DESCRIPTION OF THE MET OFFICE 2ND GENERATION WAVE MODEL

Overview

The Met Office runs a 2nd Generation spectral wave model, with both global and nested regional configurations. The wave models are forced using hourly wind fields generated in Met Office Numerical Weather Prediction (NWP) models, which include observational data from satellite, ship and data buoy networks in their assimilation schemes. Based on the local wind speed and direction, energy is input to waves through a parameterization of the exponential growth of existing wind-sea energy (linear growth in the early development stage). Wind-sea spectral peakedness and peak frequency are used to select an appropriate member of the JONSWAP family of spectra to describe the growing wind-sea energy distribution in frequency space. Directional distribution of wind-sea energy is defined using a cosine squared distribution about the mean wind-sea direction. Frequency dependency for the rate of turn of wave energy in response to turning winds is also parameterized. As the waves grow, a balance is reached between parameterizations for the input, nonlinear transfer between frequencies and dissipation of wave energy. This ensures that for a given wind speed, with sufficient fetch and duration, the limiting Pierson-Moskowitz spectrum is reached but not exceeded.

Wave energy is advected through the model domain using a 2nd order Lax-Wendroff scheme. In the Global wave model, longer period swell energy direction of propagation is modified to ensure that the energy follows a Great Circle. In shallow water (<200m depth) wave group speed depth dependency, bottom friction and depth refraction are represented in the model physics. The UK Waters Wave Model additionally includes the effects of time-varying currents on the UK continental shelf, taking hourly currents from the ~12km Storm Surge model.

The 2nd Generation model scheme mainly differs from its 3rd Generation counterparts (e.g. WAM, WAVEWATCH III) in its use of parameterization schemes for wave growth, nonlinear transfer of energy and dissipation, where more recently devised models calculate some of these explicitly (details in Holt and Hall 1992). Nevertheless, the 2nd Generation scheme is considered robust for operational wave modeling applications and compares favourably with 3rd Generation counterparts operated by other meteorological bureau in an ongoing international data exchange (Bidlot et al., 2000, 2002). Wave model verification is undertaken daily at the Met Office and uses available networks of in-situ wave buoys, ENVISAT along-track altimeter data and ERS-2 Synthetic Aperture Radar (SAR) datasets.

Operational Configurations

The Met Office suite of operational global and regional nested wave models produces regularly updated wave forecasts with lead times of up to five days. Operationally the models are configured with a spectral resolution of 13 frequency bins and 16 directional bins, representing waves with a range of periods between 25 seconds and 3 seconds (deep-water wavelengths from 975 m to 15 m).

Wave conditions worldwide are forecast using the Global Wave Model on a 5/9 degree latitude by 5/6 degree longitude grid (approximately. 60km square grid at mid-latitudes), with fields output at 3-hourly resolution to a lead time of 5 days (T+120). This model is forced using the Met Office's Global domain NWP 10m wind field and run twice daily based on 0000 and 1200 UTC analysis times. The extent of ice cover at high latitudes is updated daily using NWP global analysis data.

Boundary conditions from the Global Wave Model are used as input to a European Wave Model, based on a 1/4 degree latitude by 2/5 degree longitude grid (approximately 35km) covering the area from 30°.75N to 67°.00N and 14°.4 6W to 41°.14E and with a forecast range out to 2 days (T+48). Similarly to the Global Wave Model, this model is forced using the Met Office Global domain NWP 10m wind field and run twice daily based on 0000 and 1200 UTC analysis times.

A further increase in resolution is made for the UK Waters Wave Model, which is nested using boundary conditions from the Global Wave Model. The UK Waters Wave Model uses a 1/9 degree latitude by 1/6 degree longitude grid (approximately 12km) covering the north-west European continental shelf from 12°W between 48°N and 63°N. Two configurations of the UK Waters Wave Model are run. The first configuration is forced by high resolution (~12km grid) Mesoscale NWP 10m winds and includes effects of time-varying currents on the UK continental shelf as generated by the Met Office's operational Storm Surge Model. This model is run four times daily using analysis times 0000, 0600, 1200 and 1800 UTC and provides hourly forecasts out to T+48. The second configuration (Extended UK Waters Wave Model) does not include current effects, and is run twice daily (0000 and 1200 UTC analyses) forced by Global NWP 10m winds to provide 3-hourly forecast data out to T+120.

