Project - My-Wave

Met Office Wave Model Ensemble Prediction Systems in the 'Atlantic-Euro Zone' and USAM-CNMCA 'Nettuno' Ensemble Prediction System in the Mediterranean Sea

Reference: MyWave-D3.1

Project N°: FP7-SPACE-2011-284455	**Work programme topic:** SPA.2011.1.5.03 – R&D to enhance future GMES applications in the Marine and Atmosphere areas
Start Date of project: 01.01-2012	**Duration**: 36 Months

WP leader: Luigi Cavaleri	**Issue:** Version 1.0
Contributors: Bunney, C., Li, J. Saulter, A., Torrisi, L., Marcucci, F., Cavaleri, L., Pomaro, A., Pezzutto, P.,	
MyWave version scope: All	
Approval Date: 11 Jun 2013	**Approver: Luigi Cavaleri**
Dissemination level: Project	

DOCUMENT

VERIFICATION AND DISTRIBUTION LIST

	Name	Work Package	Date
Checked By:	Luigi Cavaleri	WP3	11 Jun 2013
Distribution			
	Øyvind Saetra (MetNo) – Project leader, for onward distribution Luigi Cavaleri (ISMAR), Marta Gomez (PdE), Roberto Inghilesi (ISPRA)		

CHANGE RECORD

Issue	Date	§	Description of Change	Author	Checked By
0.1	03/12/2012	all	First draft of document	Chris Bunney Andy Saulter Jian-Guo Li	Andy Saulter
1.0	10/12/2012	all	Document finalization	Chris Bunney Andy Saulter Jian-Guo Li	Chris Bunney
1.1	30/05/2013	all	Corrections from review	Chris Bunney	Chris Bunney
1.2	07/06/2013	all	USAM EPS documentation addition	Lucio Torrisi Francesca Marcucci Luigi Cavaleri Angela Pomaro Paolo Pezzutto	Luigi Cavaleri

TABLE OF CONTENTS

I INTRODUCTION.. 9

I.1 Work Package and report objectives..9

II DESCRIPTION OF THE MET OFFICE GLOBAL-REGIONAL ENSEMBLE PREDICTION SYSTEM (MOGREPS).. 10

II.1 Perturbation method..10

II.2 MOGREPS configurations and run cycle..11
II.2.1 MOGREPS-G..11
II.2.2 MOGREPS-UK..12

II.3 Application of MOGREPS data to the Met Office wave EPS..12
II.3.1 Method 12
II.3.2 Atlantic configuration..15
II.3.3 UK configuration..19
II.3.4 Mediterranean configuration..20

II.4 Deterministic Wave model Validation 22
II.4.1 Method 22
II.4.2 Wind data..23
II.4.3 Atlantic wave model..24
II.4.4 UK wave model..24
II.4.5 Mediterranean wave model..32
II.4.6 Deterministic verification summary..32

II.5 Wave-EPS Output data and user trials..35

II.6 Further work and expected timeline..36

III DESCRIPTION OF THE USAM-CNMCA SHORT-RANGE ENSEMBLE PREDICTION SYSTEM (COSMO-ME EPS).. 37

III.1 Application of LETKF-EPS data to the Nettuno EPS..40

III.2 Deterministic Wave model Validation..43
III.2.1 Data used for the analysis..43

IV REFERENCES.. 46

LIST OF FIGURES

Figure 1 - Representation of the ETKF - perturbations from each member are combined using the transform matrix [from Bowler et al (2008)]........11

Figure 2 - Wave EPS run cycling and model inter-dependencies........14

Figure 3 - Illustration of decay of convective scale features in the transition between a wave model forced by convective scale and global scale winds. In the top panel, the central subfigure shows significant wave height when a 4km wave model is forced by 1.5k........15

Figure 4 - The Atlantic SMC grid showing grid cell depth and numbers of tiered cells; N1-6km, N2-12km, N4-25km........17

Figure 5 - Atlantic SMC6-25 grid around the Canary Islands, Moroccan coast and Madeira......18

Figure 6 - Atlantic SMC6-25 km grid around the UK. Longitude resolution of the grid is doubled above 60N........19

Figure 7 - Significant wave height field (m) showing extent of UK 8km domain........20

Figure 8 - Significant wave height field showing extent of Mediterranean 8km model domain. .21

Figure 9 - In-situ wind and wave measurement locations with data available for the verification tests. Data were excluded from Caribbean platforms in Atlantic testing and from The Bay of Biscay platforms in Mediterranean tests........23

Figure 10 - Comparison of wind data on (green) Global and (magenta) Atlantic wave model grids against in-situ wind observations in the Atlantic region........25

Figure 11 - Comparison of wind data on (green) Global and (magenta) UK wave model grids against in-situ wind observations in the UK region........26

Figure 12 - Comparison of wind data on (green) Global and (magenta) Mediterranean wave model grids against in-situ wind observations in the Mediterranean region........27

Figure 13 - Comparison of significant wave height data from (green) Global and (magenta) Atlantic wave models against in-situ observations in the Atlantic region........28

Figure 14 - Comparison of significant wave height data from (green) UK and (magenta) European wave models against in-situ observations in the UK region........29

Figure 15 - Comparison of significant wave height data from (green) UK and (magenta) Atlantic wave models against in-situ observations in the UK region........30

Figure 16 - Comparison of significant wave height data from (green) UK and (magenta) Atlantic wave models against in-situ observations in the southern North Sea region........31

Figure 17 - Comparison of significant wave height data from (green) Mediterranean and (magenta) European wave models against in-situ observations in the Mediterranean region...33

Figure 18 - Comparison of wave peak period data from (green) Mediterranean and (magenta) European wave models against in-situ observations in the Mediterranean region........34

Figure 19 - Example wind and wave EPS forecast from ECMWF........35

Figure 20 - COSMO-ME domain........38

Figure 21 - A schematic view of the CNMCA operational data assimilation system........39

Figure 22 - Example of NETTUNO forecast (significant wave height and mean wave direction) on the Mediterranean Sea...........41

LIST OF TABLES

Table 1 - Variable settings used in wave-EPS model configurations Constants are labelled as described in Tolman (2009). c0 is a tuning parameter in definition of effective wind speed. Xs is a reduction factor for the TC96 wind input source term applied to long period swell. Γ is an empirical constant in the JONSWAP bottom friction parameterization...........13

Table 2 - RON Buoy System...........42

Table 3 - ARPAL Buoy...........43

Table 4 - ODAS ITALIA 1 Buoy...........43

Table 5 - Ifremer Buoy System...........44

Table 6 - MeteoFrance Buoy System...........44

Table 7 - Puertos del Estado Buoy System...........44

Table 8 - HCMR Buoy System...........45

GLOSSARY AND ABREVIATIONS

ARPAL	Agenzia Regionale per la Protezione Ambientale della Liguria (Liguria Regional agency for environmental protection)
CNMCA	Centro Nazionale di Meteorologia e Climatologia Aeronautica (Italian National Meteorological and Climatological Air Force Centre)
ECMWF	European Centre for Medium-Range Weather Forecasts
EPS	Ensemble Prediction System
ETKF	Ensemble Transform Kalman Filter
ISMAR	Istituto di Scienze Marine (Institute of Marine Science, Italy)
ISPRA	Istituto Superiore per la Protezione e la Ricerca Ambientale (Italian National Institute for the Environmental Protection and Research)
JCOMM	Joint technical Commission for Oceanography and Marine Meteorology
LETKF	Local Ensemble Transform Kalman Filter
MOGREPS	Met Office Global Regional Ensemble Prediction System
RON	Rete Ondametrica Nazionale (Italian national wave buoys network)
SMC	Spherical Multi-Cell grid
UKMO	United Kingdom Met Office
UKV	UK variable grid-resolution configuration of the UM
UM	Unified Model – the Met Office's atmospheric modelling system
UNO2	Upstream Non-Oscillatory 2nd Order advection scheme
USAM	Ufficio Generale Spazio Aereo e Meteorologia (General Office for Air Space and Meteorology, part of the Italian Air Force Staff)
WAM	WAve Model (name of wind wave model used at ECMWF)
WMO	World Meteorological Organisation
WW3	WAVEWATCH III ™

APPLICABLE AND REFERENCE DOCUMENTS

Applicable Documents

	Ref	Title	Date / Issue
DA 1	MyWave-A1	MyWave: Annex I – "Description of Work	September 2011
DA 2			

Reference Documents

	Ref	Title	Date / Issue
DR 1			
DR 2			

I INTRODUCTION

I.1 Work Package and report objectives

Work Package 3 will apply different ensemble techniques in wave forecast, assessing, for two separate and different areas, their performance and increased information with respect to a deterministic approach. The technique will be applied both at large and local scales, in the latter case for three specific harbours.

Different approaches can be followed in producing a meteorological, hence wave, ensemble. Two approaches will be followed in WP3, at two different scales, North-Atlantic, with focus on the European coasts, and the Mediterranean Sea. The results will be intercompared, also with respect to the deterministic approach, to assess the different level of information provided by the users and their related reliability. The results will be provided both on the open sea/ocean and coastal waters, as also for harbour management.

Within WP3 the Met Office will test wave models driven by winds from an atmospheric ensemble prediction system (EPS) in which perturbations are derived using an Ensemble Transform Kalman Filter scheme (ETKF, Bishop et al., 2001). These atmospheric models are already run in operational mode at the Met Office as part of the Met Office Global-Regional Ensemble Prediction System (MOGREPS, Bowler et al., 2008). Since the ETKF technique uses a weighted linear combination of members at each forecast re-initialization, given members retain some 'memory' of previous forecasts from run to run and generate spread in the ensemble at short forecast ranges. These characteristics of the atmospheric ensemble enable downstream models, such as wave and storm surge models, to be run as a forced system (i.e. without their own perturbation step; Bocquet, 2010) and retain spread and consistency both between subsequent forecast cycles and relative to the atmospheric members (Flowerdew, 2010).

The second approach, run by the Italian Meteorological Service (USAM) together with ISMAR, is technically different, but similarly based on the Ensemble Kalman Filter (EnKF). The Local Ensemble Transform Kalman Filter (LETKF, Hunt et al., 2007) is already implemented in the USAM numerical weather prediction analysis and prediction system (Bonavita et al., 2008, 2010). This data assimilation method is suitable also for short-range ensemble forecast applications.

This report documents Subtask 3.1.1, which is to design and set-up the Met Office and USAM-CNMCA wave-EPS. The UKMO system will comprise models covering both areas designated in WP3, namely the Northern Atlantic Ocean (including a focus region around the United Kingdom) and the Mediterranean Sea. Work has included design of the wave-EPS and configuration, test running and validation of wave models for the Atlantic, UK and Mediterranean regions. The USAM-CNMCA ensemble prediction system will describe the Mediterranean Sea as well, though by means of a different approach.

A common period of testing will be defined then, for a full cross-comparison between the two different ensemble approaches, on the Mediterranean Region, in order to obtain objective scores offering clear indications on the capability of the different systems to provide, in the long term, the best results in the Mediterranean Sea. The evaluation of subtask 3.2.1 results will be performed versus remotely sensed and in-situ measured data. The immediate purpose of this operation is a preliminary evaluation to see if the ensemble forecasts are more realistic and reliable than the deterministic forecasts, particularly when considering extreme wind and wave conditions.

II DESCRIPTION OF THE MET OFFICE GLOBAL-REGIONAL ENSEMBLE PREDICTION SYSTEM (MOGREPS)

II.1 Perturbation method

Forcing for the wave-EPS will be sourced from two atmospheric EPS run by the Met Office; a global system (MOGREPS-G) and a convection permitting UK limited area model system (MOGREPS-UK). The atmospheric model underpinning both systems is the Met Office Unified Model (UM, Davies et al., 2005). The primary source of perturbations in these ensembles is based on an implementation of the Ensemble Transfer Kalman Filter (ETKF; Bishop et al., 2001) in MOGREPS-G initial conditions. The initial conditions for MOGREPS-UK are a combination of downscaled ETKF perturbations from MOGREPS-G applied to an analysis field from the deterministic UKV model (variable grid, convection resolving UM configuration for the UK domain; Tang et al., 2012). Lateral boundary conditions (LBCs) are also downscaled from MOGREPS-G to ensure perturbations in remote generated wave fields are propagated into MOGREPS-UK ensemble members.

MOGREPS is targeted at short-range (3 – 5 day) high-detail forecasts and complements the medium-range (15 day) forecasts produced by the EPS system run at the European Centre for Medium-range Weather Forecasting (ECMWF). This latter system uses a singular vector (SV) perturbation method that is optimized to grow perturbations during the early part of the forecast. For MOGREPS, it is essential that these perturbations are available immediately at initialisation time, and in order to achieve this an ETKF scheme is utilised.

In the MOGREPS ETKF scheme perturbations to the ensemble members at forecast initialisation are based on a transformation matrix combination of individual member forecast perturbations, generated by referencing members against the ensemble mean forecast (at a lead time of T+6 hours). 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 (IC) for each member (see **Figure 1** for a graphical representation). A control forecast is also run which is based on the analysis without any perturbations (i.e. a normal deterministic run). In principle the perturbation technique is close to that of 'error breeding' (Toth & Kalnay, 1993; see also figures 1 and 2 in Bowler et al., 2008) which has the crucial property that individual members retain a 'memory' of the previous forecast from run cycle to run cycle. It is this property that enables application of the atmospheric data to the wave model as a one-way forced system, as described in Section III.

The ETKF has been demonstrated to lead to improved performance in IC generation versus error breeding by Wang et al. (2004). In simple model tests Bowler (2006) found that the best performance was achieved through use of an ensemble Kalman Filter (EnKF; Evensen, 1994), which uses member forecast perturbations versus the ensemble mean to produce a background-error covariance matrix and applies this through the data assimilation process to produce a set of perturbed analyses. However, in practise the EnKF is very expensive to implement and so the ETKF provides an operationally viable compromise. More details of the EnKF and ETKF schemes are available in Bowler et al. (2008) and Bishop et al. (2001).

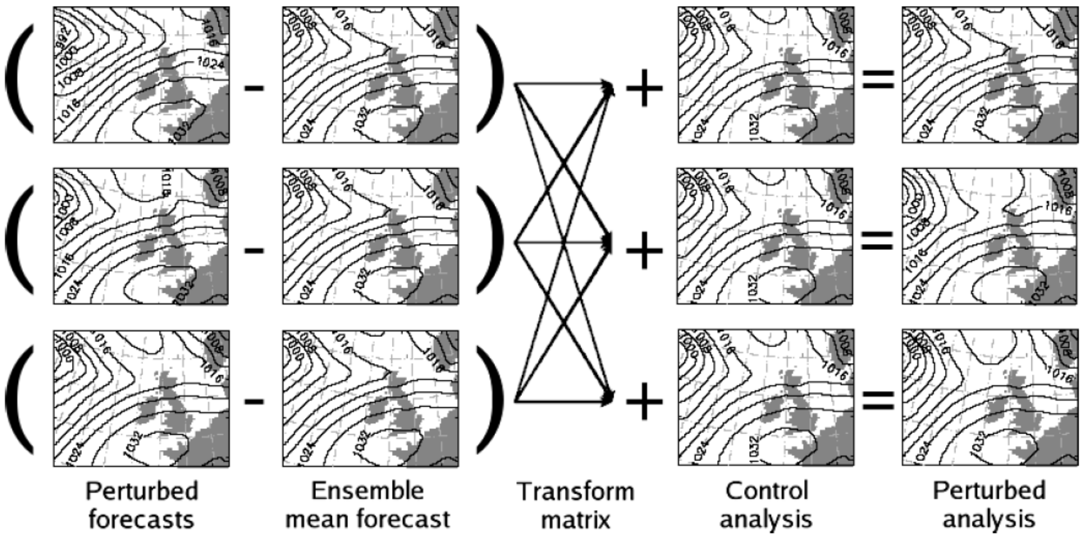


Figure 1 - Representation of the ETKF - perturbations from each member are combined using the transform matrix [from Bowler et al (2008)]

In addition to variations in initial conditions, forecast uncertainty will also be introduced as a result of uncertainties in model parameterizations of real-world physical processes. The MOGREPS models address these uncertainties by applying stochastic perturbations to the model parameterizations in two ways: 1) a 'random parameters' scheme that randomly perturbs tunable terms of those empirical parameterizations that represent processes which are too small scale to be directly resolved by the model (e.g. entrainment rate, critical Froude numbers, ice fall speed, etc. – see Bowler et al. (2008) for an exhaustive list) and affect the structural evolution of the forecast; 2) a 'stochastic convective vorticity' scheme that addresses the uncertainty in unresolved meso-scale convection by introducing a potential vorticity dipole in areas with severe convection to mimic the effects of meso-scale convective processes (implemented in MOGREPS-G only).

