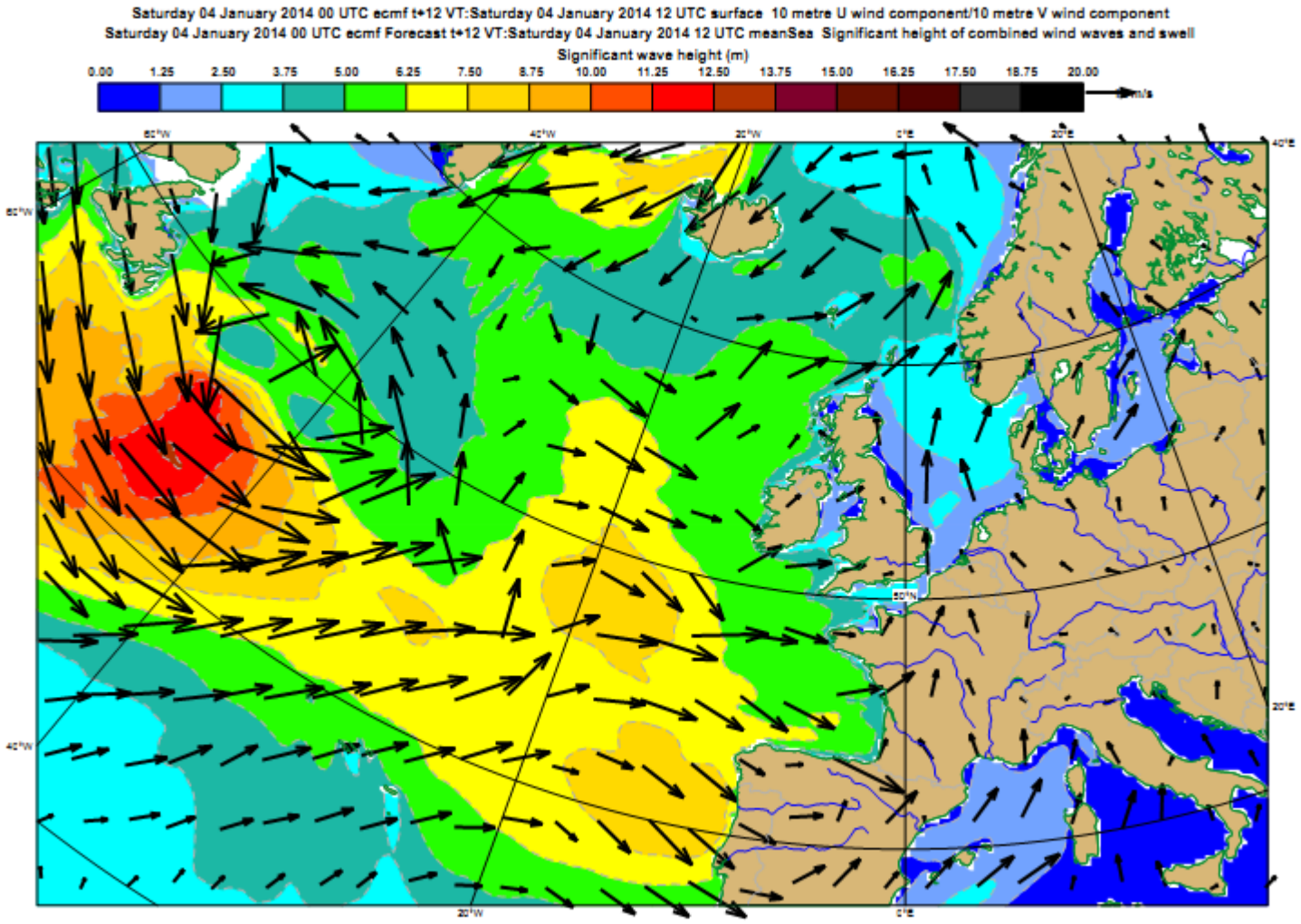
Significant wave height and mean direction

