



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

Jean-Raymond Bidlot

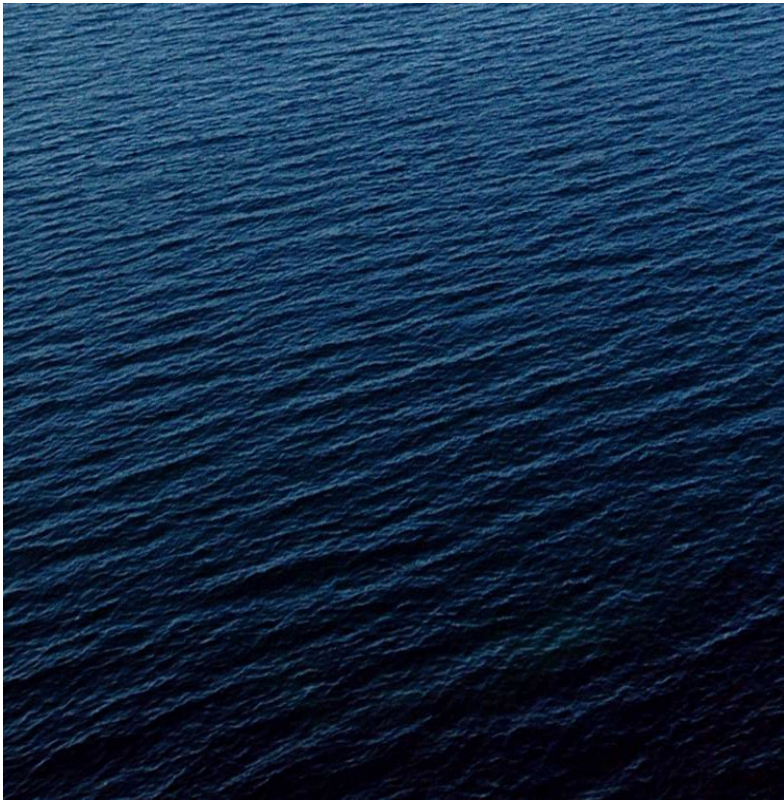
Marine Prediction Section

Predictability Division of the Research Department

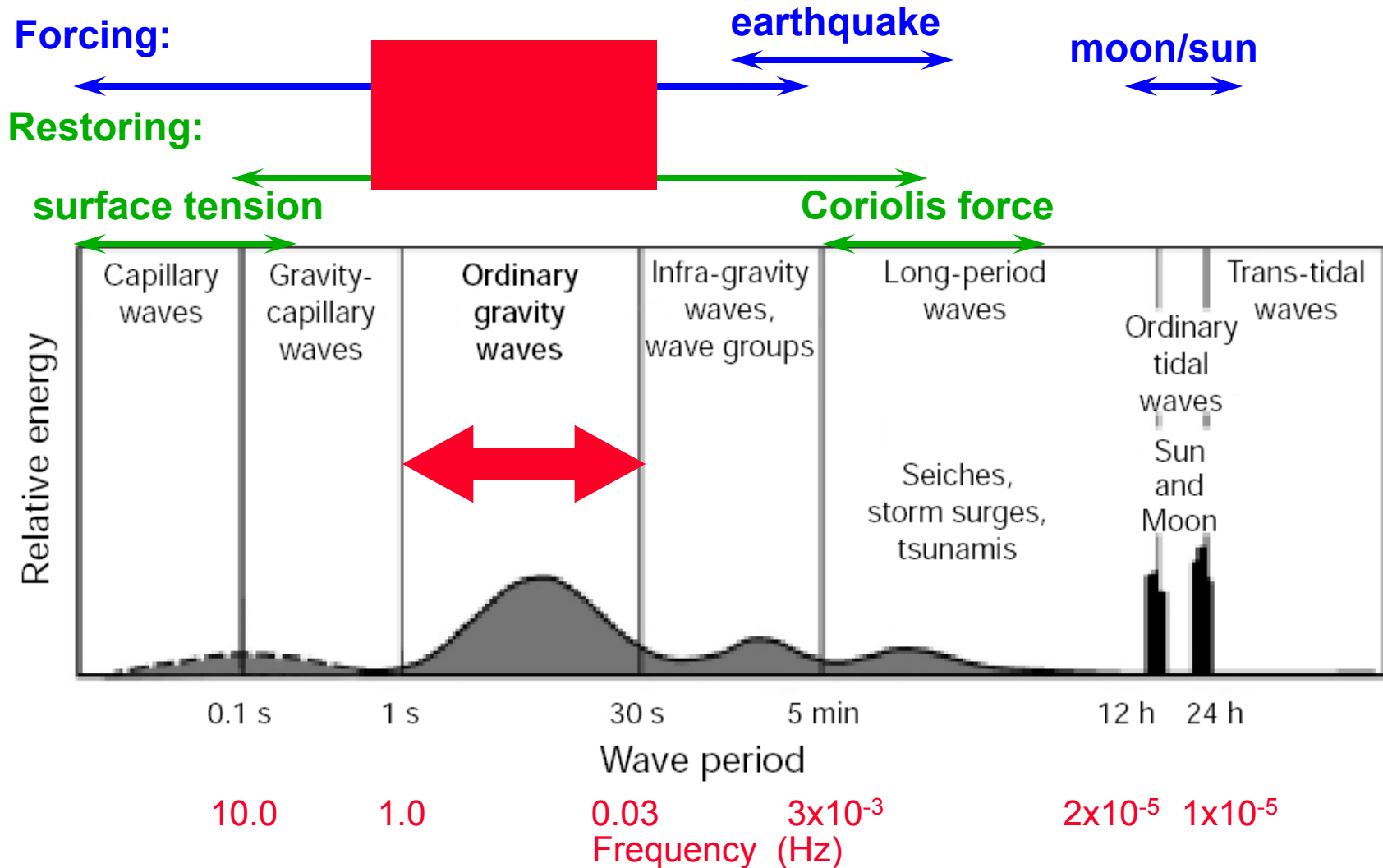
European Centre for Medium-range Weather Forecasts

Ocean waves:

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



Ocean Waves

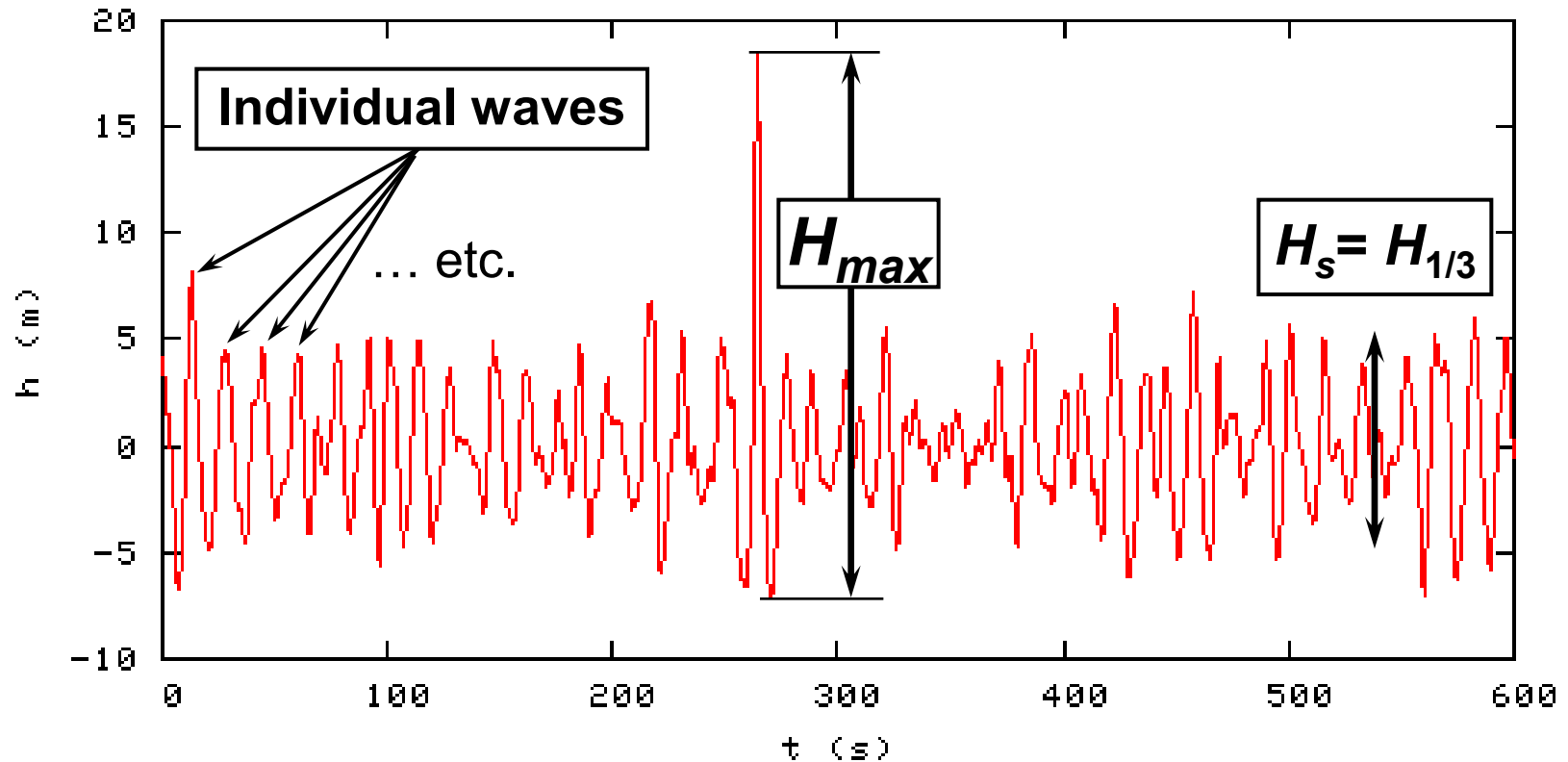


A Wave Record

Individual Waves,

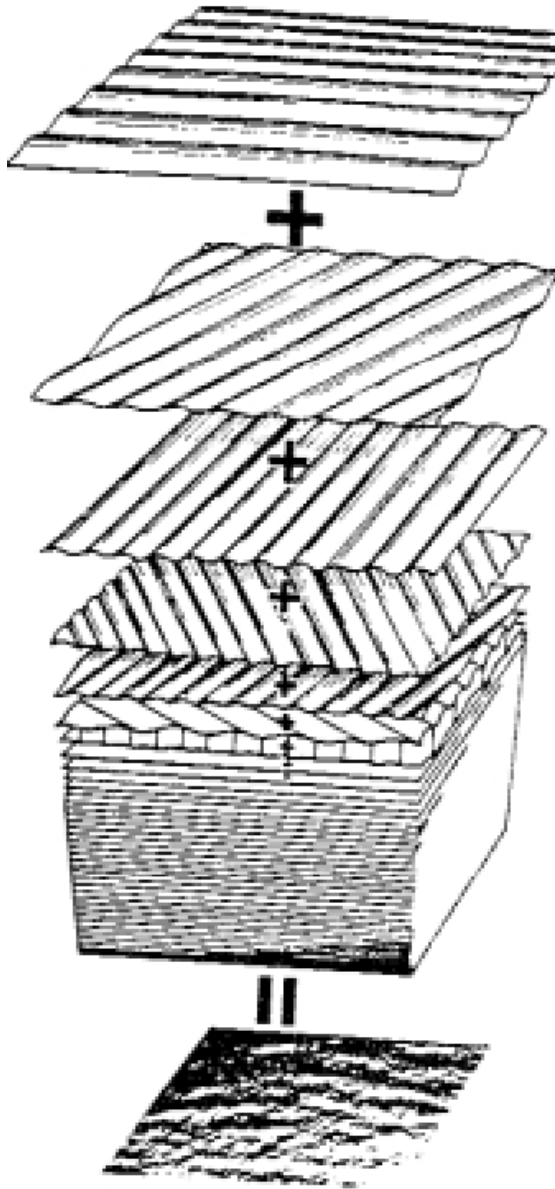
Significant Wave Height, H_s ,

Maximum Individual Wave Height, H_{max}



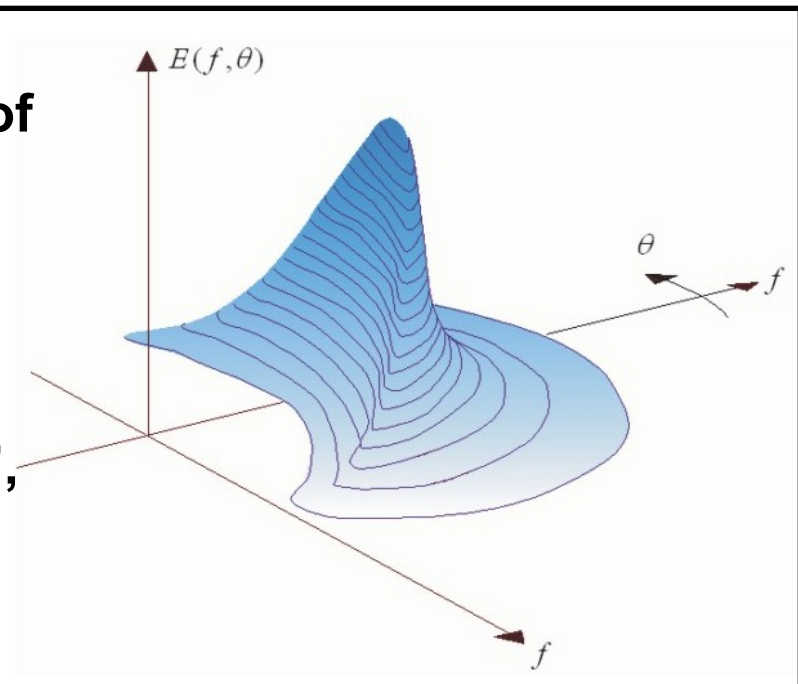
Surface elevation time series from platform Draupner in the North Sea

Wave Spectrum



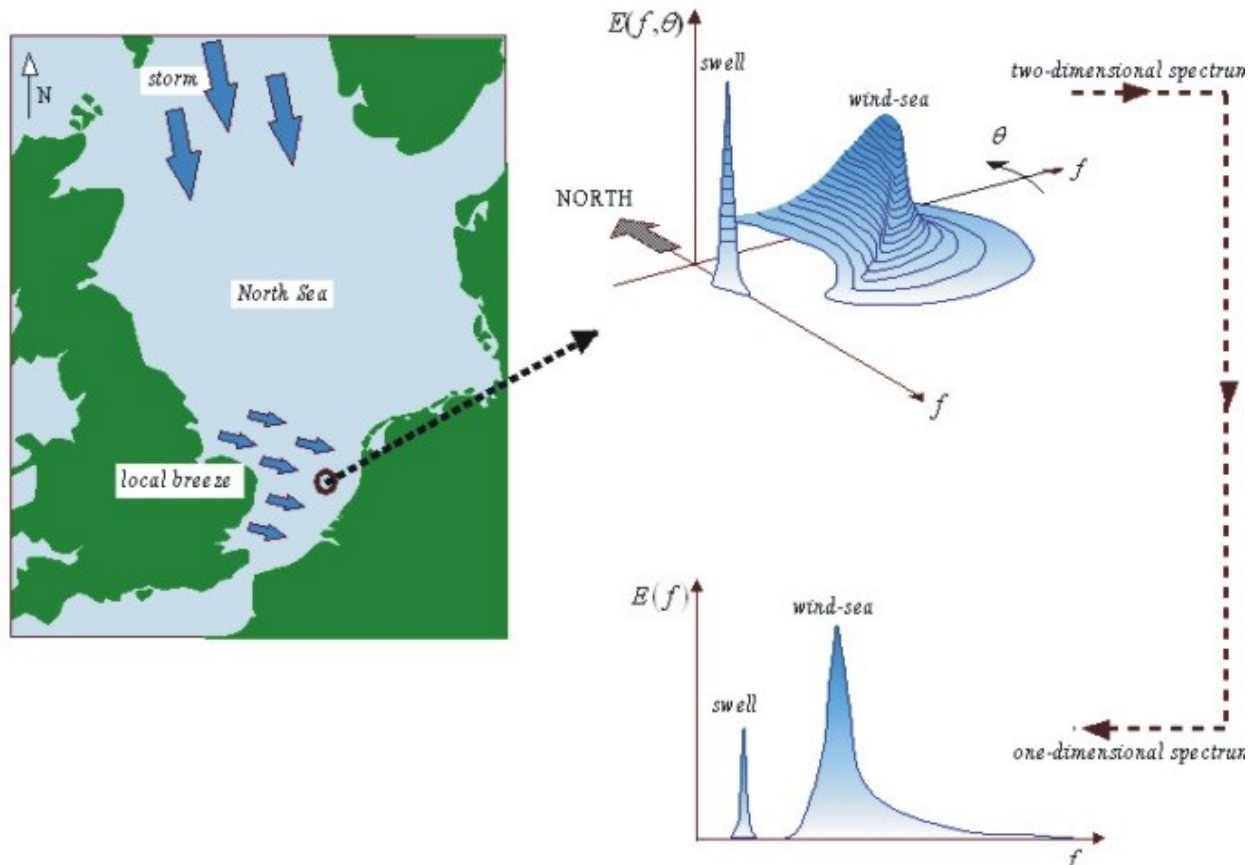
- The irregular water surface can be decomposed into (*infinite*) number of simple sinusoidal components with different **frequencies** (f) and propagation **directions** (θ).

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



Ocean Wave Modelling

- 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.

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

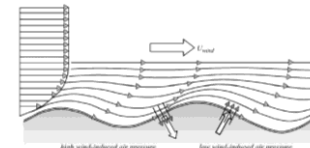


Figure 6.16 The wave-induced wind-pressure variation over a propagating harmonic wave.

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

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

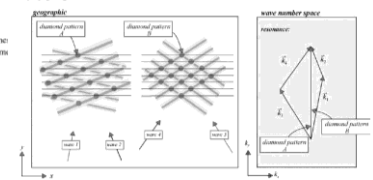
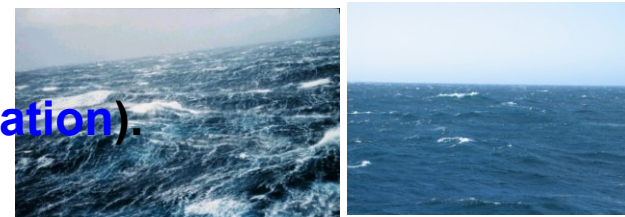


Figure 6.20 Quadruplet wave-wave interactions (realisable in deep water). Two pairs of wave components can create two diamond patterns with identical wave lengths and directions and therefore identical wave numbers. When the four waves are superimposed (not shown here), they can thus resonate. The wave-number vectors of the four wave components are shown in the right-hand panel in wave-number space with $k_1 + k_2 = k_3 + k_4$.

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):

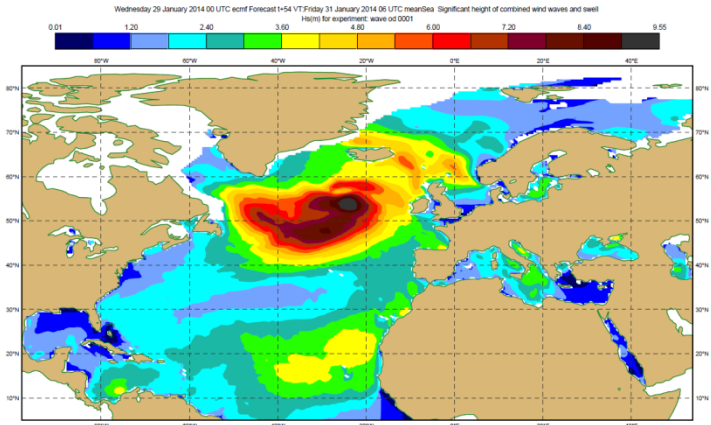
$$H_s = 4 \sqrt{\langle \eta^2 \rangle}$$

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 ($H_{1/3}$).

