2.2 Ocean Wave Model - ECWAM

Purpose

The ECMWF Ocean Wave Model (ECWAM) describes the development and evolution of wind generated surface waves and their height, direction and period. It does not dynamically model the ocean itself (see section on NEMO). It is coupled to the atmospheric forecast model (all configurations) and to the ocean model.

Structure

The ECMWF Ocean Wave Model (ECWAM) evaluates the 2-dimensional surface wave spectrum, in both oceanic and coastal waters. This describes how much wave energy is present for given sea wave frequencies and associated propagation directions. That part of the spectrum under the direct influence of the local wind is called "wind-wave" or "windsea"; the remaining part is usually referred to as "swell". Changes in the wave spectrum are derived from the processes of:

- wave advection,
- wave refraction,
- wind-wave generation,
- wave dissipation due to white capping and bottom friction,
- non-linear wave interactions.

ECWAM has two-way interaction with the Atmospheric models:

- ECWAM supplies surface roughness (according to the forecast sea state) which is used to specify boundary layer winds.
- Atmospheric models supply surface wind conditions, and these dominate sea-surface wave development.

ECWAM has two-way interaction with NEMO and the LIM2 sub-program:

- ECWAM supplies surface stress, Stokes drift and turbulent energy flux to the ocean surface.
- NEMO and the LIM2 sub-program supply ice concentration and thickness information.
Note: The bathymetry (water depth) used in the wave models was upgraded in cycle 45r1 released June 2018. Changes mostly affect wave fields in coastal areas (higher waves where the model water depth is greater than before and vice-versa). Also some ECWAM gridpoints have changed from sea to land and vice-versa. Wavegrams associated with these points will change accordingly (e.g. no wave data at grid points now on land). Users should be aware when inspecting model forecast wave data before the release of this cycle that in such areas anomalous behaviour may have been present. More information on the effects of and the locations of the changes is given in Appendix 12F.

ECWAM does not dynamically model the ocean itself but is solely concerned with ocean wave forecasting (NEMO describes dynamical modelling of the ocean). It is run in association with all atmospheric models - HRES and ENS, Extended-range ENS and Seasonal. The domain extends across the full globe.

(NB: The Stand-alone Wave model (SAW) not coupled to HRES nor ENS was withdrawn 7 Jan 2020).

Wave Data Assimilation

Space-borne altimeter wave height data are assimilated. Buoy wave data are not assimilated; instead, they serve as an independent check on the quality of modelled wave parameters.

Output from ECWAM

ECWAM is run:

- twice daily giving forecasts to Day10 for the HRES and Day15 for ENS based on 00 and 12UTC data times.
- on Mondays and Thursdays, Day15 to Day46 based on 00UTC data time.
- monthly for forecasts to 7 months ahead, and run quarterly for forecasts to 1 year ahead (in the seasonal forecast model, System 5).

Output is in the form of wave and swell height, direction and period, and wave energy flux and direction are also available. Users should note that by convention the direction of waves (and hence also wave energy flux) is described as the direction the waves are moving towards. This is opposite from the convention for wind direction which is defined as where the winds are coming from. Thus a southwesterly wind blows from the southwest; the corresponding wind-sea moves towards the northeast and is thus described as a northeasterly wind-sea.

Current coverage and resolution (see Operational configurations of IFS, ocean wave component):

- HRES-WAM global coverage on 0.125° x 0.125° latitude-longitude grid.
- HRES-SAW 90°N to 78°S on a 0.1° x 0.1° latitude-longitude grid. (Withdrawn 7 Jan 2020).
- ENS-WAM 0-15days global coverage 0.25° x 0.25° latitude-longitude grid.
- ENS-WAM 15-45days global coverage 0.5° x 0.5° latitude-longitude grid.
- SEAS-WAM Seasonal global coverage 1.0° x 1.0° latitude-longitude grid.

Wave Height Definitions

The wave height is the distance between trough and crest. However, many waves co-exist at the surface of the ocean and their distribution is given by the 2D wave spectrum. From this distribution, the significant wave height is defined as 4 times the square root of the integral over frequency and direction of the wave spectrum. It can be shown to correspond to the average wave height of the one-third highest waves, commonly known as $H_{1/3}$. The mean wave direction is the spectrally averaged propagation direction of the waves (weighted by amplitude).
Fig 2.2.1: An example of wave heights at a platform in the North Sea. Wave height is the distance between trough and crest. The significant wave height \( H_s \) is defined as 4 times the square root of the integral over frequency and direction of the wave spectrum. It can be shown to correspond to the average wave height of the one-third highest waves, commonly known as \( H_{1/3} \). Occasionally wave of different periods reinforce and interact non-linearly giving a wave considerably larger than \( H_s \) giving a maximum trough to crest height \( H_{\text{max}} \).