Ocean wave forecasts

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

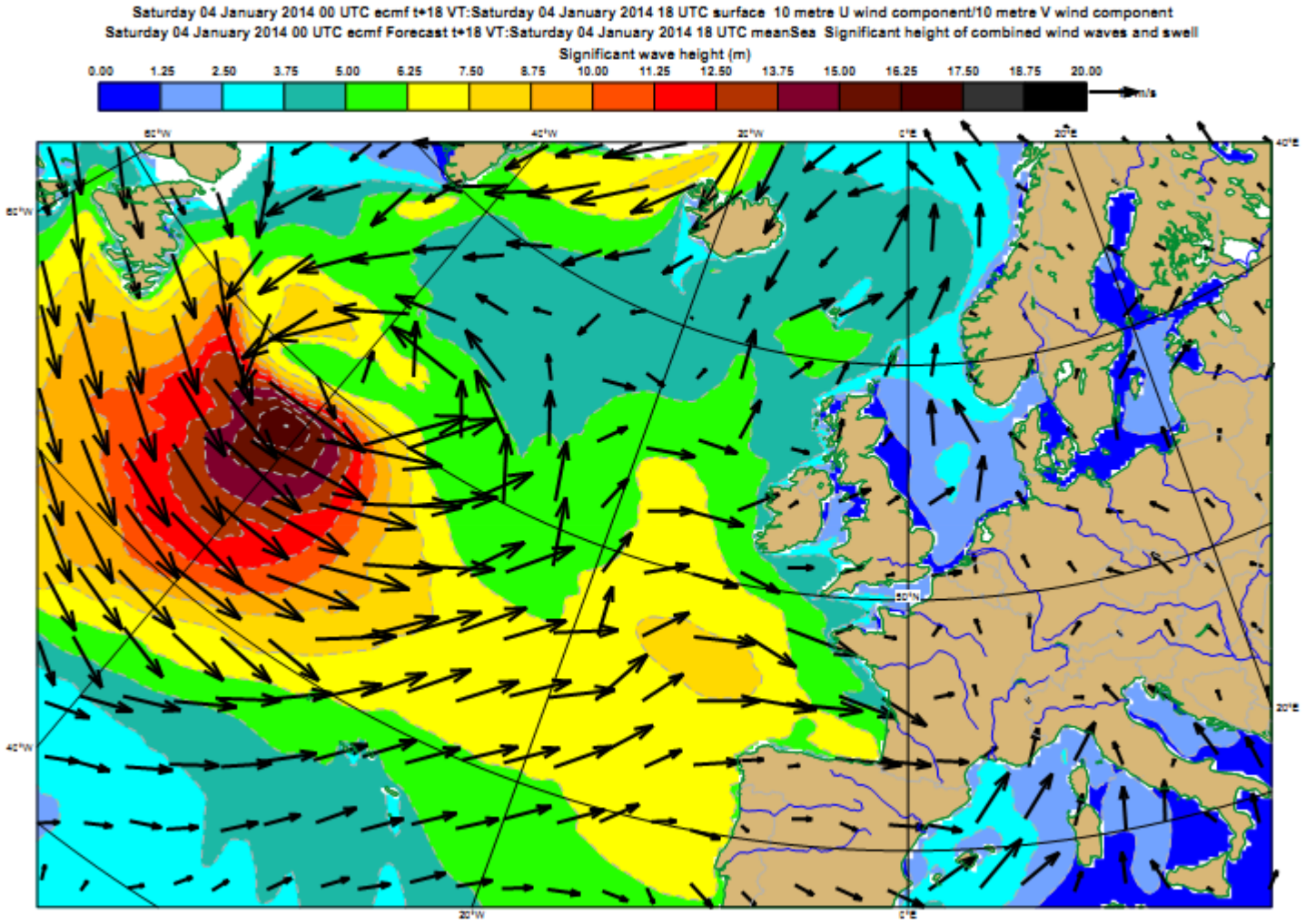
Ocean wave forecasts

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



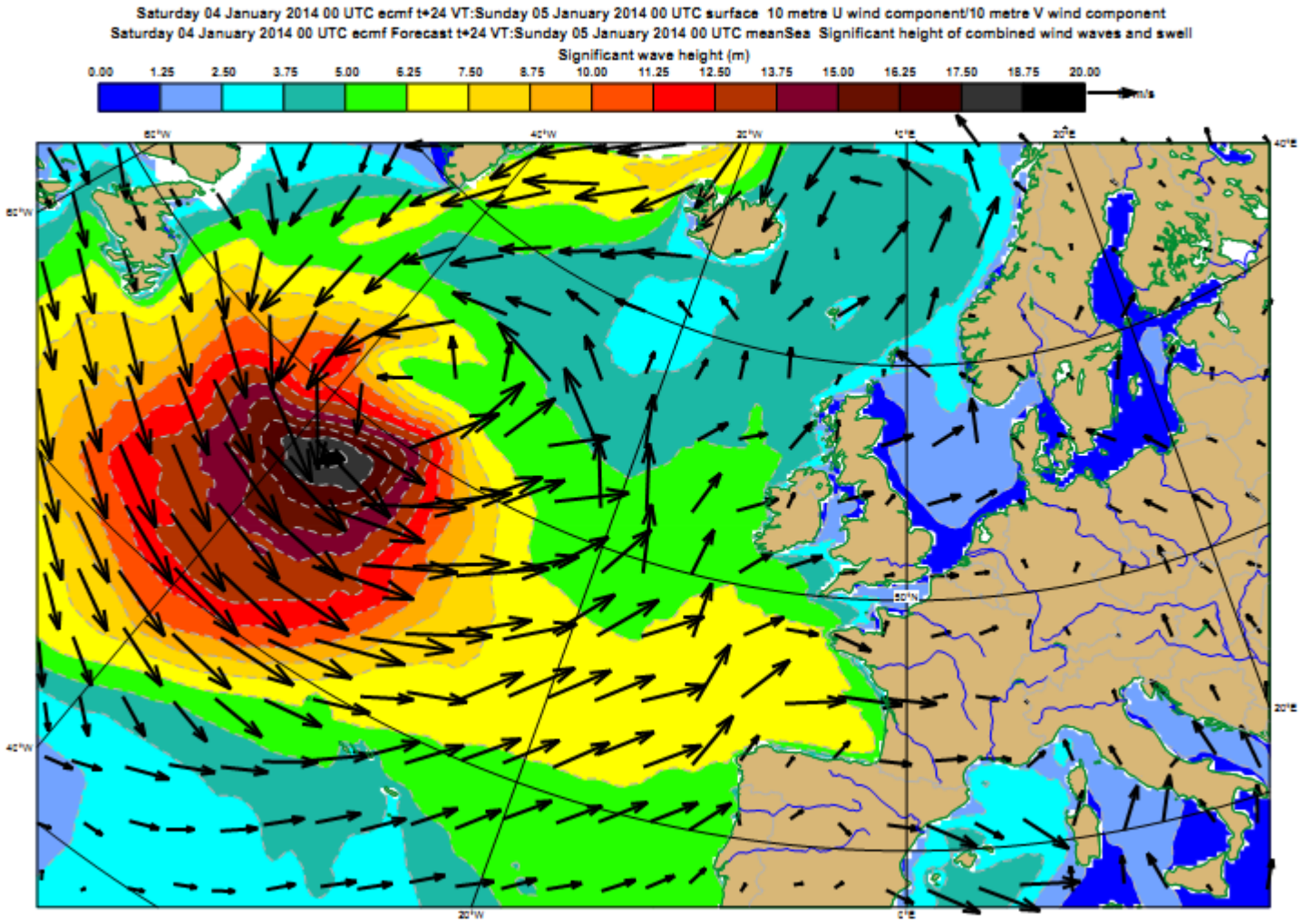
Ocean wave forecasts

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



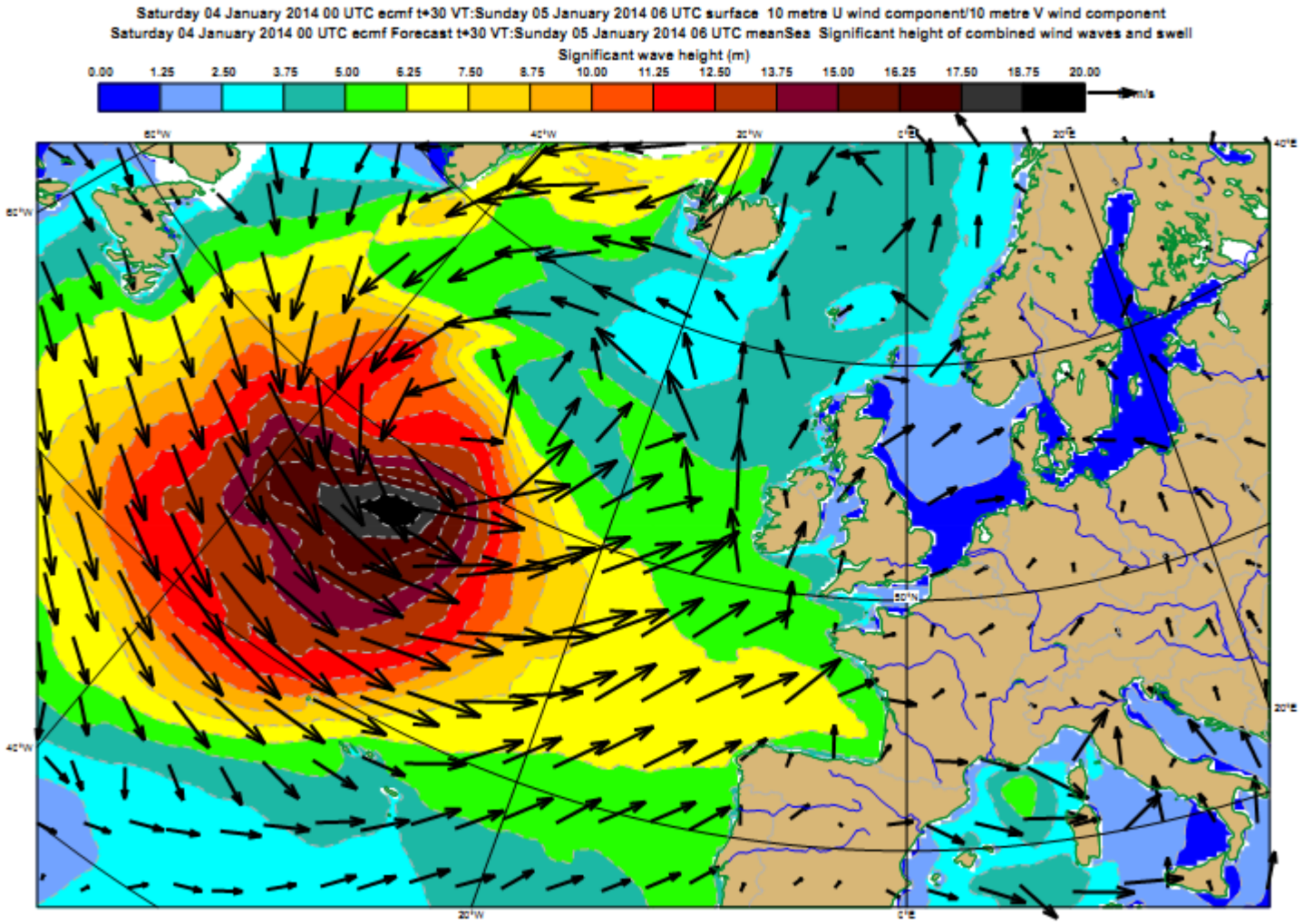
Ocean wave forecasts

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



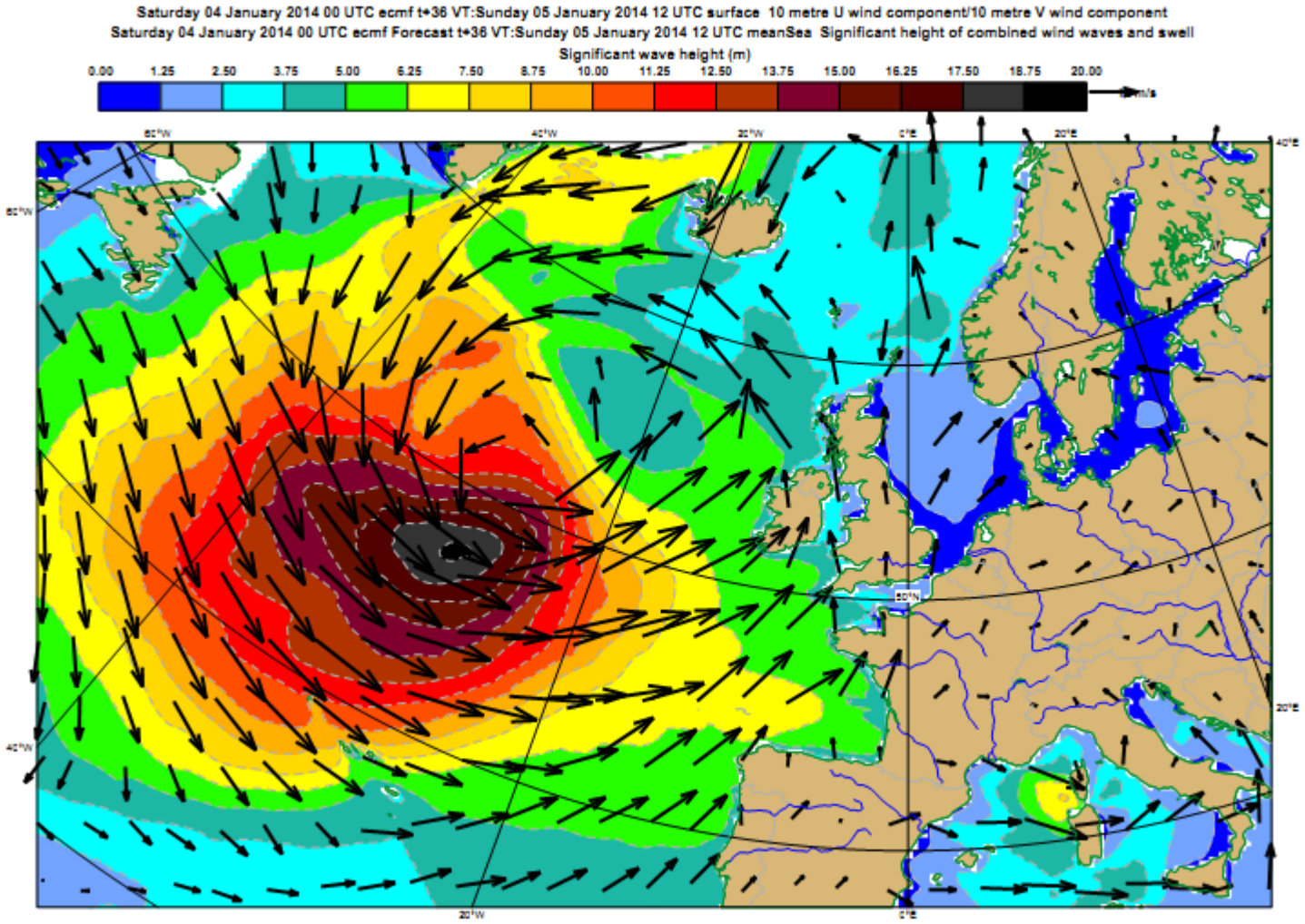
Ocean wave forecasts

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



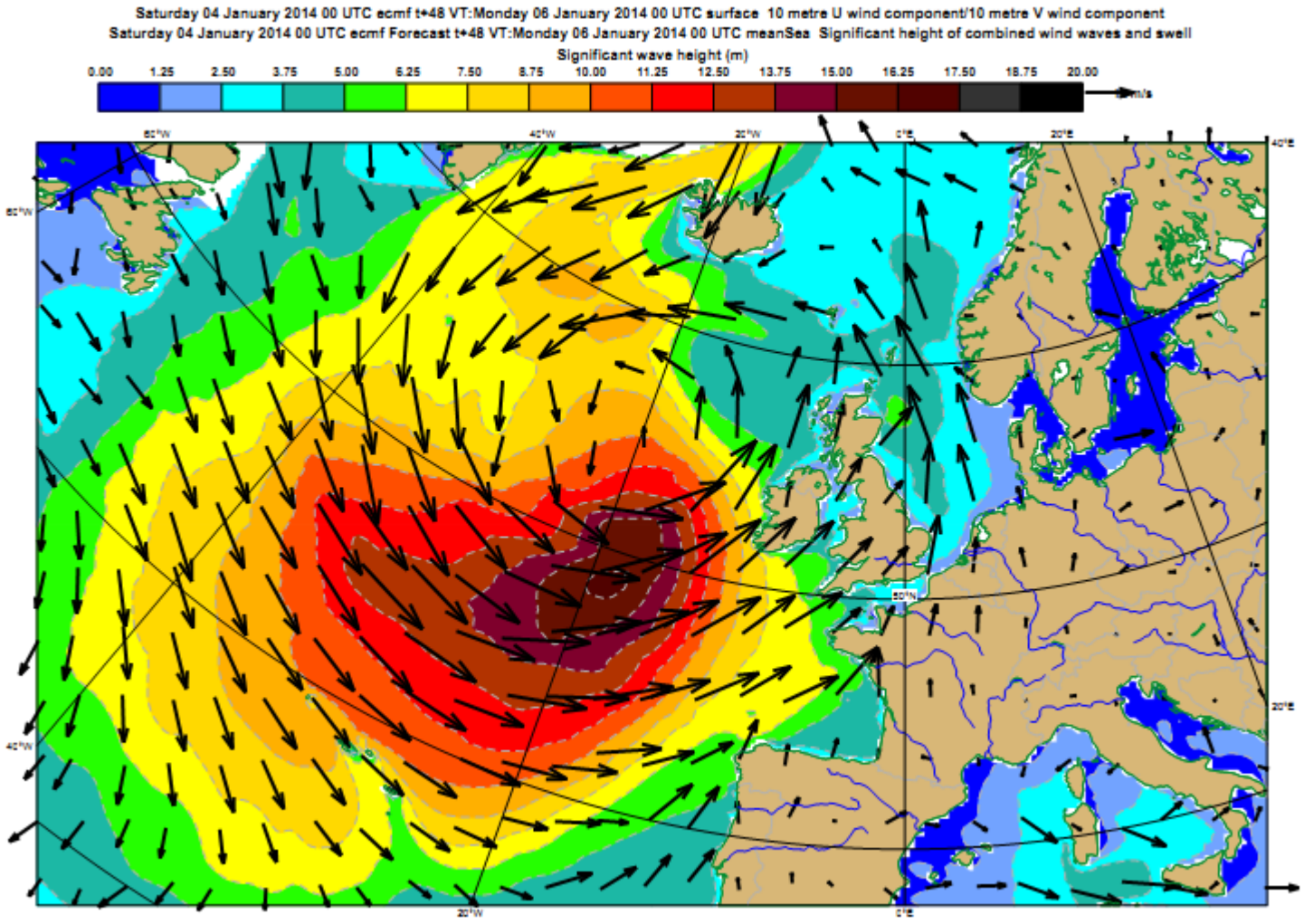