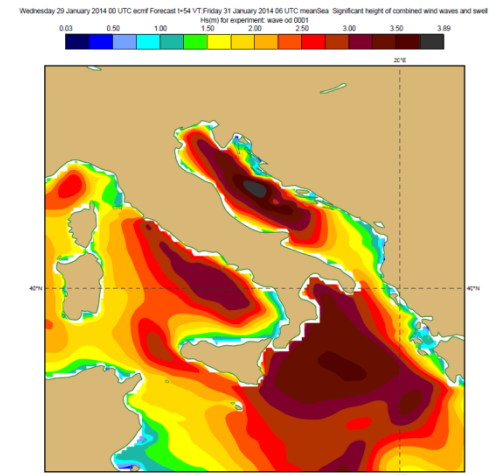
ECMWF Wave Model Configurations

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

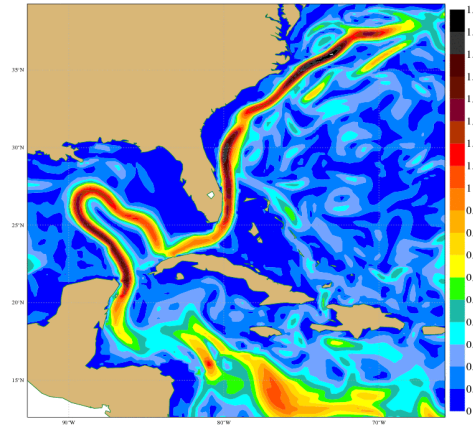


ECMWF Wave Model Configurations

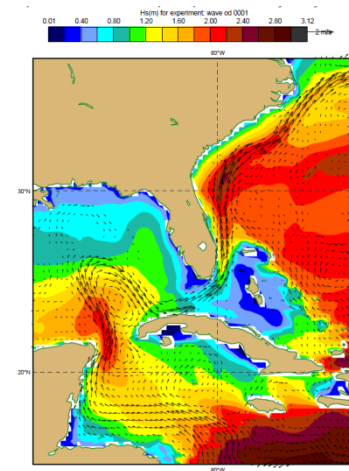
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- 36 frequencies and 36 directions
- Forced by 10m neutral wind fields from the global system.
- Data assimilation of altimeter wave heights (Jason 2).
- 2 daily forecasts (from 0 & 12 UTC) extending to day 5, output every hour.
- **Imposed surface currents from TOPAZ4 system.**

ECMWF Analysis VT-Sunday 17 June 2012 00UTC Surface: "U velocity (Exp: 0001)
Surface current speed from TOPAZ4 as used by LAW



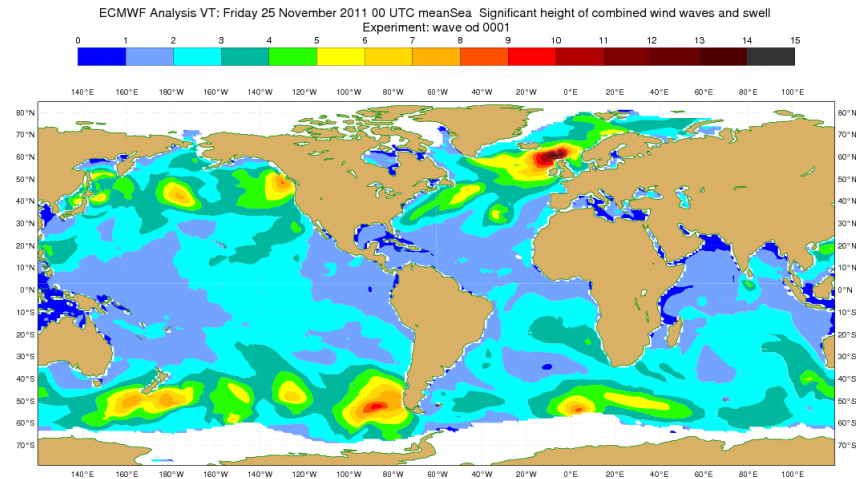
**TOPAZ4
surface currents**



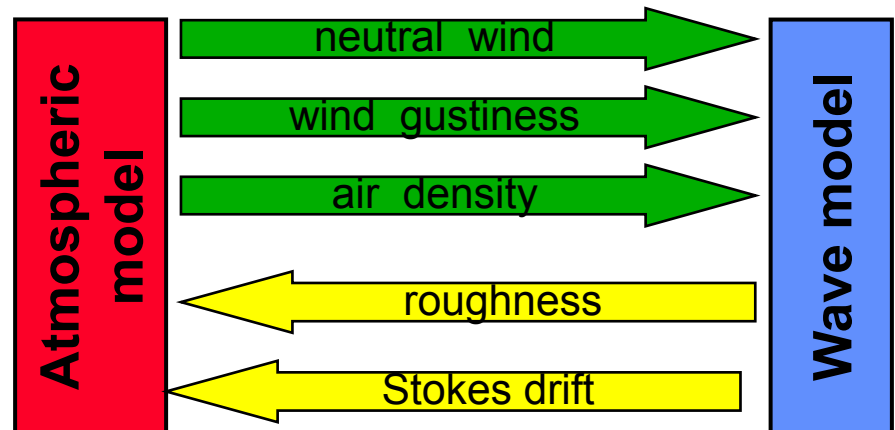
ECMWF Wave Model Configurations

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)

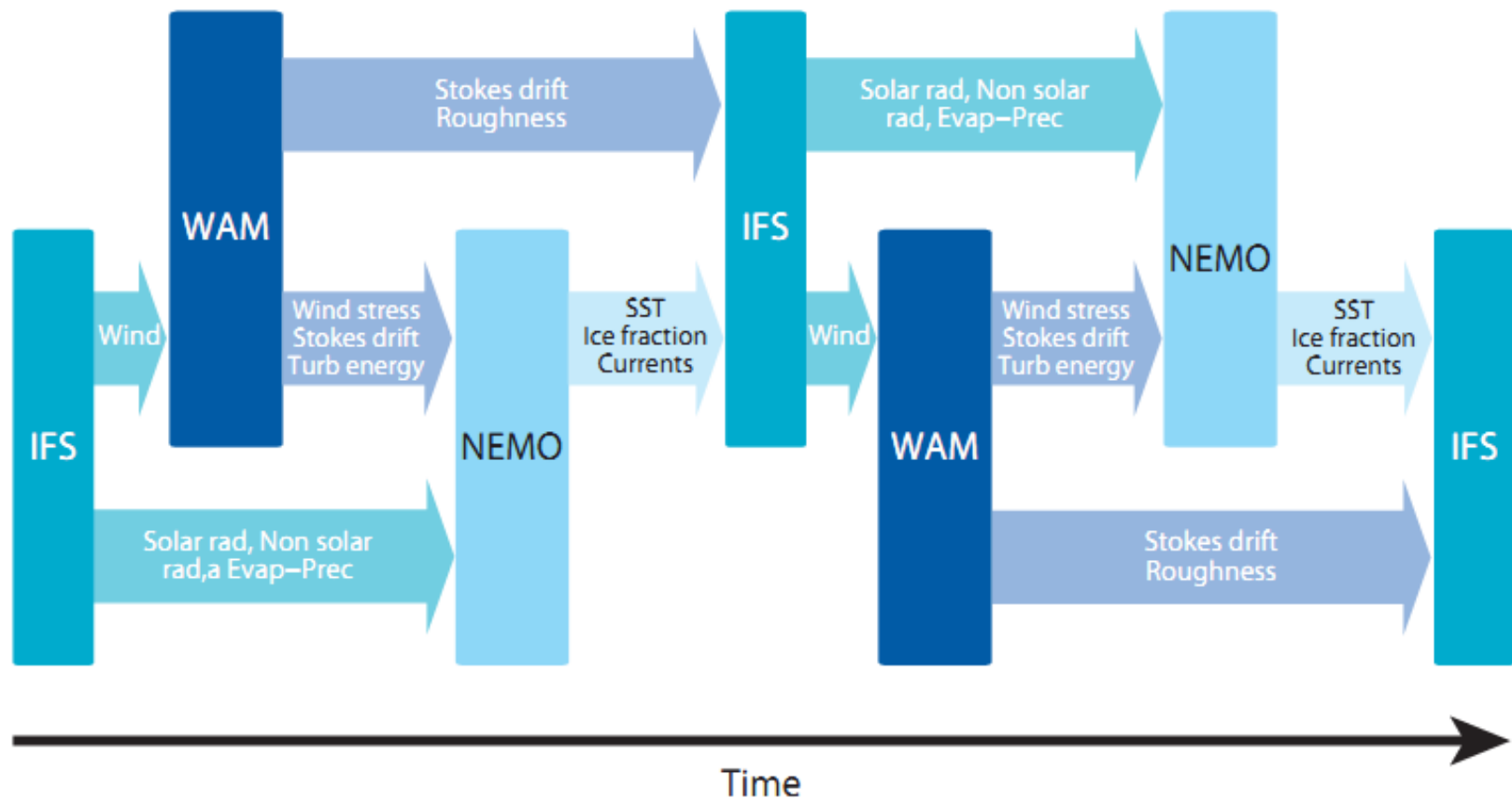
- 55 km grid spacing.
- 30 → 25 frequencies *.
- 24 → 12 directions *.
- Coupled to TL639 → TL319 model *.
- (50+1) (10+5) day forecasts from 0 and 12Z (monthly once a week).
- Coupling to ocean model.

* 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

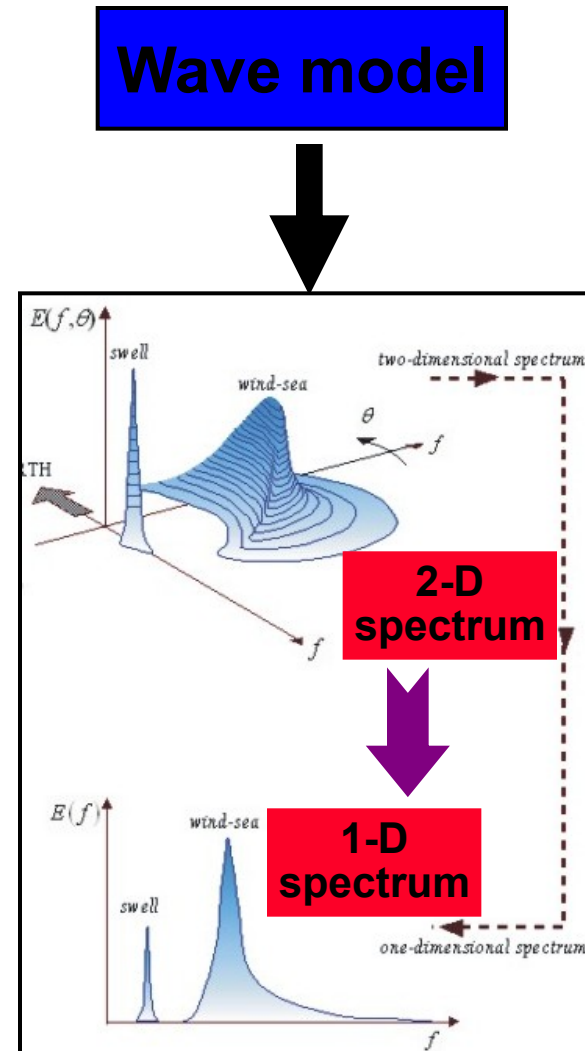


Wave Model Products

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:

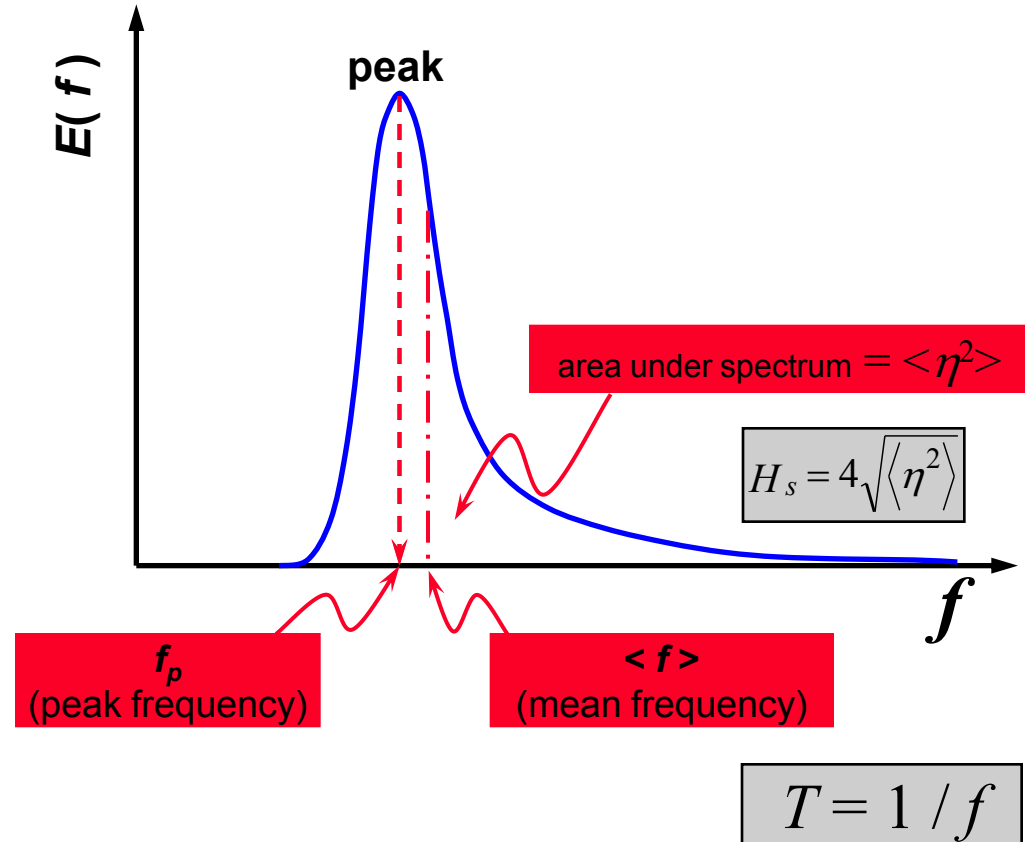
- 1-D spectrum obtained by integrating the 2-D spectrum over all directions and/or over a frequency range.



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.*

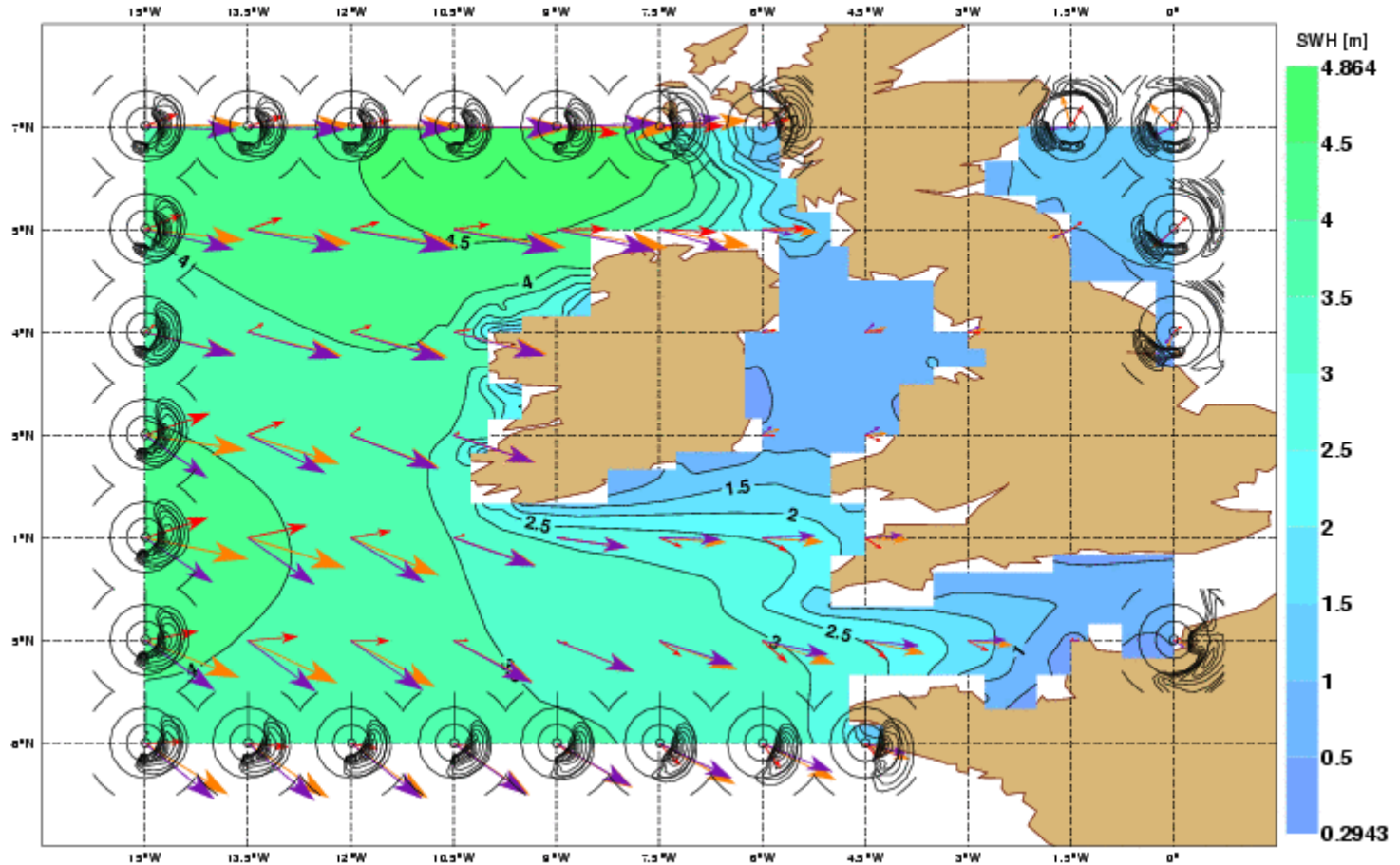
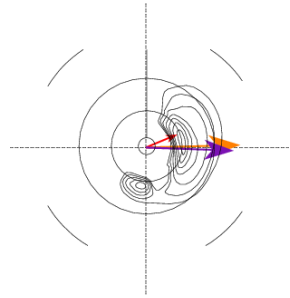


Complete list at: <http://www.ecmwf.int/services/archive/d/parameters/order=table=140/>

Wave Model Products

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

Friday 6 March 2009 00UTC ECMWF Forecast t+24 VT: Saturday 7 March 2009 00UTC
Normalised 2-D Wave Spectra EXP: 1 STREAM: WV
Orange Arrows: Total ... Red Arrows: Wind-Sea ... Violet Arrows: Swell



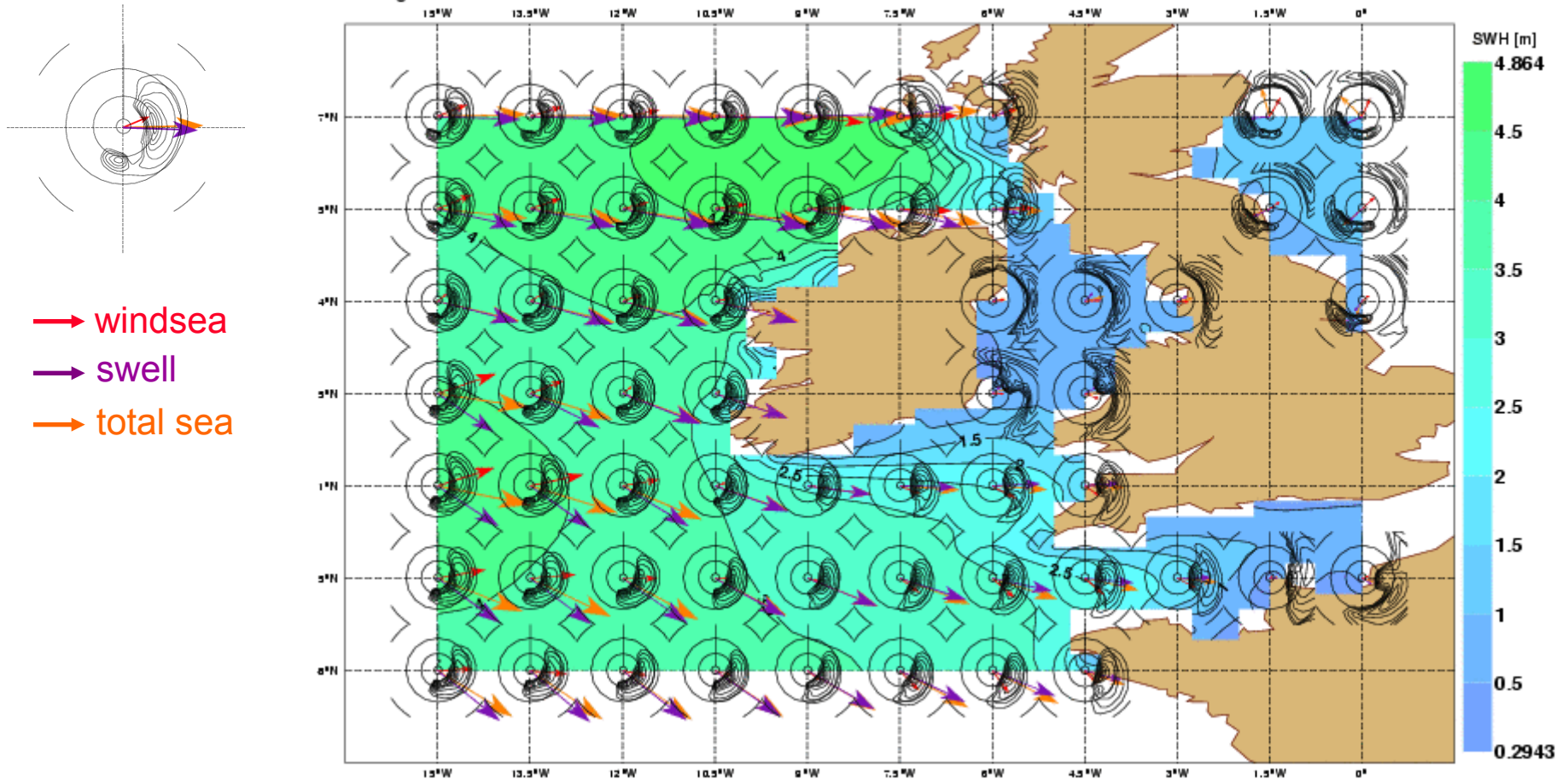
Spectra used as boundary conditions by Met Éireann

- windsea
- swell
- total sea

Wave Model Products

Plot of 2-D spectrum can become very busy !