The irregular surface of the sea can be decomposed into a number of components with different frequencies (f) and also directions (θ). The distribution of wave energy among these components is the Wave Spectrum \( E(f,\theta) \). These can be plotted in two dimensions (Fig 2.2.2A). For simplicity and ease of use the complete frequency-energy description of the sea state in 2-dimension form is simplified to 1-dimensional form by integrating over all directions and/or over a frequency range (Fig 2.2.2B).
**Wave Spectrum**

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

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

**One Dimension Frequency – Energy Plot**

\[ E(f) \]

- Peak frequency \(f_p\)
- Mean frequency \(<f>\)

**Fig 2.2.2A:** The irregular surface of the sea can be decomposed into a number of components with different frequencies \(f\) and also directions \(\theta\) and the distribution of wave energy among these components is the Wave Spectrum \(E(f)\) here plotted in two dimensions.

**Fig 2.2.2B:** For simplicity and ease of use the complete frequency-energy description of the sea state in 2-dimension form can be simplified to 1-dimensional form by integrating over all directions and/or over a frequency range.

Other parameters are defined to characterise the sea state as prescribed by the wave spectrum. In particular, the reciprocal of the frequency corresponding to the peak of the spectrum is the wave peak period. Different mean periods are calculated by spectrally averaging the spectrum and similarly for mean wave direction (see *IFS documentation part VII*, chapter10).
Very often, the sea state is composed of different wave systems. If there is any sufficient wind, there will always be a wave system associated with it, referred to as "wind-wave" or "wind-sea". The part of the spectrum that is not associated with the local wind is normally called "swell".

Swell propagates at different speeds for different frequencies and if approaching from a remote source each frequency will arrive at a given location at different times but with a well-defined peak in frequency and direction. Wind-sea is more variable in frequency and direction with a broad distribution of the waves around a peak. These can be plotted in 2-dimensional form or simplified to 1-dimensional form (Fig2.2.3).

![Fig2.2.3: A schematic example of the Wave Spectrum at a location off the Dutch coast associated with a long wave swell propagating from the northern North Sea and wind-sea propagating across the southern North Sea. At a given time there will be a swell of relatively uniform frequency and direction, and a wind-sea of rather broader frequency and direction, giving a 2D plot of wave energy against frequency and direction as in the top right diagram. For simplicity this is reduced to a 1D plot of wave energy against frequency. These peak values of swell and wind-sea can be plotted in chart form.]

Based on theory of wave-wave interaction, the estimate of highest equivalent weight ($H_{\text{max}}$) is calculated from the wave spectrum.
Fig2.2.4: Wave Energy associated with a given frequency $E(f)$ plotted against wave frequency ($f$). The Equivalent Wave Height (EWH) associated with a given wave frequency is derived from the area under the curve for that frequency bin. The significant wave height $H_s$ is derived from the total area beneath the curve.

A wide range of wave model output parameters are currently available. Parameters available as Web and ecCharts products are:

- **ecCharts:**
  - Significant wave height
  - Significant wave height of all waves with period shorter than 10 seconds
  - Significant wave height of all waves with period between 10 and 12 seconds
  - Significant wave height of all waves with period between 12 and 14 seconds
  - Significant wave height of all waves with period between 14 and 17 seconds
  - Significant wave height of all waves with period between 17 and 21 seconds
  - Significant wave height of all waves with period between 21 and 25 seconds
  - Significant wave height of all waves with period between 25 and 30 seconds
  - Significant height of wind waves
  - Significant height of total swell
  - Mean wave period
  - Mean period of wind waves
  - Mean period of total swell
  - Mean wave direction and height
  - Mean direction and height of wind waves
  - Mean direction and height of total swell
  (note the convention for description of wave direction is the direction towards which the waves are moving)

- Probability of combined events of 10m wind speed and significant wave height
- Significant wave height probability
- Mean wave period probability
- Significant wave height percentile
- Mean wave period percentile

- Wave energy flux magnitude
- Wave energy flux mean direction and magnitude - important for assessment of the impact of the waves on coastlines and offshore structures.
  (note the convention for description of wave energy flux direction is the direction towards which the waves are moving)
- 24hr maximum sig wave height from M-climate at various percentiles. M-climate data are produced twice a week on Mondays and Thursday.
  (the above products are available at the following post-processing steps: 3-hourly from T+0h to T+144h; 6 hourly from T+150h to T+240h).