II.2 MOGREPS configurations and run cycle

The MOGREPS-G and MOGREPS-UK suites described will run as operational production systems at the Met Office as of December 2012. Pertinent details of the configurations are given in the following subsections.

II.2.1 MOGREPS-G

The MOGREPS-G ensemble comprises a control plus 44 perturbed members, of which 22 run to the full forecast length of 72 hours. The remaining 22 members run short update cycles of 9 hours only in order to provide additional data for the ETKF perturbation and 4D-Var schemes. The benefits of these additional members are to provide more degrees of freedom for the data assimilation scheme and improved sampling of the probability space in the ETKF, which results in better perturbed initial conditions for the forecast members (Bowler & Tenant, personal communication).

The global UM configuration used has an N400 horizontal grid (i.e. 0.3° latitude by 0.45° longitude, approximately 32km at mid-latitudes) and 70 vertical levels. Due to the large amount of computing resources consumed in running such a model multiple times, it is not possible to run the control plus all 22 forecast members to full range at every cycle. Therefore, only the control and half of the forecast members run out to full forecast length at any one forecast cycle; the remaining members run a short 'cycle step' of 9 hours in order to maintain continuity. During the next cycle, the members that ran a short-step previously are now run to full forecast length and vice-versa. The full 22 member ensemble product can then be generated using the overlapping full forecast members from the last two runs. Thus the run cycle comprises:

- Runs 4 x daily (00z, 06z, 12z, 18z); at each cycle 11 members + control are run to full forecast length, remaining members perform short update cycle:
    - 00/12z: Ctrl + [1 – 11] run to T+72, [12 – 44] run 9hr update.
    - 06/18z: Ctrl + [2 – 22] run to T+72, [1 – 11, 33 – 44] run 9hr update.
- Note that members 23 – 44 only ever run a short 9hr update cycle and are therefore not used for forecast product generation or downscaling.

II.2.2 MOGREPS-UK

The MOGREPS-UK atmospheric ensemble is generated by applying the MOGREPS-G control and 22 forecast members to a downscaling configuration of the UM covering the UK region. This configuration uses the same domain and stretched grid methodology as the Met Office UKV model (Tang et al., 2012), with a central fine resolution set to 2.2km and outer grid resolved at 4km. The configuration has 57 vertical levels. A key property resulting from modelling the atmosphere at this scale is generation of features associated with convective scale processes. These introduce extra spatial variability into the modelled wind field, compared with MOGREPS-G, so an interesting area of research within the MyWave project will be to determine how this extra variability is transfers to the modelled wave field and what, if any, benefits this will yield for the wave-EPS (e.g. in generating valid extra spread).

Since the MOGREPS-UK members do not make use of an assimilation step there is no requirement to run an update cycle or to run models linked to MOGREPS-G's additional 22 update members. The run cycle thus comprises:

- Runs 4 x daily, offset from MOGREPS-G by 3 hours (03z, 09z, 15z, 21z); at each cycle 11 members + control run to full forecast length
    - 03z/15z: Ctrl + [1 – 11] run to T+36
    - 09z/21z: Ctrl + [2 – 22] run to T+36
- MOGREPS-G provides initial conditions downscaled from its T+3 dump and lateral boundary conditions from T+3 to T+39

II.3 Application of MOGREPS data to the Met Office wave EPS

II.3.1 Method

Since uncertainty in a wave model forecast is predominantly related to uncertainty in the wind field applied to the model (see Section 4 of Janssen, 2008) it is expected that useable levels of spread can be generated in a wave-EPS purely based on variability introduced via perturbations in wind forcing data from an atmospheric ensemble. A further condition, required to ensure that spread in the wave field is present at short lead times, is that the wave-EPS member ICs are also perturbed. In theory the ETKF approach to the atmospheric ensemble should enable not only this latter condition to be met, since perturbed initial wave model conditions from previous forecasts or update cycles of the wave model forced by each of the atmospheric members, but will also allow consistent evolution of the member wave-EPS forecasts since a new atmospheric forecast for member *n* will relate to the previous atmospheric forecast for member *n* and hence to the initial conditions for wave member *n*.

This approach has been adopted successfully in the implementation of a surge ensemble at the Met Office (Flowerdew et al., 2010). The Met Office wave-EPS will follow and test the validity of this approach in the wave forecast context. The wave-EPS will consist of three WAVEWATCH III™ (WW3; Tolman, 2009) configurations, each run to generate 22 ensemble forecast members plus a control run. The configurations will cover the following domains: the Atlantic Ocean, using a spherical multi-cell grid; the Mediterranean Sea using an 8km rotated pole grid; the UK using an 8km rotated pole grid with boundary conditions provided by the Atlantic configuration. Further details of each configuration are given in subsequent subsections.

The version of WW3 run at the Met Office includes modifications for handling of rotated pole coordinate systems, revised wave partitioning (Bunney, 2010), 2nd order advection (Li, 2008) and a spherical multi-cell unstructured grid (Li, 2011). All configurations use a spectral resolution specified with 24 directions and 30 frequencies increasing geometrically between 0.04Hz and 0.65Hz and the following common source term and propagation packages:

- Tolman and Chalikov (1996) wind input and dissipation (herein, TC96)
- Discrete Interaction Approximation (DIA; Hasselman, 1985) for nonlinear wave-wave interactions
- Upstream Non-Oscillatory 2nd order propagation scheme (Li, 2008) with diffusion following Booij and Holthuijsen (1987)

Settings for key tuning parameters from these packages for each of the configurations are given in Table 1. These packages were chosen as an optimal blend of performance and computational efficiency. The TC96 scheme runs approximately 20-30% faster than the WAM Cycle-4 package, and the UNO2 scheme is approximately 20% faster than the default 3rd order scheme in WW3. Global wave buoy verification run under the Joint WMO-IOC Technical Commission for Oceanography and Marine Meteorology Wave Forecast Validation Project (JCOMM-WFVS[1]; Bidlot et al., 2002) shows that these schemes, in the context of the Met Office global wave model, achieve significant wave height forecast bias and root mean square errors that provide good performance, compared with similar systems at other forecast centres, whilst minimizing computational cost.

Configuration	c_0	X_s	Γ	Global time-step (s)	(minimum) CFL time-step (s)
Atlantic	1.36	0.10	-0.067	1800	600
UK	1.39	0.10	-0.027	900	300
Mediterranean	1.6	0.10	-0.027	900	300

Table 1 - Variable settings used in wave-EPS model configurations Constants are labelled as described in Tolman (2009). c0 is a tuning parameter in definition of effective wind speed. Xs is a reduction factor for the TC96 wind input source term applied to long period swell. Γ is an empirical constant in the JONSWAP bottom friction parameterization

[1] recent results at http://www.ecmwf.int/products/forecasts/d/charts/medium/verification/wave/intercomparison/

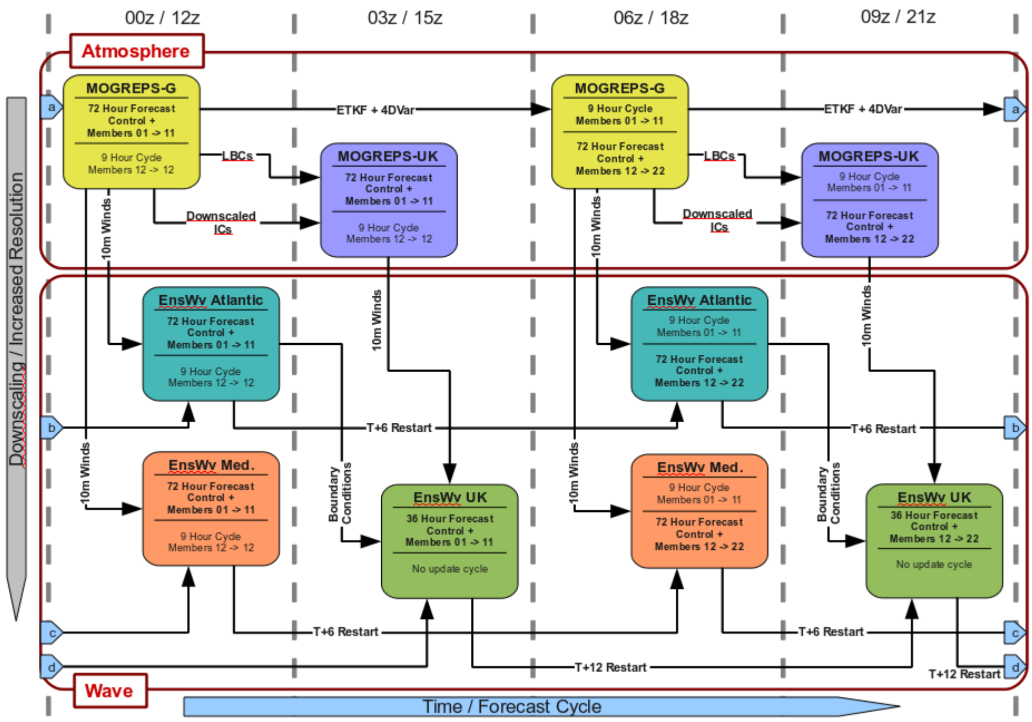


Figure 2 - Wave EPS run cycling and model inter-dependencies

Figure 2 details the model inter-dependencies and run cycling of the wave model configurations. Forcing for the wave-EPS configurations will be provided as 10m wind fields from the MOGREPS-G and MOGREPS-UK atmospheric ensembles. Ensemble wave and atmosphere members are consistently linked from cycle to cycle, i.e. wave-EPS member 1 is always driven by atmospheric member 1, in order to maintain levels of spread and ensure a stable evolution of the wave field in consecutive cycles (Bocquet, 2009). Currently, the MOGREPS-G winds have a forecast length of 72 hours and this dictates the maximum run time of the wave models. Since the data assimilation and ETKF schemes are not applied to the wave model only the control and 22 forecast members from MOGREPS-G are used. Since the atmospheric EPS runs only the control and half (11) of the forecast members to full forecast length during any one forecast cycle, a similar structure must be adopted in the wave-EPS. For wave configurations driven by MOGREPS-G the alternate 11 member atmospheric update cycle will also be followed by the wave models in order to preserve continuity in initial conditions. For the UK wave configuration, which will be forced by MOGREPS-UK, no such update cycle is available and subsequent forecast cycles will be initialised using the T+12 wave forecast field from the previous run. A risk of this approach is that some inconsistencies between the initial wave field and atmospheric forcing may be introduced. The alternative would be to run update cycles based on MOGREPS-G, however it is expected that, over the twelve hour update cycle required, variability introduced to the wave field as a result of MOGREPS-UK’s resolution of convection would be lost from the wave model and eliminate one of the desirable properties of this ensemble (see Figure 3).

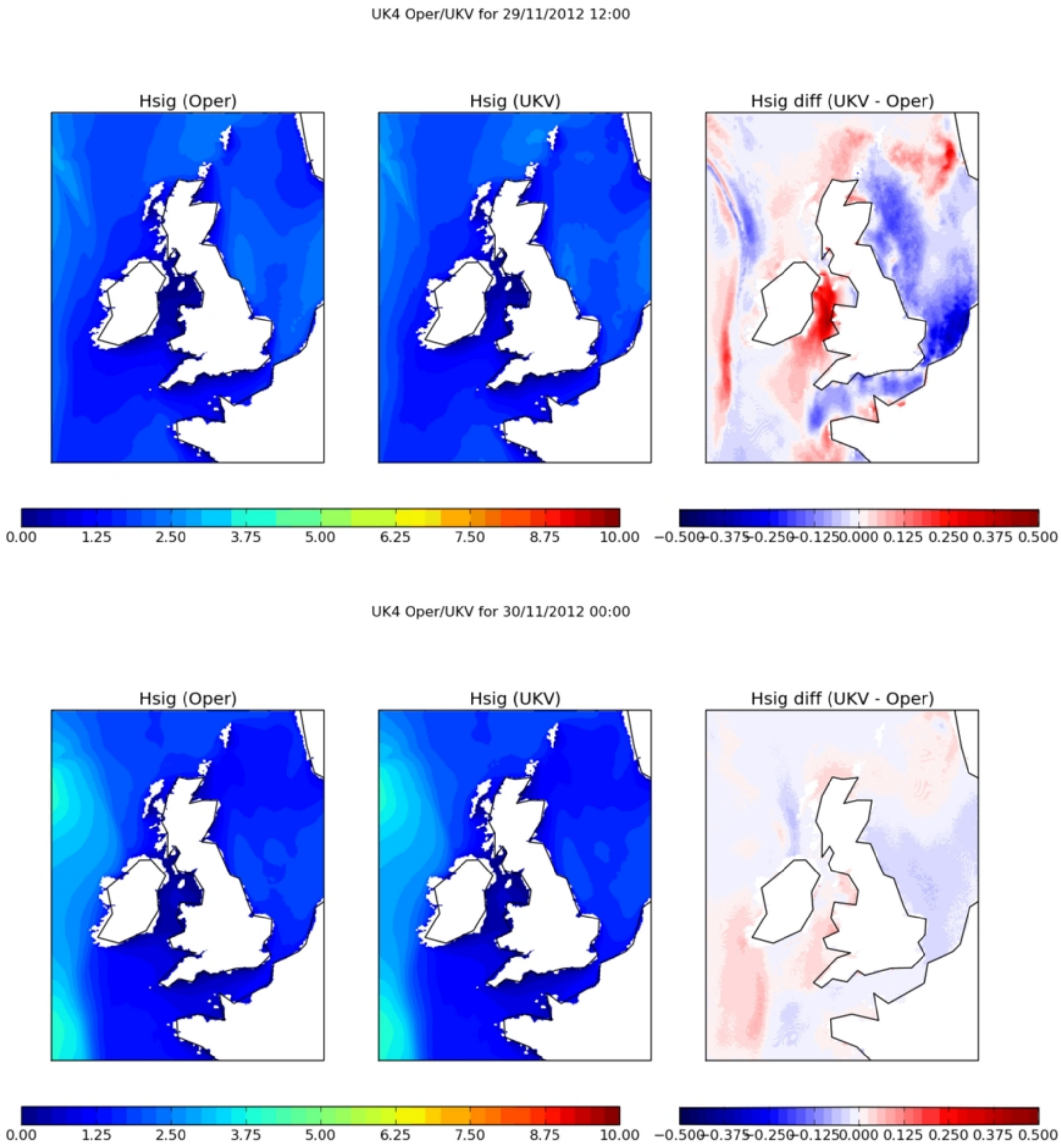


Figure 3 - Illustration of decay of convective scale features in the transition between a wave model forced by convective scale and global scale winds. In the top panel, the central subfigure shows significant wave height when a 4km wave model is forced by 1.5k

II.3.2 Atlantic configuration

The Atlantic wave model uses a Spherical Multi-Cell grid (SMC; Li, 2011) defined with 3 tiers of cell sizes scaling from approximately 6-12-25km. The choice of this scheme was based on a requirement to both deliver appropriate coastal boundary conditions for port applications being run by Puertos del Estado (in WP3.4) and run a model domain sufficiently large to produce perturbed forecasts of wave development in the open ocean. The SMC6-25 set up enables both criteria to be met whilst minimising computing resource requirements and system complexity since only a single model configuration needs to be run rather than applying a sequence of nested models at increasing resolution. Estimated run time is 0.019 hours per node per forecast day on the Met Office IBM Power 7 supercomputer.

In order to be sure that the majority of Atlantic swell generation regions are represented in the configuration and to minimise boundary inputs, the selected Atlantic domain follows coastlines all the way from the Antarctic to Arctic (Figure 4). The domain has been masked to remove branches at the outskirts, such as the Gulf of Mexico, Hudson Bay, and the Mediterranean. The choice of cell scaling was implemented based on the simplest possible strategy, i.e. using the smallest cell size at the land-sea boundary and then scaling up to the next tier where pairs of smaller cells are available at cell face boundaries. This approach minimizes the number of smaller cells in the model and hence optimizes run-time. As described in Li (2011) the SMC grid also doubles longitudinal resolution at set higher latitudes (60N, 75.5N, 82.8N) in order minimize the impact of the Courant Friedrich-Levy (CFL) condition on the wave model propagation time-step and further reduce overall model run-time. Figures 5 and 6 provide illustrations of the grid around the Canary Islands (where one of the Puertos del Estado sites is located) and the UK respectively, and show the downscaling of cells around coasts and islands and, in Figure 6, the increase in longitudinal resolution at 60N.