Friday 6 March 2009 00UTC ECMWF Forecast t+24 VT: Saturday 7 March 2009 00UTC
Normalised 2-D Wave Spectra EXP: 1 STREAM: WV
Orange Arrows: Total ... Red Arrows: Wind-Sea ... Violet Arrows: Swell



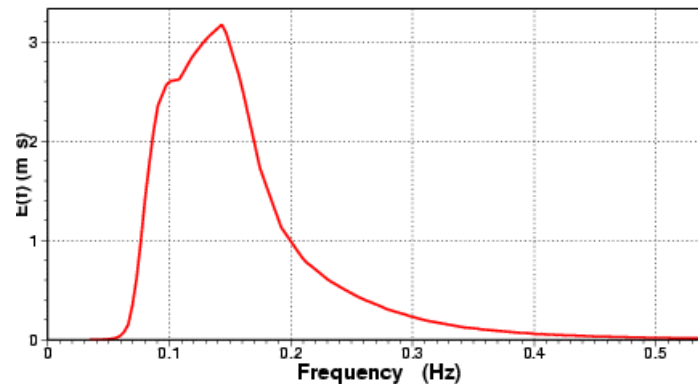
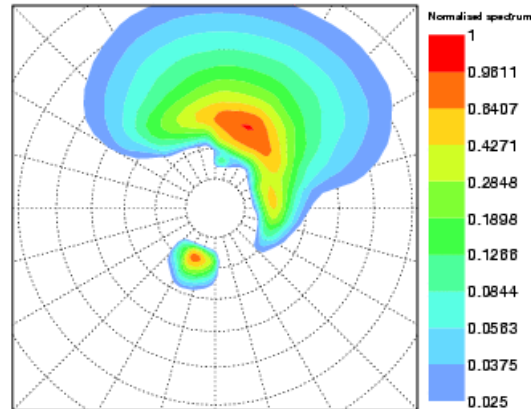
- windsea
- swell
- total sea

Wave Model Products

Except if you only look at one location ...

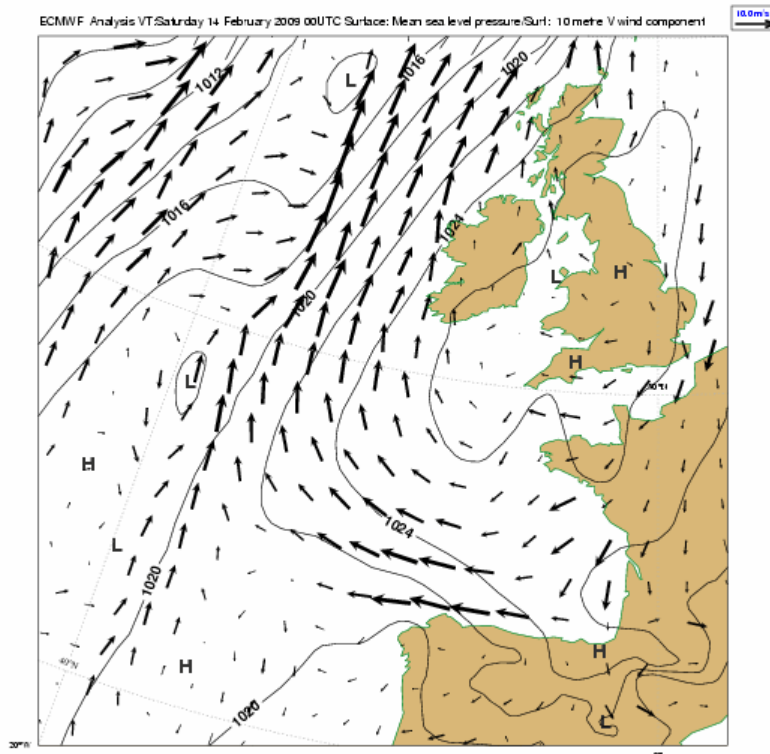
NORMALISED 2-D SPECTRUM for 0001 wave od
06:00Z on 15.02.2009
at 62095 (53.06°, -15.92°)

$H_s = 2.40$ m, $T_m = 7.23$ s, $T_p = 6.93$ s
Peakedness $Q_p = 0.96$, Directional Spread = 1.37
MWD = 19° PWD = 15°
Propagation direction is with respect to North
North is pointing upwards
Concentric circles are every 0.05 Hz

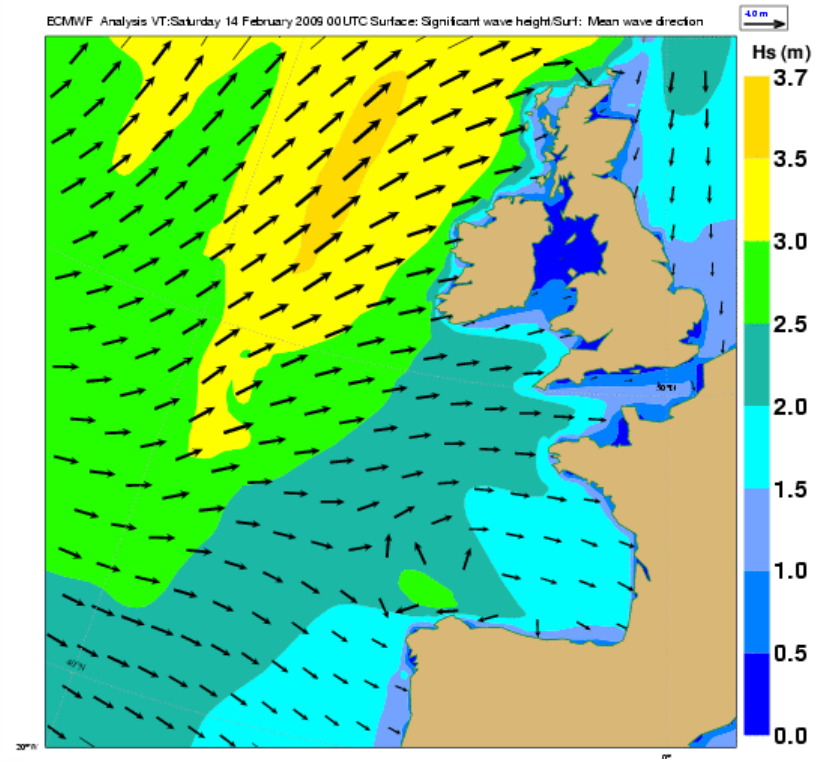


Wave Model Products

Use simple parameters:
total wave height and mean propagation direction



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

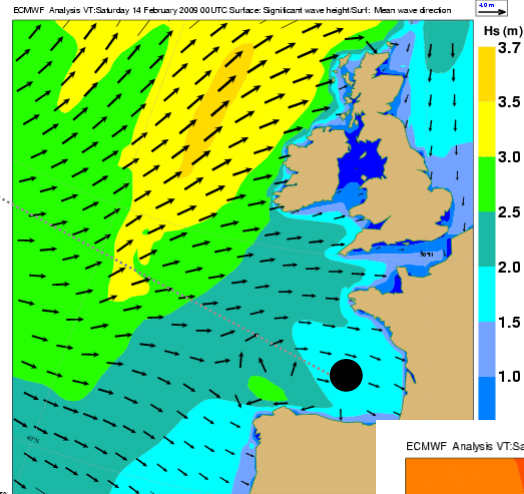
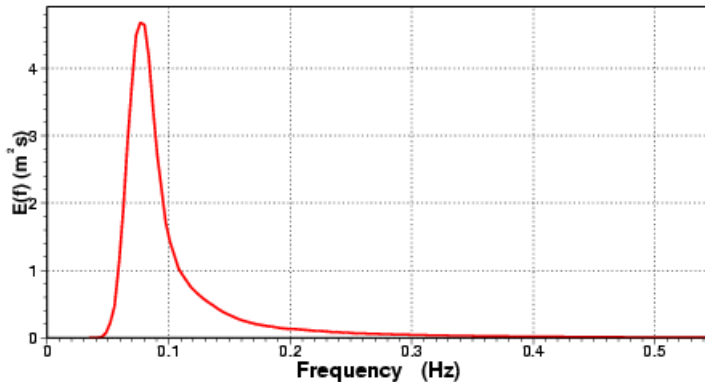
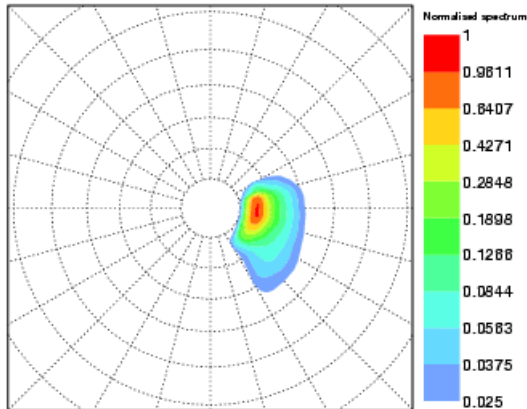


Wave height and mean direction:
Analysis : 14 February 2009, 00 UTC

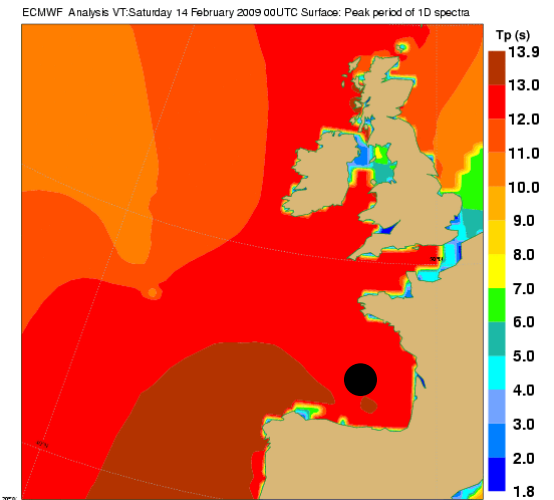
Wave Model Products

NORMALISED 2-D SPECTRUM for 0001 wave od
00:00Z on 14.02.2009
at 62001 (45.20°, -5.00°)

Hs= 1.76 m, Tm= 11.25 s, Tp= 13.51 s
Peakedness Qp = 2.18, Directional Spread = 1.38
MWD = 93° PWD = 90°
Propagation direction is with respect to North
North is pointing upwards
Concentric circles are every 0.05 Hz



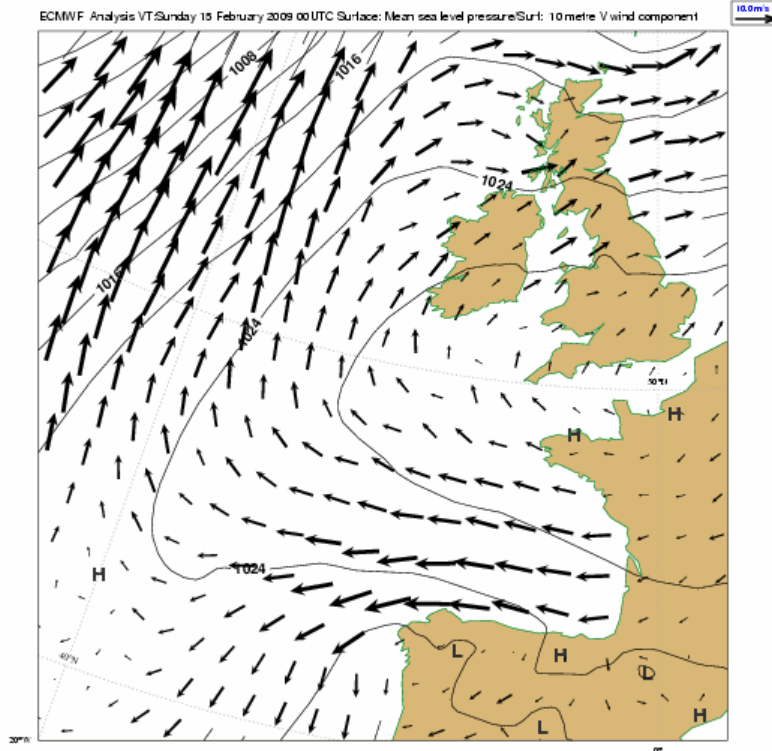
Wave height and me
Analysis : 14 February



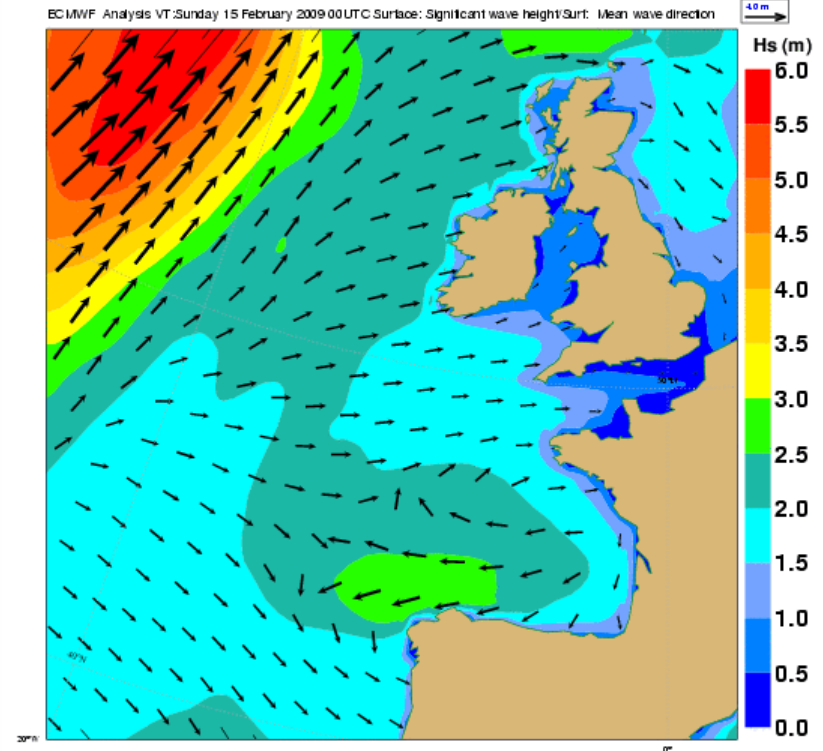
PEAK PERIOD:
Analysis : 14 February 2009, 00 UTC

Wave Model Products

Situation might be more complicated !



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



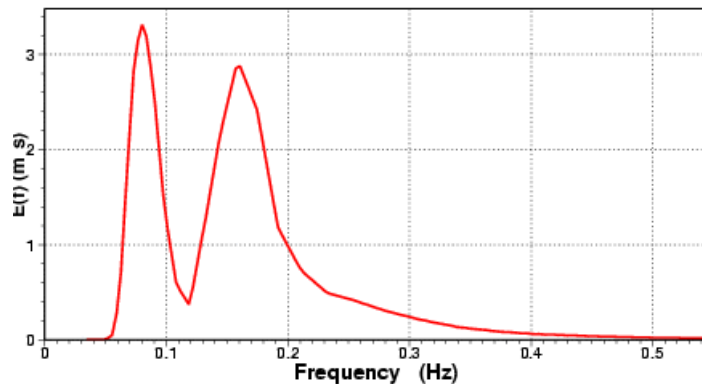
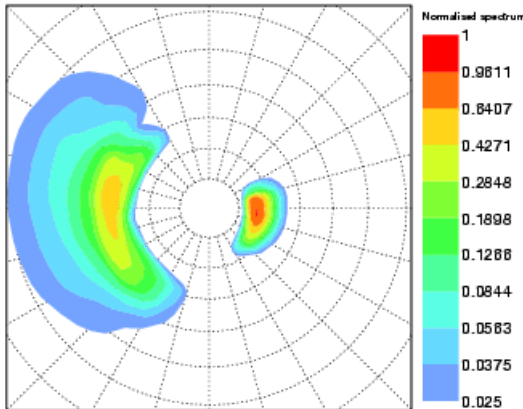
Wave height and mean direction:
Analysis : 15 February 2009, 00 UTC

Wave Model Products

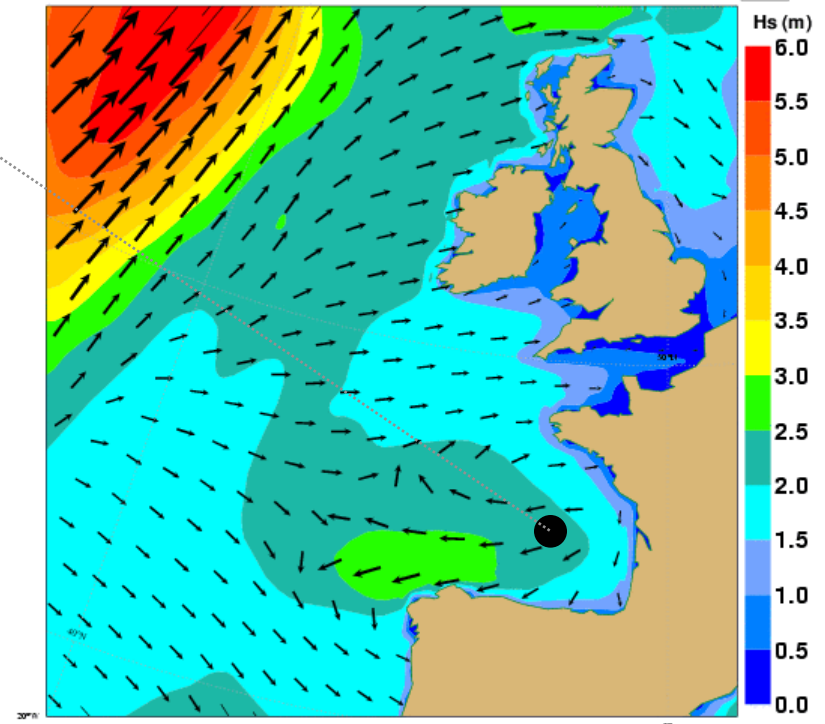
Situation might be more complicated:

NORMALISED 2-D SPECTRUM for 0001 wave od
00:00Z on 15.02.2009
at 62001 (45.20°, -5.00°)

Hs = 2.27 m, Tm = 7.69 s, Tp = 12.29 s
Peakedness Qp = 1.05, Directional Spread = 1.40
MWD = 248° PWD = 90°
Propagation direction is with respect to North
North is pointing upwards
Concentric circles are every 0.05 Hz



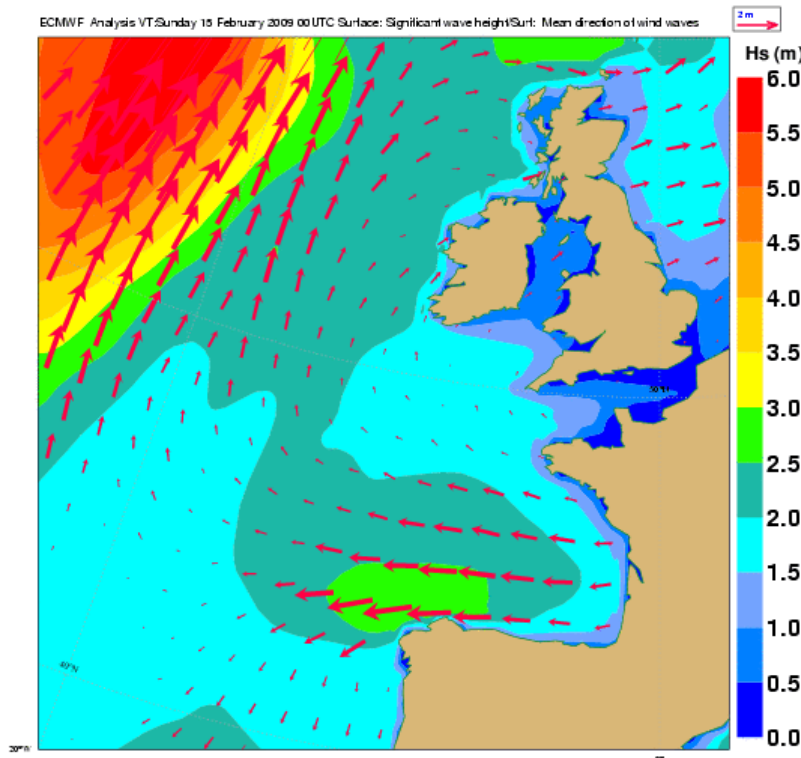
ECMWF Analysis VT: Sunday 15 February 2009 00 UTC Surface: Significant wave height Surf: Mean wave direction



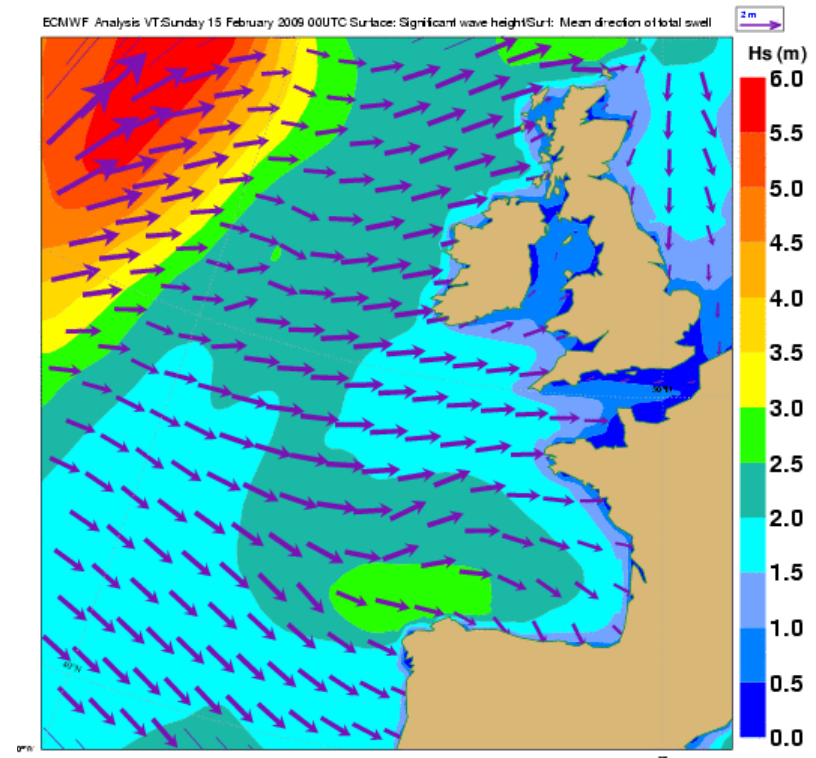
Wave height and mean direction:
Analysis : 15 February 2009, 00 UTC

