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An ensemble forecast system for prediction of Atlantic–UK wind waves

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ABSTRACT

Ensemble prediction systems (EPS) provide a numerical method for determining uncertainty associated with forecasts of environmental conditions. A system is presented that has been designed to quantify uncertainties in short range (up to 7 days ahead) wave forecasts for the Atlantic Ocean and shelf seas around the UK. Variability in the wave ensemble is primarily introduced via wind forcing taken from an Ensemble Transform Kalman Filter based atmospheric EPS. Restart files for each member in the wave ensemble use a short range forecast from a previous run of the same member, in order to retain spread in initial conditions. Wave model run times were optimised through the choice of source term physics scheme and application of a spherical multi-cell grid. Verification of the wave-EPS shows good overall performance, since a substantial component of ensemble under-spread can be attributed to observation errors. Systematic biases, relating to the choice of source term, are noted when statistics are broken down regionally and have a major impact on the quality of the forecasts at short lead times, when spread is limited.

1. Introduction

Numerical model forecasts of atmospheric and ocean conditions are inherently uncertain. Major contributions to uncertainty result from the model parameterisations of real world processes and the errors introduced in the modelled (or analysed) estimate of conditions when the forecast is initiated (Buizza et al., 2005). When the forecast is verified against an observed 'truth' in order to quantify these uncertainties, the statistics generated will include further errors intrinsic to the observation system (Saetra et al., 2004).

Ensemble prediction systems aim to dynamically quantify uncertainties associated with the estimation of forecast initial conditions, by running a number of forecasts from a perturbed set of alternative starting conditions (Kalnay, 2003), and model parameterisations, through the use of stochastically varying parameterisation settings (e.g. Lin and Neelin, 2000; Bright and Mullen, 2002). Established ensemble systems at the European Centre for Medium-Range Weather Forecasts (ECMWF) and National Centres for Environmental Prediction (NCEP) have demonstrated the benefits of using this approach to deliver probabilistic forecasts of atmosphere and wave parameters (Alves et al., 2013; Chen, 2006; Molteni et al., 1996; Saetra and Bidlot, 2004) at lead times of a few days or more ahead. At these lead times predictability of synoptic systems, which make a major contribution to variability in marine wind and wave fields, begins to break down (Molteni et al., 1996).

More recently, systems have been implemented with the aim of dynamically representing uncertainty at short range (hours to a week ahead), in order to generate more data rich and skilful alternatives to traditional deterministic forecasts. For example, the Met Office Global and Regional Ensemble Prediction System (MOGREPS, Bowler et al., 2008) comprises a global atmosphere ensemble with approximately 32 km horizontal resolution, to capture synoptic variability, and a UK ensemble which is scaled at approximately 2.2 km horizontal resolution, in order to include uncertainty associated with convective processes in the atmosphere.

Certain marine phenomena, such as storm surges and ocean surface waves, can be considered as a forced-dissipative system with a first order response to ocean surface winds and atmospheric pressure. In these cases an ensemble prediction system can be constructed where variability in the ensemble members is primarily introduced by variations in the atmospheric forecast members. This is a common approach in wave ensemble modelling and is used successfully at most operational centres, including ECMWF (Janssen, 2004) and NCEP (Alves et al., 2013; Cao et al., 2007). Flowerdew et al., (2010) demonstrate a successful application of this method to short range

Abbreviations: MOGREPS, Met Office Global and Regional Ensemble Prediction System; SMC, Spherical Multi Cell; WW3, WAVEWATCH III.

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forecasts of storm surge for the UK. In this paper the focus is on a similar application for short range wave prediction.

The system described comprises the MOGREPS-Global atmospheric ensemble driving an Atlantic Ocean configuration of the WAVEWATCH III third generation wave model (Tolman, 2009). The Atlantic wave model is intended to be used for probabilistic predictions in both the open ocean and waters around the UK at 1–7 days ahead lead times. The configuration tested in this study produced forecasts out to 3 days ahead, which meant that the longest range forecasts had a lead time similar to the temporal scale for variability, and hence predictability, of synoptic scale storm systems.

In addition to assessing overall performance of the wave ensemble, the presented verification concentrates on two forecasting areas of special interest around the UK: west facing coasts exposed to the north Atlantic and the east coast bordering the North Sea. The wave ensemble has been assessed in terms of its ability to reproduce the observed wave height distribution, deterministic error and ensemble spread relationships, and to make probabilistic forecasts of threshold exceedance. Previous studies by Tolman (1998), Tolman et al. (2002) and Saetra et al. (2004) have shown that observation errors can have a significant impact on ensemble verification results if they are not accounted for. To mitigate this impact the verification methods used in this study includes an application of wave height observation error data in order to provide an ideal performance baseline, as a variant on the concept presented by Saetra et al. (2004).

The paper is structured as follows. Section 2 presents a description of the wave Ensemble Prediction System (wave-EPS). Section 3 describes the data and methods used for verifying forecasts of significant wave height against observations. Results are presented in Section 4 and discussed in Section 5.