Ocean wave forecasts

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



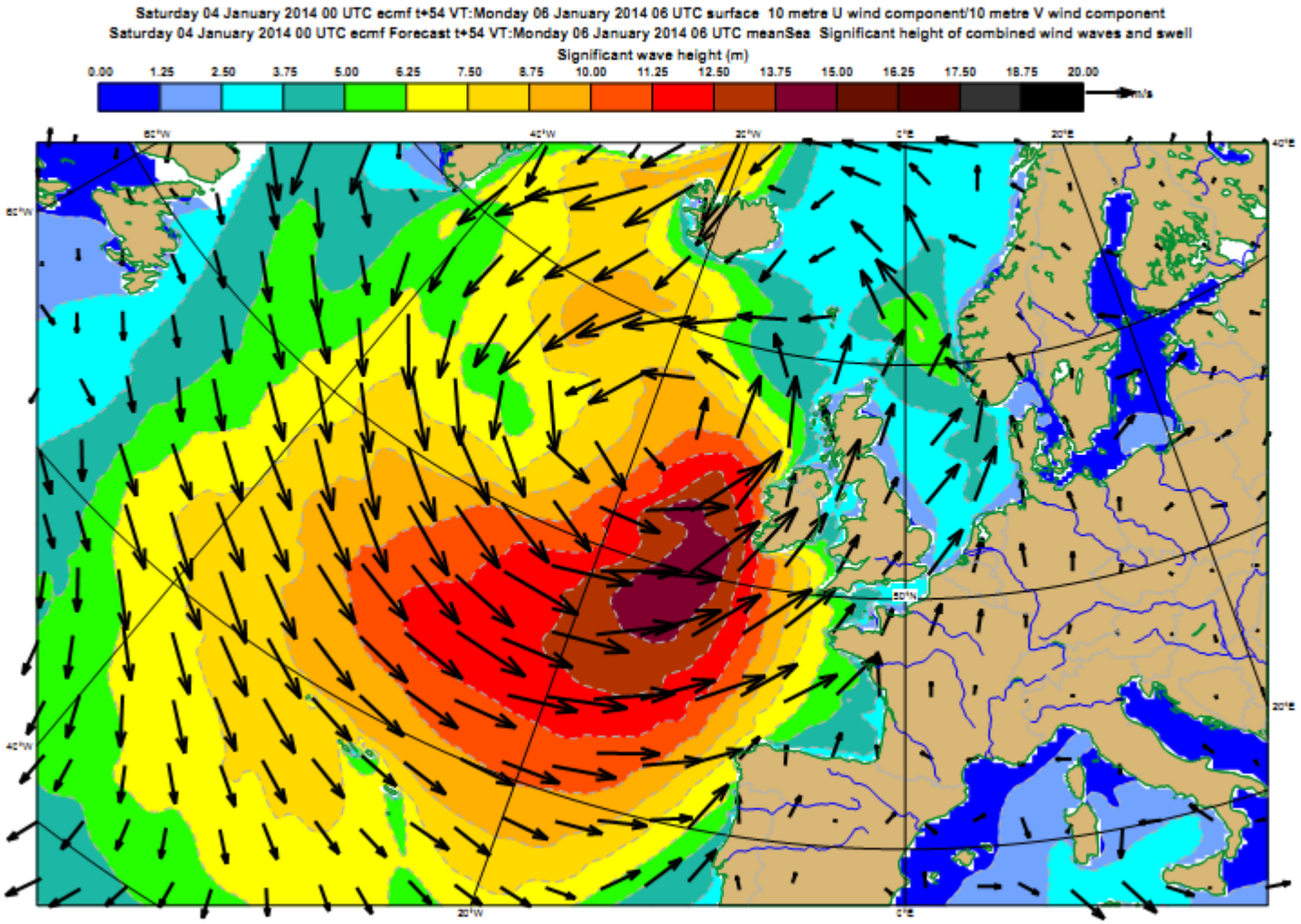
Ocean wave forecasts

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



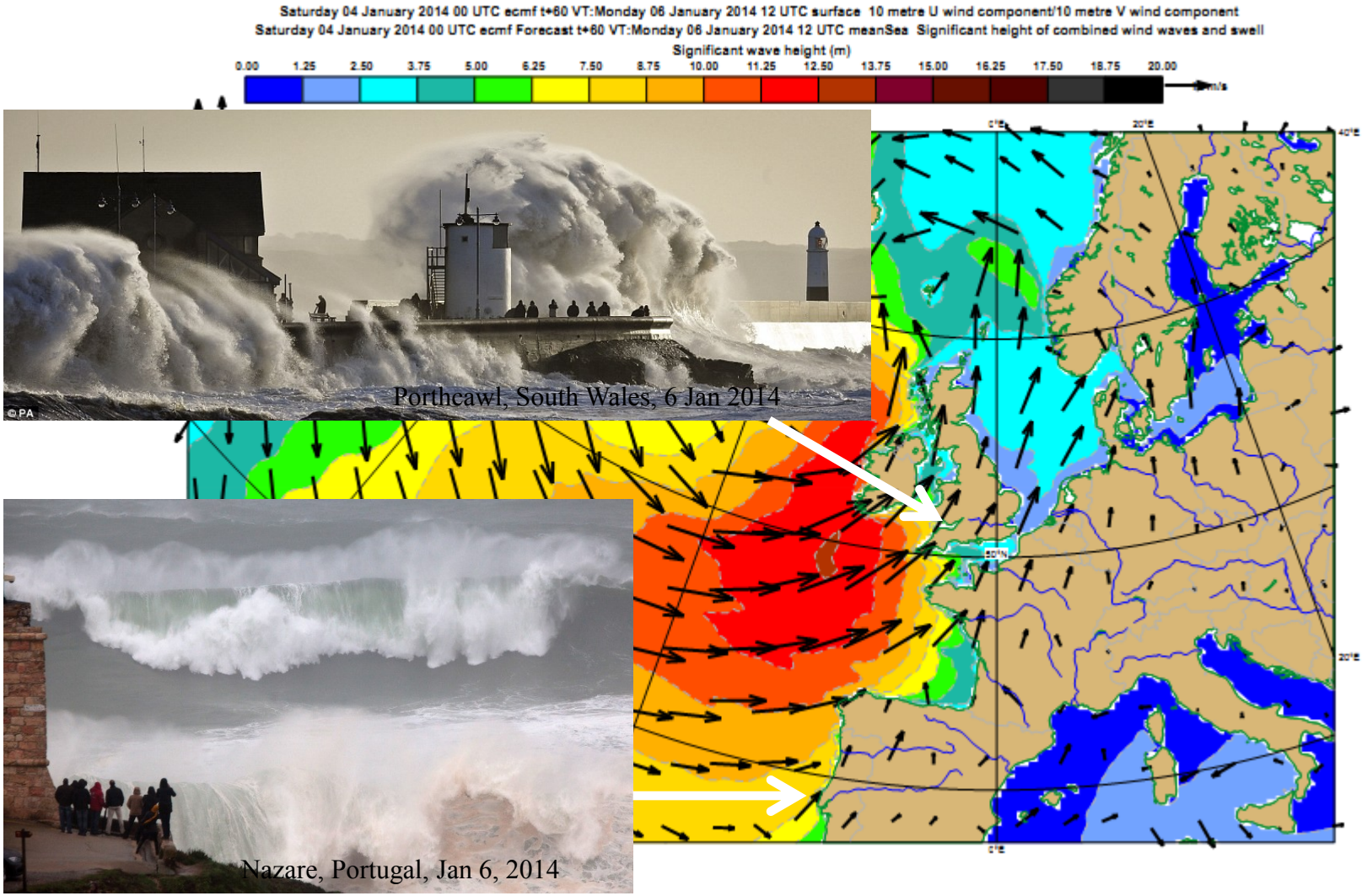
Ocean wave forecasts

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

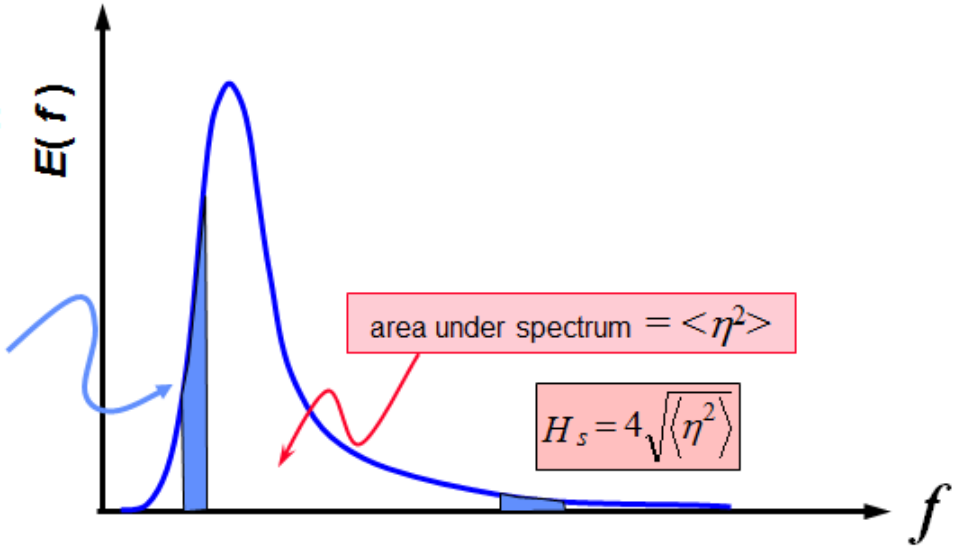


Long swell forecasts

EWH,
Equivalent Wave Height
for a given frequency bin:

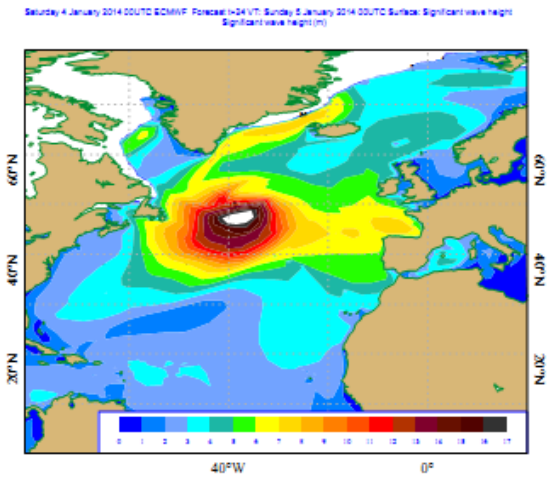
$$EHW = 4\sqrt{A}$$

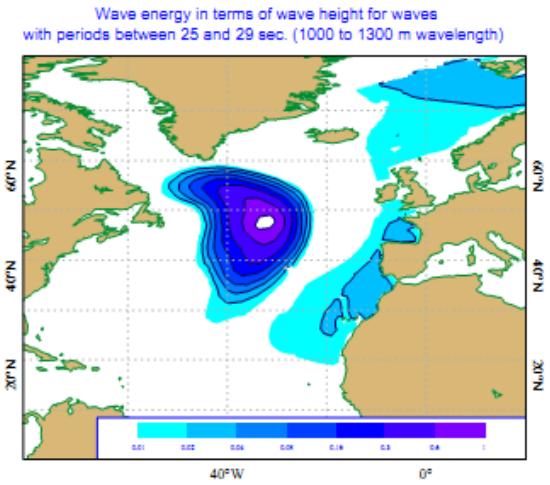
where A is the area under curve for a given frequency bin