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



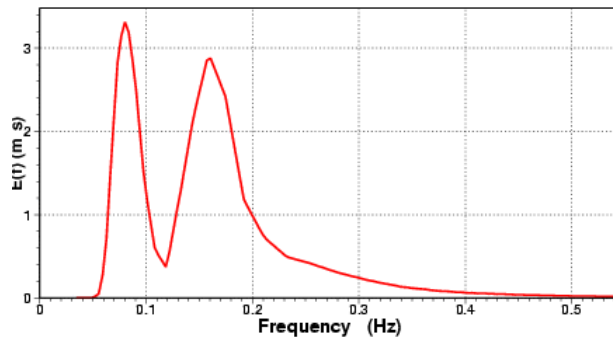
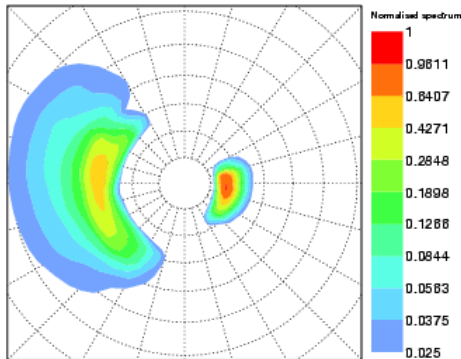
Wave height and **swell** mean direction:
Analysis : 15 February 2009, 00 UTC

Wave Model Products

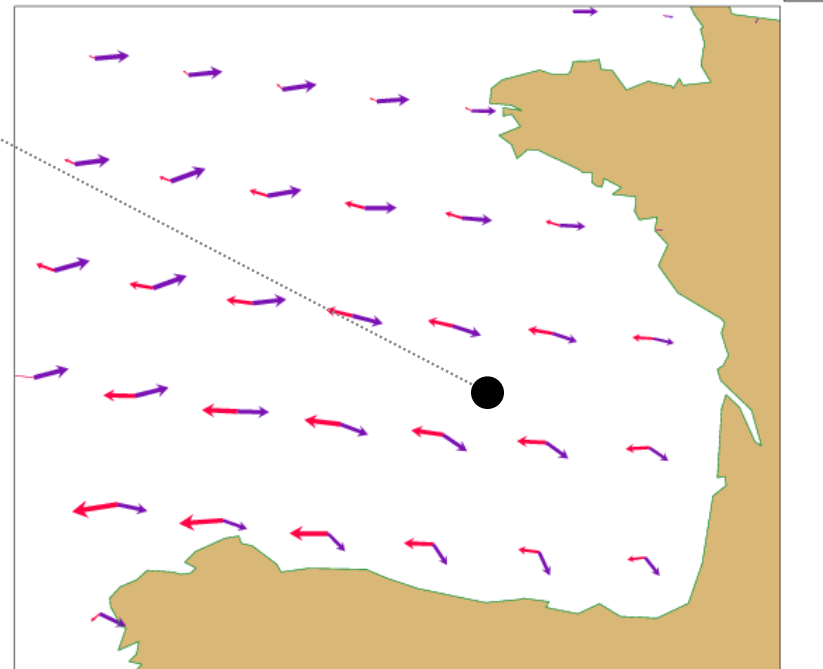
Windsea and swell: opposing sea

NORMALISED 2-D SPECTRUM for 0001 wave od
00:00Z on 15.02.2009
at 62001 (45.20°, -5.00°)

Hs= 2.27 m, Tm= 7.69 s, Tp=12.29 s
Peakedness Dp = 1.05, Directional Spread = 1.40
MWD = 248° PWD = 90°
Propagation direction is with respect to North
North is pointing upwards
Concentric circles are every 0.05 Hz



ECMWF Analysis VT: Sunday 15 February 2009 00UTC Surface: windsea: height_direction

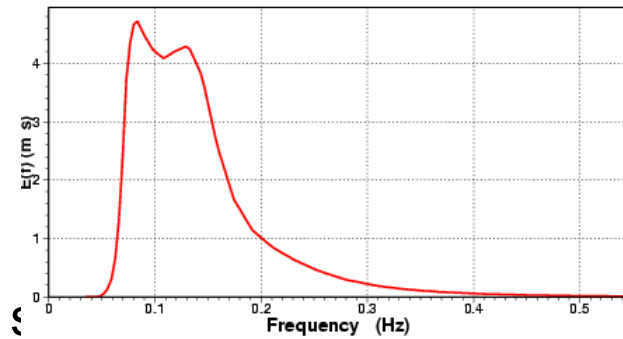
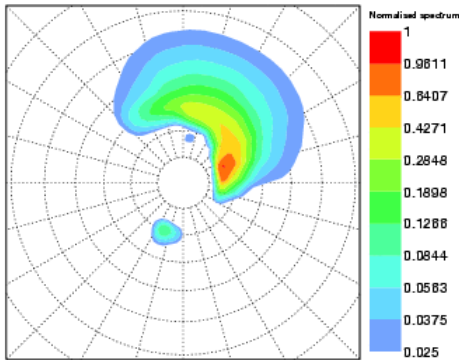


Wave Model Products

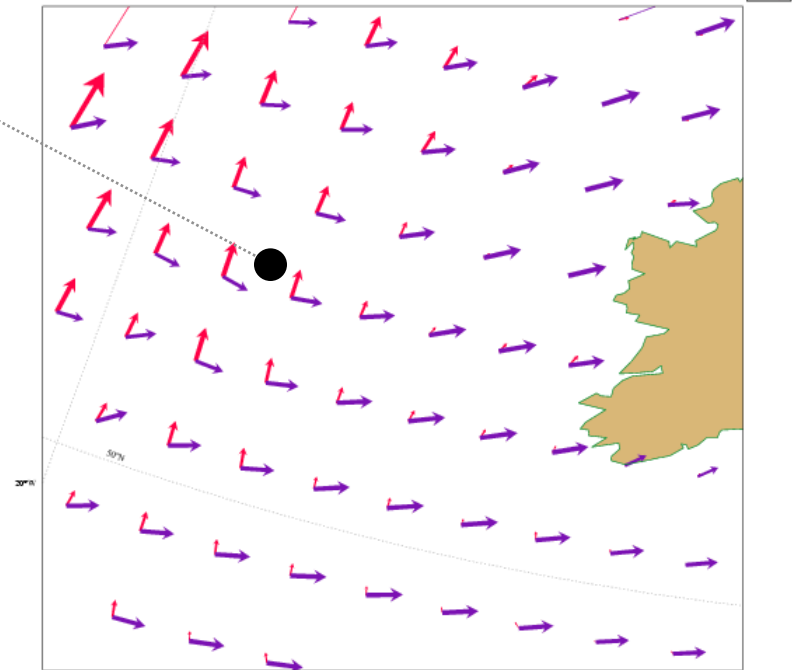
Windsea and swell: cross sea

NORMALISED 2-D SPECTRUM for 0001 wave od
18:00Z on 15.02.2009
at 62095 (53.06°, -15.92°)

Hs= 2.85 m, Tm= 8.30 s, Tp=12.29 s
Peakedness Op = 1.01, Directional Spread = 1.34
MWD = 37° PWD = 60°
Propagation direction is with respect to North
North is pointing upwards
Concentric circles are every 0.05 Hz



ECMWF Analysis VT:Sunday 15 February 2009 00UTC Surface: windsea: height_direction