Application of the SMC grid in a regional model configuration required development beyond that described by Li (2011), specifically in enabling the model to accept a wave boundary condition. In WW3 boundary conditions are applied by defining grid points with boundary data that are excluded from source term computation and which in the propagation scheme are not modified but only provide pre-set wave data in the computational stencils. These points do not need to be on the outside of the grid. Since the SMC grid works with boundary points in the same way as in the regular grid, there is no major issue in adding boundary data except for the method by which the boundary points are defined. In the present version this has been achieved by supplying the model with an additional boundary cell input file, which lists cell numbers and central longitudes and latitudes for each of the user-defined boundary grid points.

When implemented as a wave-EPS the model will be forced using MOGREPS-G wind data from the control and 22 forecast members. As there is currently no wave ensemble implementation covering the global domain, LBCs for the open sea boundaries in the Southern Ocean will be supplied from the Met Office operational deterministic global wave model (35km), and similarly a single ice field sourced from the OSTIA operational analysis system (Donlon et al., 2012) will be specified and persisted in all members. Only two cross-sections in the Southern Ocean, between Cape Horn in South America (69W) and Cape Agulhas (20E) at the tip of South Africa will be fed with wave boundary conditions. Boundary conditions at Strait of Gibraltar, Baltic Sea, Gulf of Mexico (La Habana - Miami), Hudson Bay, and Baffin Bay are ignored as they are either quite small or sheltered by nearby islands. Due to the distance between the input locations and key regions of interest for testing the EPS, impacts of these deterministic inputs on ensemble spread are expected to be small. The Atlantic wave-EPS run cycle is defined as follows:

- 4 runs: 0z/6z/12z/18z.
- Cycling follows control and first 22 members of MOGREPS-G:
    - 0z/12z: Members 1-11 run out to full 72h forecast, 12 – 22 perform short update cycle.
    - 6z/18z: Members 2-22 run out to full 72h forecast, 1 – 11 perform short update cycle.
    - Restart dumps produced at T+6.

Coverage and resolution scales in the Atlantic model should enable comparison with both the Met Office operational deterministic global (35km) and European (8km) wave models, since these are forced by similarly scaled (20km) winds from a deterministic run of the UM and take ice coverage from the same OSTIA ice analysis.

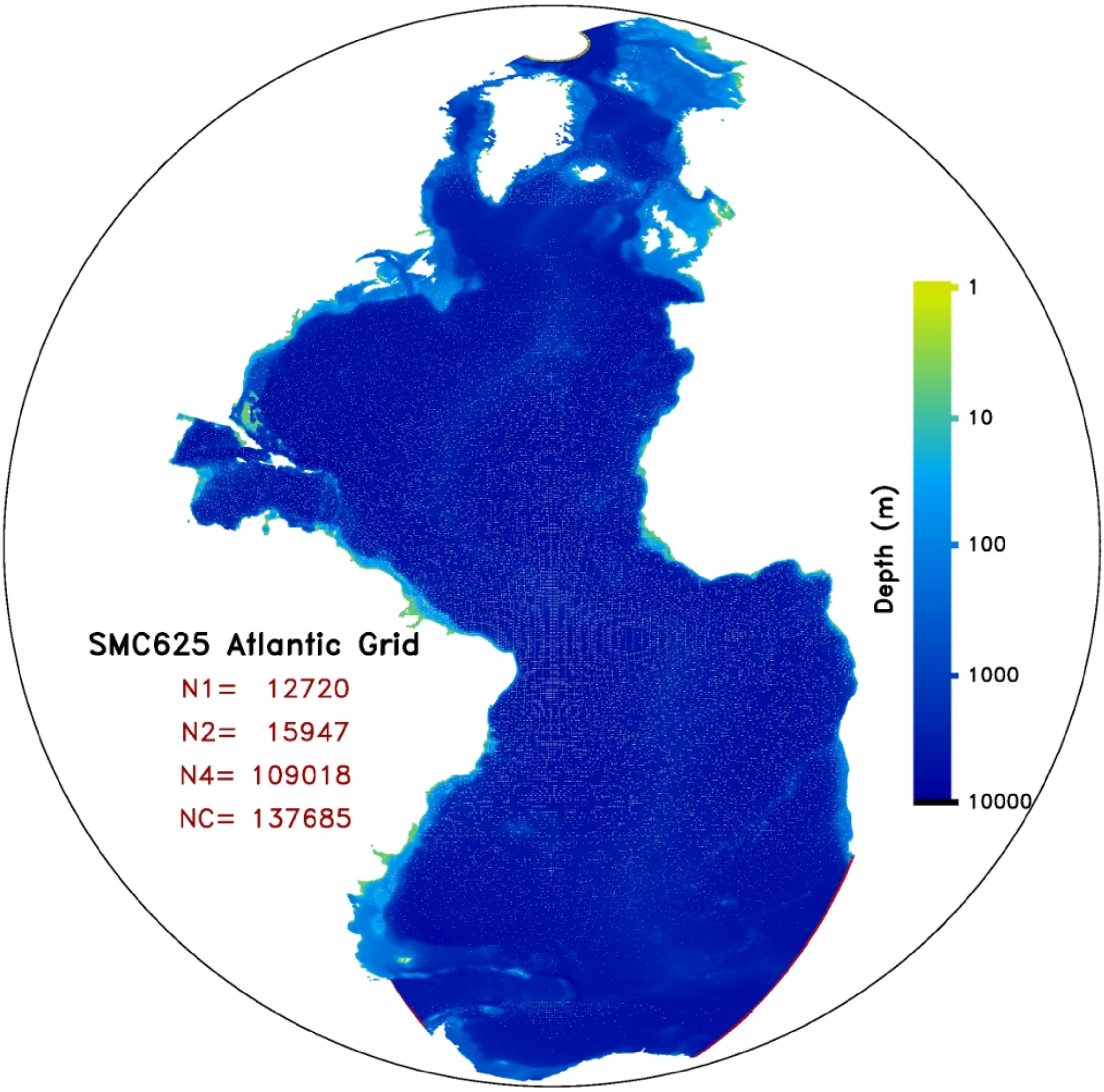


Figure 4 - The Atlantic SMC grid showing grid cell depth and numbers of tiered cells; N1-6km, N2-12km, N4-25km.

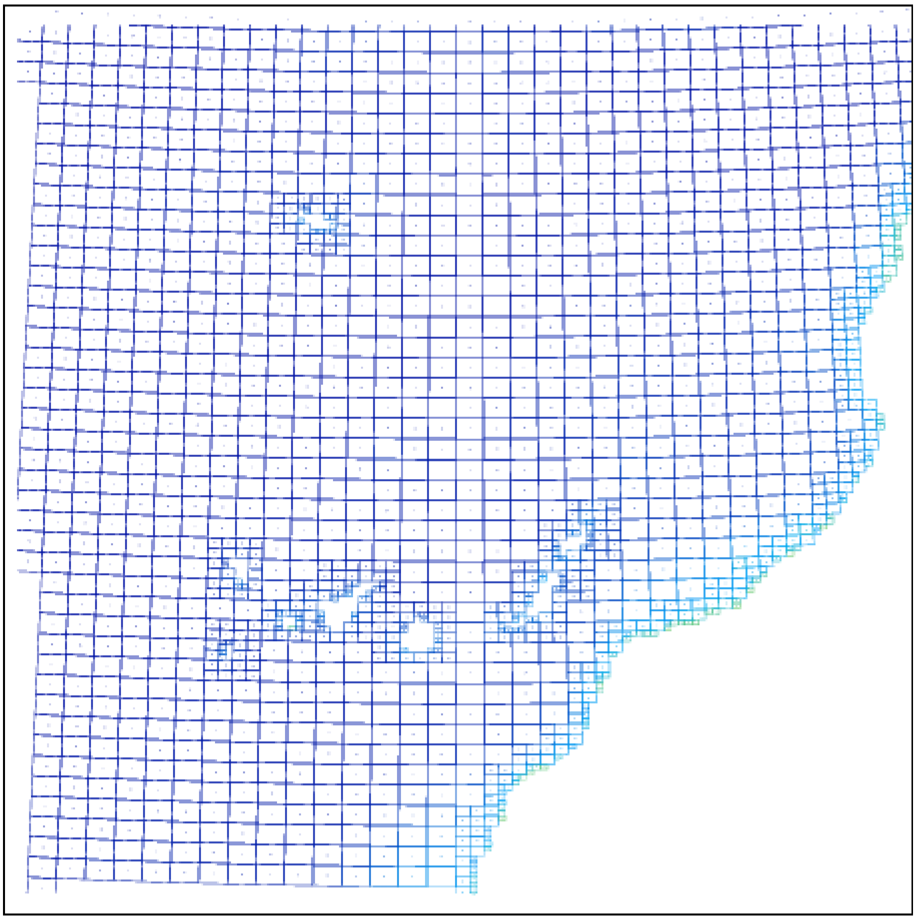


Figure 5 - Atlantic SMC6-25 grid around the Canary Islands, Moroccan coast and Madeira

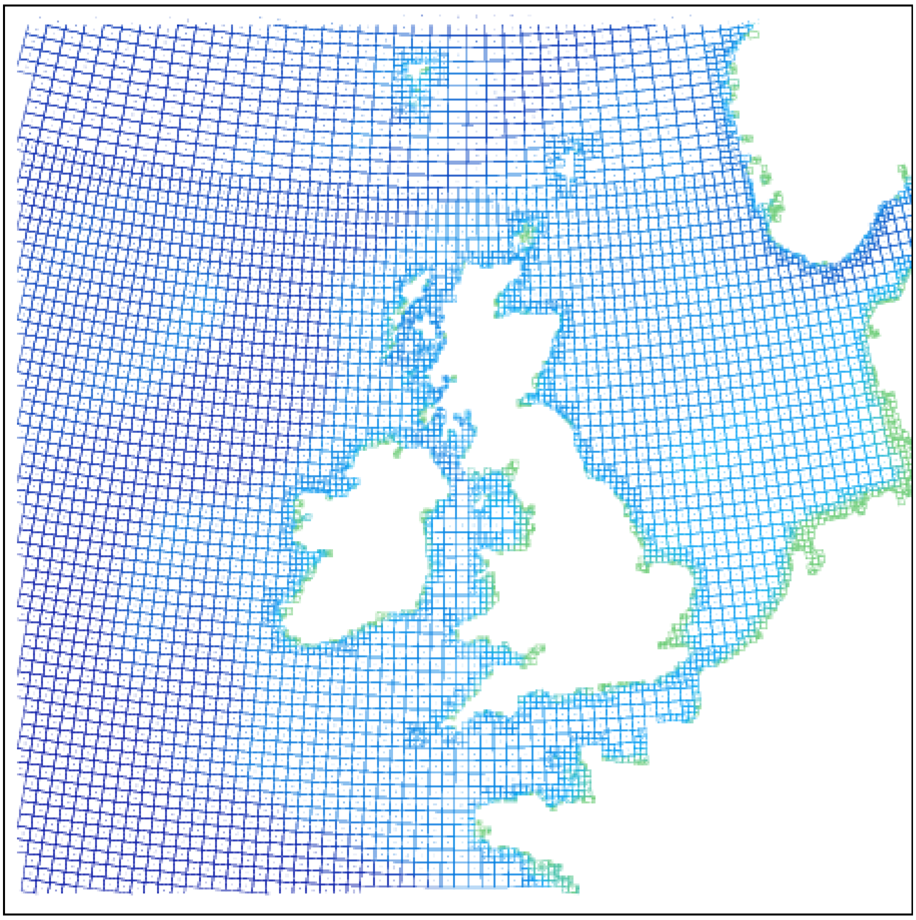


Figure 6 - Atlantic SMC6-25 km grid around the UK. Longitude resolution of the grid is doubled above 60N.

II.3.3 UK configuration

The UK configuration is defined on a rotated grid with an artificial pole offset at 37.5N and 177.5E, and with resolution at 0.08 degrees (approximately 8km). The rotated grid scheme is applied since the model covers a region (between 47N and 62N) for which a regular pole grid would lead to significant differences in zonal cell size. The effect of rotation is to place an artificial equator in the middle of the domain in order to minimize longitudinal squeezing of cells at high latitudes, leading to more consistent application of the minimum CFL time-step. Estimated run time is 0.014 node hours per forecast day on the Met Office IBM Power 7 supercomputer.

The UK wave model takes wave boundary conditions from the Atlantic model and will be driven by the convection permitting atmospheric model, MOGREPS-UK. The wave boundary condition will be consistent with the wind forcing in each member, since MOGREPS-UK member *n* will downscale from MOGREPS-G member *n*, which will also have been used to drive the Atlantic wave-EPS member *n*. As no update cycle is run for MOGREPS-UK, initial conditions for each wave member are taken from the T+12 hours forecast from the previous forecast cycle. Thus the UK wave-EPS runs are structured as follows:

- 4 runs: 3z/6z/12z/18z.
- Cycling follows control + ensemble members of MOGREPS-UK:
  - 3z/15z: Ctrl + Members 1-11 run out to full 60h forecast
  - 9z/21z: Ctrl + Members 2-22 run out to full 60h forecast

- o Restart dumps produced at T+12
- Boundary conditions at wet boundaries provided by respective member from latest Atlantic wave cycle.

The region covered by the UK wave model is shown in Figure 7. This region has a wave regime heavily influenced by seas developed in the North Atlantic as well as locally. The domain includes a number of areas of relatively shallow (less than 50m) water depth such that the shallow water physics scheme and tuning in the model are likely to influence performance.

The similarity in resolutions and consistency in boundary conditions for the UK region within both the Atlantic and UK models enable a comparison between wave-EPS data forced using global and convection permitting wind data. In addition, the UK wave-EPS can be compared to the Met Office deterministic system for the UK which applies convection permitting wind data to a higher resolution 4km wave configuration, and to models generated in WP2 (as part of subtask 4.3.2).

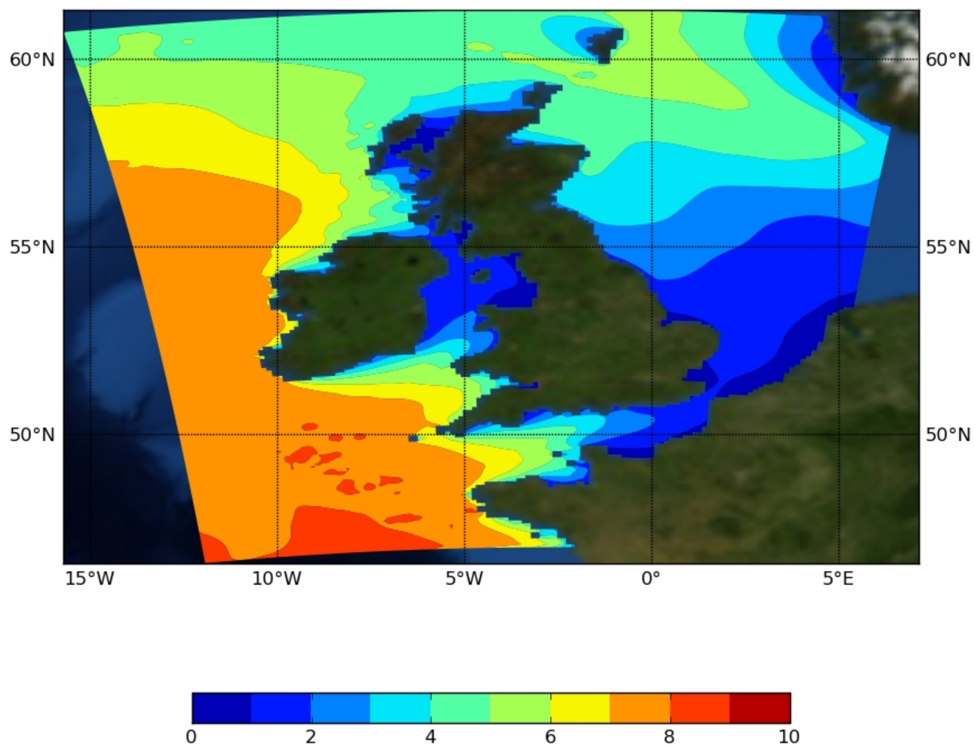


Figure 7 - Significant wave height field (m) showing extent of UK 8km domain

II.3.4 Mediterranean configuration

The Mediterranean configuration is defined on a rotated grid using a pole at 37.5N and 177.5E and with resolution at 0.08 degrees (approximately 8km). The model will be run without an input wave boundary condition at the Straits of Gibraltar. For the range of latitudes covered by the model, the use of a rotated grid is not strictly necessary. However, selecting this set-up enabled the Mediterranean model to be created using a sub-domain of the Met Office operational deterministic European wave model, and will allow direct grid-to-grid comparisons between the EPS and deterministic systems. Estimated run time is 0.008 hours per node per forecast day on the Met Office IBM Power 7 supercomputer.