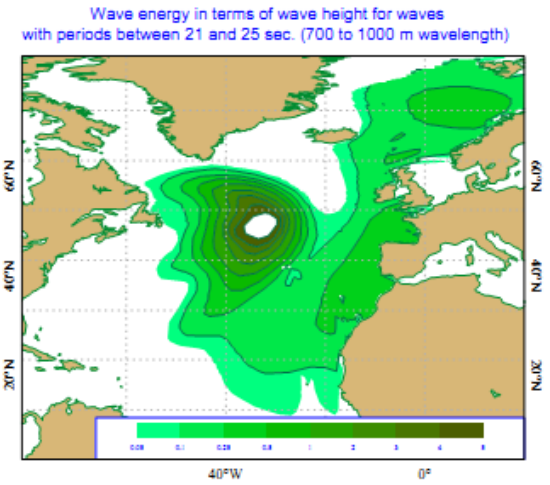


Long swell forecasts

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

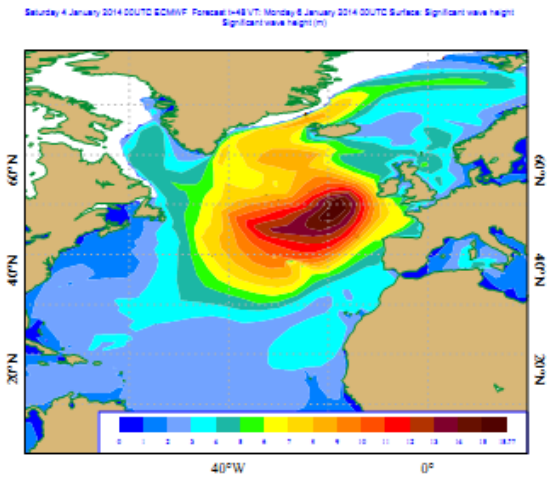


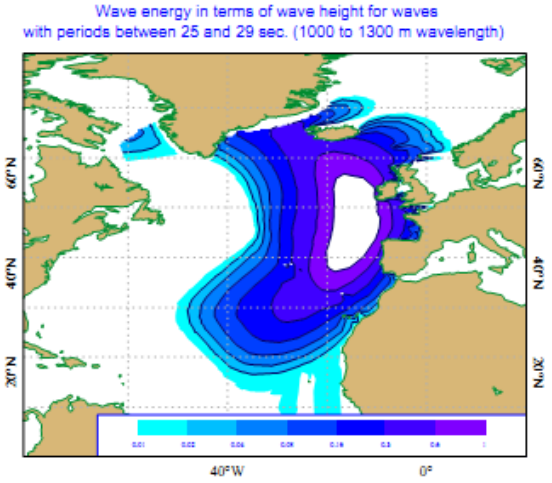


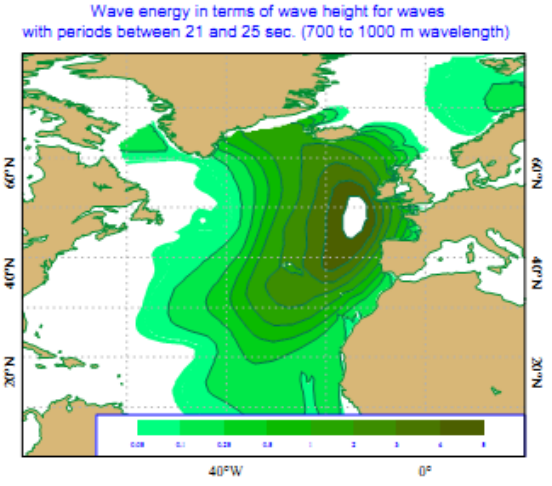


Long swell forecasts

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

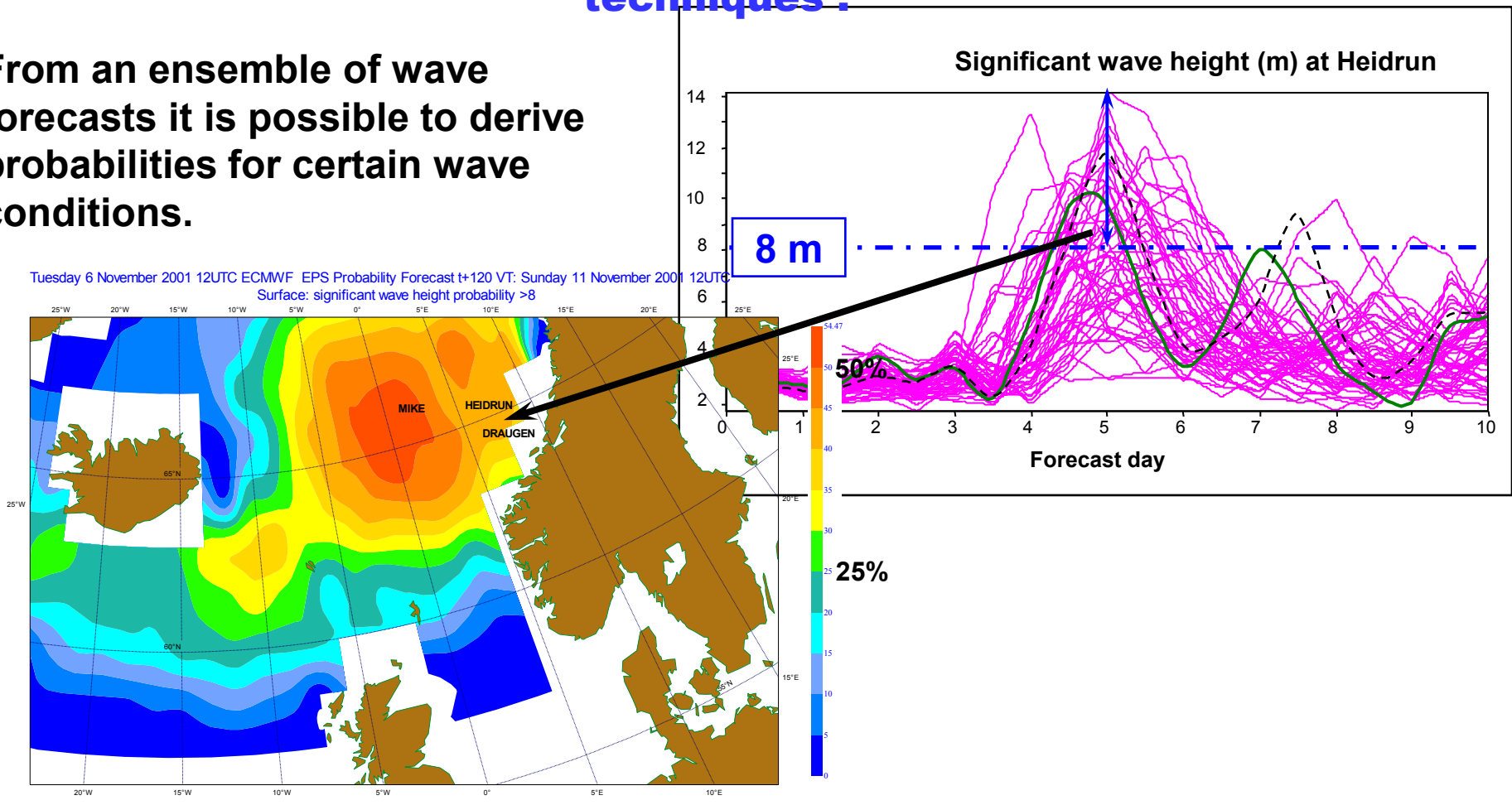






So far, everything has been presented as output from the deterministic forecast system. BUT, forecast should actually be more probabilistic. Nowadays, weather centres rely on ensemble techniques :

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



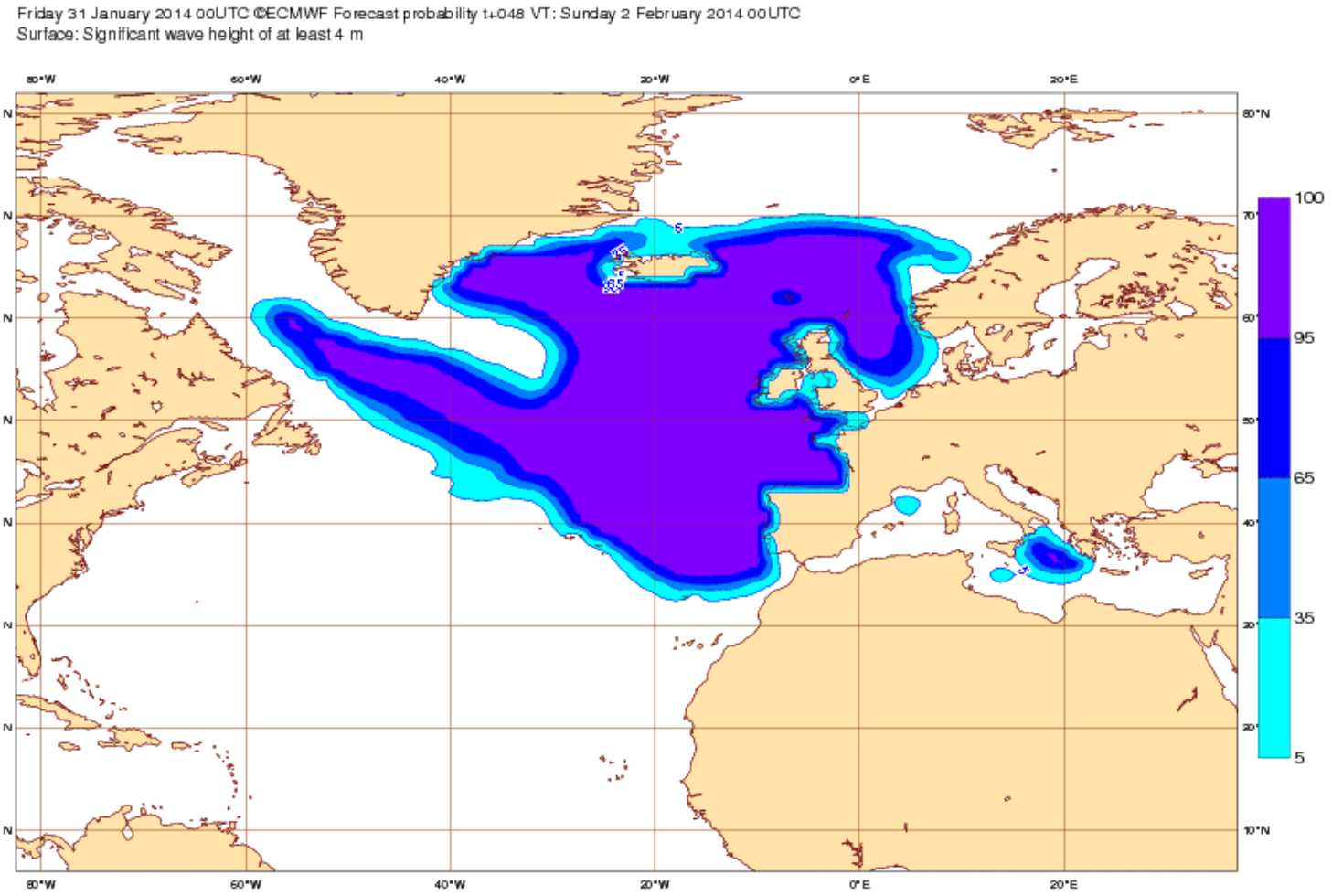
06 Nov. 2001 12 UTC ECMWF EPS probability forecast t+120

Significant wave height above 8 m

ECMWF Newsletter 95 – Autumn 2002

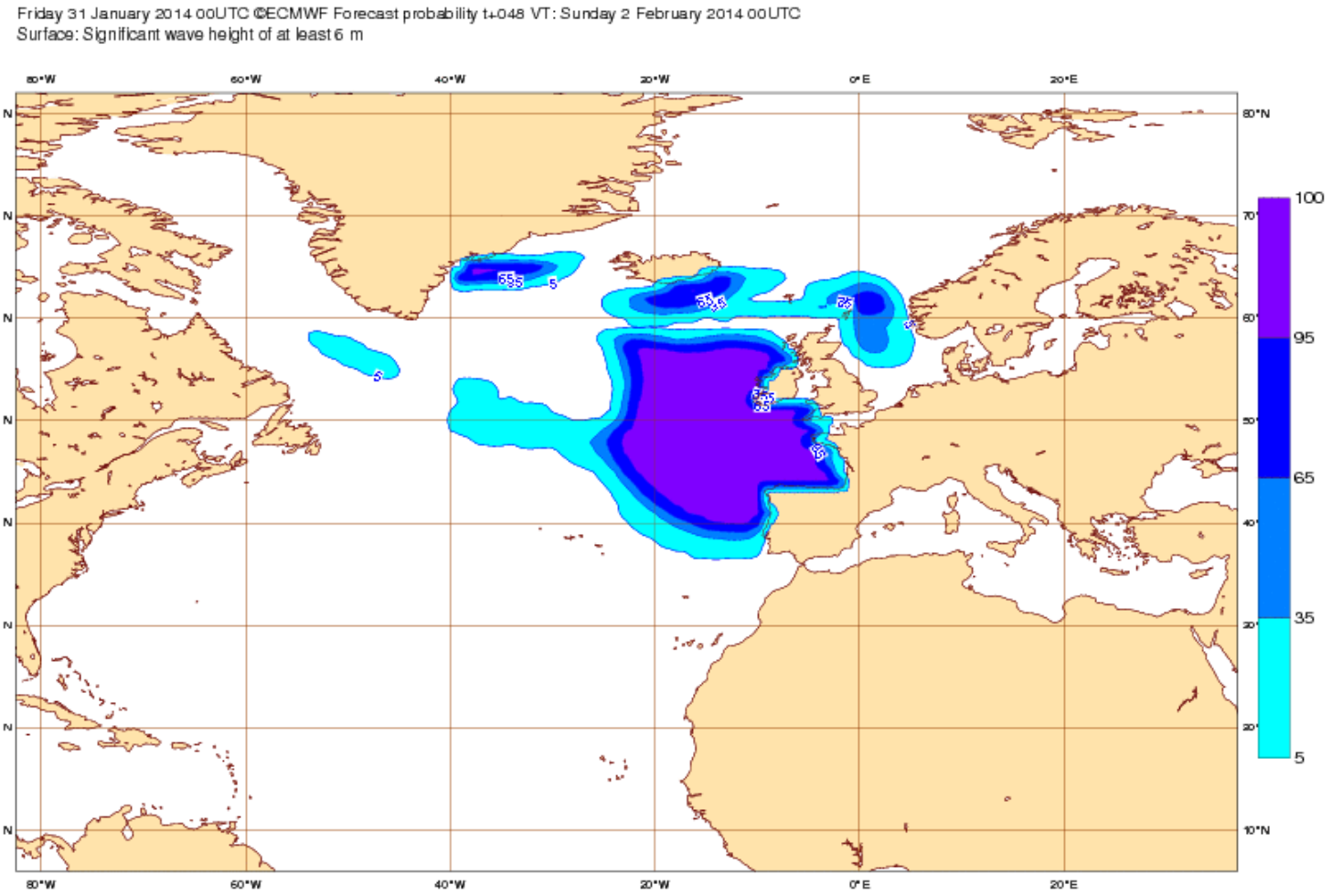
Basic EPS Wave Model Products

probability for set thresholds (4m)