Data are output from the model and variously retained in commercially available fast-access hindcast archives and research based forecast model archives. Due to data handling constraints two-dimensional (frequency-direction) spectral data are output at specific model points only and are not archived. The hindcast archives are based upon one-dimensional (frequency) spectral data output for all model grid points. These data are used to construct integrated wave parameters including significant wave height, period and direction based on the total spectrum, wind-sea and swell components. The decomposition between swell and wind-sea is made using analyses based upon archived model values of wind speed and direction. Hindcast and forecast integrated parameters (e.g. significant wave height) are generated at model run-time for each model grid point and are retained in the research forecast model archive.

Technical Description

A published description of the wave model is provided in Golding (1983). Technical details from the wave model code are provided by Holt (1994) and Stratton et al. (1995).

Spectral Modelling of Wave Fields

The Met Office 2nd Generation Wave Model is a spectral wave model (as are 3rd Generation models, e.g. WAM, WAVEWATCH III). Spectral models work by calculating the levels of wave energy that can be assigned to a two-dimensional frequency-direction domain (termed the wave spectrum) used to describe motion of the sea-surface under waves (the sea-state). Essentially the spectrum decomposes a given sea-state into a set of constituent sine waves, each with a different direction, period (inverse of frequency) and amplitude (energy).

From the two-dimensional frequency-direction spectrum standard integrated parameters representing wave conditions are generated (.e.g. significant wave height, wave peak and zero-upcrossing period, principal wave direction). With knowledge of wind strength and direction, these integrated parameters can also be assigned to wave field components defined as wind-sea or swell (see *Wind-Sea/Swell Partitioning*).

Field experiments have established families of wave spectra appropriate to different forcing circumstances, and upon which spectral wave models have been based. In the instance of the global/regional scale 2nd Generation model, the spectra used are those derived from the JONSWAP experiment that recorded wave growth over a fetch in the North Sea (Hasselmann, 1973), including the Pierson-Moskowitz spectrum which defines a fully developed wind-sea and therefore defines the fully developed limit of a JONSWAP spectrum.

Model Grid and Forcing Data

The model runs on prescribed regular latitude-longitude spatial grids. Parameter values are derived at collocated positions corresponding to grid cell centre (i.e. the grid is not staggered). Cell types comprise 'sea points', where the full set of calculations for wind-sea growth/dissipation and wave energy advection are applied; 'land points' where no calculations are performed; and ‘coast points’, where advective/dissipative schemes only are applied and which act as a buffer zone for the land.

Depth information is held on the model grid using a representative average for each cell. This assumption may prove important in some near coastal grid cells where the average depth (for example taken over a 12km grid cell in the UK Waters model, 60km cell in the global model) may mask bathymetric features affecting the local distribution of wave energy. A cut-off depth is set in the model scheme at 200m, since at depths greater than this value shallow water effects are negligible even for wave energy in the lowest frequency range.

The importance of increased spatial resolution is clearest in the near coastal zone, since this allows a better representation of the coastline itself and will increasingly resolve shallow water bathymetric features. The trade off for making these resolution changes lies in run-time, with shorter calculation timesteps required for increased spatial resolution in order not to violate conditions for energy advection (see *Wave Energy Advection*).

Models are calibrated to be forced by representative 19.5m mean wind speed and direction, such that for correct wind speed, duration and fetch the wave model will attain the limiting Pierson-Moskowitz wave height. In the operational models this forcing is provided by NWP atmospheric models operated on rotated grids. As a result the winds must first be converted to the regular latitude-longitude grid prior to ingestion by the wave model. In assessing an appropriate wave model spatial grid size, the resolution at which the forcing winds are provided is an important constraint.

Wind-Sea/Swell Partitioning

Taking a simplistic view of the wave model two main processes are represented; growth/dissipation of wind-sea; and advection of wave energy in both wind-sea and swell components of the total wave field. An essential task in the model is therefore to define which parts of the two-dimensional (frequency-direction) wave energy spectrum are wind-sea, which will respond to wind forcing, and which are swell that will be permitted to propagate freely in the model (subject to swell dissipation terms).

The spectral domain occupied by wind-sea is defined in the model using a two stage process based on the wind strength and direction prescribed for each timestep and model grid point in order to generate a spectral cut-off in frequency and direction. Initially the wind-sea to swell cut-off in frequency space is defined using:

$$F_{cut-off} = 0.8 * F_{PM} ,$$

where F_{PM} is the Pierson-Moskowitz peak frequency defined by

$$F_{PM} = 0.14 g / V_w ,$$

where g is acceleration due to gravity and V_w is wind speed at 19.5m above mean sea level and assumes neutral stability in the boundary layer. The cut-off in direction space is derived from:

$$D_{cut-off} = D_w \pm 0.63 * \pi ,$$

where D_w is wind direction in radians. The second stage of wind-sea domain definition occurs when wind-sea energy is turned, grown and recast, and is discussed in *Wind-Sea Growth/Dissipation and Spectral Reshaping*.