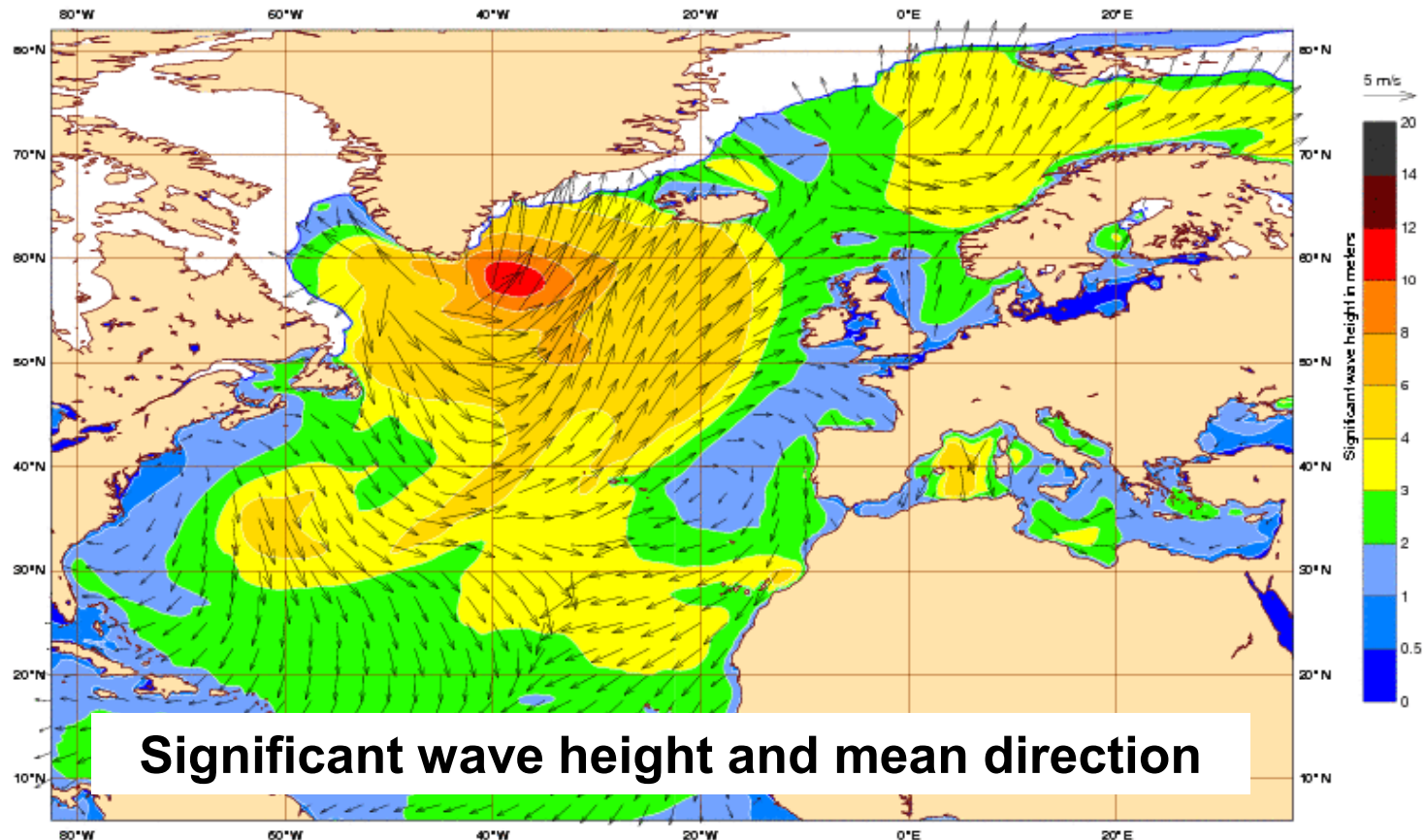


Wave model deterministic products on the web

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

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

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



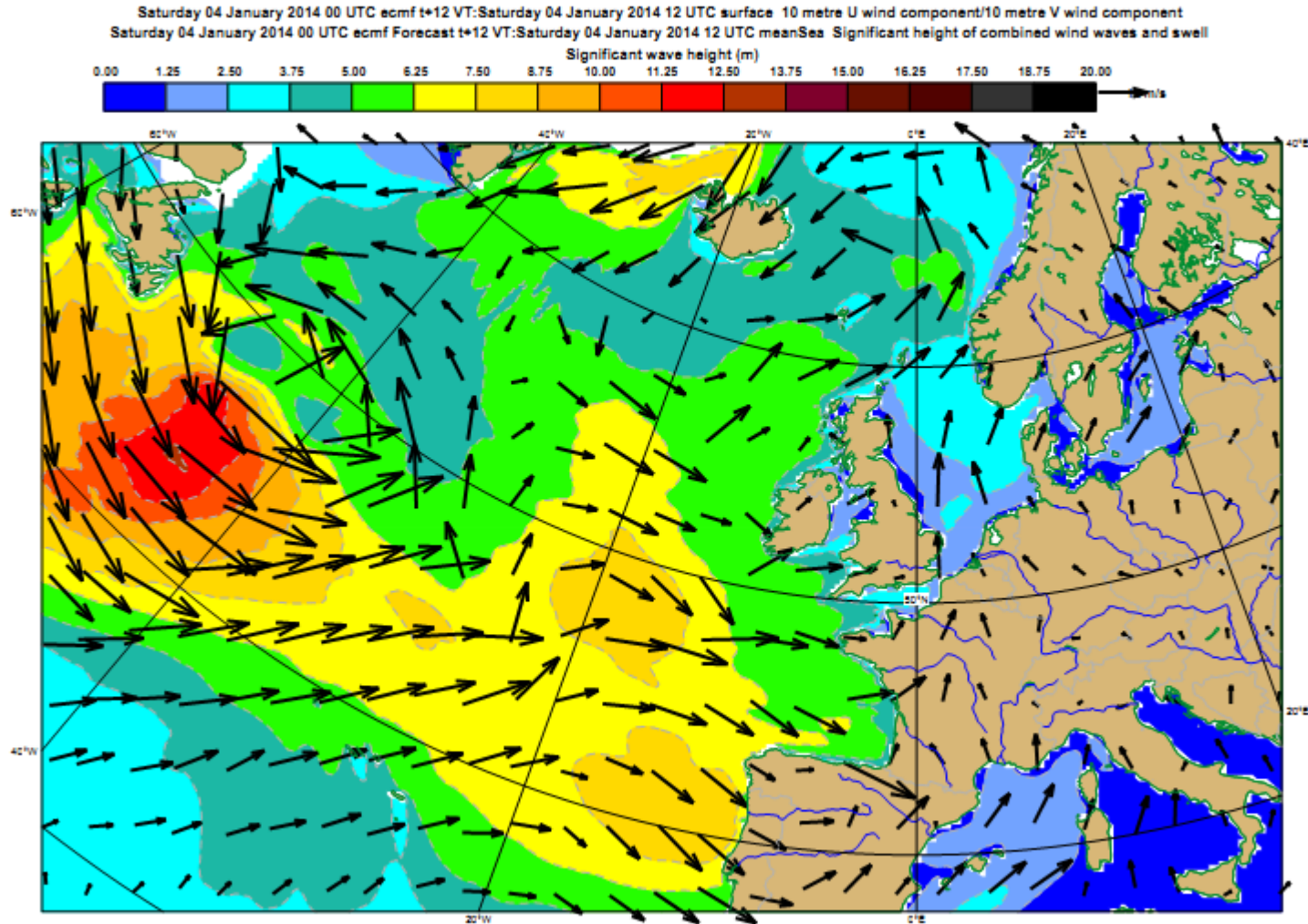
Ocean wave forecasts

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



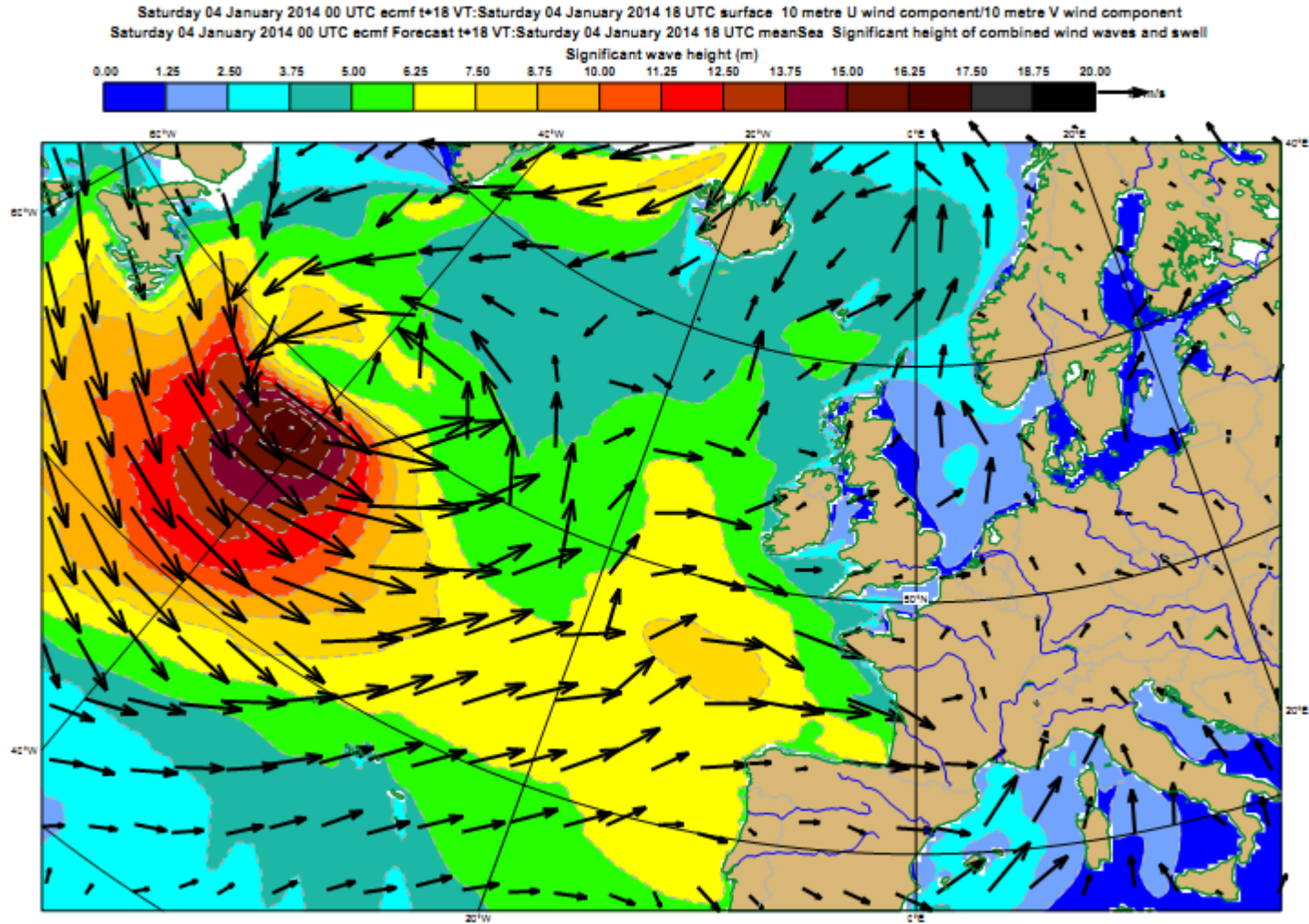
Ocean wave forecasts

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



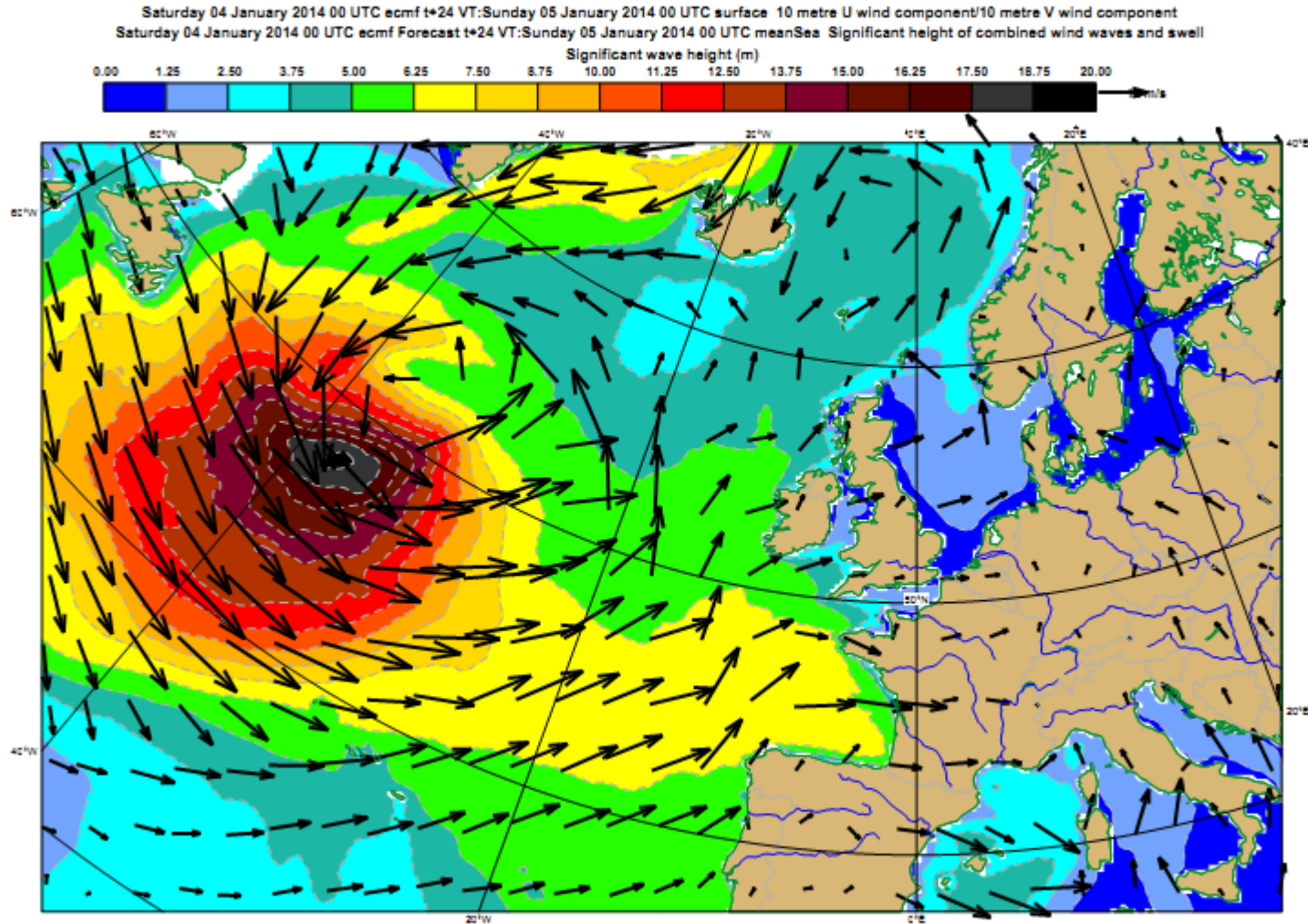
Ocean wave forecasts

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



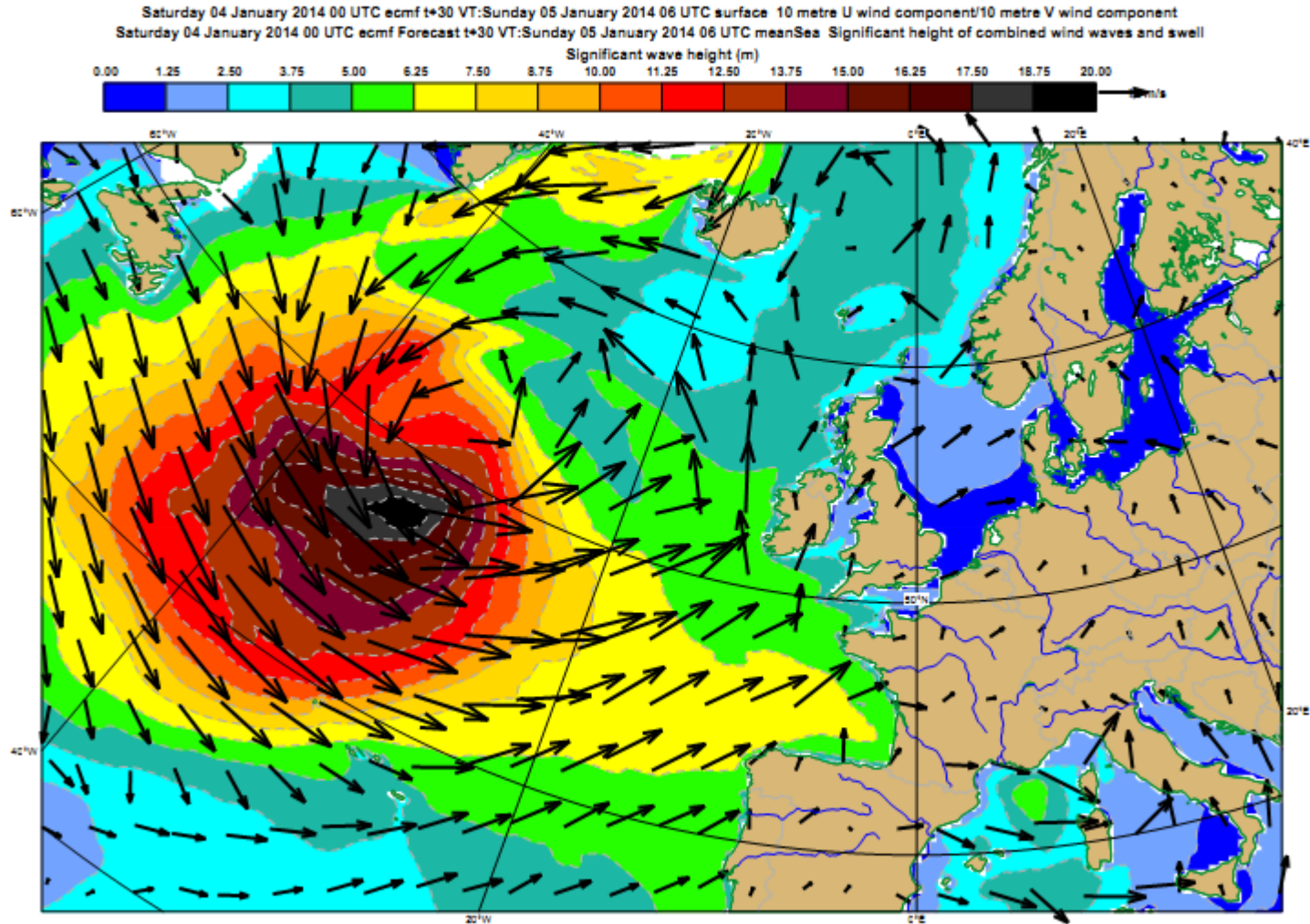
Ocean wave forecasts

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



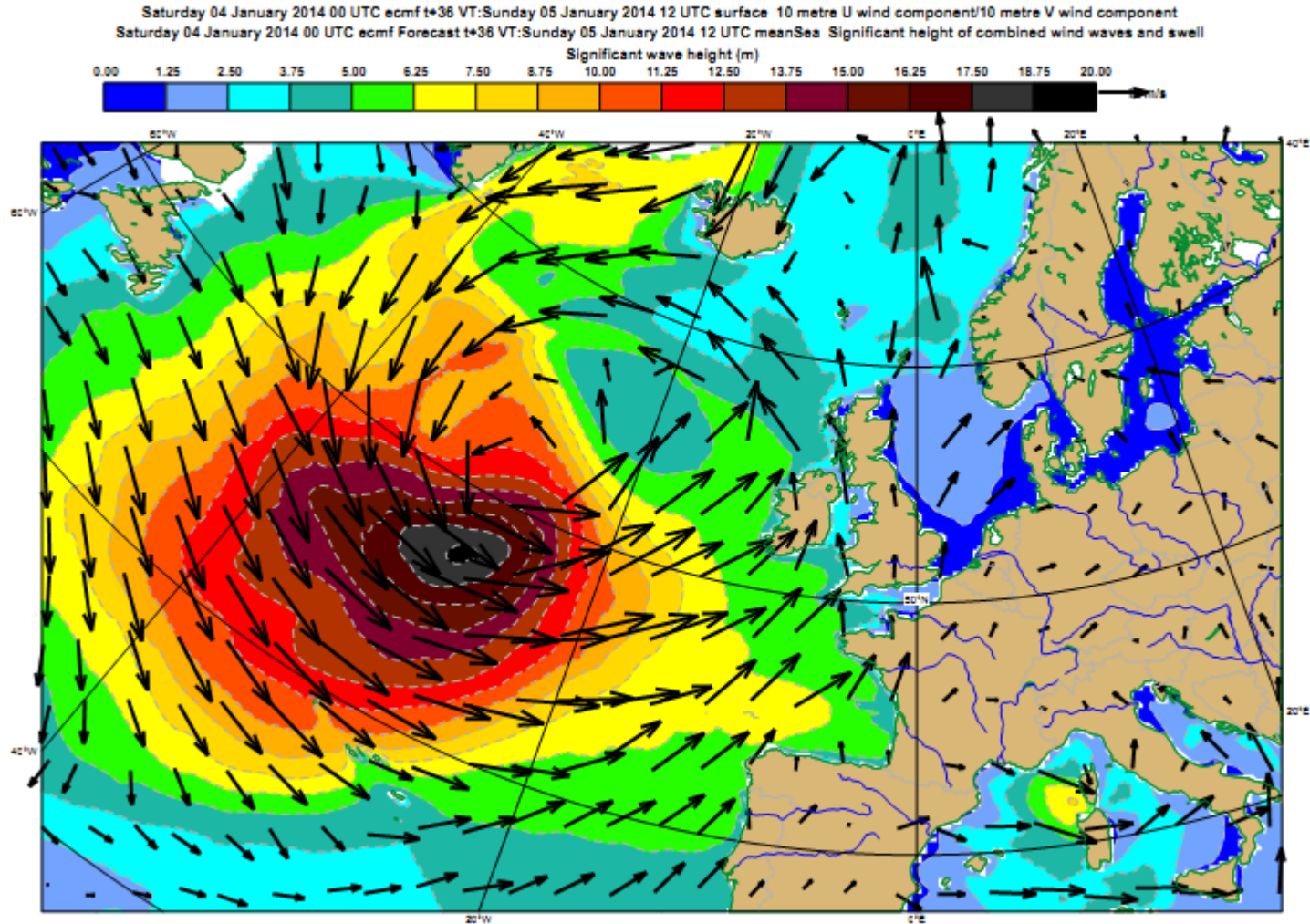
Ocean wave forecasts

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



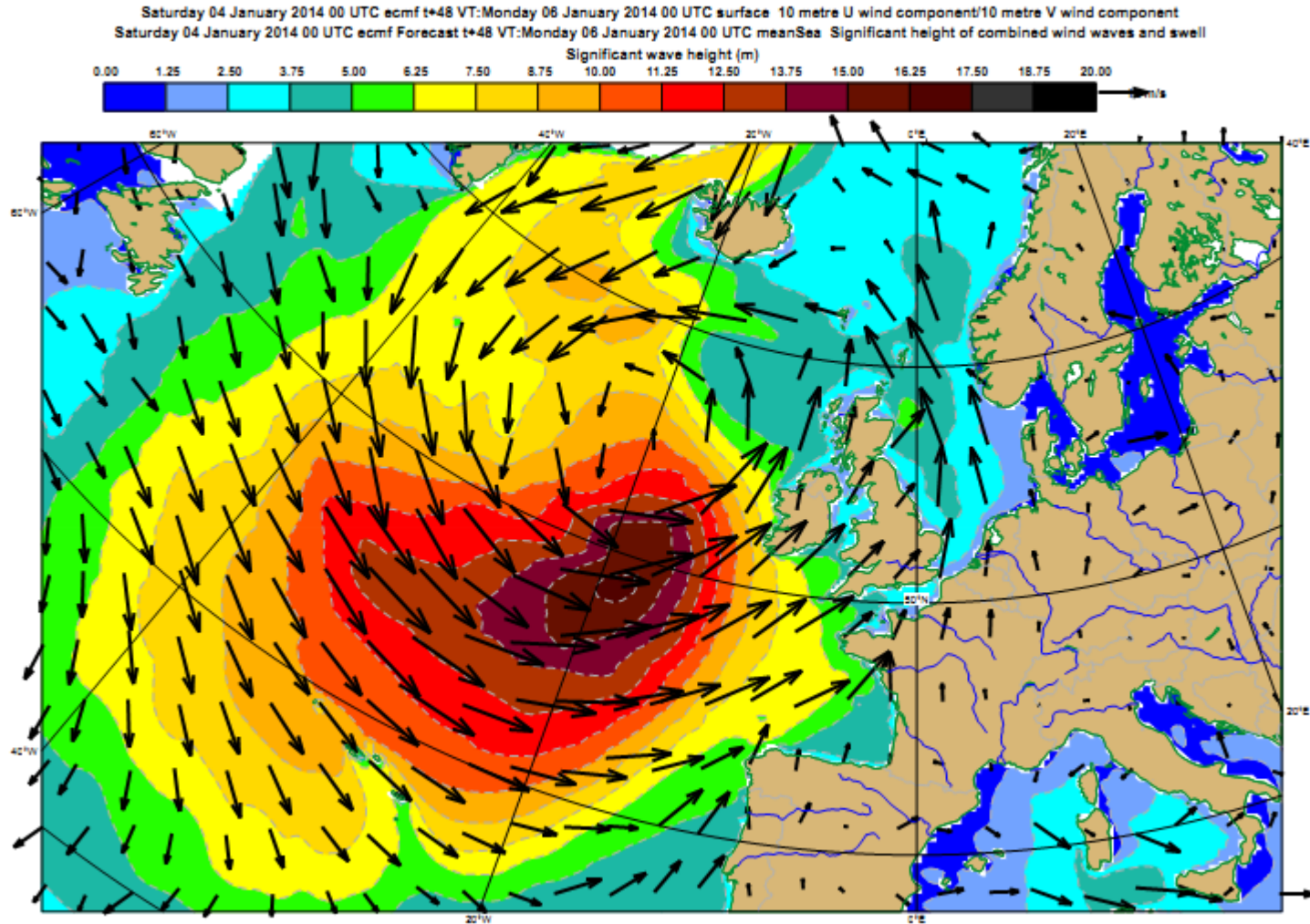
Ocean wave forecasts

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



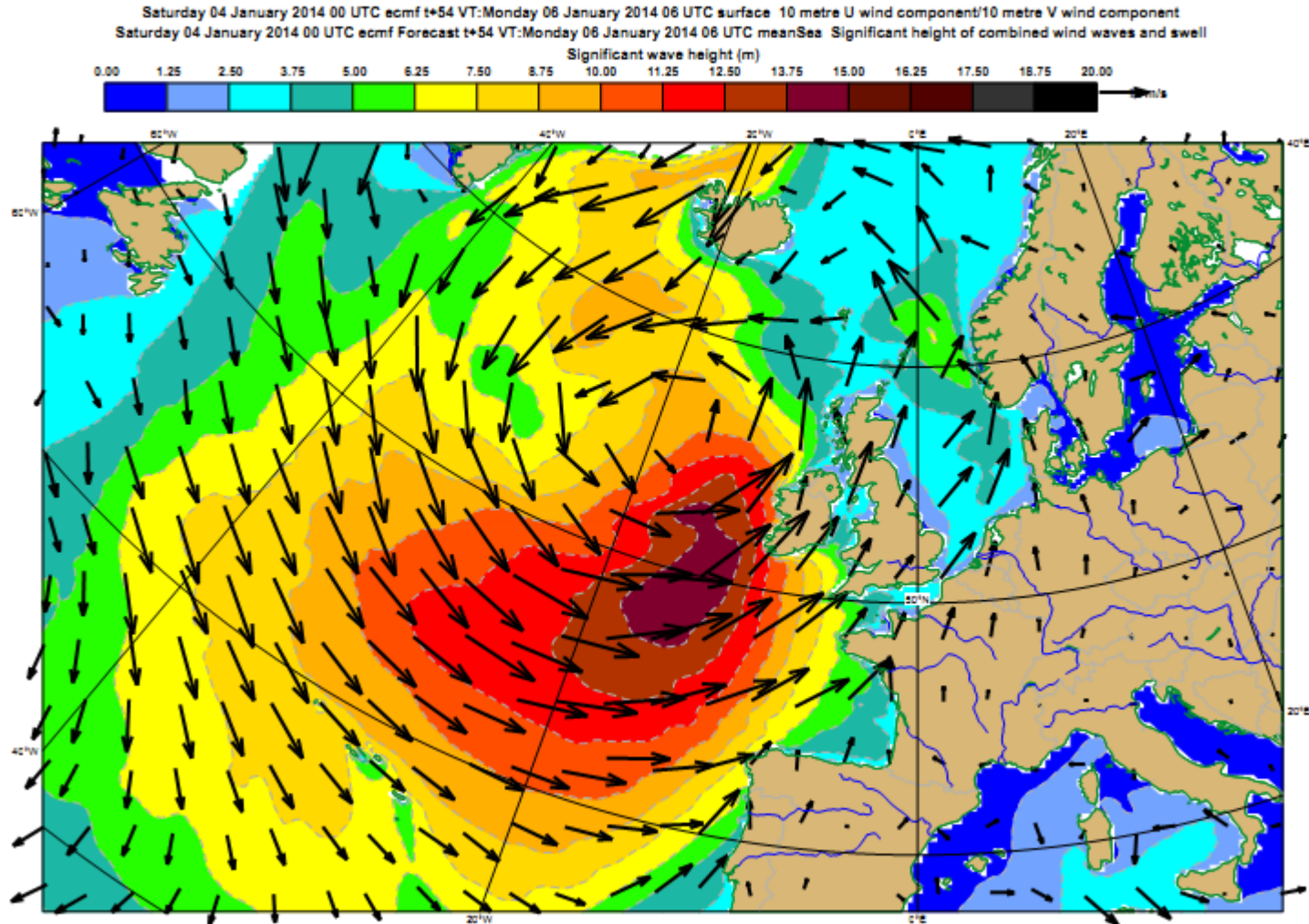
Ocean wave forecasts

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



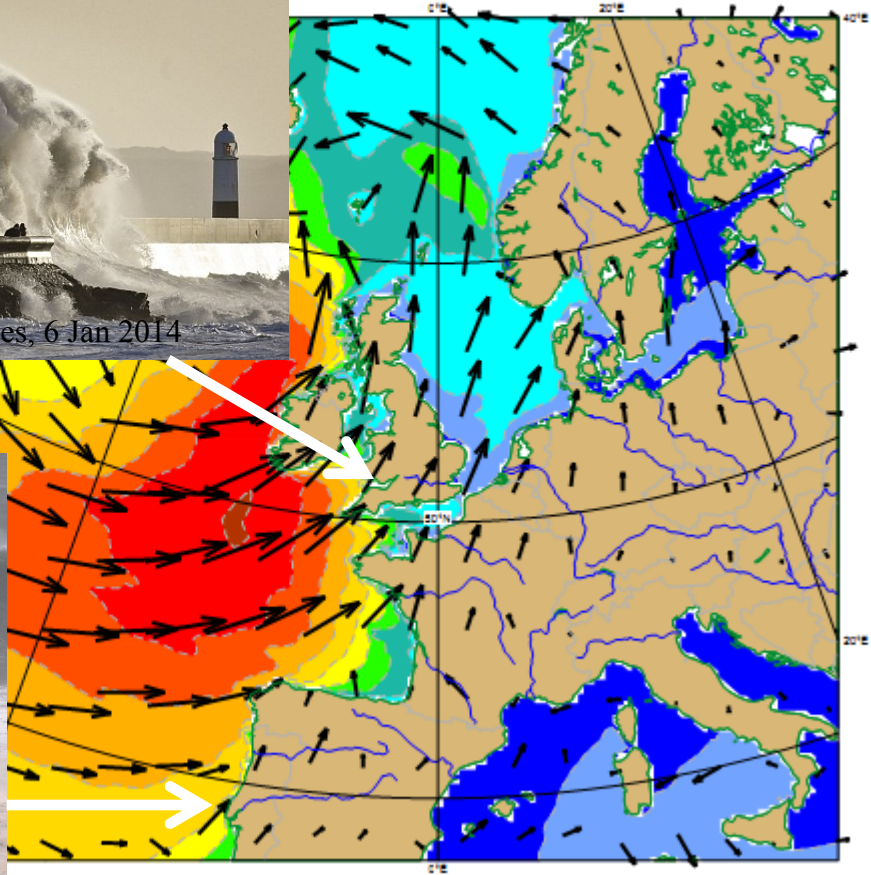
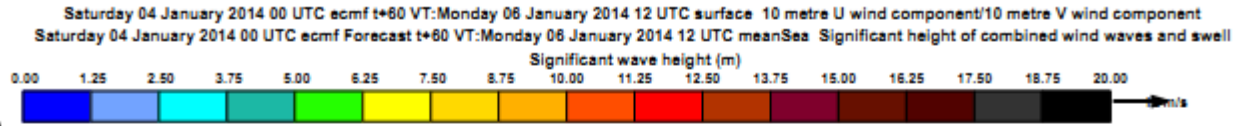
Ocean wave forecasts

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

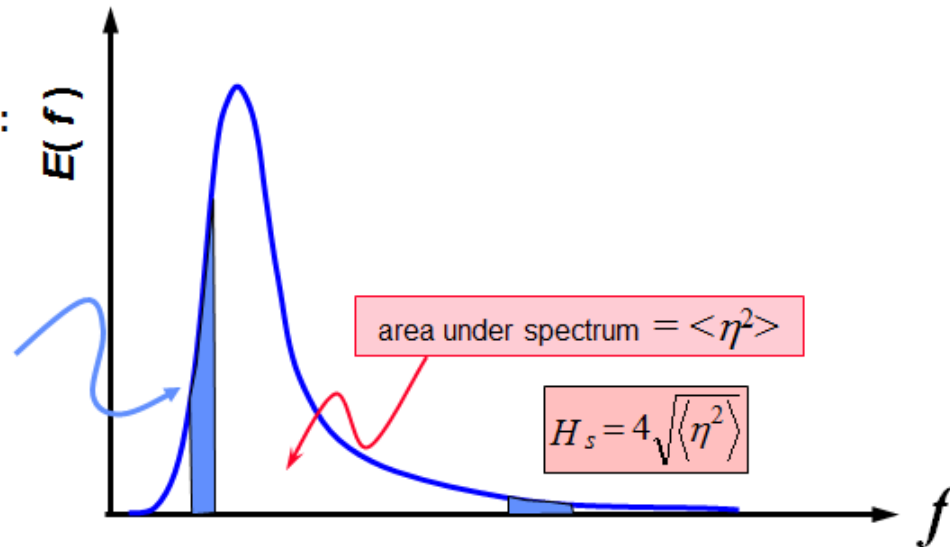


Long swell forecasts

EWH,
Equivalent Wave Height
for a given frequency bin:

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

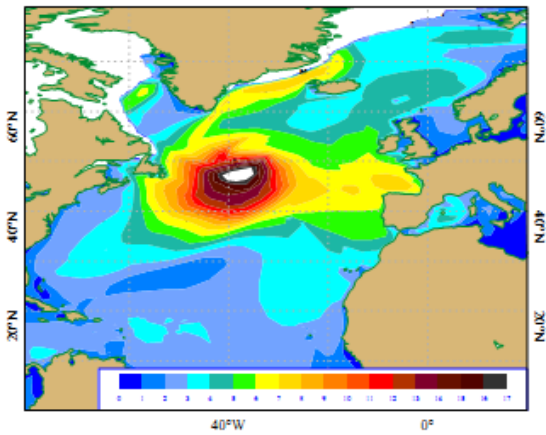
where A is the
area under curve for
a given frequency bin



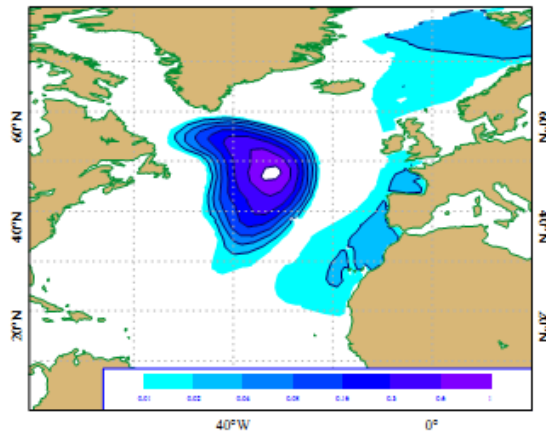
Long swell forecasts

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

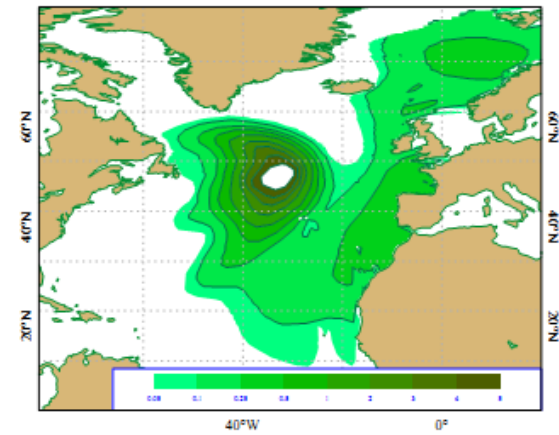
Saturday 4 January 2014 00UTC ECMWF Forecast 04 UT, Sunday 5 January 2014 00UTC Surface Significant wave height



Wave energy in terms of wave height for waves with periods between 25 and 29 sec. (1000 to 1300 m wavelength)



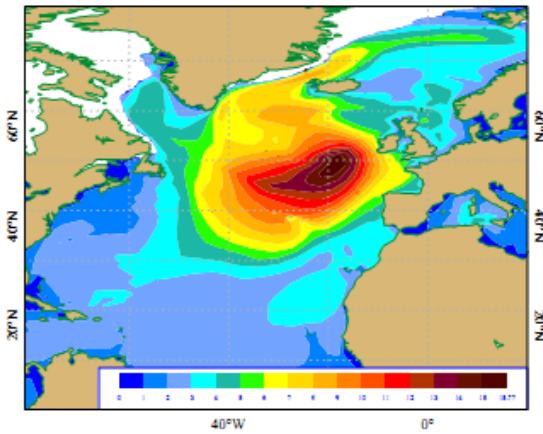
Wave energy in terms of wave height for waves with periods between 21 and 25 sec. (700 to 1000 m wavelength)



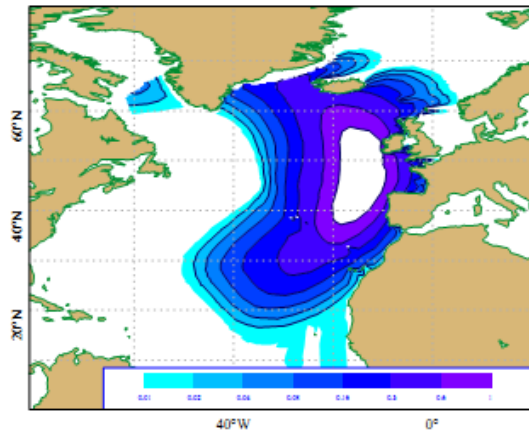
Long swell forecasts

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

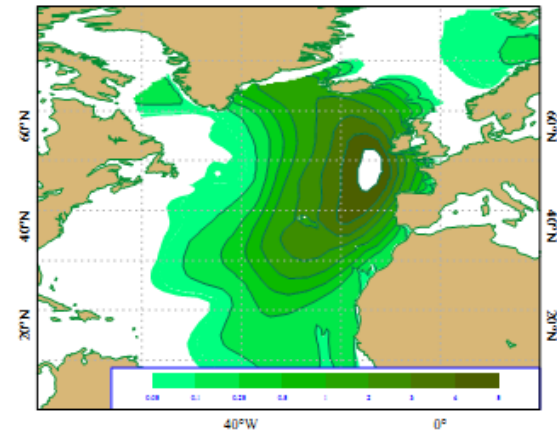
Saturday 4 January 2014 00UTC ECMWF Forecast (48 VT) Monday 6 January 2014 00UTC Surface Significant wave height
Significant wave height (m)



Wave energy in terms of wave height for waves with periods between 25 and 29 sec. (1000 to 1300 m wavelength)



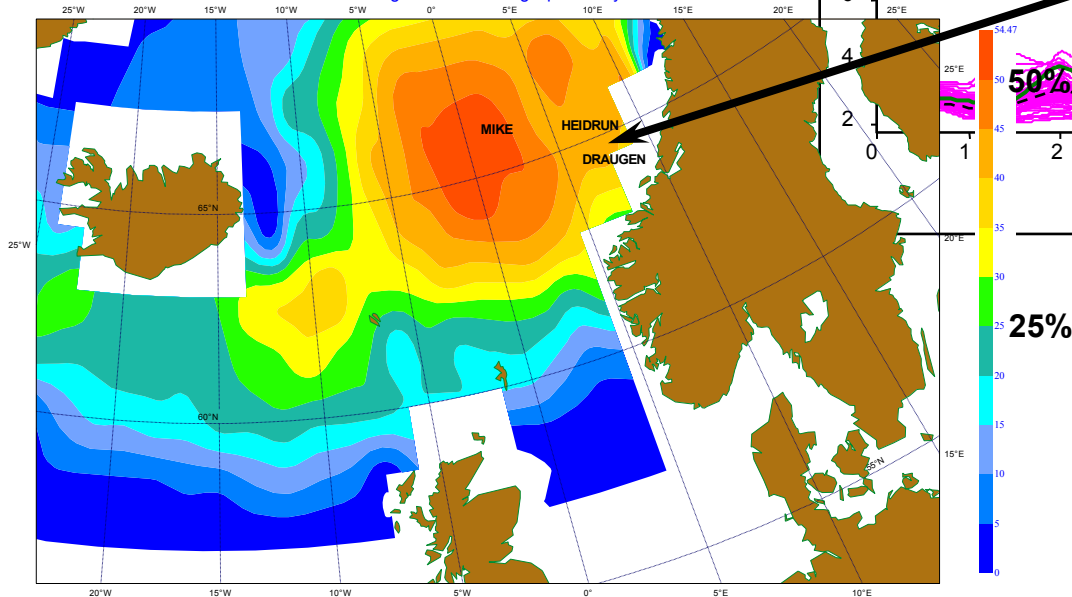
Wave energy in terms of wave height for waves with periods between 21 and 25 sec. (700 to 1000 m wavelength)



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 :

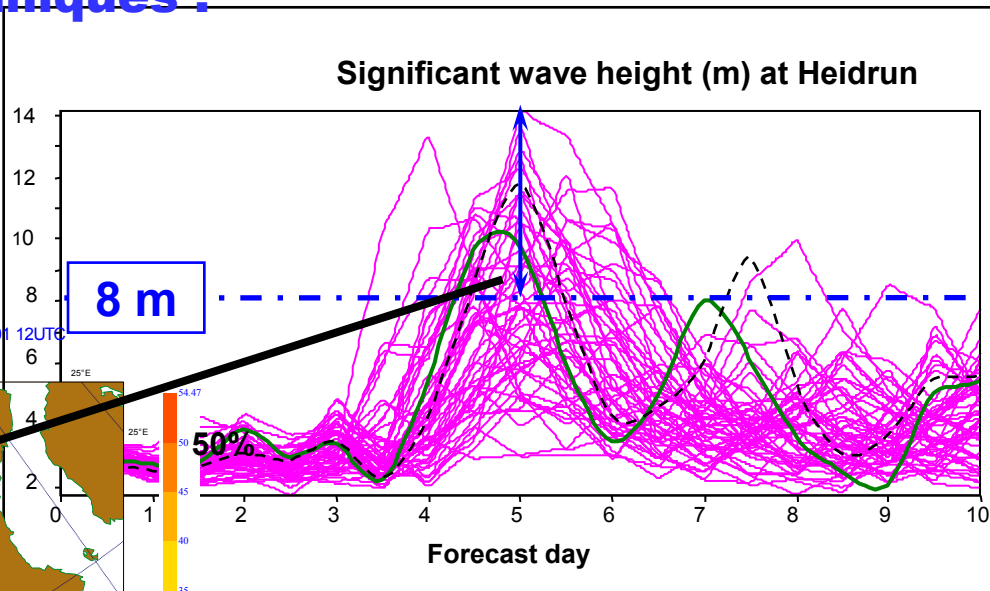
From an ensemble of wave forecasts it is possible to derive probabilities for certain wave conditions.

Tuesday 6 November 2001 12UTC ECMWF EPS Probability Forecast t+120 VT: Sunday 11 November 2001 12UTC
Surface: significant wave height probability >8



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

Significant wave height above 8 m

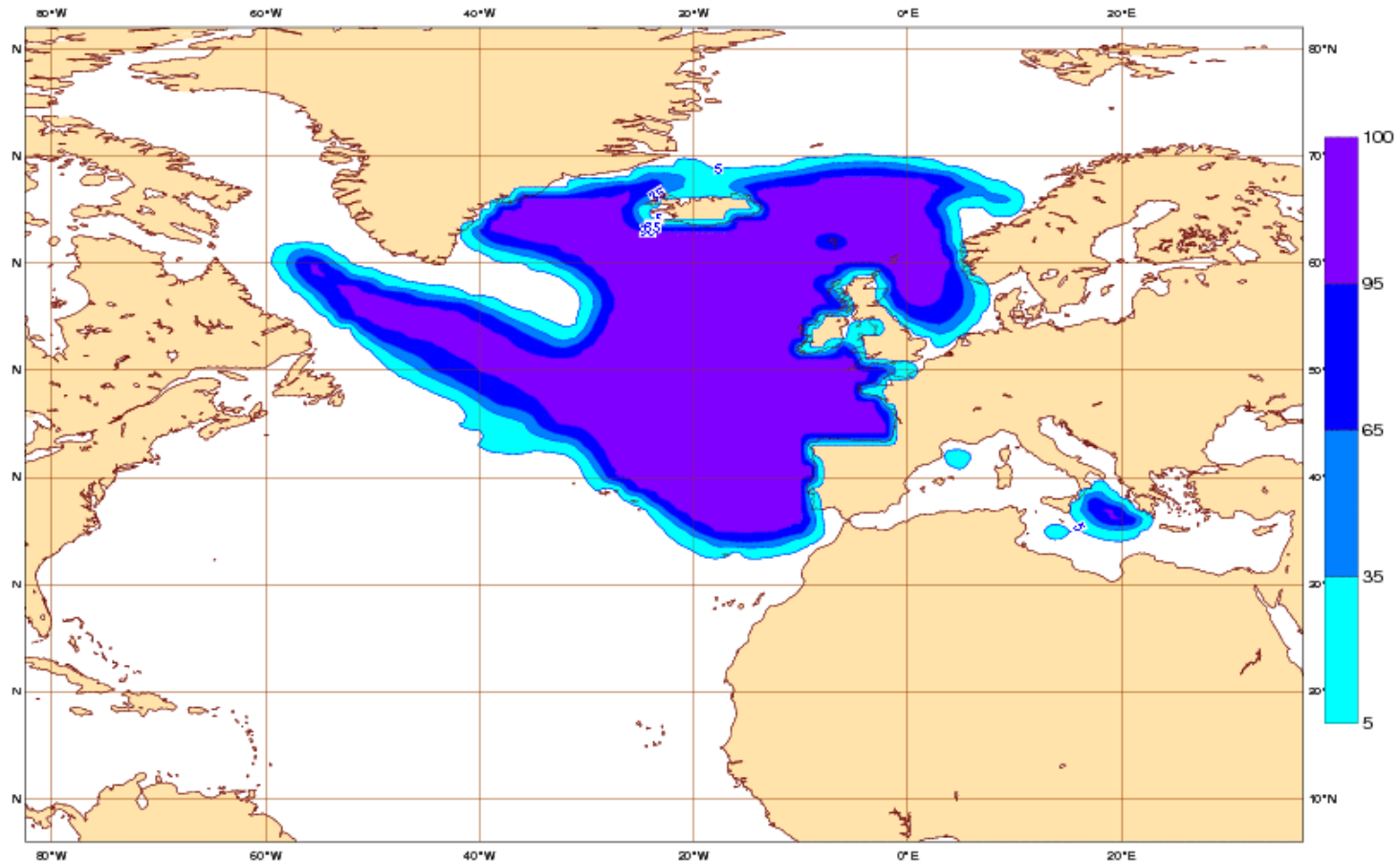


ECMWF Newsletter 95 – Autumn 2002

Basic EPS Wave Model Products

probability for set thresholds (4m)

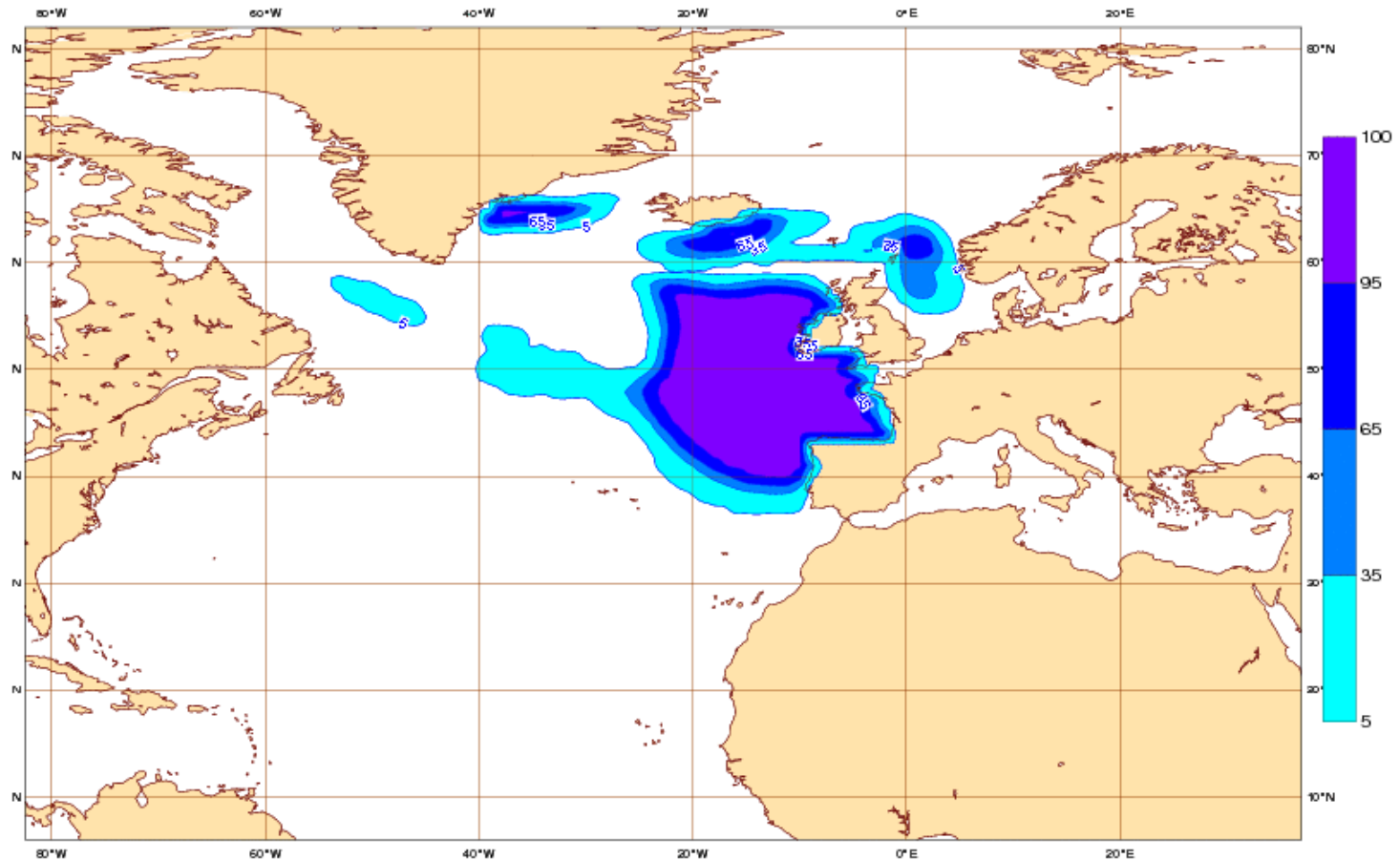
Friday 31 January 2014 00UTC ©ECMWF Forecast probability t+048 VT: Sunday 2 February 2014 00UTC
Surface: Significant wave height of at least 4 m



Basic EPS Wave Model Products

probability for set thresholds (6m)

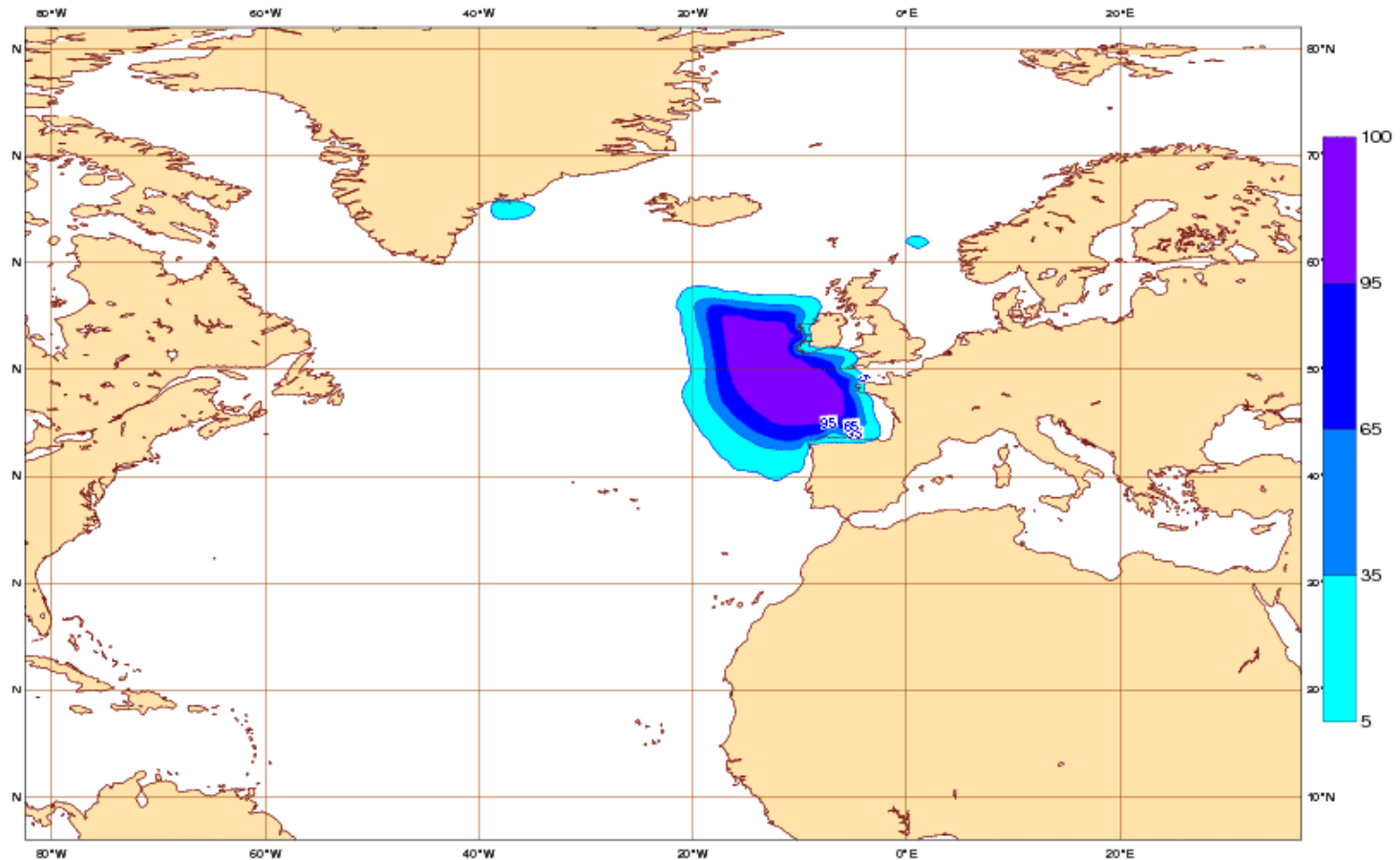
Friday 31 January 2014 00UTC ©ECMWF Forecast probability 1+048 VT: Sunday 2 February 2014 00UTC
Surface: Significant wave height of at least 6 m