- Significant wave height extreme forecast index
  (product is available at post-processing steps: 12-hourly from T+0h to T+168).
ECMWF Medium-range Forecast Graphical Products:

- Significant wave height / Mean wave direction and height
- Significant height of total swell / Mean direction and height of total swell
- Significant height of wind waves / Mean direction and height of wind waves
- Mean wave period / Mean wave direction and height
- Mean period of total swell / Mean direction and height of total swell
- Mean period of wind waves / Mean direction and height of wind waves
- (the above products are available at the following post-processing steps: 12-hourly from T+0h to T+168h)
- Significant wave height probability >= a height (height under user control)
- Mean wave period probability >= a period (period under user control)
- (the above products are available at post-processing steps: 12-hourly from T+0h to T+360h)
- Significant wave height extreme forecast index (M-climate quantile under user control)
- (product is available at post-processing steps: 24-hourly from T+0h to T+168).

Wavegrams are also available to show a time series of significant wave height, mean wave direction, and mean wave period for any sea location.

Fig2.2.5: Sequence of ocean wave forecasts. Significant wave height forecast (colours) and 10m wind (arrows) from data time 00UTC 4 January 2014, step 12 hours. Wave heights at 1.25m intervals as scale.

Swell propagates outwards well away from the source. Increased swell (e.g. reaching a coast) can give forewarning of a storm system well before any indication in the atmosphere. Fishermen have long used the arrival of long-period swell as an indication of an approaching storm even if the sky is clear, and surfers often benefit from significantly large swell in calm conditions well away from the swell source region.
Fig 2.2.6: 180h forecast for significant wave height (contours) for all waves with periods between 21 and 25 seconds (shading), initialised at 00UTC 2 December 2016. The highest significant wave heights (contours) are still confined to the storm location in the Atlantic south of Iceland, while long waves from that storm are already affecting coastlines from Iberia to South Greenland (coloured).

Waves with different periods propagate with different speeds – longer periods travel fastest. These can be tracked through the forecast period and areas where different wave trains potentially interact can be identified.
Fig2.2.7: Chart showing forecast significant wave heights for several ranges of wave periods (Blue, 10-12s; Green, 12-14s; Yellow, 14-17s; Red, 17-21s). Forecast data based on data time 00Z 25 October 2017. The faster southward propagation of the long period waves over the shorter period waves from their source off NW Africa is clear.

The Extreme Forecast Index (EFI) can be used to indicate the significance of forecast significant wave heights when compared with the range of wave heights that might usually be expected as defined by the M-climate.

Fig2.2.8: In this example the colours west of Ireland denote a low-point in wave heights, or potentially a form of ‘weather window’ for certain types of marine/shipping operations. Equally this EFI can signify periods with anomalously big waves (yellow to red shading).
Additional information using wind-sea and swell charts

Use of the mean wave height and direction is the simplest method of describing the forecast wave regime in a given area and it is easy to be beguiled into just using this output for forecasts to customers. However, the mean wave direction and height is made up of contributions from wind-sea and swell with different wave periods and they interact in a complex manner. It is important to investigate the forecast wind-sea and swell separately to give an understanding of likely sea conditions in an area (e.g. for a ship requiring a particularly smooth passage) or at a location (e.g. an oil rig).

When wind-sea and swell move in similar directions the wave heights can give information on the likely sea state as one is superimposed on the other, particularly where both have a significant and comparable wave height. On occasion the swell and wind-sea may be moving in opposite directions (an opposing sea) and wave heights give information on the likely rougher sea state to be expected. Often the wind-sea and swell are at right-angles (a cross sea) and where the wind-sea and swell heights are similar the sea can be very disturbed and difficult for shipping. An illustration is given in Figs2.2.9, 2.2.10 & 2.1.11.

Fig2.2.9: ecChart of mean wave direction (height is indicated by the length of the arrow). This gives an overview of wave conditions with northwesterly waves (i.e. moving towards the northwest) indicated near point A and easterly waves i.e. moving towards the east) near point C (by convention wave directions are described as the direction they are travelling towards). However, it is important to investigate the contributions to the mean wave directions and heights from inspection of the wind-sea and swell at this time.
The forecast wind-sea has developed in response to the forecast winds around a depression in mid-Atlantic with waves moving northwestwards near point A and southeastwards near point B with arrow length suggesting wave heights of around 3m (wave heights are also available as charts, not shown here). Near point C wind-sea waves are relatively small and move towards the northeast.

