Marine Forecasting at the Bureau of Meteorology

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Introduction

In recent years, marine industries have contributed approximately 9% to Australia's Gross Domestic Product (Marine Science and Technology Plan Working Group, 1999). Some major contributors to this are the offshore oil and gas industries and marine tourism. These industries are highly dependent on accurate marine forecasts, so numerical wave forecasts are an important product of operational meteorological forecasting centres. This extended abstract describes the history of operational numerical wave forecasting at the Bureau. It also presents an outline of some current research and planned future developments in the marine forecasting system.

History of numerical wave modelling at the Bureau

The emphasis in this abstract is on the details of the wave models and upgrades to these models that have been implemented at the Bureau, rather than developments in numerical wave modelling in general. Also, note that these are limited to changes that have an impact on the forecast products. This therefore does not include any changes that have been made to the software in order to improve speed or computational efficiency. In addition, the changes made when porting the software to a new computing environment are not described here.

1983: Parametric wave model

The first numerical wave model to be implemented at the Bureau was the "TDL model' in 1983. (NMC, 1986) This was a model developed at the U.S. National Weather Service's Techniques Development Laboratory (TDL) (now the Meteorological Development Laboratory). This was a simple parametric wave model based on empirical relationships for swell height and wind-sea height dependant on wind speed, fetch and duration.

1986: First generation

In the early 1980's a spectral wave model was developed in the Bureau (NMC, 1986). This model was a significant step forward from the parametric models. It was classified as a first generation spectral wave model, which is a model in which the prediction of the wave energy is made according to an energy conservation equation. The wave energy transport equation is:

$$\frac{\partial F}{\partial t} + \nabla.\left(\mathbf{c}_{\mathbf{g}} F\right) = S_{in} + S_{nl} + S_{d} \qquad (1)$$

where $F(f,\theta)$ is the wave spectrum (i.e., the spectral density of wave energy) as a function of frequency (f) and direction (θ), $\mathbf{c}_{\mathbf{g}}$ is the group velocity as a function of frequency, and the terms on the right hand side represent the source terms: S_{in} is the energy input due to wind forcing, S_{nl} the non-linear energy transfer between groups of resonant waves and S_d the dissipation of energy due to whitecapping. The wave energy is resolved into a finite number of discrete frequency and direction bands. The Significant Wave Height (SWH) is proportional to the mean energy averaged over all frequencies and directions, specifically:

$$SWH = 4\sqrt{\overline{F(f,\theta)}} \qquad (2)$$

The limitations of the first generation models are that the non-linear interaction terms in Equation (1) are ignored. The non-linear interactions act to distribute energy amongst different frequencies in the model. Ignoring them can lead to significant underestimation of the amount of energy in the low frequency wave components.

The model was implemented over two domains: OWM over the Southern Hemisphere below 15° S (resolution of approx. 500 km) and a nested model ARWM (resolution of approx 250 km) over the Australian region. The wind inputs used for each model were the 1000 hPa winds from the then operational atmospheric models: HASP and FINEST. The SWH forecasts from these models were shown to be a significant improvement over those from the TDL model (NMC, 1986). Due to limited computer resources, the models were not implemented until September 1986.

After several years of operational use, it was found that the regional model (ARWM) tended to overforecast wave heights in strong wind situations (NMOC, 1988). This was addressed by changing the forcing fields to be the winds at 10m above the surface. These were obtained by assuming a logarithmic boundary layer profile to reduce the 1000 hPa winds from FINEST to a height of 10 m.

1994: Third generation

Third generation models are those in which the non-linear interaction terms are included, and no restrictions are placed on the shape of the evolving wave spectrum. In the 1980's, the WAMDI group developed the WAM Model (WAMDI, 1988; Komen *et al.*, 1994). This was released to users in December 1991, but only in stand-alone mode (i.e., no nesting).

Computational resources at that time were not sufficient to run a global model at the resolution necessary for accurate wave forecasts in the Australian region, and a model run over the local domain only would not be able to incorporate swell propagating from outside the region. Remote swell is a significant component of the wave fields in the Australian region, so for these reasons, the implementation of WAM was left until a nested version (WAM cycle 4) was available in 1994 (NMC, 1994)

This version of the WAM model included a dynamic coupling between wind and waves (Janssen 1989, 1991). Bender and Leslie (1994) and Bender (1996) compared the original Cycle 3 (Snyder *et al.* 1981; Komen *et al.* 1984) and Cycle 4 physics to independent waverider buoy data over a one-month period (July 1992) and concluded that a wave-forecasting model for the Australian region should be based on the Cycle 3 physics. Although this led to underestimation of wave heights, it was shown that by upgrading the first-order propagation numerics to third-order (which led to overprediction of wave height) and increasing the magnitude of the dissipation term by approximately 40%, a good match with the buoy observations could be achieved.