The Mediterranean wave-EPS will be run based on forcing from MOGREPS-G, resulting in the following run conditions:

- 4 runs: 0z/6z/12z/18z.
- Cycling follows control plus first 22 members of MOGREPS-G:
    - 0z/12z: Ctrl + Members 1-11 run out to full 72h forecast, 12 – 22 perform short update cycle.
    - 6z/18z: Ctrl + Members 12-22 run out to full 72h forecast, 1 – 11 perform short update cycle.
    - Restart dumps produced at T+6.

The region covered is shown in Figure 8. Although the Mediterranean can generally be considered as a benign wave climate in comparison to open waters of the North Atlantic some sea areas are exposed to extreme wind forcing and have sufficiently long fetches to generate high energy seas, for example sea-states driven by the Mistral wind (known as the Maestrale in Italy) over the Gulf of Leon have reached in excess of 8m (Bertotti et al., 2012). The predominance of relatively young wind-seas in the wave climate of the Mediterranean has some issues for the TC96 physics used in our default WAVEWATCH III set-up, and has led to adopting a more aggressive setting for effective wind speed (Tolman, 2009) versus the value usually used for open ocean models (see Table 1). Verification of this change is discussed in Section IV.

Once running, in addition to verifying against the Met Office operational deterministic model, data from the Mediterranean wave-EPS will be exchanged and compared with systems run by USAM. One task for the comparison will be to explore whether fundamental differences between the two wave-EPS result from the different scales of wind forcing used (approximately 32km for the Met Office system and 7km for USAM's). For example whether significantly different properties in the wind fields are introduced where flows are influenced by topography, for example in the case of Mistral winds which are accelerated through the Rhone valley, and how these subsequently affect the forecast wave fields.

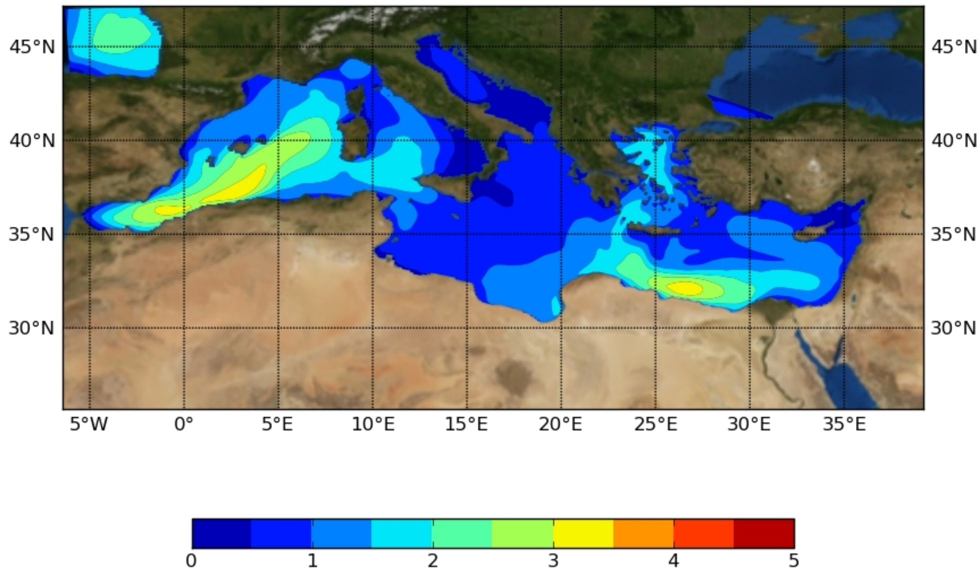


Figure 8 - Significant wave height field showing extent of Mediterranean 8km model domain

II.4 Deterministic Wave model Validation

II.4.1 Method

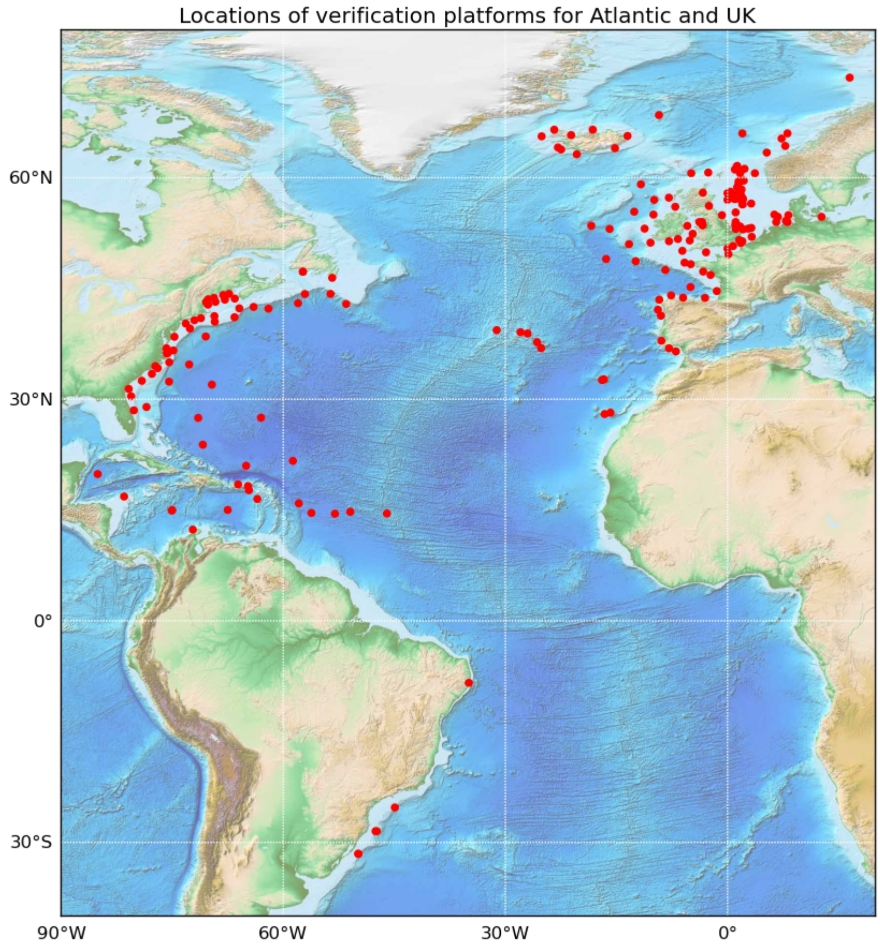
Prior to deployment within the ensemble forecasting framework, the three model configurations have been validated based on their ability to replicate observed wave data when forced by 'best available' wind fields. These tests provide a baseline measure of model performance prior to working with the MOGREPS wind data and check whether major systematic biases are liable to be present.

In order to have a sufficient time-series of wind data which was scaled similarly to the MOGREPS system that will be used to drive the wave EPS, the validation study was based on 1-year (2011) of analysis winds from the Met Office's N512 (25km) global configuration of the UM. Ideally a complementary test for the UK wave configuration using a convection permitting atmospheric model would have been made, but a sufficient time-series of atmospheric fields was not available. The baseline for validation comprised quality controlled in-situ measurements provided to the Met Office via the JCOMM-WFVS. The resulting verification data for the wave-EPS models were also cross-compared with results from the Met Office's existing suite of operational wave models. A map of the in-situ sites used in the comparison is given in Figure 9. One departure from statistics usually presented in the JCOMM-WFVS is that the verification here used point observations rather than the 4-hour average observation, described in Bidlot and Holt (2006), used to overcome scaling issues between observations and global atmospheric and wave models. Adopting point observations as a baseline leads to a more conservative view of the model performance in short lived extreme conditions and illustrates where the baseline data are observed with limited precision. In all cases the observed data were matched up with a 'nearest neighbour' data value from the model (i.e. the model data were not interpolated in space or time).

Statistics presented in this section are based on an analysis for the whole of 2011 and use standardised figures aimed at assessing several aspects of model performance. The figures comprise 6 panels and compare two models against an observed baseline such that:

- The top left panel shows overall distributions of the parameter verified plus summary statistics
- The top right panel shows bias and root mean square error (RMSE) through the model forecast range (stratified at 5% intervals) plus a summary of overall bias and RMSE
- The middle left panel compares distributions of model-observation errors from the two models in 'quantile-quantile' form plus summary statistics; solid marker lines are at 5, 25, 50, 75 and 95% quantiles and dotted markers are at 5% intervals
- The middle right panel shows the Taylor plot (Taylor, 2001) of (unbiased) model performance, which is based on normalised variance and correlation relative to the observed baseline; perfect performance would see a data point located at (1,0) on the plot axes. A linear fit relationship for the models against observations is also given.
- The two bottom panels show quantile-quantile (Q-Q) distributions of model versus baseline data above and below a given percentage threshold; the two plots are shown since wind and wave parameter distributions are generally skewed and it is difficult therefore to view the model's ability to replicate both the most frequent conditions and the distribution upper tail in a single plot.

Overall the information in these plots is expected to capture both the model's ability to replicate the observed climate (without temporal accuracy) and the errors introduced when the ability of the model to replicate the observed temporal signal is tested.



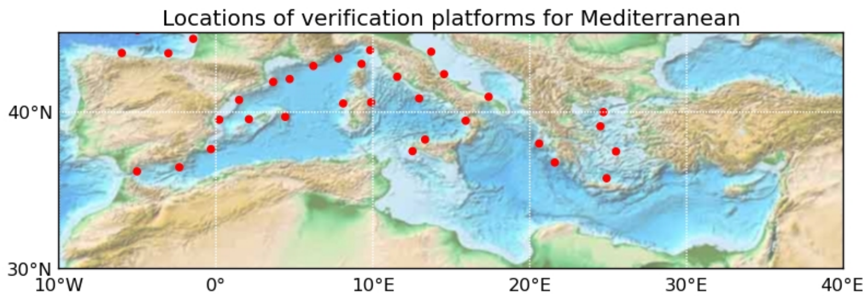


Figure 9 - In-situ wind and wave measurement locations with data available for the verification tests. Data were excluded from Caribbean platforms in Atlantic testing and from The Bay of Biscay platforms in Mediterranean tests.

II.4.2 Wind data

Wind speed data comparisons to in-situ platform data are provided in Figures 10-12 for collections of stations in the Atlantic, UK and Mediterranean domains respectively. The data are compared to results from the Met Office operational global wave model in order to test whether the interpolation of the atmospheric model wind data onto different wave configuration grids has affected the wind fields. Q-Q and distribution plots follow a 'stepped' structure due to a majority of the wind observations being provided with limited (1 m/s) precision.

The figures show virtually identical wind speed error statistics between the wave-EPS grids and global model grid for the Atlantic and UK areas, and only a marginal difference for the Mediterranean grid. The wind errors are consistent between Atlantic and UK areas where model and observations have similar variability and have a Pearson correlation coefficient of 0.91. Biases are small, with a tendency for the model to slightly over-predict between the 60-95th percentile, although the maximum observed wind speed is approximately 1.5m/s faster than the model maximum. Scatter indexes for Atlantic and UK are approximately 22%, and 90% of the wind speed errors fall between -2.5 and 2.5m/s. The distribution of wind speed errors in the Mediterranean has a similar range, although overall correlation between the observed and modelled series is lower (correlation approximately 0.85) and scatter index is 33%.

II.4.3 Atlantic wave model

Significant wave height data from the Atlantic domain are compared with verification data for the Met Office (30km) operational global wave model (Figure 13). The Atlantic domain shows a clear improvement in both RMSE and bias, resulting from improved correlation between the model and observed data and significant reduction of positive bias errors above the 75th percentile level. The Atlantic model appears to sample higher waves well up to the 99th percentile of the significant wave height distribution, although the maximum wave model value is 1.6m below the maximum observation. Scatter index for the model is approximately 22%, and 90% of significant wave height errors fall between -0.5 and 0.6m.

II.4.4 UK wave model

Significant wave height data from the UK domain are compared in Figure 14 with verification data for the Met Office (8km) operational European wave model. Although similarly scaled, the two models are differentiated by the boundary models used; the European model domain extends to 15-30W and 72N and is boundaried by the 30km global wave model, whilst the UK model extends to 12-16W and 62N and is boundaried by the 25-12-6km Atlantic domain. Nevertheless performance from the two models is virtually identical. Both models have a reasonably low overall bias (0.07m), scatter indexes of approximately 20% and correlation coefficient greater than 0.96. The models have a slightly high bias in sampling waves from 20th to 98th percentile although the maximum wave model value is 1.8m below the maximum observation. 90% of significant wave height errors fall between -0.5 and 0.7m.

Since the UK data will be compared with the Atlantic model under different wind forcing conditions during the wave-EPS testing, the configuration trials offer an opportunity to compare the models under the same wind forcing. Figure 15 shows that performance of the models is virtually identical. In part this may be due to the location of a number of observation platforms close to the UK-Atlantic boundary. As a check, Figure 16 shows the same comparison against a more limited set of platforms sited in the southern North Sea, as far as possible from the boundary region. In this instance some limited improvement between UK and Atlantic model verification can be seen, particularly in overall variability, correlation and sampling bias for wave heights above the 98th percentile.

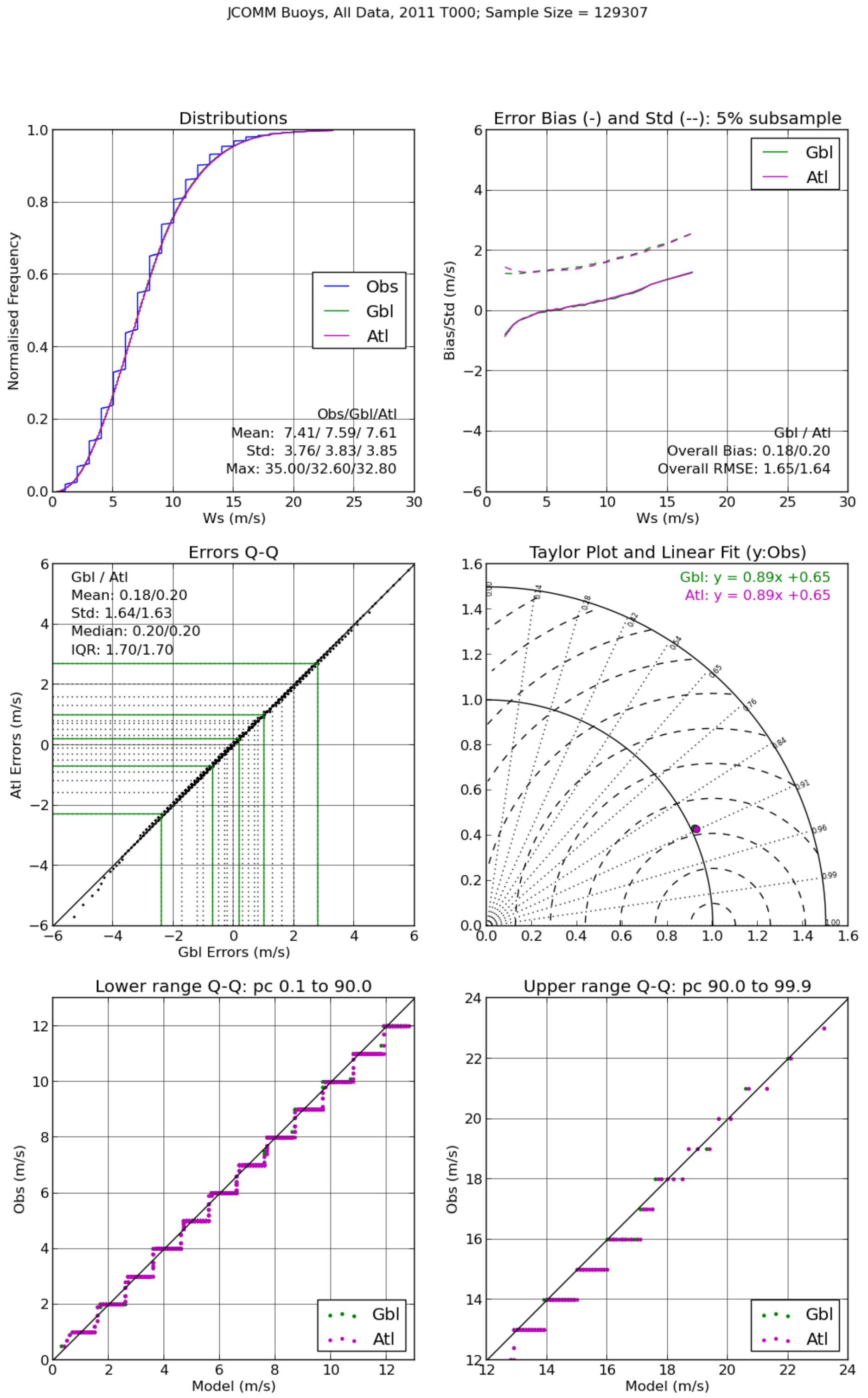


Figure 10 - Comparison of wind data on (green) Global and (magenta) Atlantic wave model grids against in-situ wind observations in the Atlantic region