The forecast total swell has been developed in response to earlier weather systems elsewhere and has propagated across the Atlantic. Swell is moving northwards near point A and southwestwards near point C with arrow length suggesting wave heights of around 2m (wave heights are also available as charts, not shown here). Near point B swell waves are relatively small and move towards the southeast.

The forecast wind-sea (blue) and swell (black) shown on a single chart. To the north of point B the wind-sea and swell waves have a similar direction of travel, to the east of point B wind-sea dominates with only weak swell contribution but almost at a right-angle. Near points A and C the wind-sea and swell waves differ widely in direction but with similar heights (a cross sea).

The forecast mean wave directions derived from the wind-sea and mean swell (as shown in Fig2.2.9) superimposed on the previous chart (Fig2.2.11 left) illustrating the important additional information gained from consideration of the wind-sea and mean swell forecasts. The mean wave directions give no indication of that sea passage to the west of Portugal is likely to be through confused rough seas.

Considerations when using output from ECWAM

Not yet modelled are the interaction of waves with sea-surface currents. In particular areas, (e.g. Gulf Stream or Agulhas current), the current effect may give rise to localised changes of up to a metre in the wave height.

Sea ice is not static but forms or extends with low air temperature or sea-surface temperatures, and can move with winds and sea current. NEMO passes information to ECWAM regarding the extent and movement of the sea ice field forecast by LIM2, allowing a more realistic definition of what is open sea throughout the forecast period. However, wave products near coasts, ice-edges and, to a lesser extent, within small and enclosed basins (e.g. Baltic Sea) may well be of lower quality than for the open ocean.

In the current operational version of the wave model, the interaction between waves and sea ice is not actually represented. Rather, when the sea ice cover (ci) is above 30%, the 2d wave spectra are reset to a certain noise level (a function of the local wind speed and direction, weighted by the fraction of open water (1-ci)). However, for all wave integrated parameters, such as significant wave height, all values with a sea ice cover above 30% are set to missing (i.e. no valid values). Therefore, if the 2d spectra are used instead of the integrated parameters to seek information over areas where the model sea ice cover is above 30%, it will appear as if there are some valid values (the noise level), whereas the wave integrated parameters will appear as missing.

Because the so called noise level spectra are a function of the local winds, under strong wind conditions the resulting wave height might well be up to ~40cm.

Wave products near coasts, ice-edges and, to a lesser extent, within small and enclosed basins (e.g. Baltic Sea) may be of lower quality than for the open ocean. This may be due to an uncertain resolution of the land-sea mask or of the detail of the ice edge and hence also the boundary of the water area. Spurious areas of ice or incorrect extent of ice will act as if they were a coastline or island and stop waves from propagating correctly, possibly decaying the waves completely and incorrectly sheltering an otherwise exposed location. Equally, small islands may not be identified by the land-sea mask and hence allow waves to propagate unhindered. Note however that the wave model has a scheme that attempts to represent the impact of unresolved islands on the global propagation of waves.

It should be stressed that the 2d wave spectra within the sea ice area are not really a fair representation of the actual wave/sea ice interaction, more like what would happen if the ice were to become open suddenly leaving the sea to be impacted upon by winds directly above. They should therefore not be used.
Fig2.2.12: Significant height of combined wind waves and swell (Hs). The coloured areas show the difference between the heights derived from the 2d spectra (used where >30% sea ice cover is forecast) and from the wave model (as if open sea). Some large differences are evident, illustrating the need to treat the values of wave height with caution where sea ice is present.

Additional Sources of Information

(Note: In older material there may be references to issues that have subsequently been addressed)

- Definitive information on the ECMWF WAVE MODEL is available in the IFS Documentation PART VII: ECMWF WAVE MODEL.
- Read an in depth view of the structure of ECWAM which gives a description of the theory behind the ECWAM model.
- Read more on satellite measurement of wave height.
- Read more on ocean waves at ECMWF.
- Read more on ocean wave modelling.
- Model output parameters and full list of available ECWAM output.
- Watch a comprehensive lecture on ocean wave forecasting at ECMWF or air-sea interaction and earth system modelling.