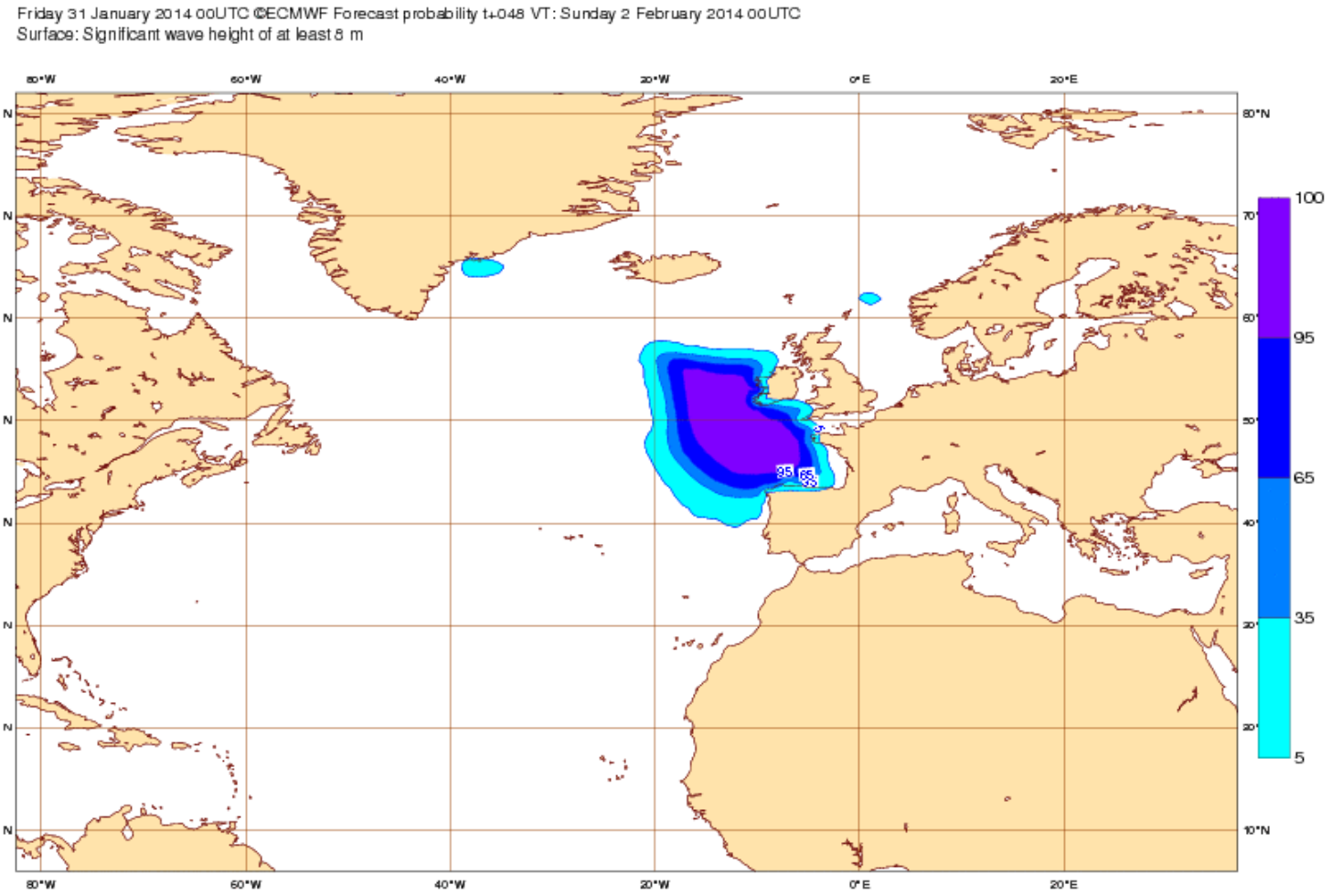
Basic EPS Wave Model Products

probability for set thresholds (6m)



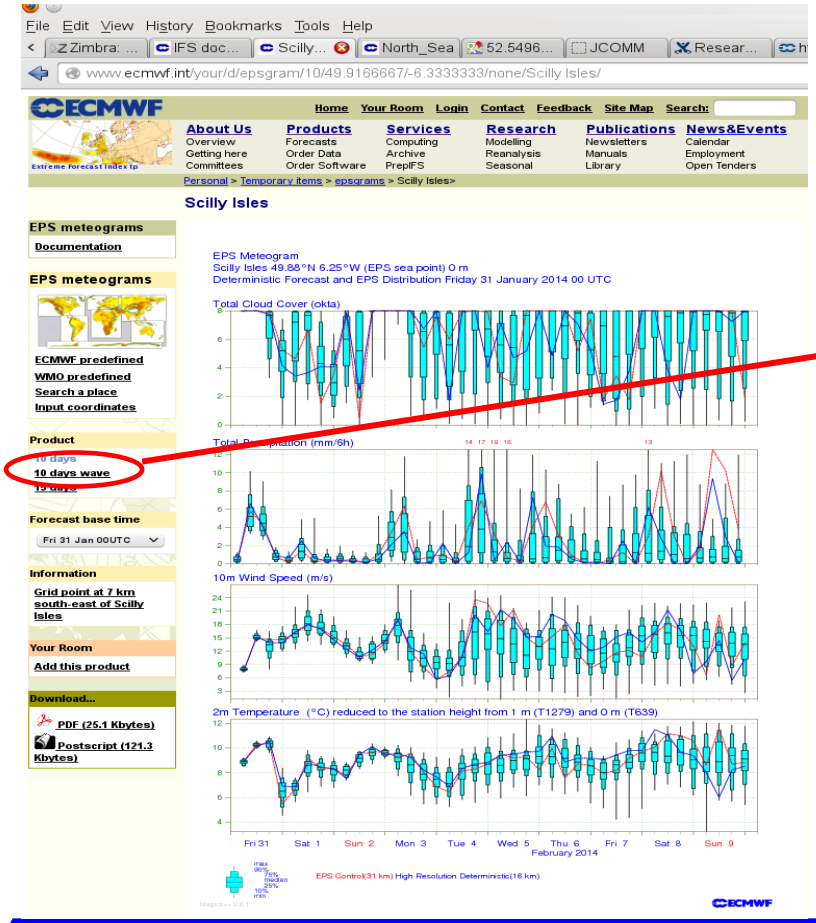
Basic EPS Wave Model Products

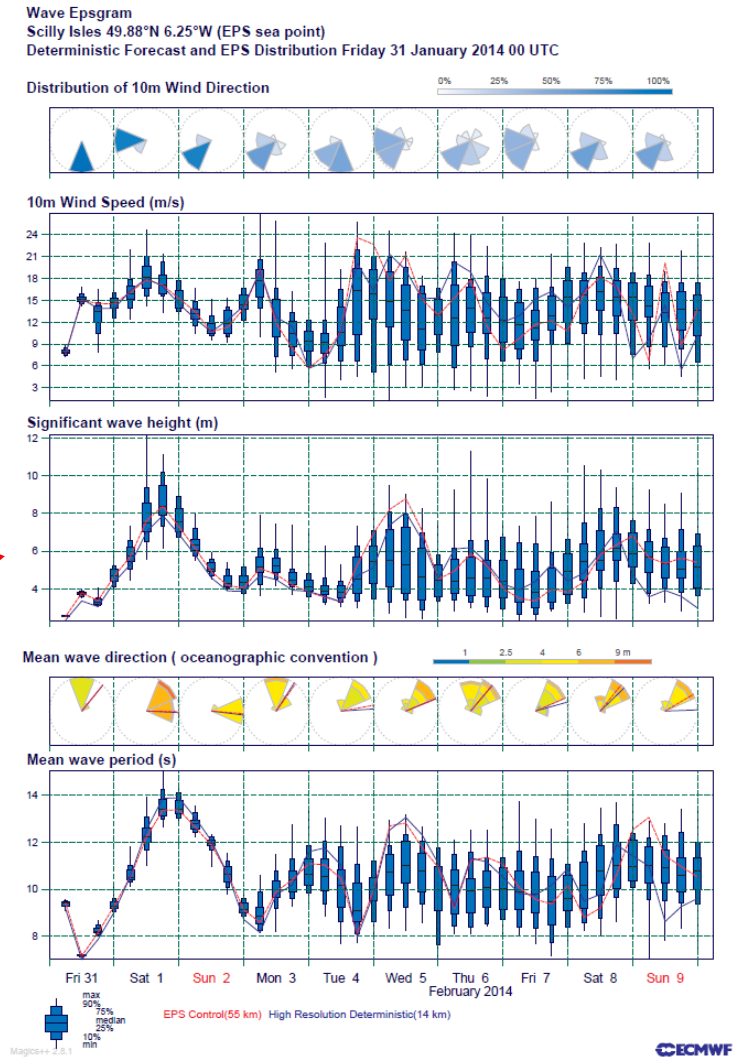
probability for set thresholds (8m)



A bit more compact: Wave EPSgram:

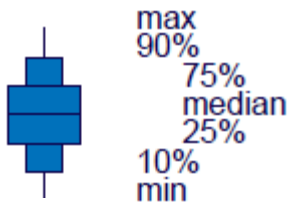
Like normal EPSgram but for wind direction, wind speed, significant wave height, mean wave direction and mean period.





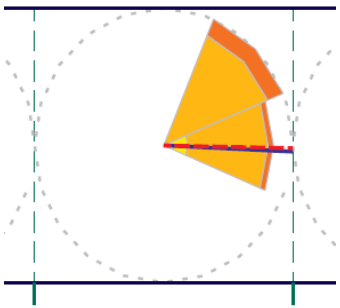
Isles of Scilly, west of Cornwall

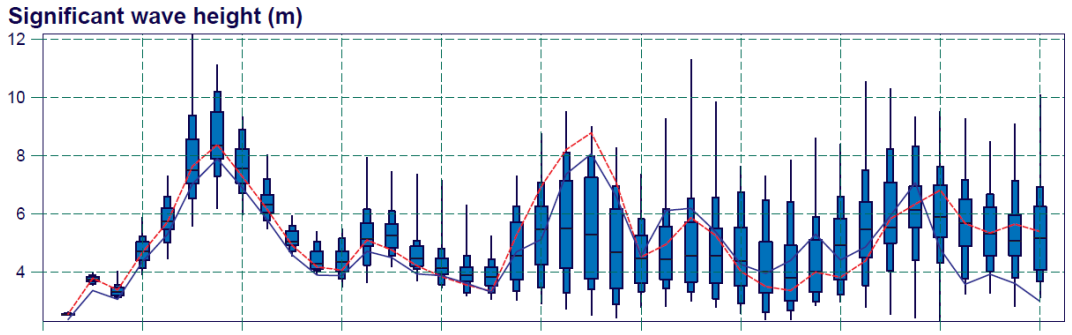
A bit more compact: Wave EPSgram:

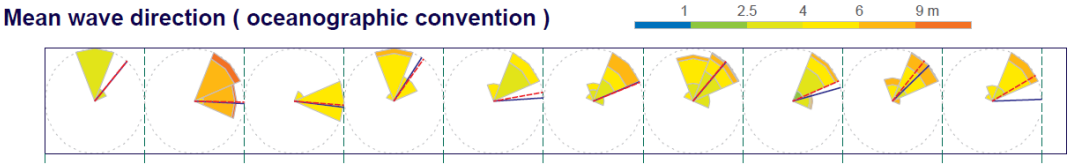


EPS Control(55 km) High Resolution Deterministic(14 km)