Basic EPS Wave Model Products

probability for set thresholds (8m)

Friday 31 January 2014 00UTC ©ECMWF Forecast probability 1+048 VT: Sunday 2 February 2014 00UTC
Surface: Significant wave height of at least 8 m

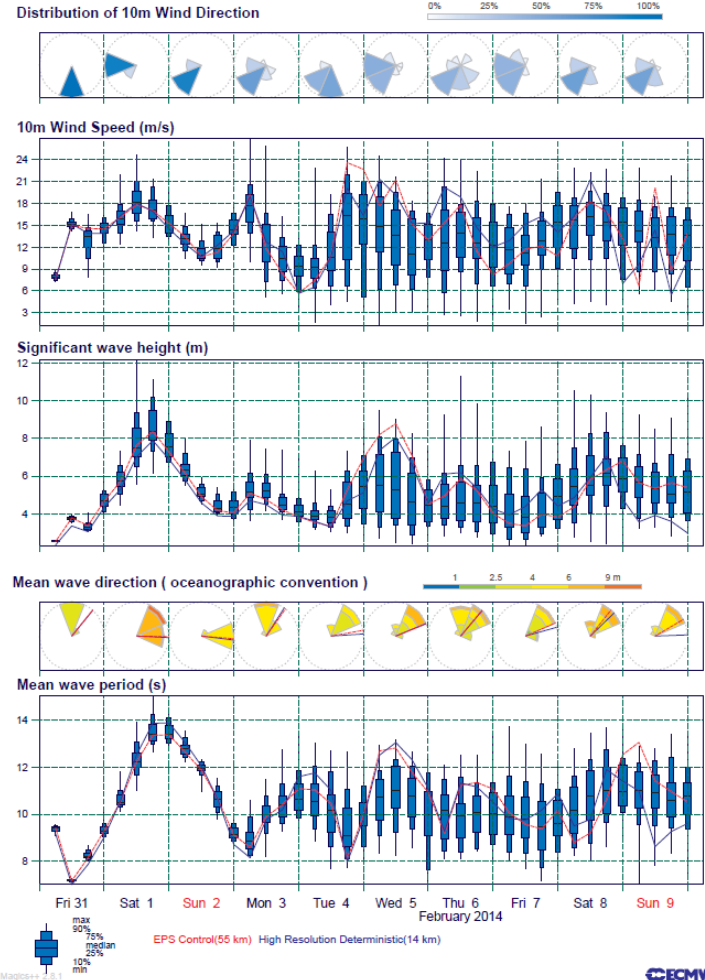


A bit more compact: Wave EPSgram:

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

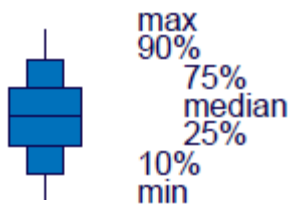
The screenshot shows the ECMWF website interface. In the 'Product' dropdown menu, '10 days wave' is selected and circled in red. A red arrow points from this selection to the right-hand side of the slide. The main content area shows a 'Wave EPSgram' for Scilly Isles, including charts for Total Cloud Cover, Total Precipitation, 10m Wind Speed, 2m Temperature, and a legend for EPS Control and High Resolution Deterministic forecasts.

Wave Epsgram
Scilly Isles 49.88°N 6.25°W (EPS sea point)
Deterministic Forecast and EPS Distribution Friday 31 January 2014 00 UTC

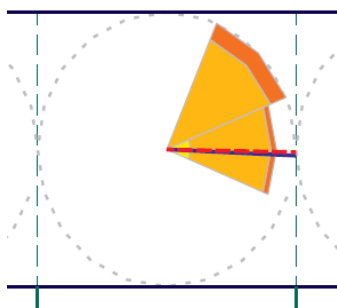
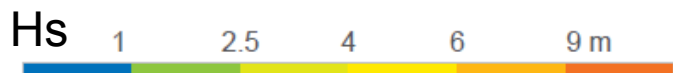


Isles of Scilly, west of Cornwall

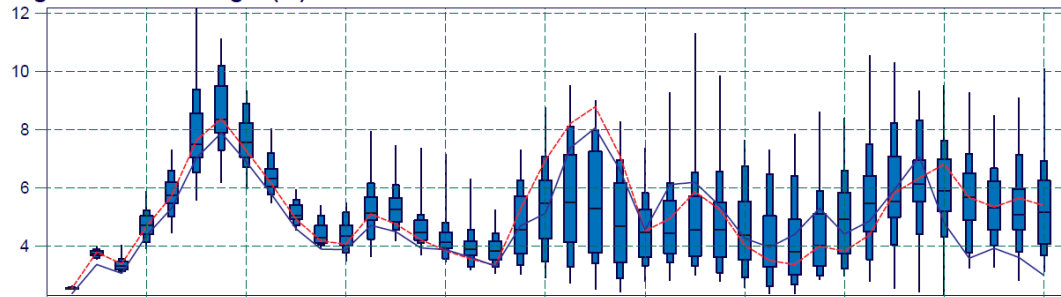
A bit more compact: Wave EPSgram:



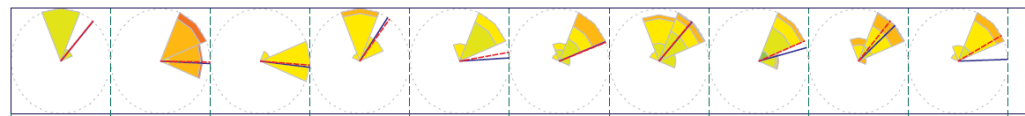
EPS Control(55 km) High Resolution Deterministic(14 km)



Significant wave height (m)



Mean wave direction (oceanographic convention)



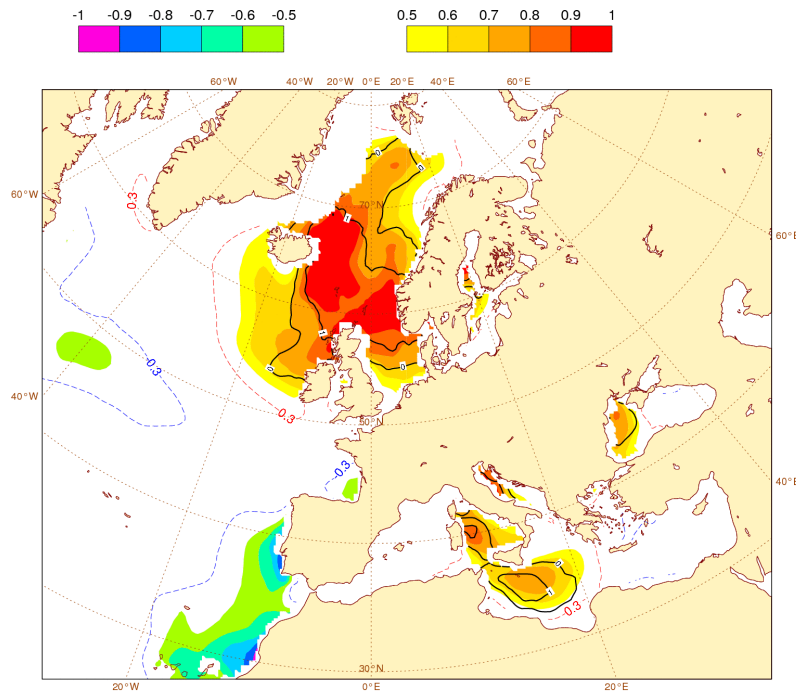
Each octant is coloured based on the distribution of the significant wave height associated with each mean direction. The coloured areas correspond to the fractional number of ensemble members with wave height in the range specified by the coloured ruler.

EFI plots

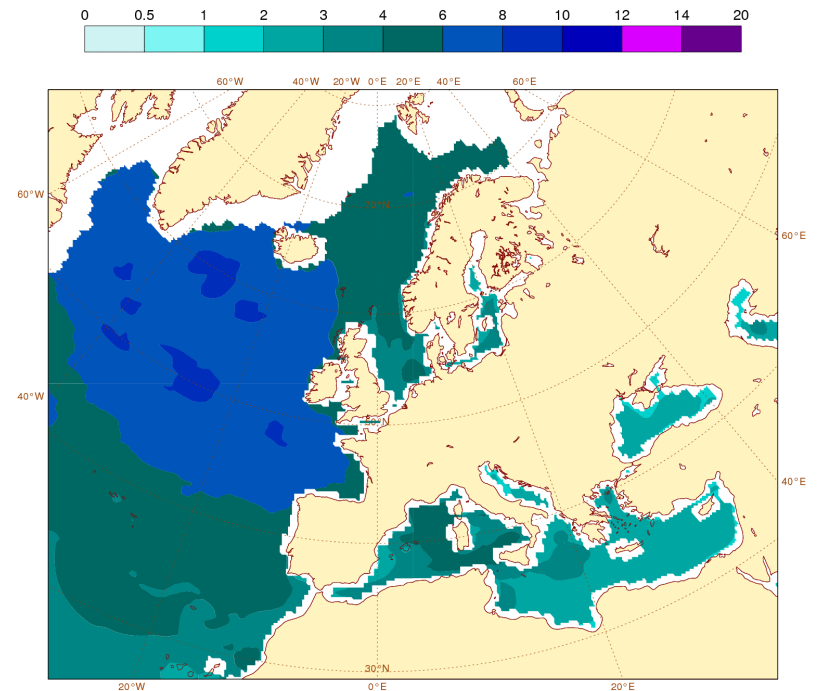
From the new model climate, it is possible to derive indices that indicate deviations in probabilistic terms from what is 'expected'.

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

Fri 11 May 2012 00UTC ©ECMWF t+72-96h VT: Mon 14 May 2012 00UTC - Tue 15 May 2012 00UTC
Extreme forecast index and Shift of Tails index (black contours 0,1,5,10,15) for max significant wave height



Thu 10 May 2012 00UTC ©ECMWF VT: Mon 14 May 2012 00UTC - Tue 15 May 2012 00UTC 72-96h
max significant wave height (in m) Model climate Q99 (one in 100 occasions realises more than value shown)

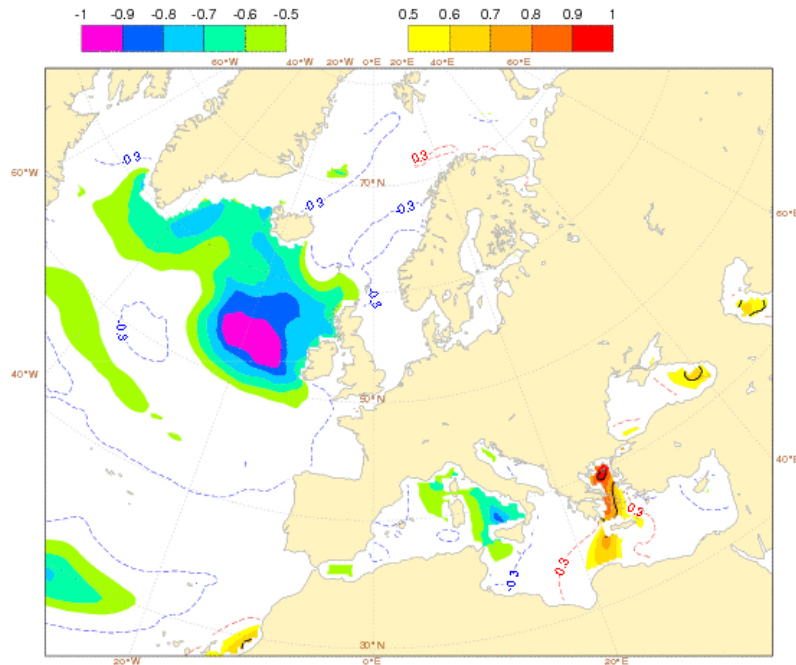


Since June 2012 : new set of EFI plots

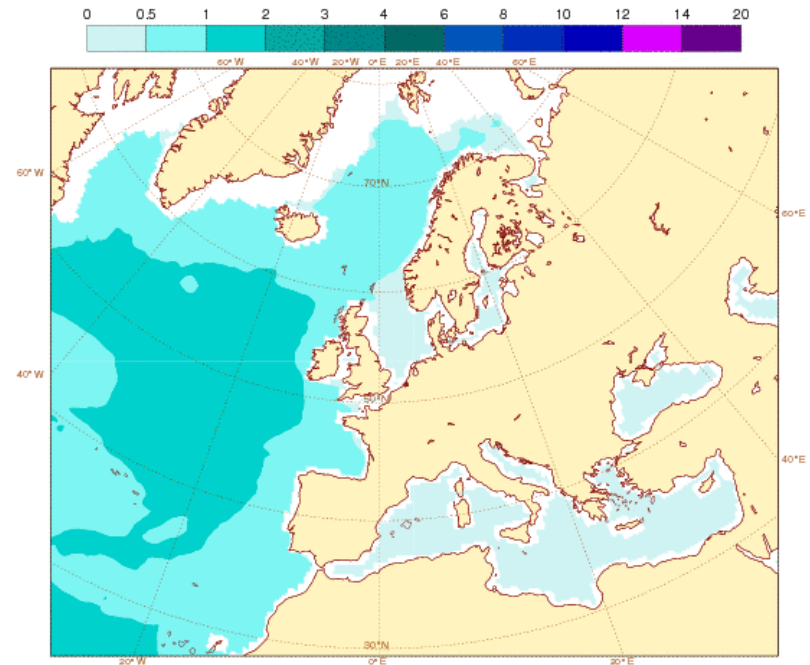
From the new model climate, it is possible to derive indices that indicate deviations in probabilistic terms from what is 'expected'.

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

Fri 15 Jun 2012 12UTC ©ECMWF t-60-84h VT: Mon 18 Jun 2012 00UTC - Tue 19 Jun 2012 00UTC
Extreme forecast index and Shift of Tails (black contours 0,1,5,10,15) for max significant wave height



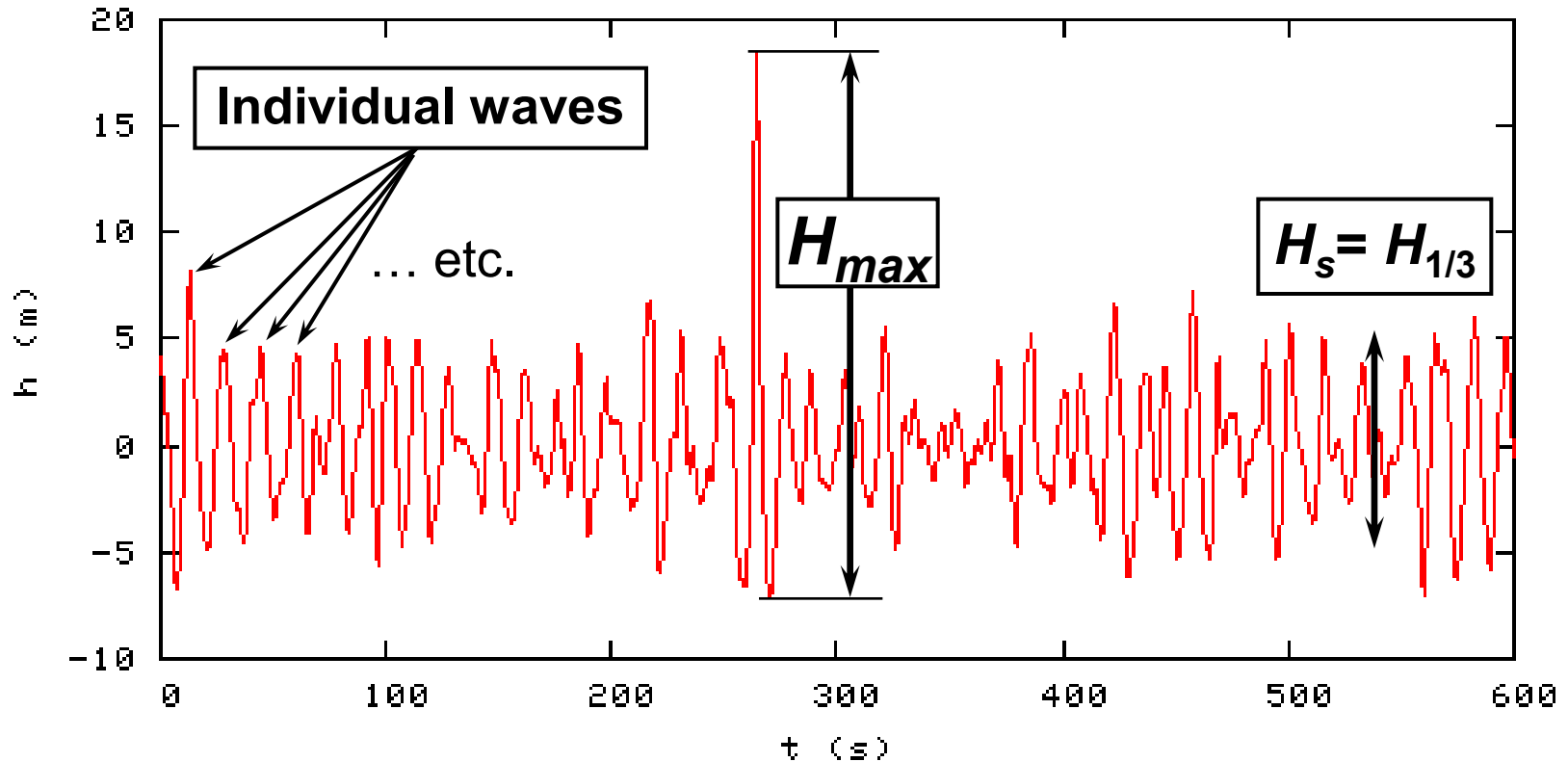
Thu 14 Jun 2012 00UTC ©ECMWF VT: Mon 18 Jun 2012 00UTC - Tue 19 Jun 2012 00UTC 60-84h
max significant wave height (in m) Model climate Q1 (one in 100 occasions realises less than value shown)



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



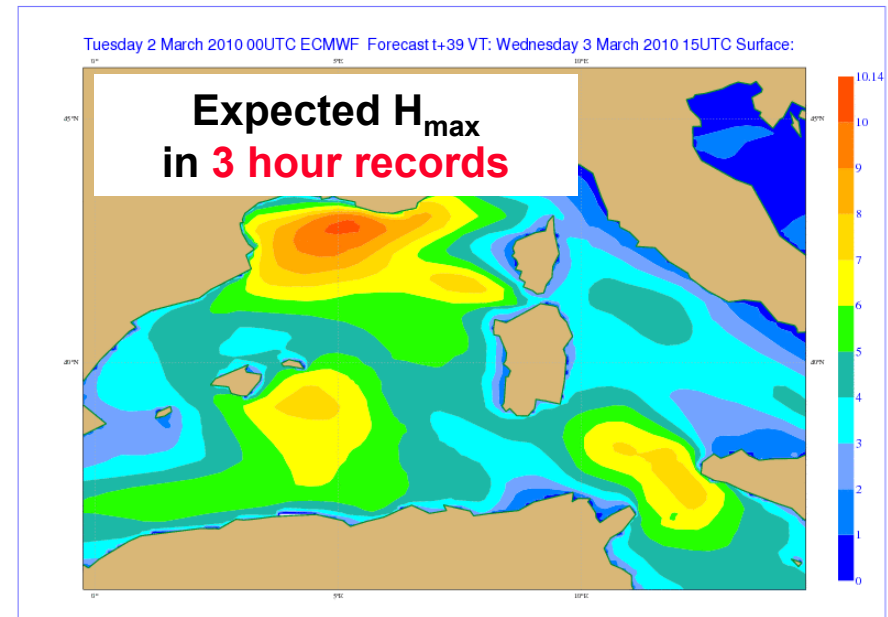
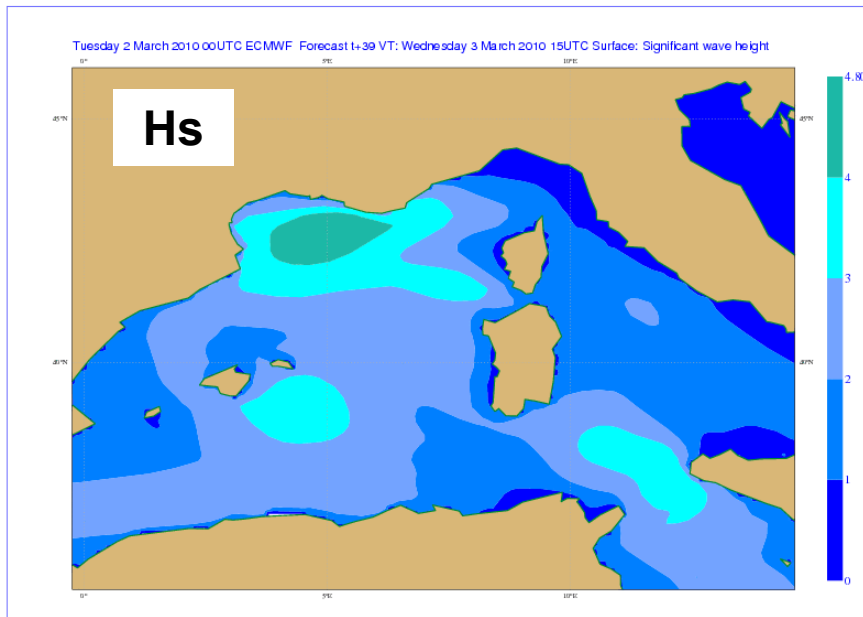
Individual Waves, Significant Wave Height, H_s , Maximum Individual Wave Height, H_{max} , and Freak Wave