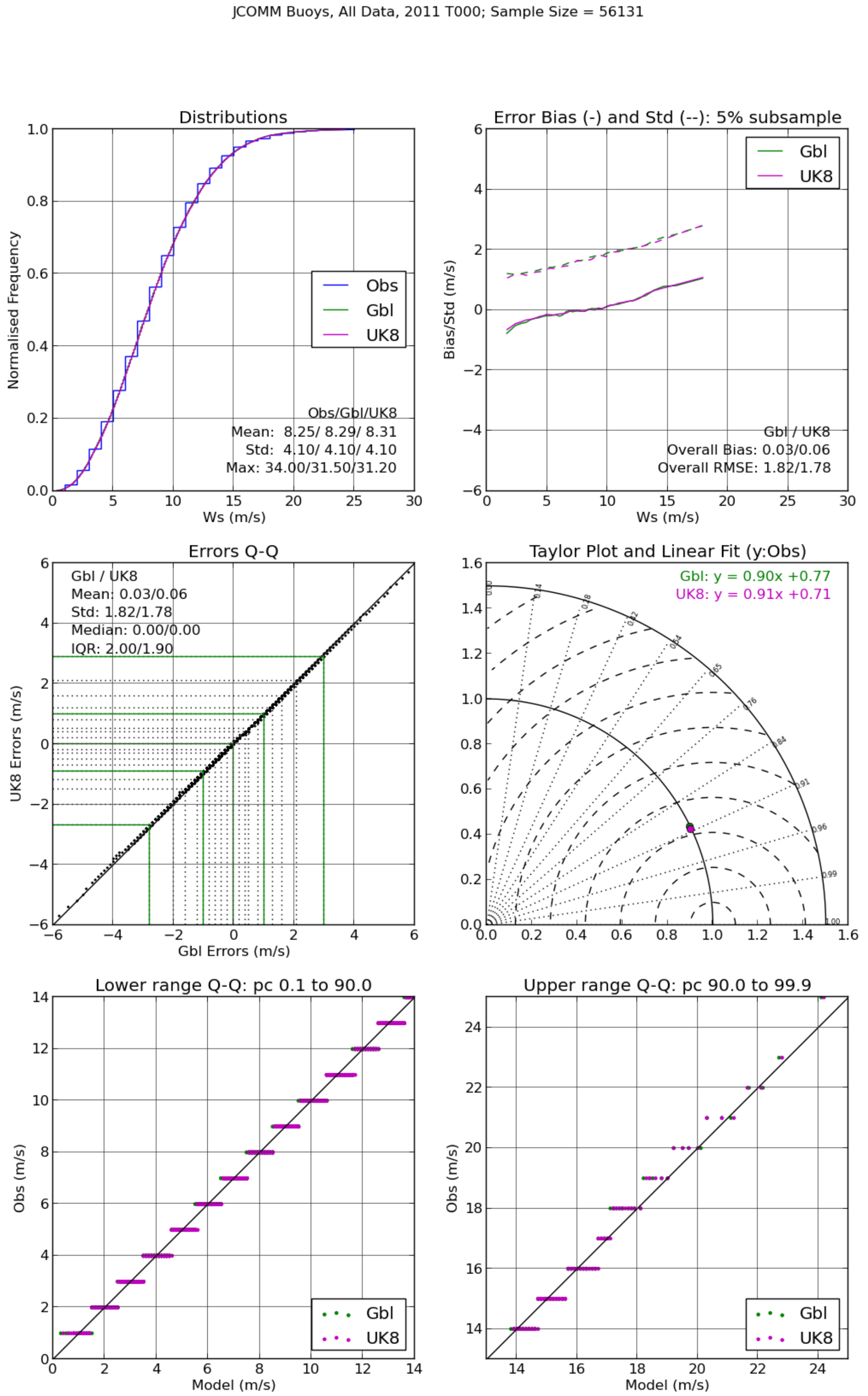


Figure 11 - Comparison of wind data on (green) Global and (magenta) UK wave model grids against in-situ wind observations in the UK region

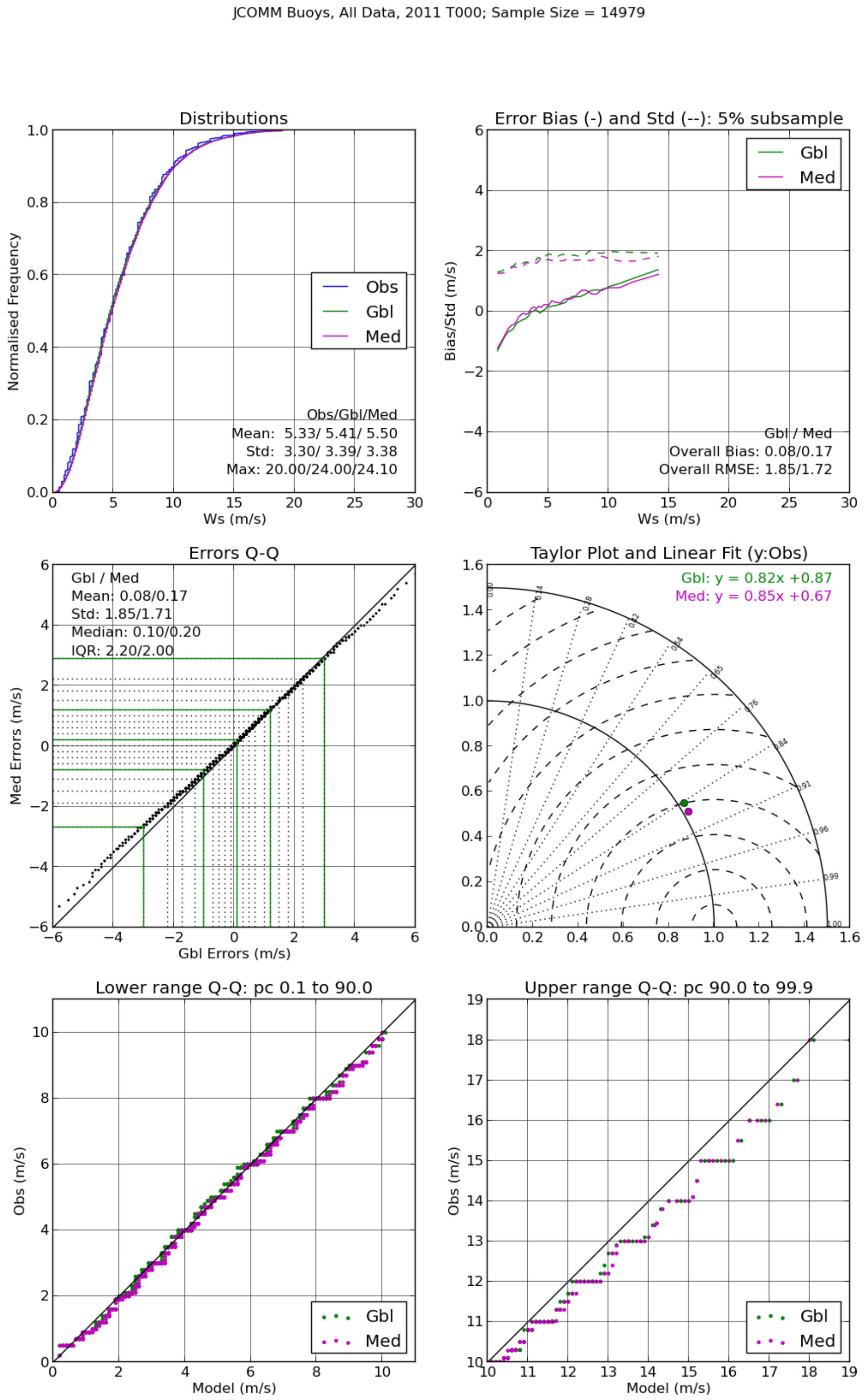


Figure 12 - Comparison of wind data on (green) Global and (magenta) Mediterranean wave model grids against in-situ wind observations in the Mediterranean region

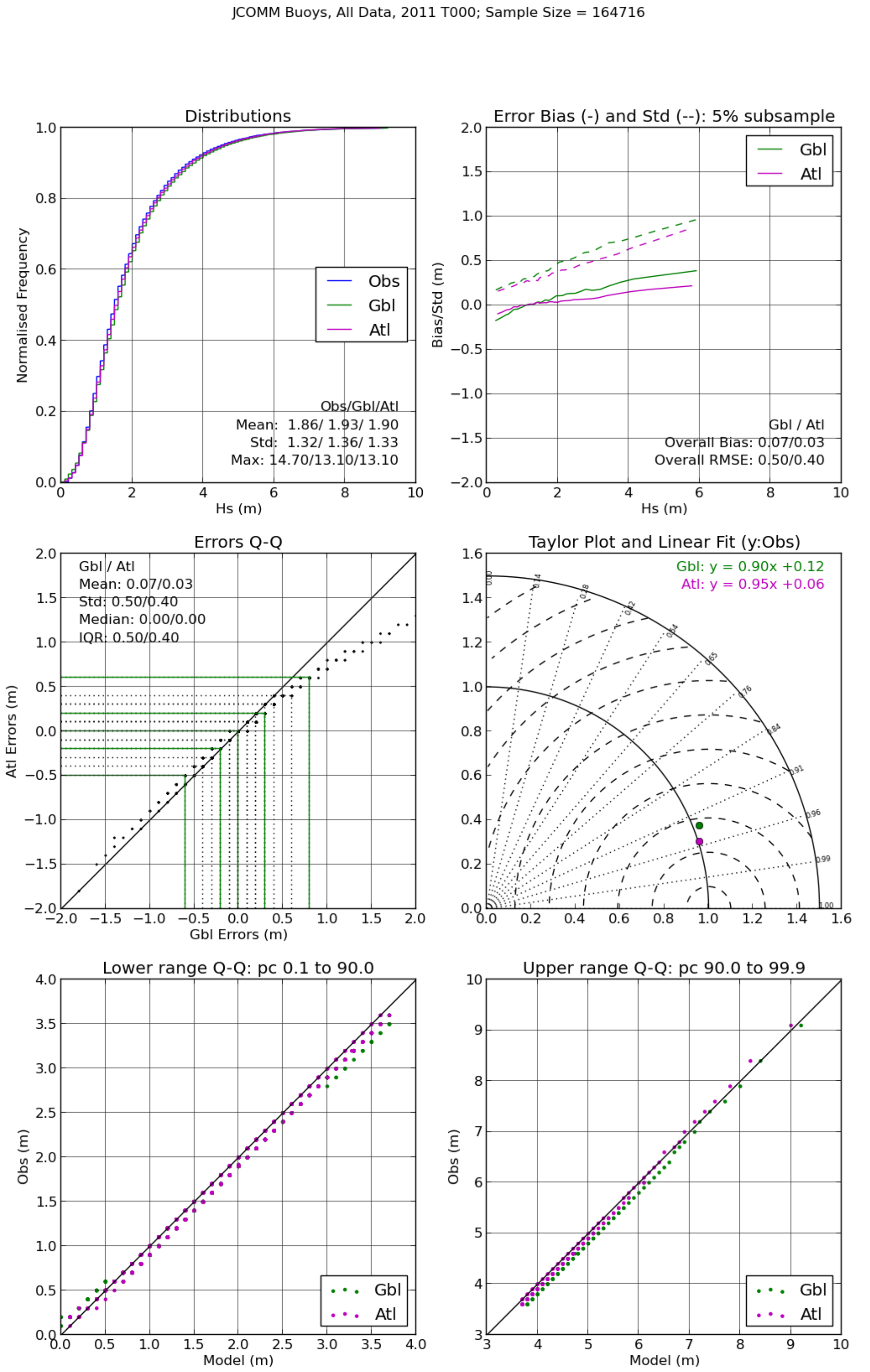


Figure 13 - Comparison of significant wave height data from (green) Global and (magenta) Atlantic wave models against in-situ observations in the Atlantic region

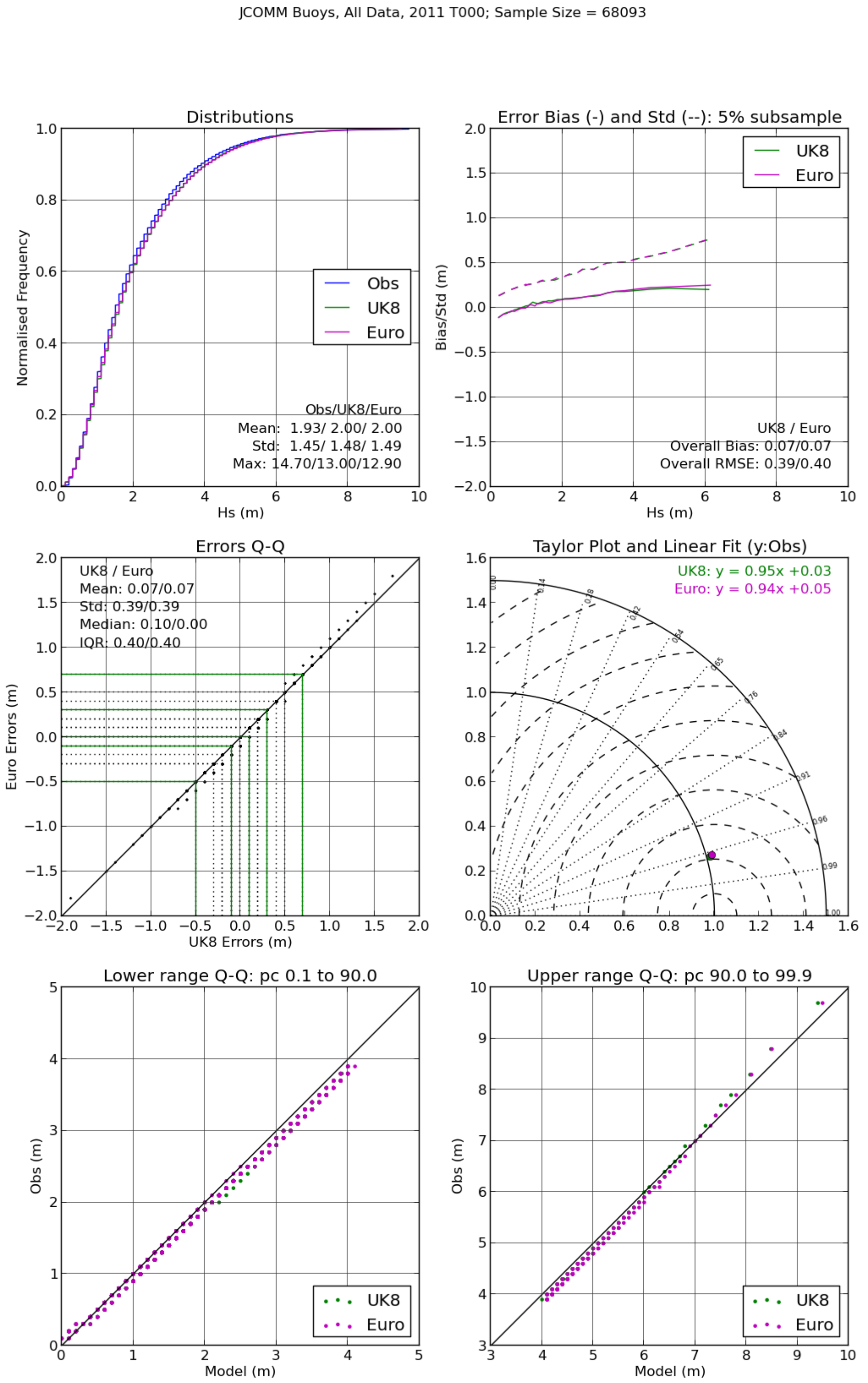


Figure 14 - Comparison of significant wave height data from (green) UK and (magenta) European wave models against in-situ observations in the UK region