Hs 1 2.5 4 6 9 m





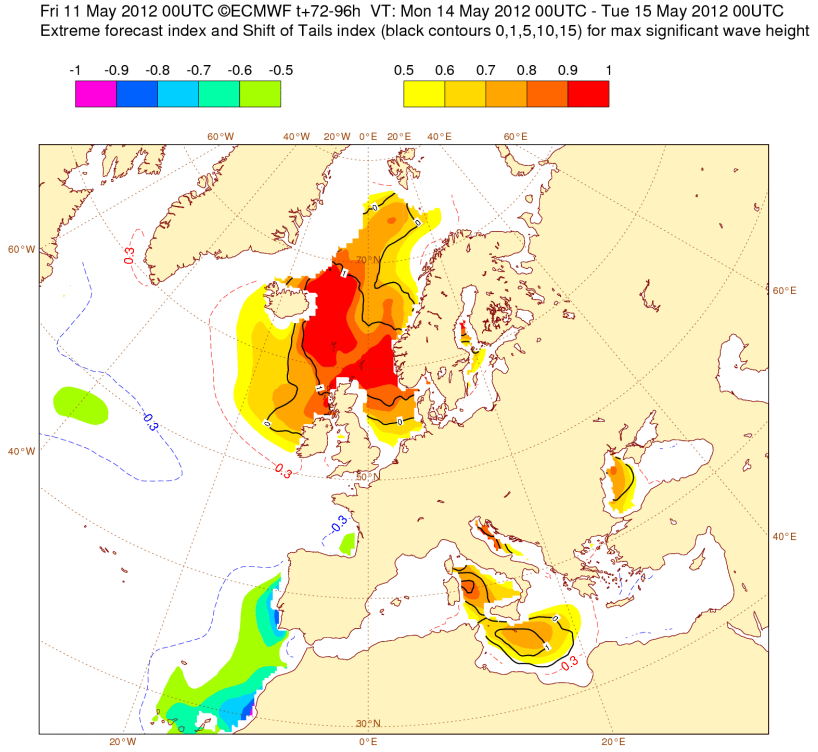


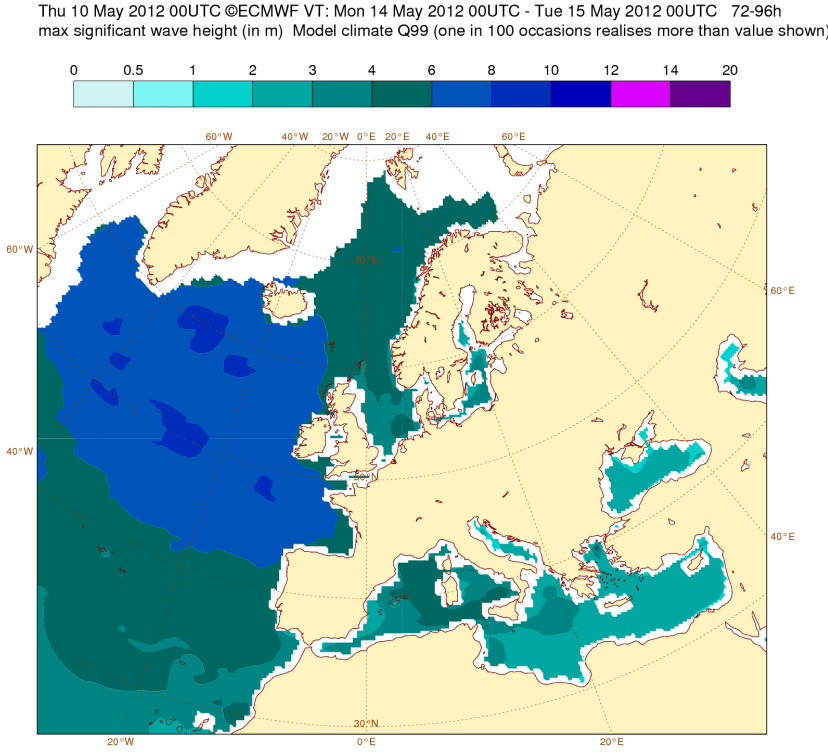
Each octant is coloured based on the distribution of the significant wave height associated with each mean direction. The coloured areas correspond to the fractional number of ensemble members with wave height in the range specified by the coloured ruler.

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 above climate.

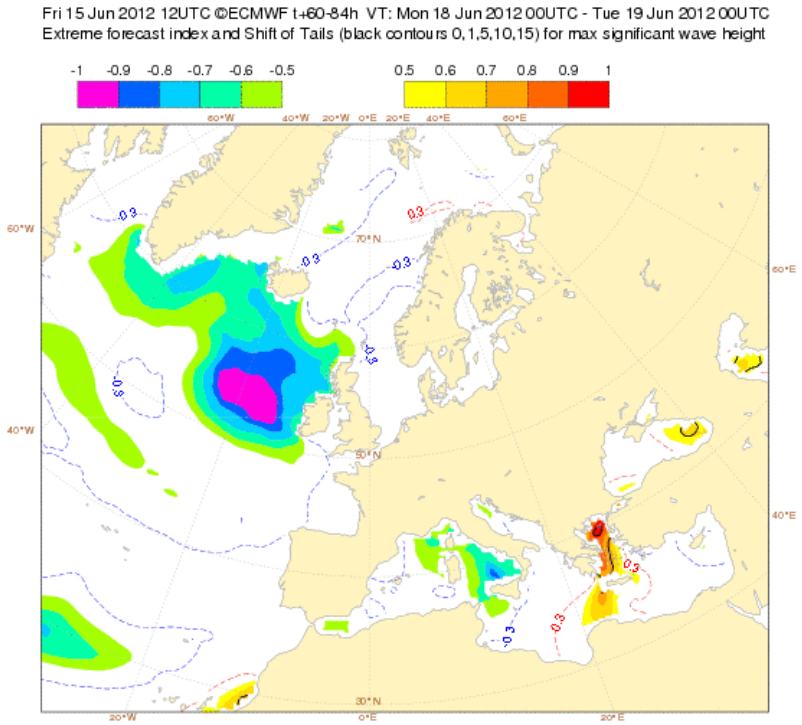


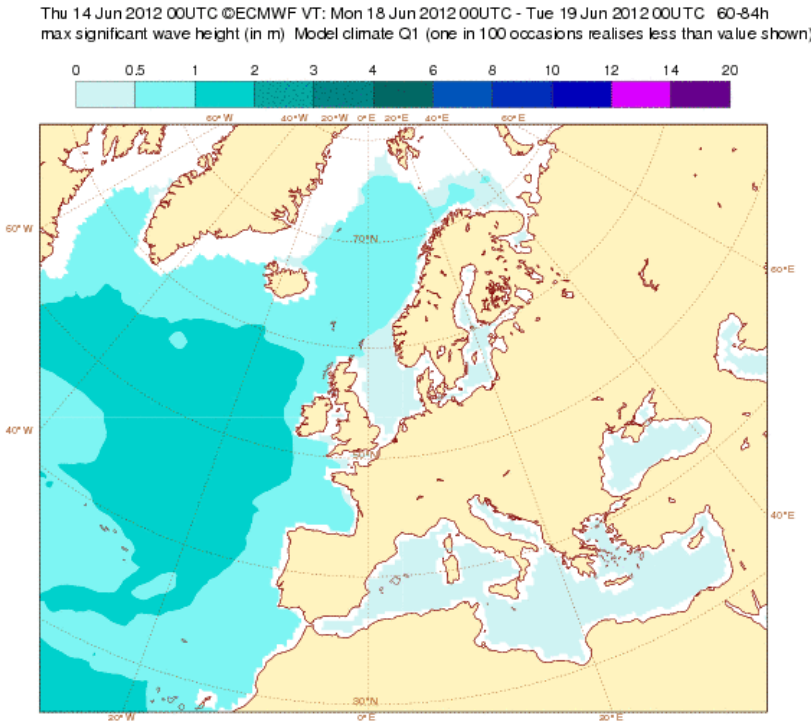


Since June 2012 : new set of EFI plots

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.

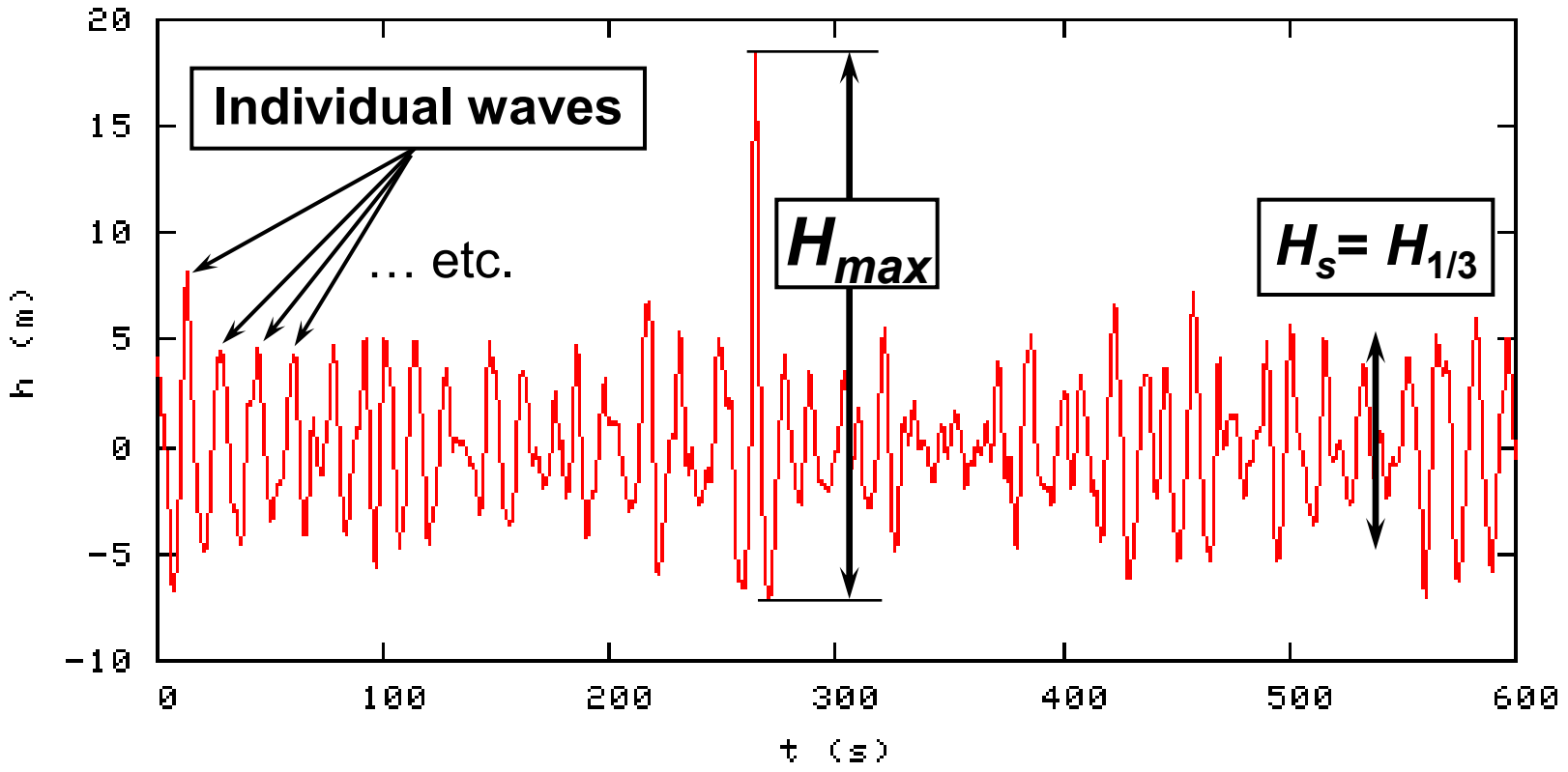




We are not always dealing with nice ‘predictable’ waves:

ECMWF

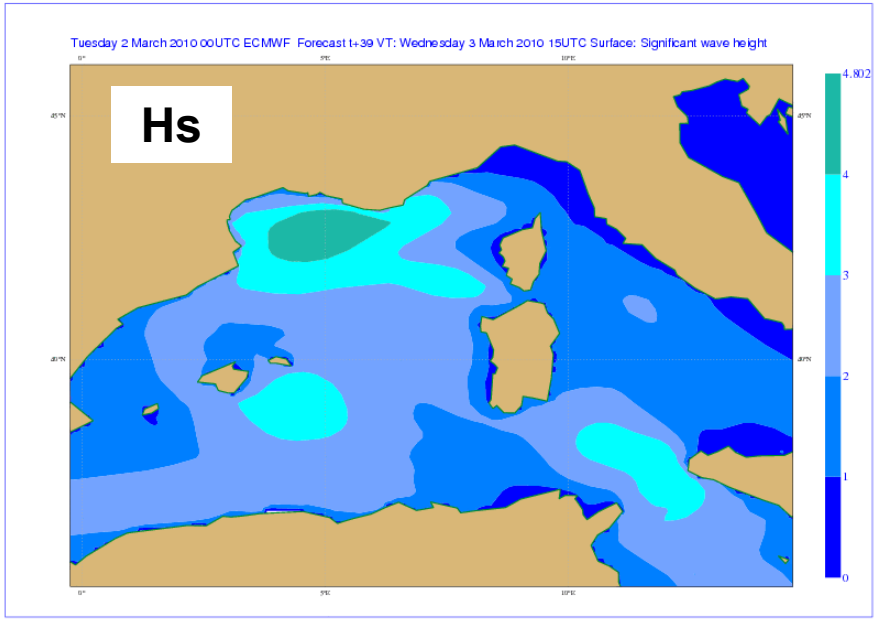
Individual Waves, Significant Wave Height, H_s, Maximum Individual Wave Height, H_{max}, and Freak Wave

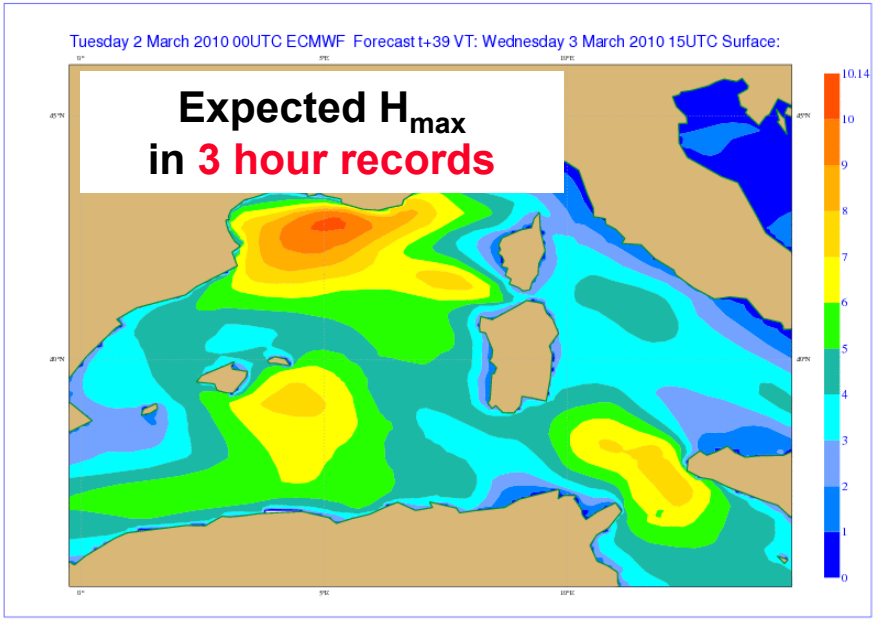


If $H_{max} > 2.2\ H_s$ ➔ freak wave event

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. Its value can be derived from the 2d wave spectrum:





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

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

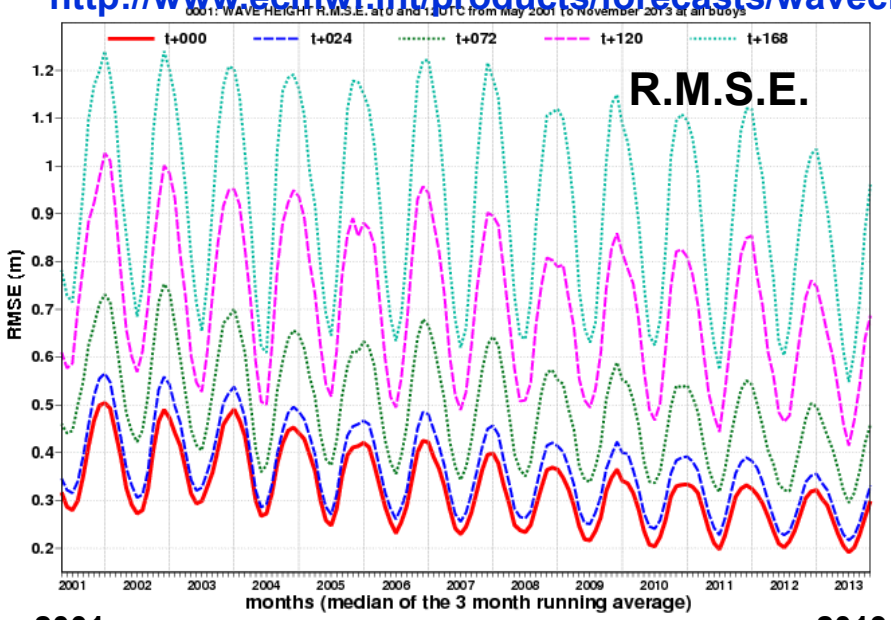
Verification:
What Do You Compare Against ?

- **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:

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



7 day FC

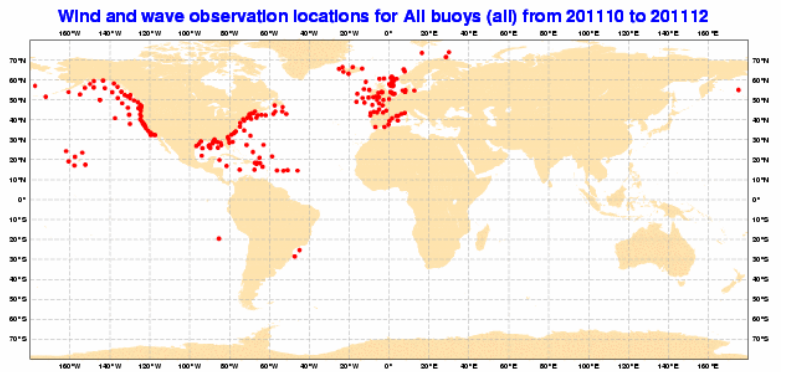
5 day FC

3 day FC

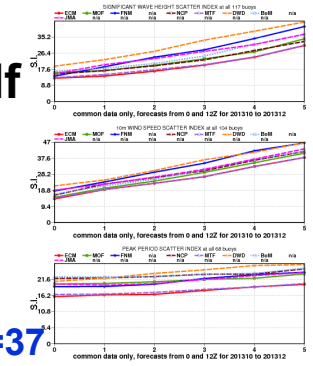
1 day FC

analysis

In-situ wave observations



Note: GTS wave data now also available for Korea, Australia, Italy and Greece.

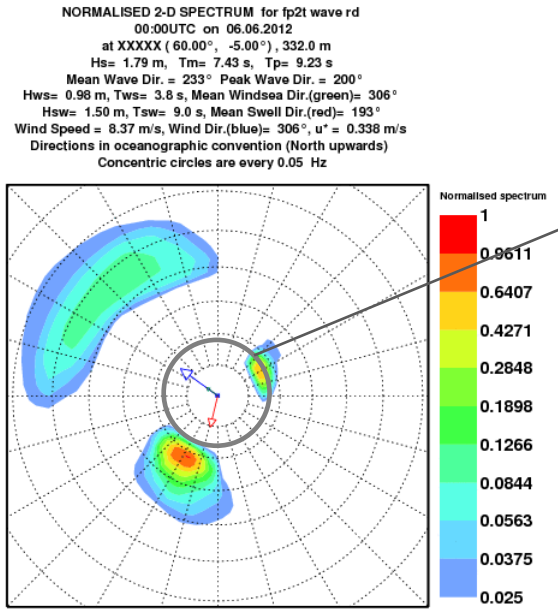


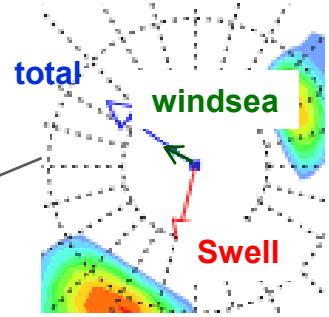
See also the Wave Forecast Verification Project maintained on behalf of the Expert Team on Waves and Storm Surges of the WMO-IOC Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM)

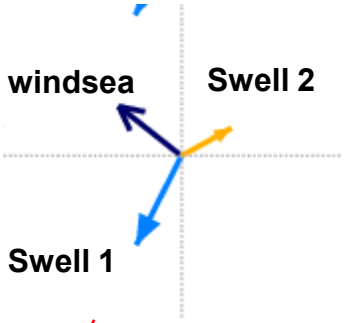
http://www.jcomm.info/index.php?option=com_content&task=view&id=131&Itemid=37

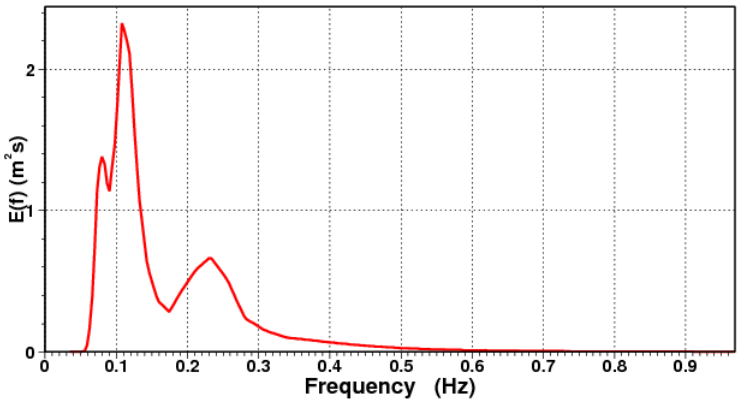
Future developments: spectral partitioning

Operational:

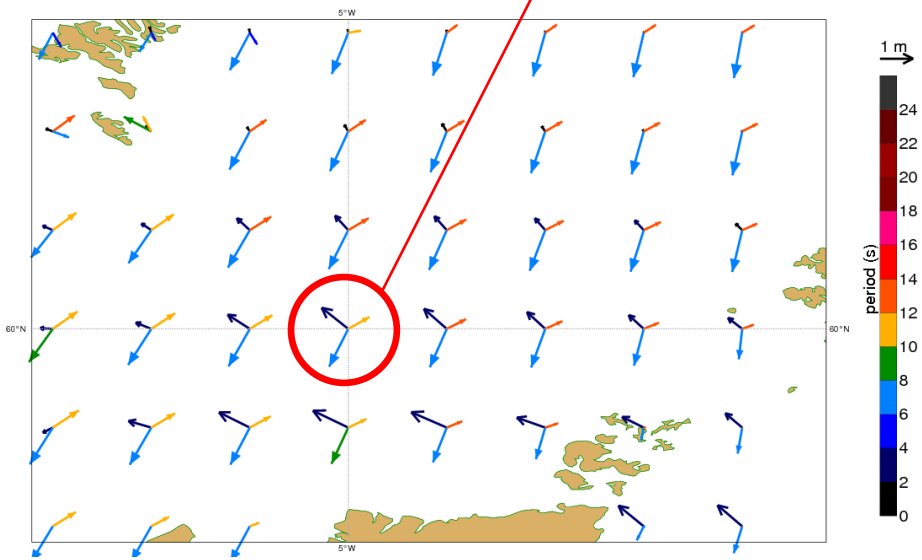




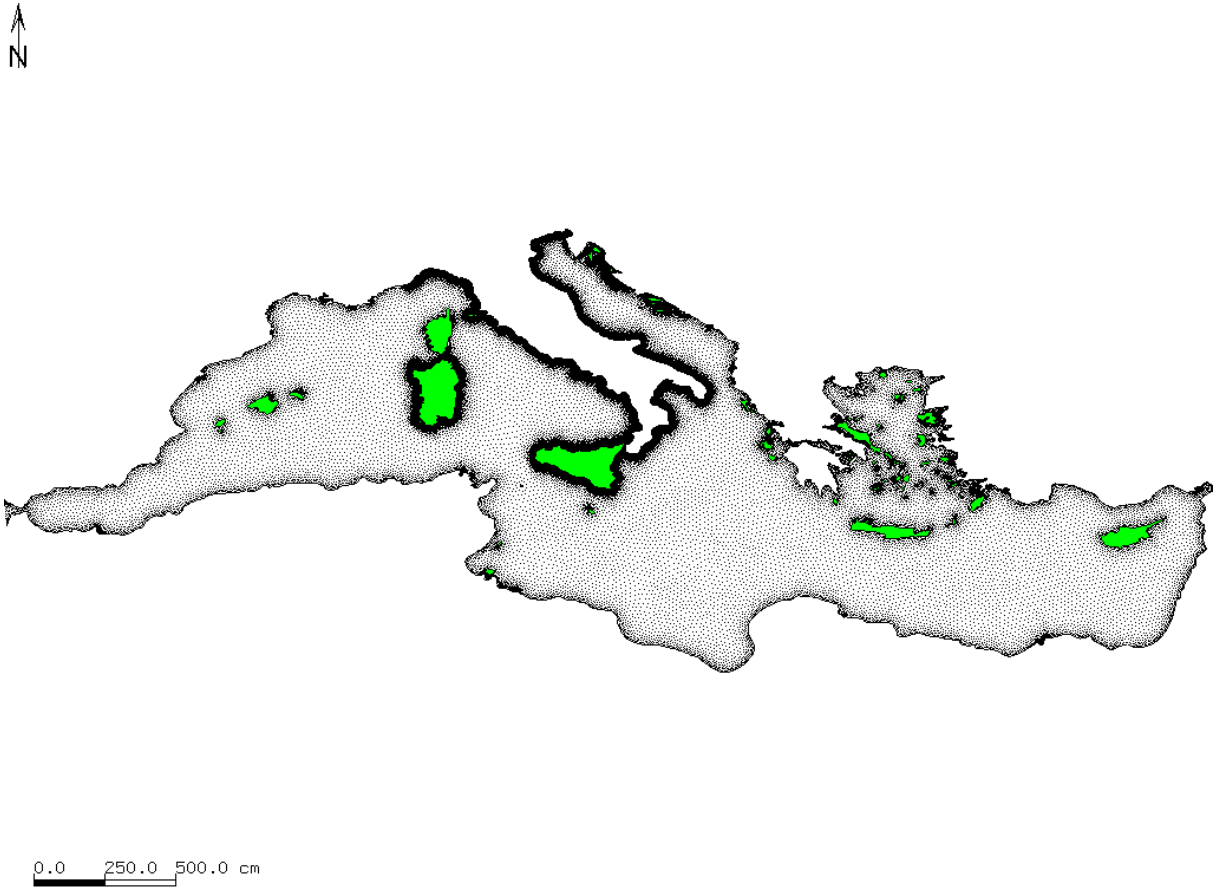




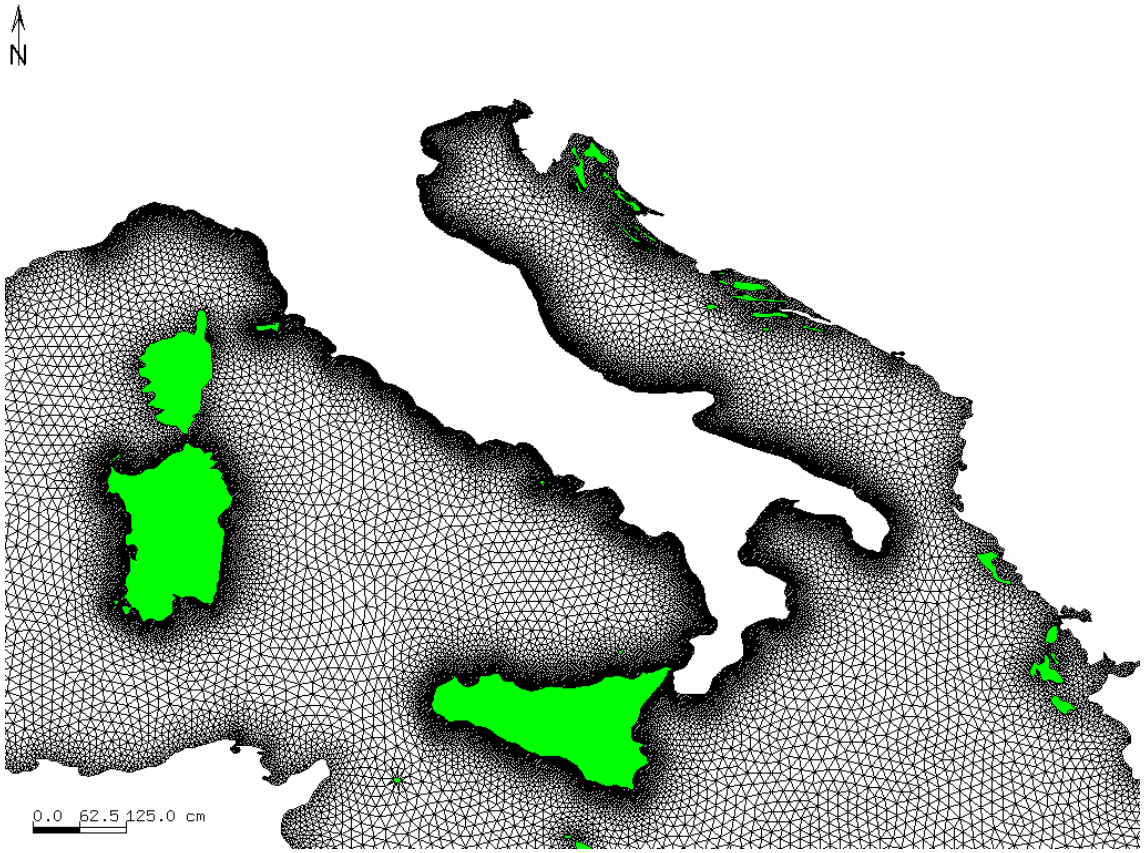
New decomposition:



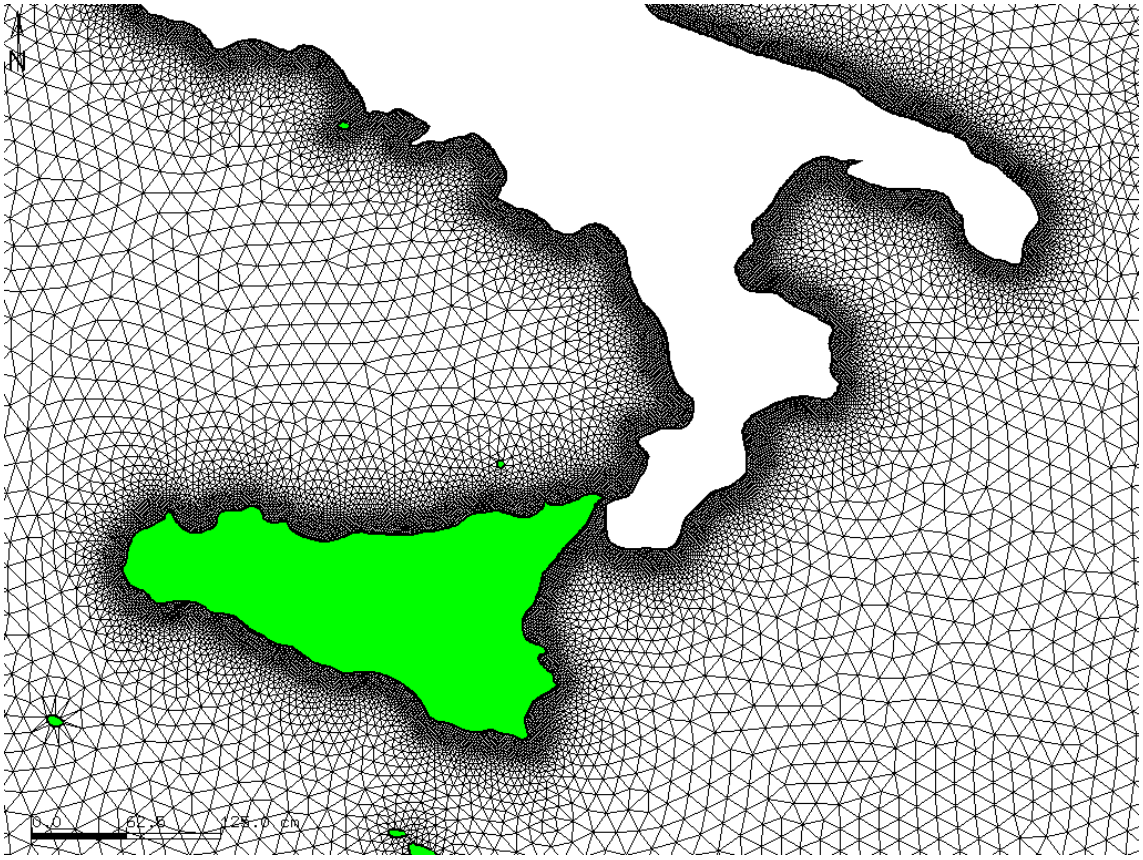
Future developments: unstructured grid



Future developments: unstructured grid



Future developments: unstructured grid



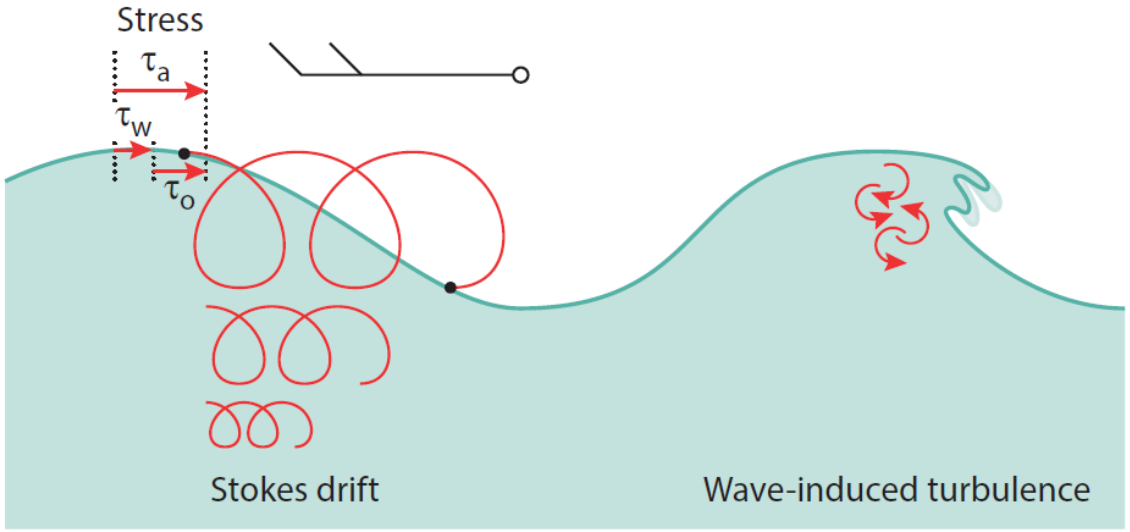

Questions/comments ?

IFS-WAM-NEMO coupled system.

Wave-ocean interaction

Three wave effects have recently been implemented in NEMO:

- Stokes-Coriolis forcing: The Stokes drift sets up a current in the along-wave direction. Near the surface it may become substantial ($\sim 1\,\mathrm{m/s}$). The Coriolis effect works on the Stokes drift and adds a new term to the momentum equations known as the Coriolis-Stokes force
- Stress: As waves grow under the influence of the wind, the waves absorb momentum (τ_w) which otherwise would have gone into the ocean directly (τ_o)
- Mixing: As waves break (right), turbulent kinetic energy is injected into the ocean mixed layer, significantly enhancing the mixing.



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/CY38r1/index.html