The initial operational configuration for AUSWAM, on 1st June 1994, was therefore the Cycle 4 framework (with nesting), the WAM Cycle 3 physics, and the propagation numerics were upgraded from 1st-order to 3rd-order. The spatial resolution for the global domain was 3° and a regional model (with domain 57°S to 9°S and 87°E to 174°E) was nested within it at 1° spatial resolution. The spectral resolution for both models was 30° in direction with 25 frequency bins ranging from 0.0418 Hz to 0.4114 Hz.

Forcing for the models were surface winds from the then operational global and regional atmospheric models, GASP and RASP75, respectively. Specifically, winds at 10 m were obtained from the lowest levels of the models by applying the marine boundary layer program: MARBL (McIntosh and Hubbert, 1992).

1998: Shallow water

On July 24th 1998, a high-resolution (0.25°) version of WAM that included shallow water effects was introduced. This was run over the southeast of Australia (124°E to 164°E and 24°S to 50°S) and forced by winds from MESOLAPS.

1999: Data assimilation

The physics and numerics of AUSWAM remained essentially unchanged since its initial implementation. The only major change to have occurred is the inclusion of the assimilation of satellite altimeter observations of SWH, which commenced in August 1999 (NMOC, 1999), with data from the ERS-2 altimeter. The data assimilation scheme is described in detail in Greenslade (2001).

Other changes

There have been other minor changes to the implementation of the wave models over the years, such as changes in spatial resolution, wind forcing etc. These changes are listed below.

- **Jan 1999:** Forecasts from the global wave model were extended from 48-hours to 96-hours.
- **August 2000:** The wave spectra discretisation in all models was rotated by 15° so that the bins were centred at 15°, 45°, 75° etc. from North (previously centred at 0°, 30°, 60°, etc. from North). This prevents the appearance of elongated north-south patterns of SWH that can occur when north-south propagating wave energy is blocked by small islands covering individual grid-points (Bidlot et al., 1997, Greenslade 2000). At this time, the bathymetry was also upgraded to use a version provided by the Australian Geological Survey Organisation (AGSO, now Geoscience Australia) (NMOC, 2000).
- **April 2001**: The spatial resolution of the global wave model was increased from 3° to 1°. At this time the frequency and spatial resolution of the wind forcing for the global model was increased from 12-hourly to 3-hourly intervals and from 2.5° to 1° spatial resolution and the wind fields presented to the wave model changed from being instantaneous “snapshots” of the surface fields to being smoothed in time with a 6-hour window. The impact of these changes on the accuracy of the wave forecasts is discussed in Greenslade (2004).
- **August 2002**: The regional wave model resolution was increased from 1° to 0.5°, and the frequency of the wind forcing was increased from 3-hourly to 1-hourly. The domain of the high-resolution wave model was expanded to cover the Australian region (0° to 50°S, 100°E to 165°E) and the spatial resolution was upgraded from 0.25° to 0.125°.
- A comparison between global ERS-2 observations of SWH and *in situ* buoy data showed that the altimeter tended to overestimate low SWH and underestimate high SWH. A bias adjustment to the ERS-2 data resulted in improved wave forecasts (Greenslade and Young, 2004a) and this was also incorporated operationally in August 2002 (NMOC, 2002).

Current and future research

Some of the recent, current and future efforts to upgrade and improve the accuracy of the wave forecasting system are described in this section.

Greenslade and Young (2004b) showed that the description of the background errors in the data assimilation system could be improved by having the spatial scale dependent on latitude, as opposed to constant in space. This was shown to improve the forecast skill of the wave model by up to 10%. This upgrade is currently being trialled in NMOC.

The ERS-2 altimeter observations have been replaced with observations from the JASON altimeter. ENVISAT data are currently being received at the Bureau in real-time and these data will also be incorporated into the data assimilation system.

It is generally accepted that the accuracy of wave forecasts is strongly dependent on the accuracy of the surface winds used to force the wave model (Cardone et al., 1995). Space-borne scatterometers provide frequent and accurate marine wind observations with good global coverage that can be used for verification of the surface winds from the atmospheric models. There are ongoing efforts being made to verify the surface winds from the Bureau's operational atmospheric models. Quikscat data has been successfully assimilated into GASP and this is currently being trialled in NMOC prior to operational implementation.

Work has begun on development of a two-way coupling between the wave model and the atmospheric model. Currently, the surface roughness in the atmospheric model depends only on surface wind velocity. There is however, observational evidence (e.g. Taylor and Yelland, 2001) to suggest that the roughness of the ocean (i.e., the drag coefficient) is sea-state dependent, with rougher surface waves extracting more momentum from the lower levels of the atmosphere. This suggests that a system in which information on the surface roughness can be passed back to atmospheric model is more physically realistic.

As computational resources increase, there is scope to increase model resolution. The first priority for this will be an increase in the directional resolution of the wave spectra to 15° (from the current 30°). As the wave models move to higher spatial resolution, it will become possible to resolve areas closer to the coastline, and provide wave forecasts in regions of shallow water. In this event, the WAM model may not be adequate. Other wave models, for example the SWAN model (Booij *et al.*, 1999) specifically designed for shallow water regions will need to be tested and evaluated.

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