2. The Atlantic wave ensemble prediction system

2.1. Atmospheric component

The Met Office wave-EPS comprises a wave model that that is driven by hourly 10 m wind fields from the global configuration of MOGREPS (herein MOGREPS-G; Bowler et al., 2008). The atmospheric model is configured on a reduced N400 Gaussian grid (800 × 601 grid points; approximately 32 km at mid-latitudes) with 70 vertical levels and is based on the Met Office Unified Model (Davies et al., 2005).

A primary source of variability in the atmospheric ensemble members results from application of an Ensemble Transfer Kalman Filter (ETKF; Bishop et al., 2001) to perturb the members' initial conditions. The ETKF is used since MOGREPS is targeted at short-range high-detail forecasts and therefore has an emphasis on quantifying uncertainty as early as possible in the forecast. This makes it essential that perturbations to the forecasts are available immediately at initialisation, rather than grown over time as for a singular vector scheme (Buizza and Palmer, 1995; Molteni et al., 1996). The ETKF perturbations are based on a transformation matrix combination of individual member forecast perturbations, which are generated by referencing members against the ensemble mean forecast (at a lead time of T+6 h; Bowler et al., 2008). The member perturbations are then added to a control member analysis, generated using the Met Office 4D Variational Assimilation scheme (4D-Var; Rawlins et al., 2007), in order to produce an initial condition for each member. The perturbation technique is close to that of 'error breeding' (Toth and Kalnay, 1993).

MOGREPS-G also applies stochastic perturbations to the model parameterisations in two ways. A 'random parameters' scheme perturbs tuneable terms of empirical parameterisations that represent processes which are too small scale to be directly resolved by the model and affect the structural evolution of the forecast (e.g. entrainment rate, critical Froude numbers, ice fall speed, and others; Bowler et al., 2008). A 'stochastic convective vorticity' scheme is used to

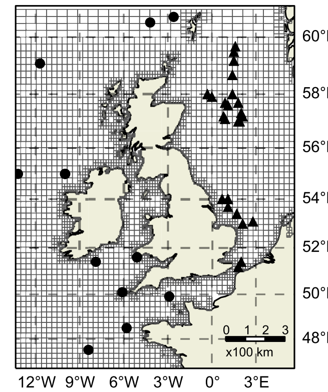

Fig. 1. Detail of SMC grid around the UK (from Li and Saulter, 2014). Markers show observation locations for North Sea (triangles) and Western Approaches (circles).

address uncertainty in unresolved meso-scale convection by introducing a potential vorticity dipole in areas with severe convection. This latter scheme mimics the effects of meso-scale convective processes.

2.2. Wave component

For consistency with other operational systems, the Met Office's Atlantic Wave Ensemble (Bunney et al., 2012) was developed based on version 3.14 of the WAVEWATCH III^{TM} wave model (hereafter WW3; Tolman, 2009). The model configuration was formulated on a multi-resolution Spherical Multi Cell grid (SMC; Li, 2012), using a propagation scheme based on the 2nd order upstream non-oscillatory advection scheme of Li (2008). This grid scheme uses refined resolution grid cells towards the coastline from 25–12–6 km (Fig. 1) and is used to optimise wave model run time in the open ocean, whilst retaining an appropriate representation of the coastline around the UK.

Model run times were minimised for these experiments by using the Tolman and Chalikov (1996) source term package for wave growth and dissipation (ST2 option, tuned for Met Office winds by setting STABSH =1.36 and SWELLF=0.1). In version 3.14 of WW3 the use of this source term package saves in the order of 30% wall clock time over the ST3 option that enables variations of WAM-4 physics (Janssen, 1991; Bidlot et al., 2007a; Ardhuin et al., 2010). At the time the model was developed, constraining run time as much as possible was an important factor in order to be able to add the wave ensemble to an operational environment where resources are limited.

The domain of the wave model covers the entirety of the Atlantic basin and is bounded by land mass on all edges, except where it intercepts the southern ocean south of the African and South American continents. These open sea edges have boundary conditions applied to them from the Met Office's global wave model. 10 m wind fields from the MOGREPS ensemble are ingested hourly and ice field updates are provided once daily, at the 0600UTC run, from the Met Office Operational Sea Surface Temperature and Sea Ice Analysis system (OSTIA; Donlon et al, 2011).

Initial conditions perturbations and stochastic physics schemes are not applied to the ensemble wave members, so variations in the forecasts are introduced purely as a result of spread in the atmospheric ensemble. If the wave ensemble members were to be restarted from the same control condition (i.e. the control member), this would imply that a spin-up period would occur at the start of the forecast during which the wave ensemble went from a position of zero spread to a value physically consistent with the spread in wind forcing. This is not an ideal behaviour for short range forecasting, since a degree of initial condition error should be inevitable for a wave model that does not have its own data assimilation scheme. To mitigate this, initial conditions spread is generated by each member