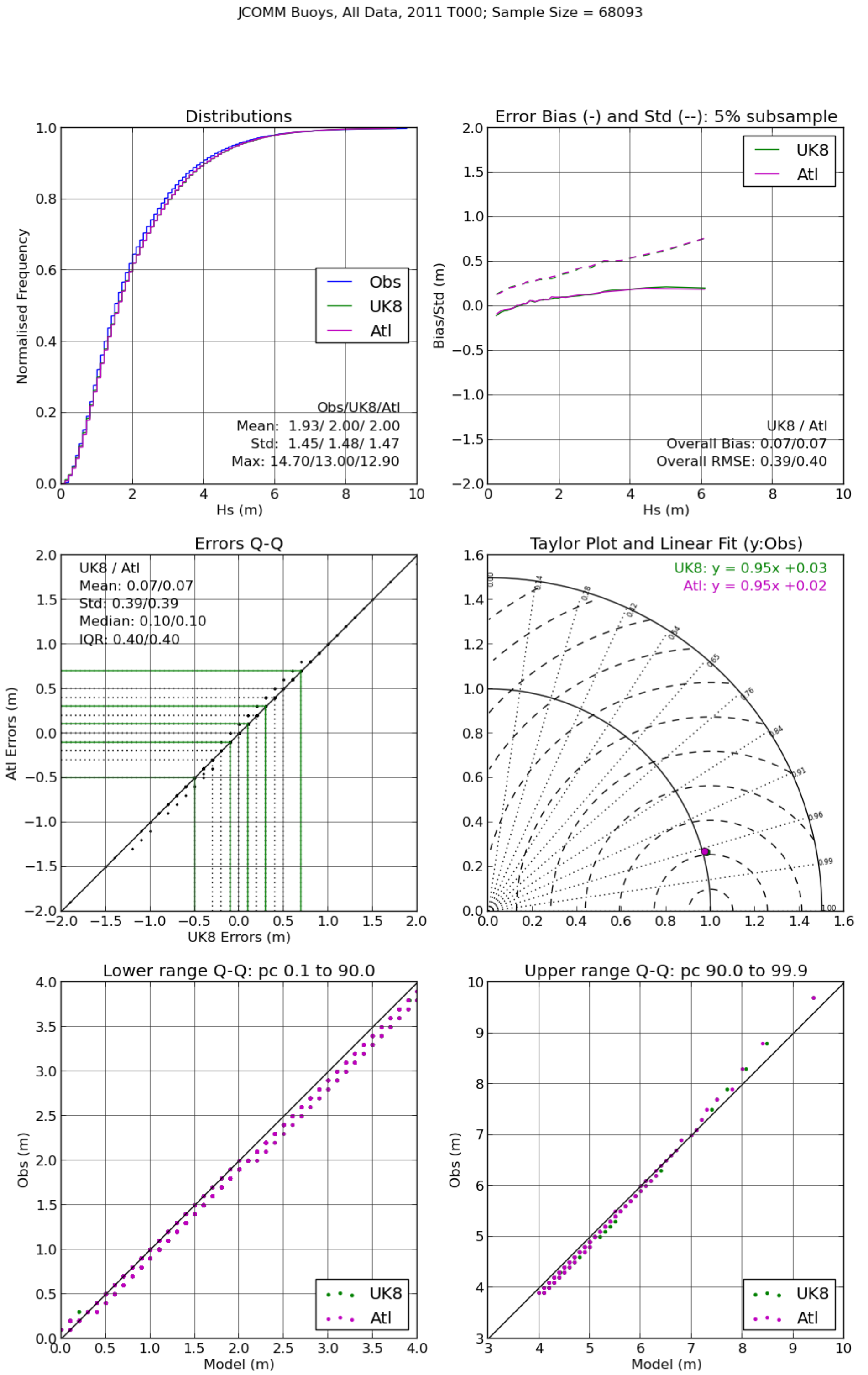


Figure 15 - Comparison of significant wave height data from (green) UK and (magenta) Atlantic wave models against in-situ observations in the UK region

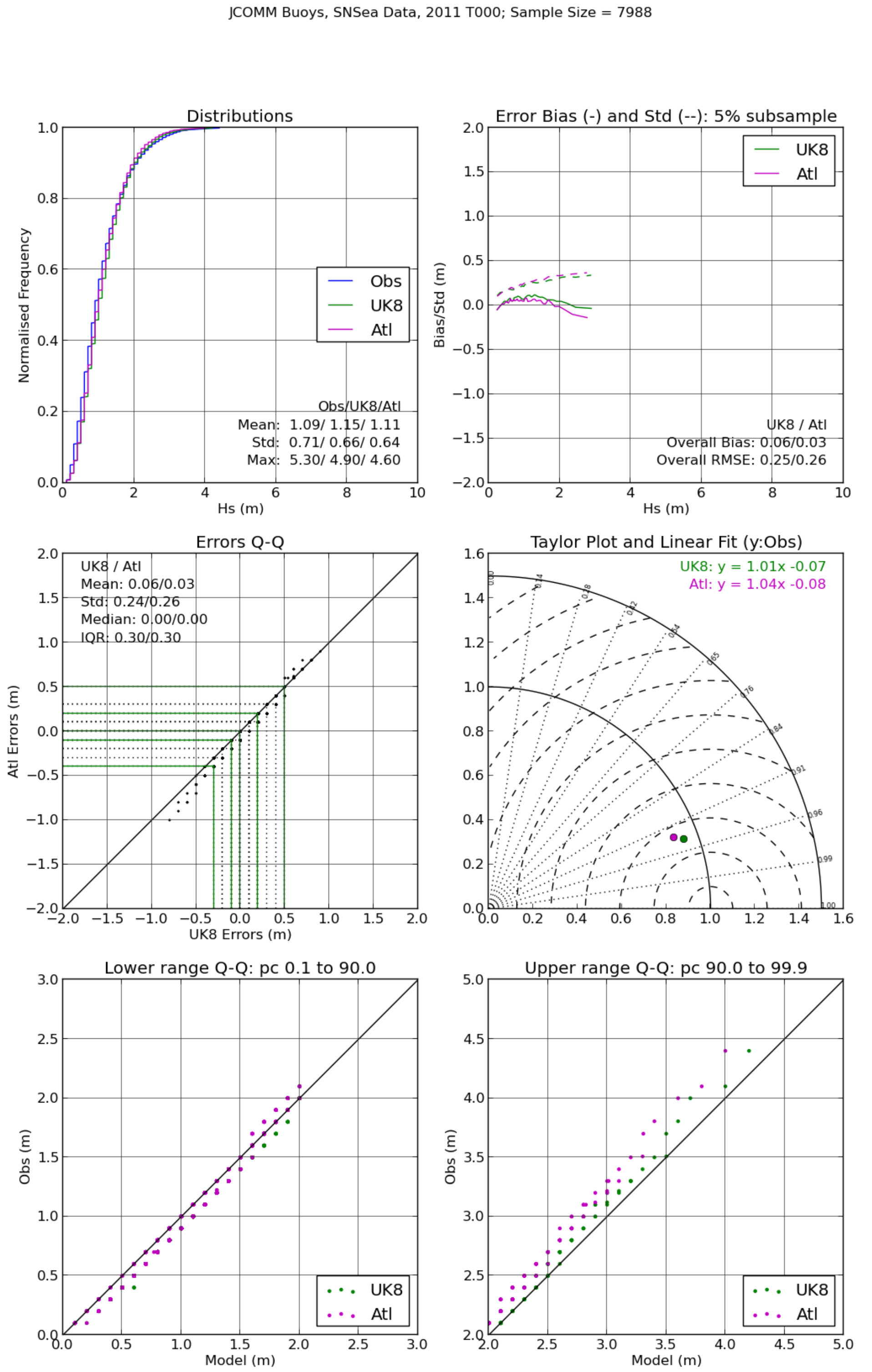


Figure 16 - Comparison of significant wave height data from (green) UK and (magenta) Atlantic wave models against in-situ observations in the southern North Sea region

II.4.5 Mediterranean wave model

Significant wave height data from the Mediterranean domain are compared in Figure 17 with verification data for the Met Office (8km) operational European wave model. The key difference between the two models is the setting of the parameter c_0 used by Tolman (2009) to define effective wind speed, and which can be used as a coarse tuning coefficient for wind wave growth (Tolman, personal communication). In the European model this coefficient has been determined based on performance in regions influenced by developed waves from the Atlantic, but in the Mediterranean model c_0 was adjusted with the aim of better replicating young wind-sea wave growth. For significant wave height, this adjustment has reduced an under-prediction bias from -0.15m in the European model to -0.05 in the Mediterranean and reduced RMSE slightly from 0.29 to 0.26m. Scatter index is close to 28%, similar to that for the driving winds. In general the Mediterranean model has replicated the observed wave climate up to the 99th percentile, and generates a maximum value within 0.3m of the observed maximum. However, it should be noted that these values fall well below the maximum noted in Bertotti et al. (2012).

Since the model had been tuned significantly relative to normal operational systems at the Met Office, a comparison was also made for wave peak period as a preliminary check on the wave spectrum (Figure 18). As generally seen for wave models in the JCOMM-WFVS, peak wave period verification is poorer than for significant wave height. Nonetheless the retuned Mediterranean results are an improvement on the operational model. 90% of errors fall between -2 and 1 seconds which, along with the period quantile-quantile plots and results from the significant wave height verification, suggests that even with the tuning the wave field is slightly underdeveloped by the model.

II.4.6 Deterministic verification summary

In tests using identical wind fields the wave-EPS configurations show performance that is consistent or improved compared to the current suite of operational deterministic wave models run at the Met Office. The verification suggests that when run using EPS wind data, the major forecast differences between the wave-EPS models and their operational counterparts will (in general) result from perturbations in the wind data. When comparing Atlantic and UK wave-EPS data some consideration of the influence of the Atlantic boundary condition on the UK model will need to be made, for example identifying verification sites a reasonable distance from the UK-Atlantic boundary region. Tuning of the TC96 physics has been applied in the Mediterranean which has resulted in a bias correction to both significant wave height and peak period statistics.

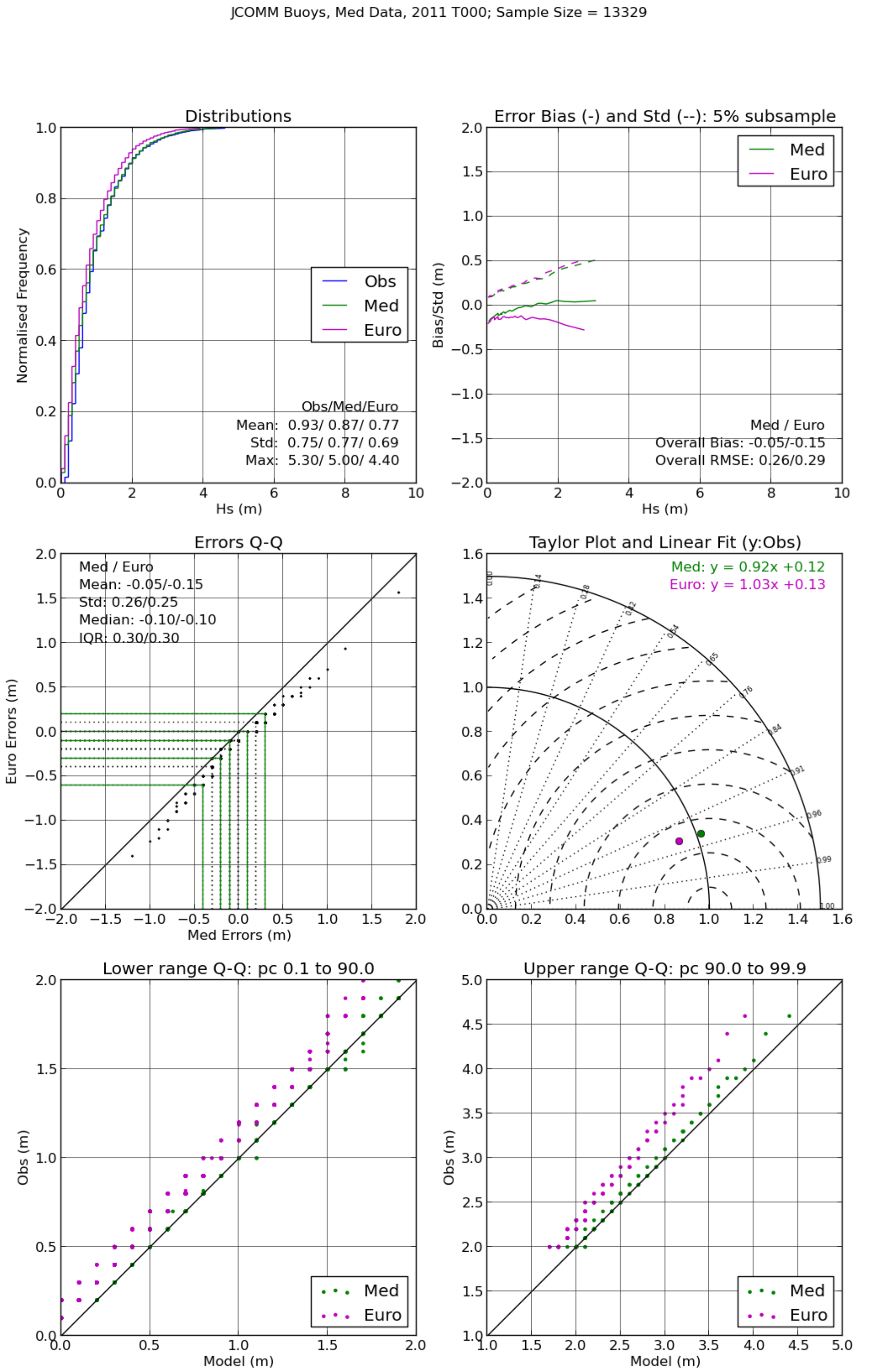


Figure 17 - Comparison of significant wave height data from (green) Mediterranean and (magenta) European wave models against in-situ observations in the Mediterranean region

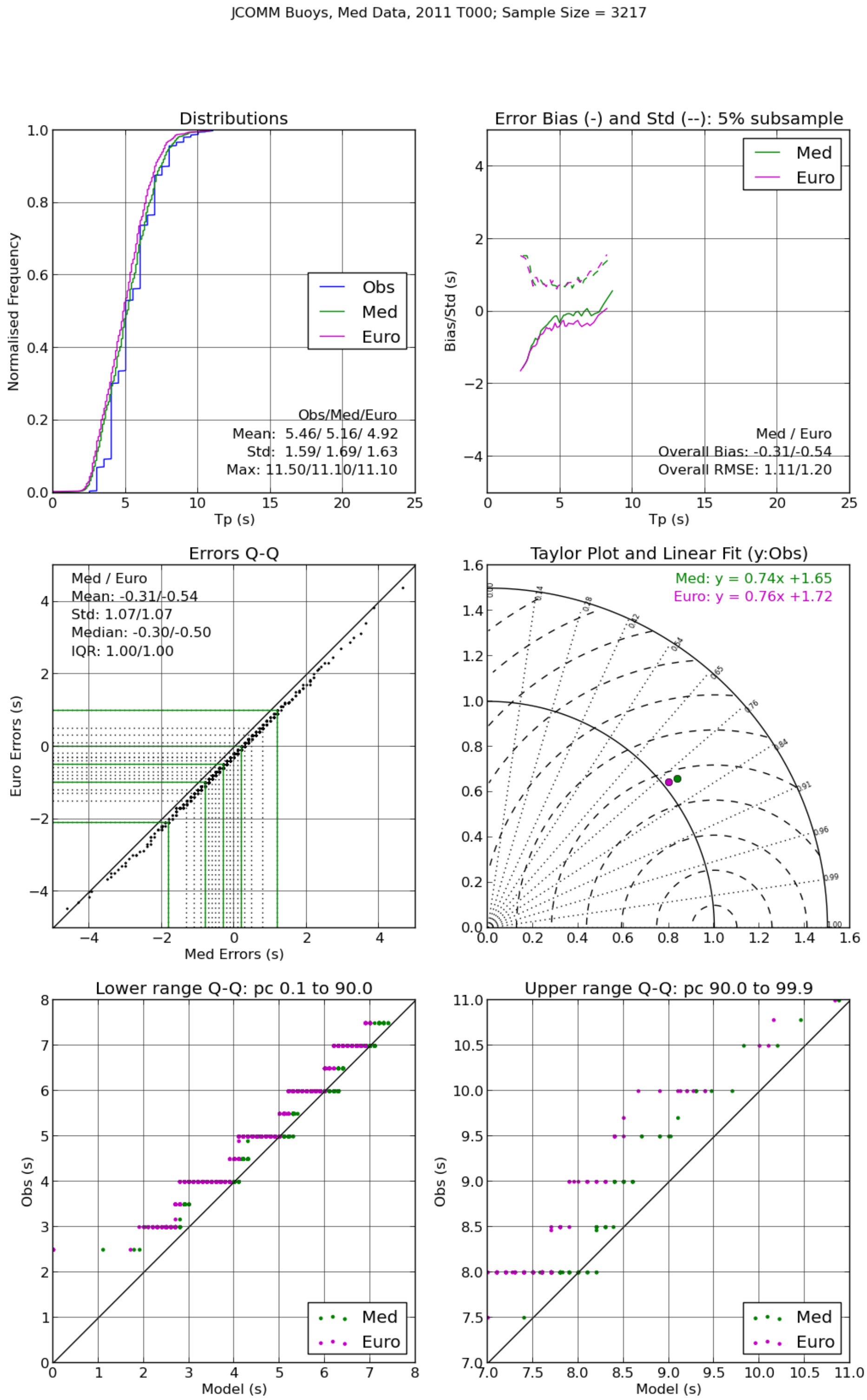


Figure 18 - Comparison of wave peak period data from (green) Mediterranean and (magenta) European wave models against in-situ observations in the Mediterranean region

II.5 Wave-EPS Output data and user trials

Generating an ensemble of wave forecasts will provide a number of options for new products and visualization. Bocquet (2009) reviews and outlines a number of wave products closely related to those provided by the European Centre for Medium-Range Weather Forecasts (ECMWF). Figure 19 shows an example of the ECMWF site specific probabilistic forecast for wind and waves, using wind speed and direction plus significant wave height, mean wave period and direction data.