If $H_{max} > 2.2 H_s \rightarrow$ 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>

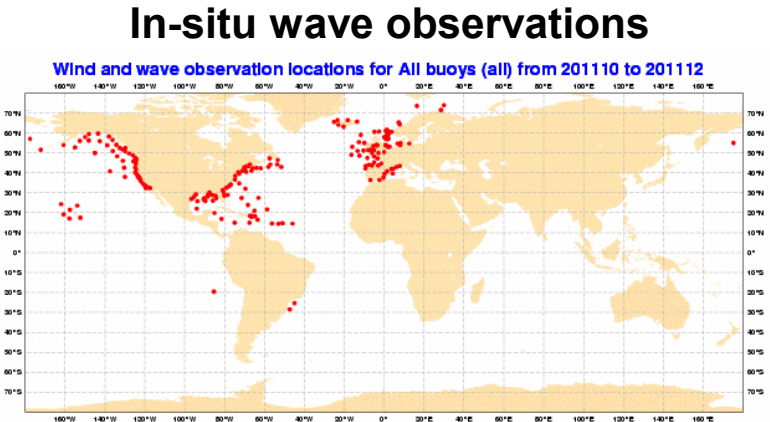
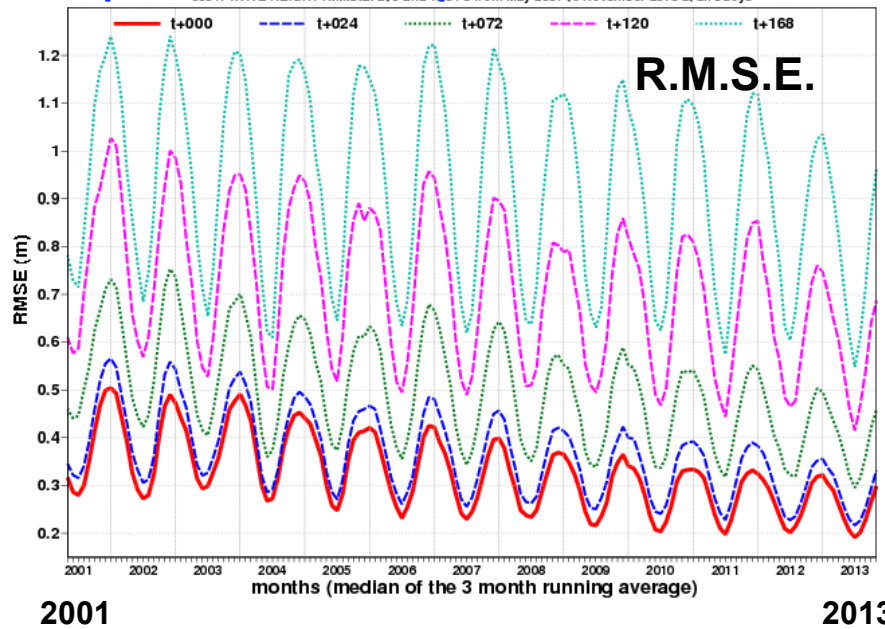
Verification: What Do You Compare Against ?

- **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>

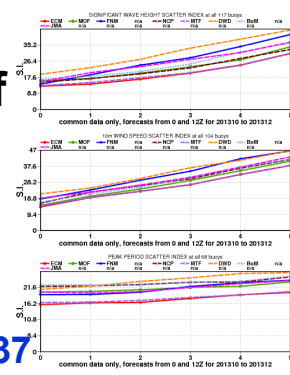


- 7 day FC
- 5 day FC
- 3 day FC
- 1 day FC
- analysis

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)

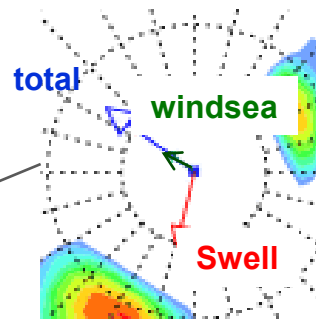
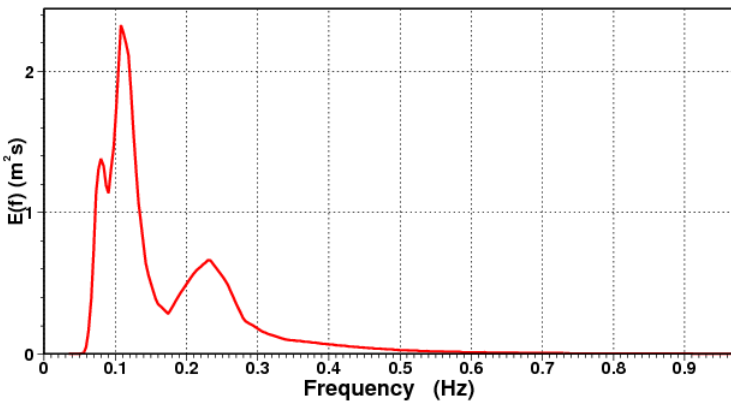
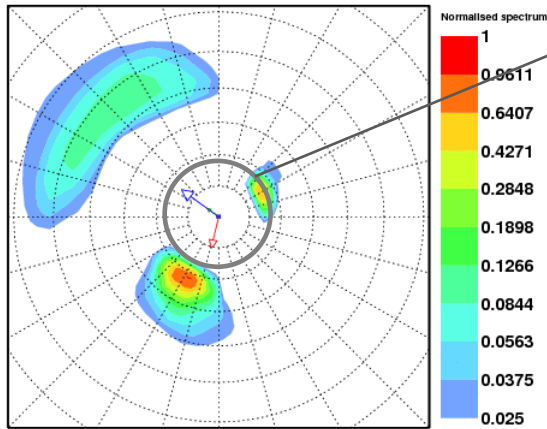
http://www.jcomm.info/index.php?option=com_content&task=view&id=131&Itemid=37



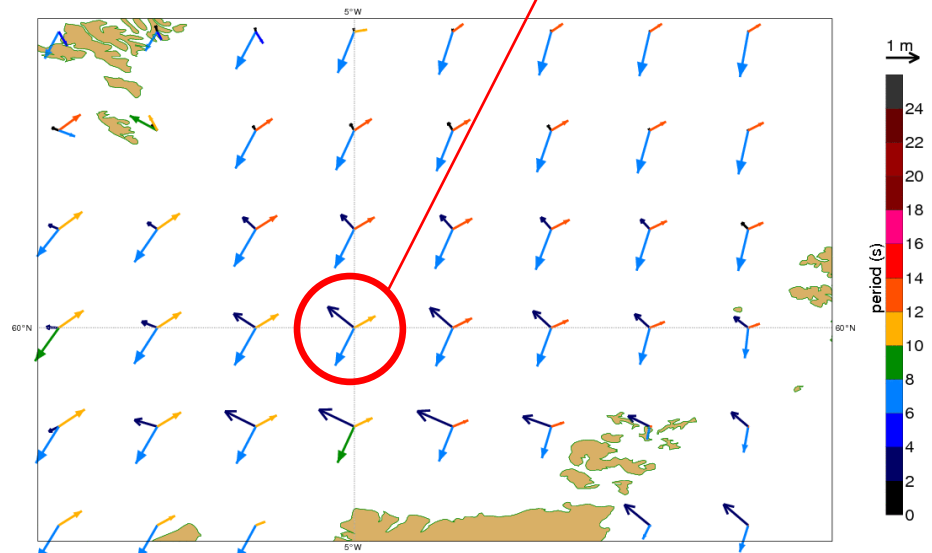
Future developments: spectral partitioning

Operational:

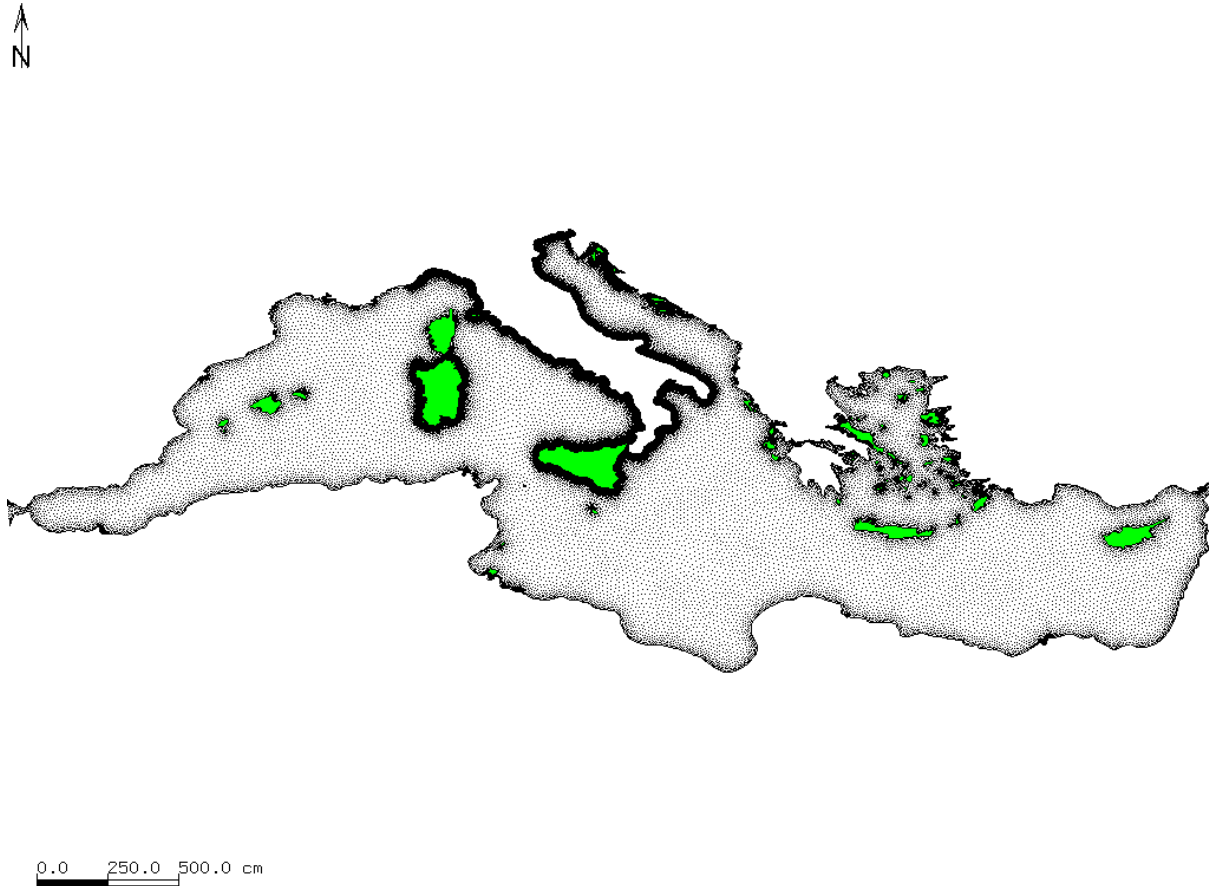
NORMALISED 2-D SPECTRUM for fp2t wave rd
 00:00UTC on 06.06.2012
 at XXXXX (60.00°, -5.00°), 332.0 m
 Hs= 1.79 m, Tm= 7.43 s, Tp= 9.23 s
 Mean Wave Dir. = 233° Peak Wave Dir. = 200°
 Hws= 0.98 m, Tws= 3.8 s, Mean Windsea Dir.(green)= 306°
 Hsw= 1.50 m, Tsw= 9.0 s, Mean Swell Dir.(red)= 193°
 Wind Speed = 8.37 m/s, Wind Dir.(blue)= 306°, $u^* = 0.338$ m/s
 Directions in oceanographic convention (North upwards)
 Concentric circles are every 0.05 Hz



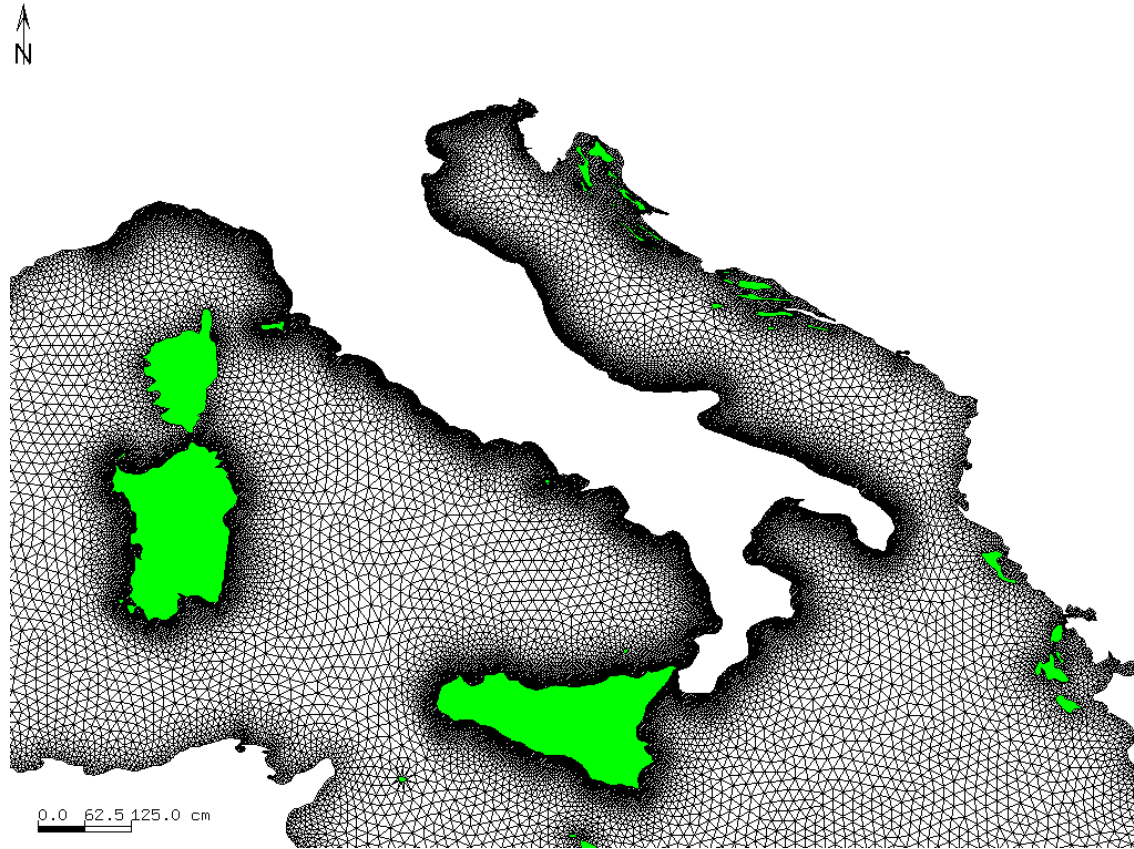
New decomposition:



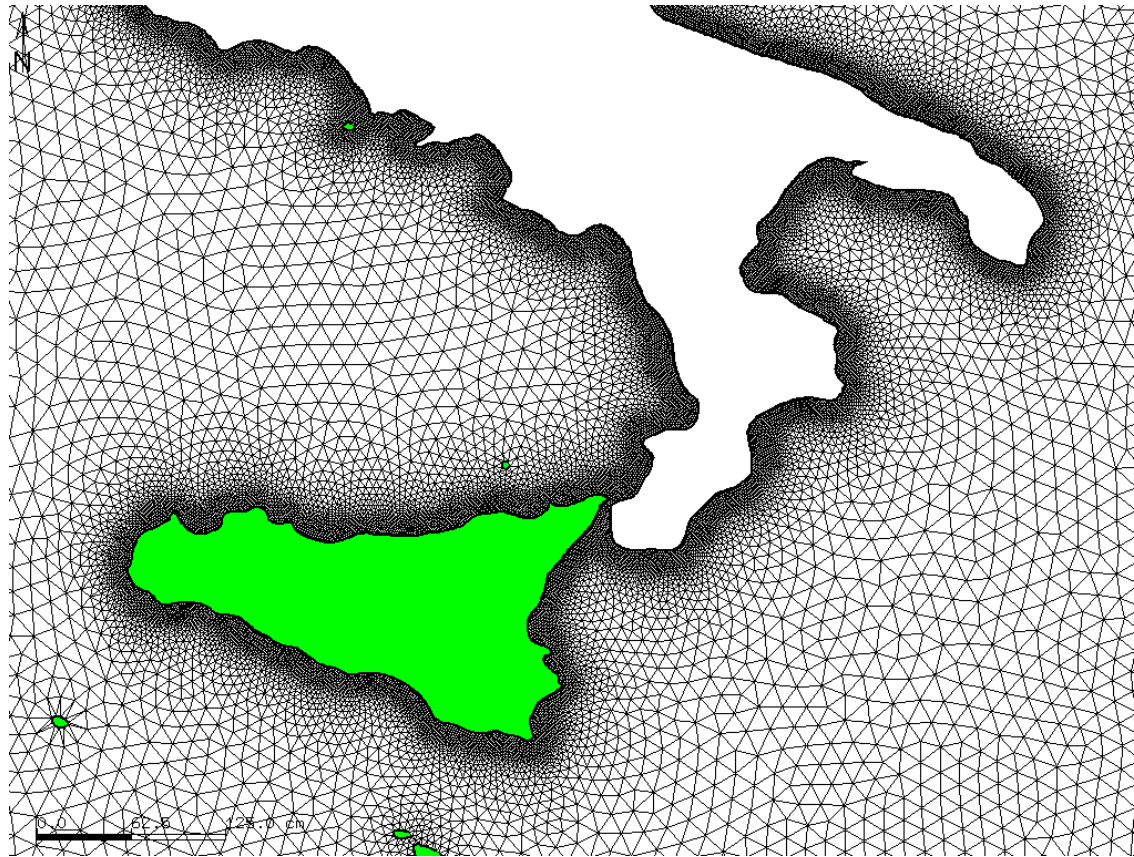
Future developments: unstructured grid



Future developments: unstructured grid



Future developments: unstructured grid



A photograph of a sunset over a rocky coastline. The sun is low on the horizon, casting a bright orange and yellow glow across the sky and reflecting on the wet rocks in the foreground. The sky is filled with soft, grey clouds. The text "Questions/comments ?" is overlaid in a bold, blue font across the upper portion of the image.

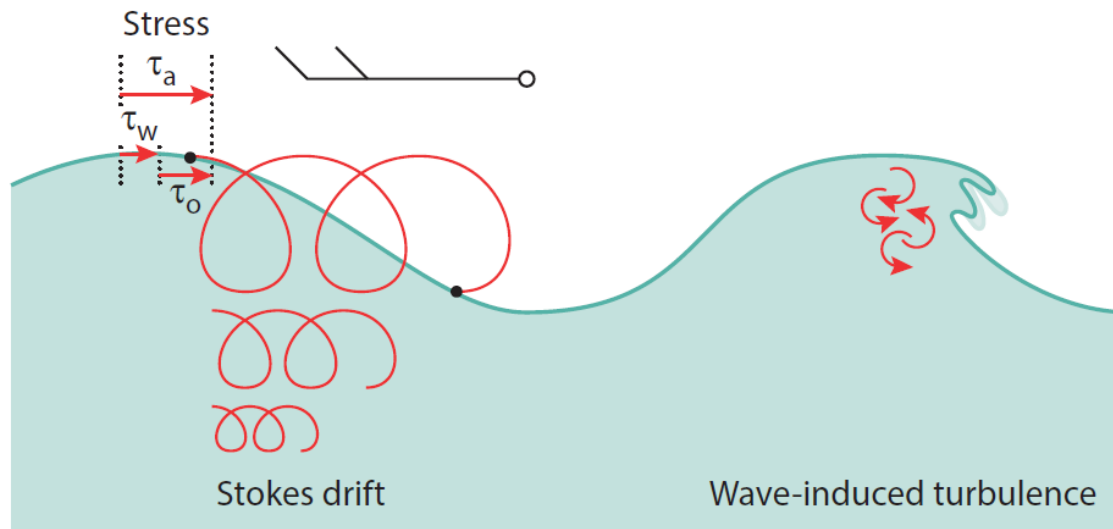
Questions/comments ?

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 ($\sim 1\text{ m/s}$). 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>