One drawback of this method is that there will be circumstances when the range of frequencies and directions assigned to receive wind-sea energy coincides with some frequencies and directions containing swell energy (i.e. when a strong wind is shifts and blows at a direction close to that in which swell is propagating). In such cases swell energy is appropriated into the wind-sea energy calculations. The result may include redistribution of some swell energy to higher frequencies and modified directions in the spectrum as a result of the model recasting the wind-sea (see *Wind-Sea Growth/Dissipation and Spectral Reshaping)*. This process has been termed ‘poaching’ by Met Office wave modelers.

Poaching can lead to enhanced wind-sea growth and excessive swell dissipation within the model scheme since swell energy is lost from comparatively low frequencies whilst the wind-sea energy present at the time is overestimated compared to reality. Under such growth conditions the wind-sea is likely to be assigned an artificially low peak frequency.

There may be some remnant sign of the old swell after poaching has occurred since wave energy at the lowest wind-sea frequencies may attain a direction some way between that of the majority of the new wind-sea and that of the old swell. This is due to the fact that where wave energy is already present the model tries to take account of this and slowly ‘relaxes’ that energy toward the new wind-sea direction (see *Wind-Sea Growth/Dissipation and Spectral Reshaping)*.

Wind-Sea Growth/Dissipation and Spectral Reshaping

Energy from the atmosphere is transferred to ocean waves through growth of the wind forced component of the wave spectrum (wind-sea). Calculation of the wind-sea at each model timestep comprises the following steps:

1. Calculate existing wave energy in new wind-sea frequency-direction (f,θ) range (*see Wind-Sea/Swell Partitioning*).
2. Turn the existing wind-sea.
3. Calculate source terms for linear and exponential growth of wind-sea, deep and shallow water dissipation (applied across the whole wave spectrum, i.e. inclusive of swell) and add source terms to define new wind-sea energy.
4. Reshape new wind-sea spectrum to parameterize nonlinear wave interaction using appropriate JONSWAP family member.

Using the model partitioning scheme described in *Wind-Sea/Swell Partitioning*, existing wind-sea energy is integrated by direction for each frequency bin. These calculations include determination of the mean wave direction associated with each frequency bin ($D_{mean,f}$). Where increasing wind includes frequency bins containing no wave energy, the mean direction is set to the wind direction for later use.

Commonly the wind will back or veer in addition to changing in speed. Wind-sea response is to follow this change in direction, but at a lag dependent upon frequency. In the model scheme turning the wind-sea follows two steps. First a frequency based relaxation factor is calculated using

$$RF = 0.0004 * f^2$$

which is then applied to produce a frequency based turn angle

$$\theta_{turn,f} = RF * \sin\left(D_w - D_{mean,f}\right) * \left(1/F_{PM}\right).$$

The turned wind-sea is then recast for each frequency based upon summed energy, a principal direction equal to

$$DP_f = D_{mean,f} + \theta_{turn,f}$$

and using a cosine squared directional spread. This process is described in further detail by Ephraums (1986).

Subsequent to creating the turned wind-sea, parameterized source terms for growth and dissipation of wave energy, plus nonlinear interaction between wave frequencies are applied. Two exceptional growth circumstances exist; where no wind-sea energy pre-exists, a linear growth parameterization inputs energy into the highest frequency bin; a parametric parameterization is used for wind-sea growth under low wind speed conditions (less than 7ms^{-1}; Holt, 1994). Otherwise exponential growth of wind-sea (Snyder, 1981) is calculated based on a growth factor:

$$GF_1 = E_{PM} / E_{WS1},$$

where E_{WS1} is the energy residing in the existing turned wind-sea and E_{PM} is Pierson-Moskowitz energy defined by

$$E_{PM} = \left(V_w / 1.4g\right)^4 .$$

The growth factor is used to define both a peak frequency for the growing wind-sea based on:

$$f_p = F_{PM} * GF_1^{0.33} ,$$

and determine frequency based growth terms (constrained to be greater than zero) following:

a) For all frequency bins below the top frequency,

$$GT_f = GC * f * W\left(V_w, f\right) * E_{f,\theta} ,$$

where $W(V_w,D_w,f,\theta)$ is a wind speed versus wave speed function defined as:

$$W\left(V_w, D_{w,} f, \theta\right) = \left[V_w * \cos\left(D_w - \theta\right) / c_f\right] - 1.0 .$$

for which D_w-θ represents the angular difference between wind direction and the spectral direction bin, whilst c_f is wave phase speed for the given spectral frequency.