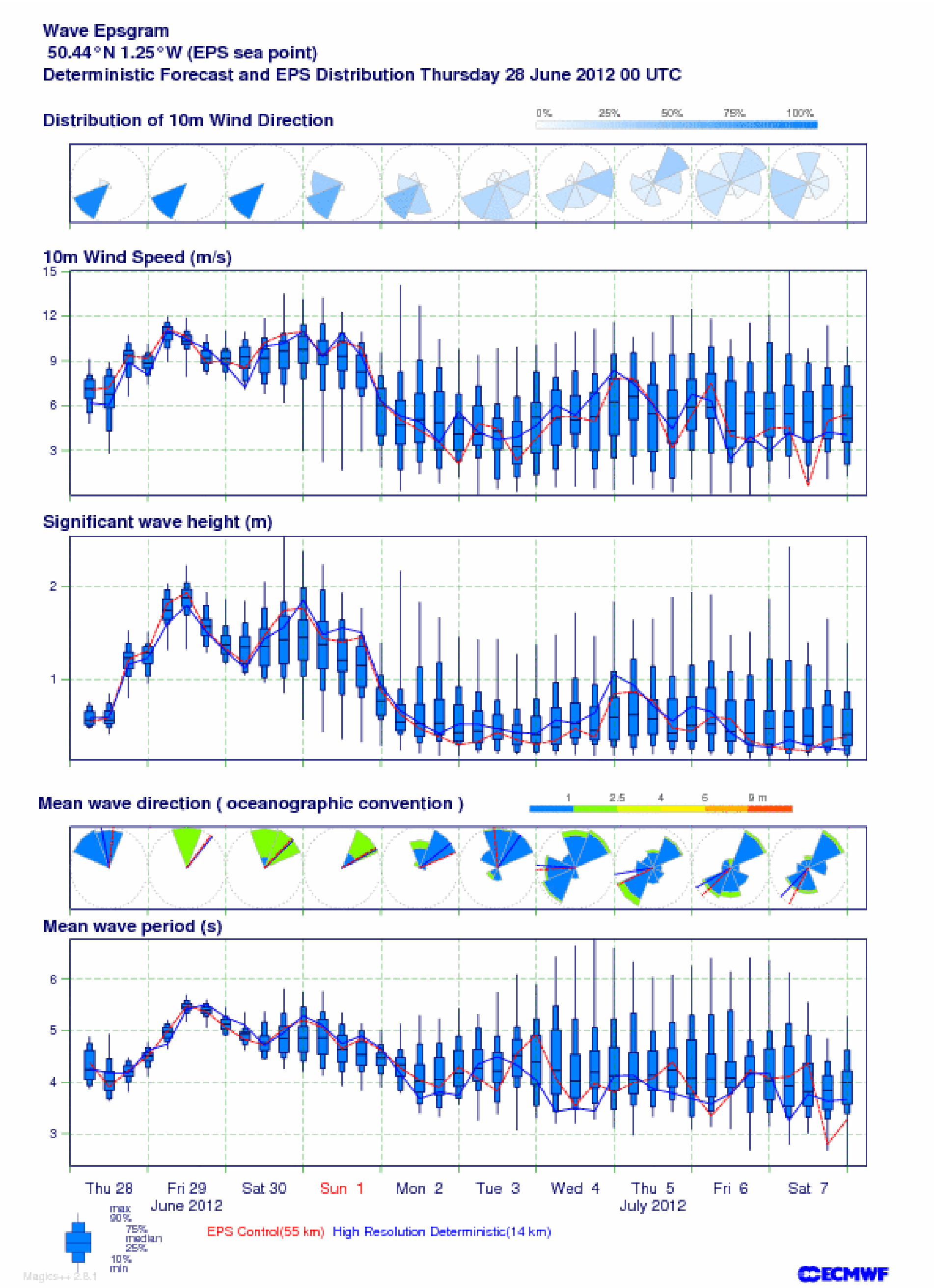


Figure 19 - Example wind and wave EPS forecast from ECMWF

One significant output difference between the Met Office WW3 model and ECMWF WAM model is that the former will produce multiple wave train partitions that are subsequently assigned as wind-sea and swell according to wind conditions (Hanson and Phillips, 2001; Bunney, 2010) whilst the latter provides a single wind-sea and swell field determined based on wind input to the wave spectrum. Since any dependence on wind conditions may lead to variability in how wind-sea and swell are classified even when the underlying wave spectra are similar, some further consideration is required as to whether the Met Office wave-EPS will work with partitioned data that includes a wind dependent wind-sea definition or otherwise. How best to present probability data from multiple partitions will also need to be addressed.

Some additional infrastructure work is required to put outputs from the Atlantic SMC model data on a practicable operational footing; for example by interpolating the unstructured grid data onto a predefined set of regular product grids.

In addition to data exchanges identified in WP3, the Met Office also intends to trial outputs from the wave-EPS with a number of user groups. In particular the UK Environment Agency will receive and assess products alongside their present operational use of the Met Office surge-EPS. Similar trials are expected with Met Office commercial marine forecasters and in collaboration with the WaveSentry project[2].

II.6 Further work and expected timeline

Having designed the wave-EPS and validated the component wave models the work at the Met Office will move into the implementation phase. This is expected to deliver a functioning wave-EPS early in 2013. Subsequently, data will be exchanged within the project and with targeted users in order to validate both the wave-EPS and its products. An outline of the anticipated work schedule is following:

- **[Jan 2013]**: Development of software for pre-processing of driving fields from MOGREPS atmospheric ensemble and scheduling wave-EPS runs.
- **[Feb 2013]**: Implementation of the ETKF driven wave-EPS in Met Office (parallel) operational suite.
- **[Mar 2012]**: Completion of parallel suite testing; wave-EPS runs regularly in Met Office operational suite.
- **[Apr 2013]**: Data will be provided regularly for project partners based on:
    - Defined performance metrics to be exchanged with ISMAR for intercomparison with LETKF ensemble model in Mediterranean;
    - Determined format, locations and delivery method of lateral boundary conditions to be provided to PdE to drive down-scaled harbour ensemble models.
- **[Feb 2013 – Jun 2014]**: Model runs and exchange of data.
- **[Jun 2013 – Jun 2014]**: Application of verification and intercomparison procedures from subtask 3.3.3 to data produced throughout the life of the project. Results will be compared for the Atlantic-UK system and the Mediterranean system using both deterministic and ensemble modelling approaches against an observed baseline. Reports will be produced as deliverables D3.5 and D3.6.

[2] http://groupspaces.com/wavesentrykn/join/

III DESCRIPTION OF THE USAM-CNMCA SHORT-RANGE ENSEMBLE PREDICTION SYSTEM (COSMO-ME EPS)

The CNMCA short-range ensemble prediction system is based on the Ensemble Kalman Filter (EnKF) approach (Bonavita, Torrisi and Marcucci, 2008, 2010), for the data assimilation component (estimation of the initial conditions), and the COSMO regional model (www.cosmo-model.org) for the prognostic one.

The EnKF is an assimilation technique that uses the Monte Carlo approach through an ensemble of forecasts which allows to include information on the flow-dependent error of day, in particular the Local Ensemble Transform Kalman Filter (LETKF - Hunt et al. 2007) scheme has been implemented at CNMCA. The LETKF method combines two methods: the ETKF (Bishop et al. 2001) and the LEKF (Ott et al. 2004). The first method uses a transform matrix to directly transform the forecast error covariance to an analysis error covariance in a smaller subensemble space, thus reducing computational cost. Instead of assimilating data sequentially, the LEKF updates independent grid points simultaneously using only observations in a localized subspace. The LETKF has been chosen, because it is easy to implement, intrinsically parallel and more efficient and flexible for nonlocal observations such as satellite radiances.

The CNMCA-LETKF data assimilation system is operationally used to initialize the high-resolution non-hydrostatic model COSMO integrated over the Mediterranean-European region (called COSMO-ME, Fig.1). The atmospheric short-range ensemble prediction system based on the LETKF system and the COSMO model is under testing at CNMCA.

The main characteristics of the CNMCA-LETKF data assimilation system are:

- 6 hourly intermittent data assimilation cycle, of which a schematic view is given in Fig.2.
- Domain and resolution: the system is running on the Mediterranean-European domain with 40 ensemble members plus a deterministic member, having a 0.09° grid spacing (≈10 km) and 45 vertical levels. The configuration is defined on a rotated regular grid, the coordinates of rotated north pole are (47.0,-10.0).
- Observations: the observational dataset operationally ingested comprises radiosonde ascents (RAOB), surface pressure observations from land and sea stations (SYNOP, SHIP, BUOY), manual and automatic aircraft observations, atmospheric motion vectors from Meteosat, European wind profilers, scatterometer winds from METOP and AMSU-A radiances from METOP and NOAA satellites.
- Lateral Boundary conditions: they are from IFS deterministic run perturbed using ECMWF-EPS.
- Surface perturbations: climatological perturbed sea surface temperature.

- Model and sampling error: "Relaxation-to-prior spread" multiplicative inflation method according to Whitaker et al. 2010 and climatological additive noise.

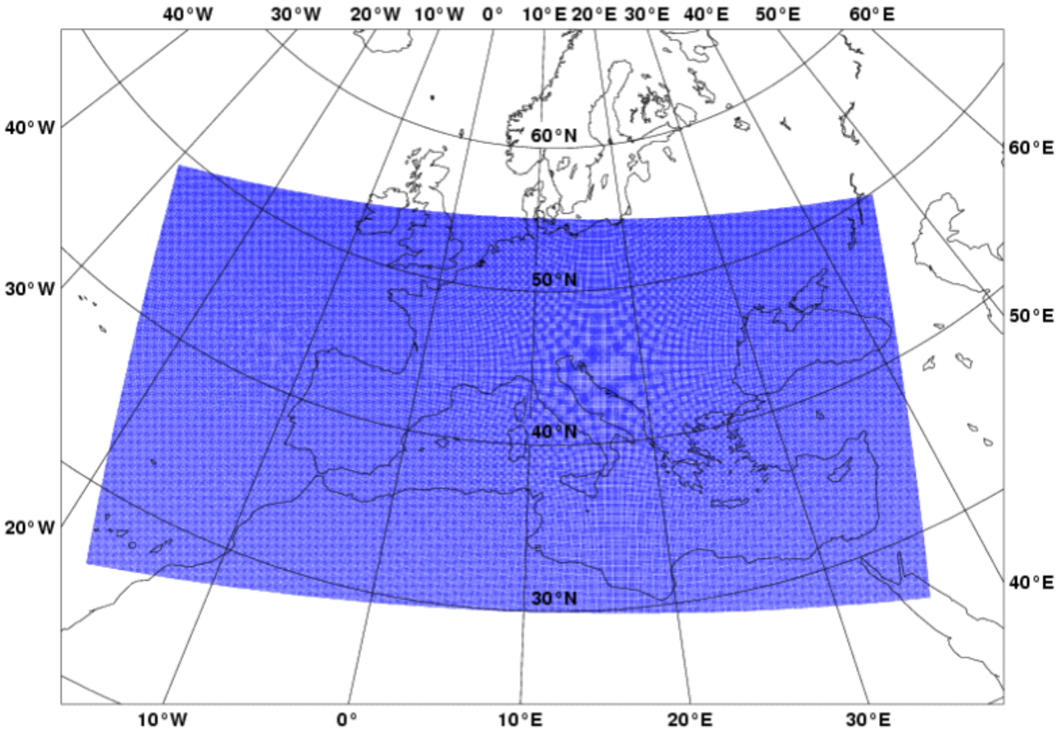


Figure 20 - COSMO-ME domain

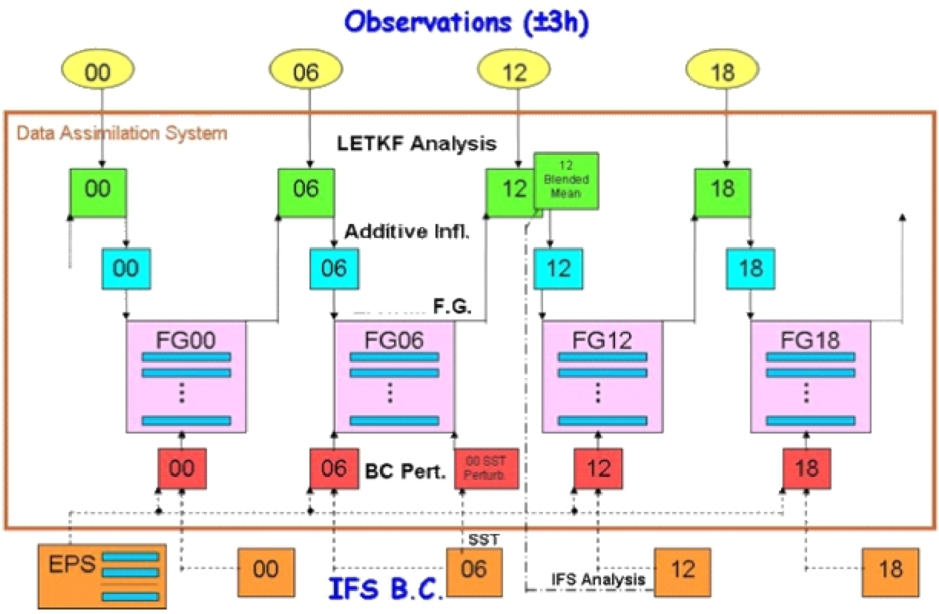


Figure 21 - A schematic view of the CNMCA operational data assimilation system

The relevant characteristics of the atmospheric COSMO-ME EPS are:

1. Domain and resolution: COSMO model is integrated on the same domain of the CNMCA-LETKF system.

2. IC and BC: initial conditions are derived every 6 hours from the CNMCA-LETKF system. Lateral boundaries conditions are from IFS deterministic run perturbed using ECMWF-EPS.

3. Model error: stochastics physics perturbation tendencies will be evaluated.

4. Forecast range: the 40+1 COSMO forecast members will run up to 48 hours in order to produce the wind forecast to be given as input to the NETTUNO system at 00 UTC.

III.1 Application of LETKF-EPS data to the Nettuno EPS

In the framework of MyWAVE project a “sea state” EPS based on the NETTUNO system (Bertotti and Cavaleri, 2009) and the COSMO-ME EPS will be tested.

Nettuno is a high resolution local scale wave forecast system operational in the Mediterranean Sea based on the COSMO-ME and WAM models. COSMO-ME (http://www.cosmomodel.org/content/tasks/operational/usam/default.htm) is the 7 km CNMCA operational version of the non-hydrostatic regional model developed by the Consortium for Small-Scale Modelling (COSMO; Steppeler *et al.*, 2003) integrated over the European-Mediterranean area. COSMO-ME is initialized by the CNMCA analysis system and driven by the IFS forecast fields. The operational CNMCA data assimilation system is now based on the LETKF algorithm (Bonavita et al., 2008, 2010). WAM (Komen et al., 1994) was the first so-called third generation wave model, where each physical process is fully and singularly described with a minimum of parameterisation. It is a spectral model, amply described in literature, see, among others, WAMDI-Group (1988) and Janssen (2008). In NETTUNO, WAM is run with 36 directions and 30 frequencies starting from ≈0.05 Hz, then increasing with a 1.1 geometrical progression. It is forced with hourly COSMO-ME wind forecasts.