b) For the top frequency bin

$$GT_f = GC * FP * W_T\left(V_w, D_w, f, \theta\right) ,$$

where $W_T(V_w,D_w,f,\theta)$ is a wind speed versus wave speed function defined as:

$$W_T\left(V_w, D_w, f, \theta\right) = \left[V_w * \cos\left(D_w - \theta\right) * f_p * 2\pi / g\right] - 1.0 .$$

In both cases *GC* represents a growth constant calculated based on timestep and a number of other predefined constants, including a fixed value drag coefficient.

Dissipation parameterizes deep-water mechanisms for energy loss including ‘whitecapping’. This is calculated using a dissipation term set up such that dissipation balances the Snyder (1981) growth term appropriately for fully developed wave conditions (Holt, 1992). The dissipation calculations are based upon the total energy existing in the entire spectrum (i.e. both wind-sea and swell), subject to hardwired upper and lower limits. For wind-sea (f,θ) bins the dissipation term (*DT*) is then:

$$DT = A * \left(s / s_{PM}\right)^2 * E_{f,\theta} * \left(2\pi * f\right)^2 ,$$

where *A* is a tunable constant ($4.5*10^{-5}$), and *s* and s_{PM} are respectively integral wave steepness terms for modelled existing energy and Pierson-Moskowitz spectral energy based on:

$$s = \left[\sum E\left(f, \theta\right)\right]^4 / g^2 .$$

Calculated source terms (including shallow water dissipation terms, see *Shallow Water Physics*) are simply added to existing (f,θ) bin energies to yield the grown-dissipated wind-sea. The final parameterization is that of nonlinear interaction between the wind-sea frequencies. This is made by fitting the grown-dissipated wind-sea to an appropriate JONSWAP spectrum family member and re-shaping the wind-sea spectrum accordingly. In the model JONSWAP members are pre-calculated for a sample set of peak frequencies (f_p, 220 in operational model) and JONSWAP gamma (γ, 24 in operational model) and stored as normalized spectral shapes following:

$$JONSWAP_{norm,f} = JONSWAP_{dim,f} \Big/ \sum JONSWAP_{dim,f} * df ,$$

where

$$JONSWAP_{dim,f} = \frac{1}{f^5} * \exp\left[-1.25 * \left(\frac{f}{f_p}\right)^{-4}\right] * \gamma^{\exp\left[\frac{\left(\frac{f}{f_p} - 1\right)^2}{2\sigma^2}\right]}$$

for frequencies above a spectral cut-off defined by

$$f_{cut-off} = 0.8 * F_{PM}$$

In the operational model σ is given the constant value 0.08.

Grown-dissipated wind-sea f_p and γ for selection of the normalized JONSWAP member are defined using the growth factor for this third iteration of wind-sea energy, i.e.

$$GF_3 = E_{PM} / E_{WS3}$$

so that

$$f_p = F_{pm} * GF_3^{0.33},$$

and

$$\gamma = 2.3 * \left[1.0 - (1.0/GF_3)^2 \right] + 1.0,$$

such that the maximum value for γ is set at 3.3.

A final partition of wind-sea energy is made based upon this latest value of peak frequency to provide the frequency cut-off. The resulting wind-sea energy is reshaped using the selected normalized JONSWAP member, and applied to the appropriate frequency bins, being distributed in spectral directional space by using the turned wind-sea principal directions and a cosine squared energy distribution.

Wave Energy Advection

Wave energy is propagated through the ocean at wave group speed (c_g, half the wave phase speed in deep water). This process is replicated across the model grid using a numerical energy advection scheme satisfying the equation:

$$\frac{\partial E}{\partial t} + c_g \frac{\partial E}{\partial x} = 0$$

The first criterion required for a stable model advection scheme is that the condition,

$$c_g \frac{\Delta t}{\Delta x} \leq 1$$

where Δx is model grid length (which will be a minimum at high latitudes) and Δt the timestep be satisfied. Since the latitude-longitude grid is predefined, satisfying this criteria sets the timestep and as a result the calculation time involved in a model run, with a higher spatial resolution model requiring a shorter timestep and longer run-time for a given forecast period.

In order to ensure numerical stability and accuracy in model advection a Lax-Wendroff scheme (Richtmeyer and Morton, 1967; Gadd, 1978) is employed. The scheme uses a two-step approach, first making a diffusing step to an intermediate gridpoint and timestep ($\Delta t/2$), and then using these values to evaluate the next whole timestep. Applied to the simple advection equation with m representing spatial grid cells and n timesteps, the scheme is:

$$E^*_{m+1/2,n+1/2} = 1/2\left(E_{m+1,n} + E_{m,n}\right) - \left(c_g \Delta t / 2\Delta x\right)\left(E_{m+1,n} - E_{m,n}\right)$$

$$E_{m,n+1} = E_{m,n} - \left(c_g \Delta t / \Delta x\right)\left(E^*_{m+1/2,n+1/2} - E^*_{m-1/2,n-1/2}\right)$$

Substituting the diffusing step into the whole timestep equation yields terms that indicate the scheme is second order in both time and space.

Within the global and large scale regional wave models it is also necessary to account for Great Circle turning of propagating wave energy for all but the highest frequencies (less than 0.15Hz, periods longer than 6 seconds). Great Circle turning is required due to the curvature of the earth, which without a correction term would be unaccounted for in the regular grid representation used by the wave model. Placing the energy advection equation in spherical co-ordinates, the result is to add an extra term for Great Circle turning, i.e.

$$\frac{\partial E'}{\partial t} + \frac{\partial E'}{\partial \varphi} + \frac{\partial E'}{\partial \lambda} + \frac{\partial E'}{\partial \beta},$$

where φ, λ and β respectively relate to terms for latitude, longitude and great circle turning. Turning is calculated using a forward difference scheme, as outlined in Stratton and Ephraums (1986).

Swell Dissipation

Swell dissipation is based on the same scheme as described for wind-sea (see *Wind-Sea Growth/Dissipation and Spectral Reshaping*). However, that parameterization scheme was designed to compensate for the fact that results from boundary layer coupled models (Chalikov and Makin, 1991; Burgers and Makin, 1993; Janssen, 1991) demonstrated an overprediction of wind-sea growth in the Snyder (1981) method employed by this model. It was therefore found that adopting the same dissipation parameterization for swell terms (for which no wind forced growth occurs) would lead to excessive dissipation of swell (Holt, 1992, 1994). As a result a reduced dissipation factor is applied to swell using:

$$DT = A*\left(s/s_{PM}\right)^2 * E_{f,\theta} * \left(2\pi * f\right)^2 * 0.33.$$

Shallow Water Physics

In shallow water three principal processes are accounted for in the model scheme (Holt, 1993).

Wave phase and group speeds must be calculated using the full wave dispersion relationship:

$$c = \sqrt{gk * \tanh kh}\ ,$$

where k is wave number (=2*π/*wavelength*) and h depth, and

$$c_g = \frac{1}{2}\left(1 + \frac{2kh}{\sinh 2kh}\right) * c\ .$$

At the start of a model run a look-up table of appropriate shallow water wave speeds is derived. This table can then be interrogated for calculations performed for model designated shallow water points.

Refraction is a forced redirection of wave energy due to changes in wave speed, and is discussed in detail in Golding (1983). This is dealt with in the model using a forward difference scheme.

A term is included in the model to allow additional wave energy dissipation due to bottom friction at shallow water points.

For the UK Waters wave model effects of time-variant currents on the continental shelf are also accounted for. This procedure is detailed by Buckley (1999).

Post-Processing Wind-Sea/Swell Partition

Separate from the wave model, hindcast archive data extraction also uses a wind-sea/swell partition scheme in order to produce integrated parameters (e.g. significant wave height) from archived one-dimensional (frequency) spectral data. Several of the steps used to create this partition in the model cannot be replicated from the output data, and so the approach to defining the wind-sea is in post processing is based on the initial cut-off criteria described in *Wind-Sea/Swell Partitioning*, but with some modification.

The direction cut-off uses:

$$D_{cut-off} = D_w \pm \pi/2$$

The frequency cut-off is modified to account for the fact that in reality, the sea requires a certain length of time to respond to the wind blowing over it. Initially the relationship

$$F_{cut-off} = 0.8 * F_{PM}$$

is used. However, the wind-sea from which this 'first-guess' was made may not have reached the theoretical fully-developed state described by the Pierson-Moskowitz spectrum. So the difference between the model actual and theoretical states is used to calculate a more realistic peak frequency for the wind-sea based on:

$$F_{cut-off} = 0.7*10^{(-0.04*XX)},$$

$$XX = -25*\log\left(F_{final}\right)$$

and

$$F_{final} = F_{PM}*\left(E_{PM}/E_{model}\right)^{0.31}$$

where E_{model} is the first-guess wind-sea energy.

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