The regular geographical grid has 3’ resolution and covers the area between 30° and 46° North in latitude and -6° and 36.5° East in longitude. The corresponding spatial resolutions is 5.5 km and 4 km respectively. An image of the NETTUNO significant wave forecast is shown in Fig.3.

The sea state probabilistic forecast is obtained driving the wave model using the hourly COSMO-ME EPS wind forecast members. While the operational deterministic COSMO meteorological model runs with 7 km resolution, the ensemble members will be run with 10 km resolution and 45 levels. Analysis meteorological conditions are also evaluated and stored at 6 hour interval (00, 06, 12, 18 UTC).

The NETTUNO-EPS consists of 40+1 members, that are integrated at 00 UTC up to 48 hour forecast in the Mediterranean basin. The ensemble is run once a day at 00 UTC.

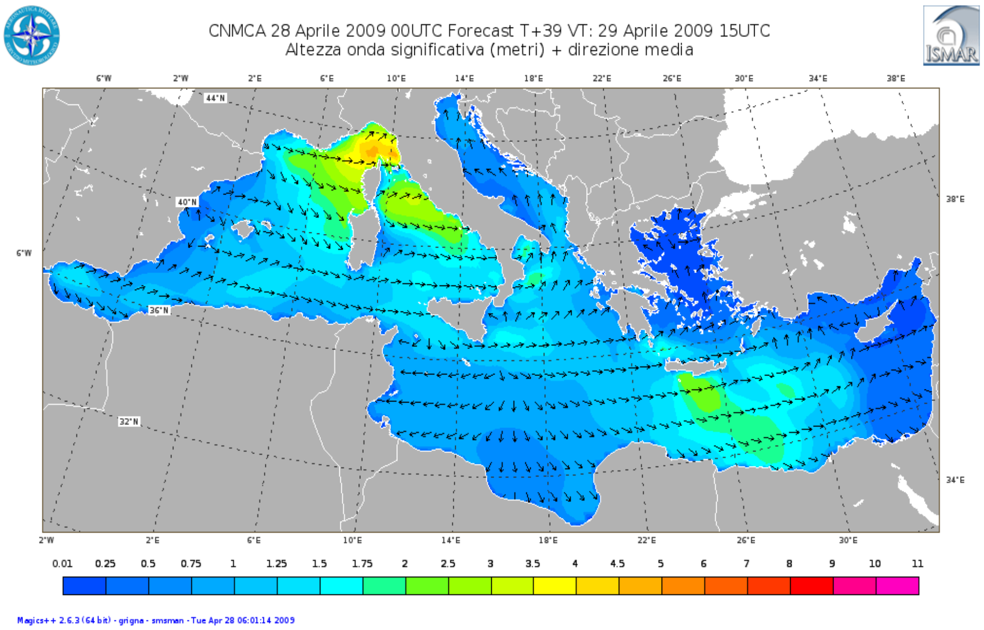


Figure 22 - Example of NETTUNO forecast (significant wave height and mean wave direction) on the Mediterranean Sea

The period June 1 – July 1 is to be used for a proper calibration of the perturbation of the meteorological physics in order to have the correct ensemble spreading in the meteorological forecast.

Subsequently a six month test period for the ensemble system is planned, starting from July 1 up to December 31, in order to allow proper consideration of both the summer and winter seasons.

The output of both the meteorological and wave models will be saved at one-hour interval (surface sea wind and waves for the WAM wave model). 2D spectra will be saved in addition, in correspondence to the available RON buoy positions in the Mediterranean Sea, listed below:

Buoy Code	Shore Station	Geographical coordinates		
		WGS84	LAT	LON
61207	Catania	37.434 - 15.147	37° 26' 24'' N	15° 08' 48'' E
61208	Mazara	37.518 - 12.533	37° 31' 05'' N	12° 32' 00'' E
61209	Palermo	38.258 - 13.333	38° 15' 30'' N	13° 20' 00'' E
61210	Crotone	39.024 - 17.220	39° 01' 25'' N	17° 13' 12'' E
61211	Cetraro	39.451 - 15.917	39° 27' 12'' N	15° 55' 06'' E
61212	Siniscola	40.617 - 9.892	40° 37' 00'' N	09° 53' 30'' E
61213	Alghero	40.549 - 8.107	40° 32' 55'' N	08° 06' 25'' E
61214	Ponza	40.867 - 12.950	40° 52' 00'' N	12° 57' 00'' E
61215	Monopoli	40.975 - 17.378	40° 58' 30'' N	17° 22' 40'' E
61216	Civitavecchia	42.133 - 11.689	42° 14' 41'' N	11° 33' 14'' E
61217	Ortona	42.407 - 14.536	42° 24' 24'' N	14° 32' 12'' E
61218	Ancona	43.825 - 13.719	43° 49' 26'' N	13° 43' 10'' E
61219	La Spezia	43.929 - 9.828	43° 55' 45'' N	09° 49' 40'' E
61220	Venezia	45.333 - 12.517	45° 20' 00'' N	12° 31' 00'' E
61221	Cagliari	39.110 - 9.454	39° 06' 54'' N	09° 24' 18'' E

Table 2 - RON Buoy System

The choice of the most convenient parameters or scores to be used for the evaluation of the ensemble forecast performance will be shared between ISMAR and UKMO. This will allow to use the same metrics. An agreement is also under discussion for the choice of the available climatology to be used for the evaluation of the ensemble skill scores.

III.2 Deterministic Wave model Validation

III.2.1 Data used for the analysis

The performance of the CNMCA Ensemble Prediction System (EPS) for waves and marine surface winds will be evaluated using buoy and platform data, as well as satellite altimeter and scatterometer observations in the Mediterranean Sea.

According to the MyWave project framework, ISPRA is responsible for the organization and the collection of all the available measured data to be used within the EPS validation procedures.

As far as buoys data is concerned, in addition to the Italian wave buoy system (RON, 15 buoys, located at Alghero, Ancona, Cagliari, Catania, Cetraro, Civitavecchia, Crotone, Mazara, Monopoli, Ortona, Palermo, Ponza, La Spezia, Siniscola and Venezia), various European agencies managing wind (some) and wave measuring buoys in the Mediterranean Sea have been contacted: Spain, France and Greece. Other Italian buoys available on GPS will be also the ARPAL buoy positioned west of the Gulf of Genoa:

Buoy Code	Shore Station	Geographical coordinates		
		WGS84	LAT	LON
61200	ARPAL	**43.922 - 8.181**	43° 55' 00'' N	08° 10' 50'' E

Table 3 - ARPAL Buoy

and the Moored Offshore Platform ODAS ITALIA 1, positioned at:

Buoy Code	Shore Station	Geographical coordinates		
		WGS84	LAT	LON
6100010	ODAS ITA 1	**43.836 - 9.100**	43° 50' 08'' N	09° 06' 00'' E

Table 4 - ODAS ITALIA 1 Buoy

The available buoys managed by Ifremer (France) are:

Buoy Code	Shore Station	Geographical coordinates		
		WGS84	LAT	LON
61284	Ifremer	**43.319 - 4.866**	43° 19' 08'' N	04° 51' 58'' E

Table 5 - Ifremer Buoy System

The available buoys managed by MeteoFrance (France) are:

Buoy Code	Shore Station	Geographical coordinates		
		WGS84	LAT	LON
61001	MeteoFrance	**43.425 - 7.890**	43° 25' 30'' N	07° 53' 24'' E
61002	MeteoFrance	**42.100 - 4.700**	42° 06' 00'' N	04° 42' 00'' E

Table 6 - MeteoFrance Buoy System

The available buoys managed by Puertos del Estado (Spain) are:

Buoy Code	Shore Station	Geographical coordinates		
		WGS84	LAT	LON
61196	PdE	**41.920 - 3.640**	41° 55' 12'' N	03° 38' 24'' E
61281	PdE	**39.520 - 0.200**	39° 31' 12'' N	00° 12' 00'' E
61280	PdE	**40.680 - 1.470**	40° 40' 48'' N	01° 28' 12'' E
61417	PdE	**37.650 - -0.330**	37° 39' 00'' N	00° 19' 48'' W
61430	PdE	**39.560 - 2.100**	39° 33' 36'' N	02° 06' 00'' E
61198	PdE	**36.570 - -2.320**	36° 34' 12'' N	02° 19' 12'' W

Table 7 - Puertos del Estado Buoy System

The available buoys managed by HCMR (Greece) are:

Buoy Code	Shore Station	Geographical coordinates		
		WGS84	LAT	LON
68422	HCMR	**36.829 - 21.608**	36° 49' 44'' N	21° 36' 29'' E
-	SARON	**37.610 - 23.569**	37° 36' 36'' N	23° 34' 08'' E

Table 8 - HCMR Buoy System

For further information, ISMAR has contacted also Israel for the possible supply of buoy data for the period of interest, in order to extend the observational structure. A decision on the this possibility will be shortly communicated.

In the Mediterranean Sea, buoy data will be complemented with selected remote sensing data, in particular the wave altimeter data derives from CNES/NASA Jason-1, CNES/NASA Jason-2 and ESA/NOAA CryoSAT-2. This will be extracted from the GLOBWAVE archive and processed in order to provide controlled values, while scatterometer data will be available from Ascat-A and Ascat-B, operated by EUMETSAT and OceanSat-2, from ISRO. aThis data will be supplied by KNMI.

All this data is in NetCDF format and will be provided on a monthly basis according to the following procedure. As far as buoy and altimeter measurements are concerned, ISPRA will retrieve the data and load it at the MyWave website within the 15 of the following month. A similar action will be carried out for scatterometer data, available on the Mediterranean Sea and provided by KNMI,

For the analysis of the system performance ISMAR will consider six months of daily operational products and compare them with all the measured data made available by ISPRA according to the procedure previously described. The final result should provide a clear idea of the system performance and possibly a reasoned stimulus to further advance. Each measurement will be identified by date-time and geographical coordinates (when considering scatterometer data, each measure will be referred to the centre of the relative area). The model data, available at 1-hour interval, will be linearly interpolated in space and time in order to match the available observations. This co-located data will then be the reference for the following analysis.

The analysis of the performance will evaluate both overall and seasonal performance, since the reference period includes both winter and summer seasons.

IV REFERENCES

Bertotti, L., Cavaleri, L., Loffredo, L. & Torrisi, L. (2012). Nettuno: analysis of a wind and wave forecast system in the Mediterranean Sea. Accepted for publication on *Monthly Weather Review*

Bertotti L., Bidlot, J.-R., Bunney, C., Cavaleri, L., Delli Passeri, L., Gomez, M., Levefre, J.-M., Paccagnella, T. Torrisi, L., Valentini, A. and Vocino, A. (2012) "Performance of different forecast systems in an exceptional storm in the Western Mediterranean Sea". *Quarterly Journal Royal Met. Soc.*, **138(**662), pp.34-55

Bertotti, L. & Cavaleri, L. (2009). Wind and wave prediction in the Adriatic Sea. *J. Mar. Sc.*, 78, 227-234

Bidlot, J.-R., Holmes, D. J., Wittmann, P. A., Lalbeharry, R., and Chen, H. S. (2002) Intercomparison of the performance of operational ocean wave forecasting systems with buoy data. *Weather Forecast*., **17**, pp. 287–309

Bidlot, J.-R. and M. W. Holt (2006) Verification of operational global and regional wave forecasting systems against measurements from moored buoys. *JCOMM Technical Report No 30.* WMO/TD-No 1333. [Available online: http://www.jcomm.info/index.php?option=com_oe&task=viewDocumentRecord&docID=6741]

Bishop, C. H., Etherton, B. J. and Majumdar, S. J. (2001) Adaptive Sampline with the Ensemble Transform Kalman Filter. Part I: Theoretical Aspects. *Monthly Weather Review*. **129**. p 420 – 436.

Bocquet, F.-X., (2009) Development of a wave ensemble system at the Met Office. Proc. 11th Int. Workshop on Wave Hindcasting and Forecasting and Coastal Hazard Symp., Halifax, NS, Canada, JCOMM Tech. Rep. 52, WMO/TD-1533, IOC Workshop Rep. 232. [Available online at http://www.waveworkshop.org/11thWaves/index.htm.]

Bonavita, M., Torrisi, L. & Marcucci, F. (2010). Ensemble data assimilation with the CNMCA regional forecasting system. *Q. J. R. Meteorol. Soc.,* 136, 132-145

Bonavita, M., Torrisi, L. & Marcucci, F. (2008). The ensemble Kalman filter in an operational regional NWP system: Preliminary results with real observations. *Q. J. R. Meteorol. Soc.*, 134, 1733-1744

Booij, N. and Holthuijsen, L. H. (1987) Propagation of ocean waves in discrete spectral wave models. *J. Comput. Physics*, **68**, p 307–326.

Bower, N. E., Arribas, A., Mylne, K. R., Robertson, R. B. and Beare, S. E. (2008) The MOGREPS short-range ensemble prediction system. *Q. J. R. Meteorol. Soc.* **134**: p 703 – 722

Bowler, N. E. (2006) Comparison of error breeding, singular vectors, random perturbations and ensemble Kalman filter perturbation strategies on a simple model. *Tellus*. **58a**. 538 – 548.

Bunney, C. C. & Saulter, A. (2010) Wave Model Partitioning Methods: Recommendations for Met Office Systems. Met Office Internal Technical Document. June 2010

Davies, T., Cullen, M. J. P., Malcolm, A. J., Mawson, M. H., Staniforth, A., White, A. A. & WOOD, N. (2005) A new dynamical core for the Met Office's global and regional modelling of the atmosphere. *Q. J. R. Meteorol. Soc.*, **131**, p. 1759 – 1782.

Donlon, C.J., M. Martin, J. D. Stark, J. Roberts-Jones, E. Fiedler and W. Wimmer (2012), The Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA), *Rem. Sens. Env*., **116**, 140-158.

Evensen, G. (1994) Sequenctial data assimilation with a nonlinear quasi-geostrophic model using Monte-Carlo methods to forecast error statistics. *J. Geophys. Res. – Oceans*. **99**(C5). 10143 - 10162

Flowerdew, J., Horsburgh, K., Wilson, C. & Mylne, K. (2010) Development and evaluation of an ensemble forecasting system for coastal surges. *Q. J. R. Meteorol. Soc.* **136:** p 1444 – 1456

Hanson J. L. and O.M. Phillips (2001) Automatic analysis of ocean surface directional wave spectra. *J. Atmos. Oceanic Tech*, **18(**277), p 293

Hasselmann, S. and Hasselmann, K. (1985) Computations and parameterizations of the nonlinear energy transfer in a gravity-wave spectrum, Part I: A new method for efficient computations of the exact nonlinear transfer integral. *J. Phys. Oceanogr.*, **15**, 1369–1377.

Janssen, P. A. E. M. (2008) Progress in ocean wave forecasting. *J. Comp. Phys*., **227**, p 3572 – 3594

Komen, G.J., Cavaleri, L., Donelan, M., Hasselman, K., Hasselmann, S. & Janssen, P.A.E.M. (1994). Dynamics and Modelling of Ocean Waves. Cambridge University Press: Cambridge, UK., 532pp.

Li, J. G. 2012: Propagation of Ocean Surface Waves on a Spherical Multiple-Cell Grid. *J. Comput. Phys.*, **231**, p 8262 - 8277.

Li, J. G. (2001) Global transport on a spherical multiple-cell grid, *Monthly Weather Review*, **139**, p 1536 - 1555

Li, J. G. (2008) Upstream nonoscillatory advection schemes. *Monthly Weather Review*, **136**, 4709 – 4729

Rawlins, F., Ballard, S. P., Bovis, K. J., Clayton, A. M., Li, D., Inverarity, G. W., Lorenc, A. C. & Payne T. J. Payne (2007) The Met Office global four-dimensional variational data assimilation scheme. *Q. J. R. Meteorol. Soc*. **133.** p 247 – 362.

Tang, Y., Lean, H.W. and Bornemann, J. (2012) The benefits of the Met Office variable resolution NWP model for forecasting convection. *Meteorol. Appl.* In publication: available online at http://onlinelibrary.wiley.com/doi/10.1002/met.1300/abstract

Taylor, K. E. (2001) Summarizing multiple aspects of model performance in a single diagram. J. Geophys. Res., **106(**7) p 183–7192

Tolman, H. L. and D. V. Chalikov (1996) Source terms in a third-generation wind-wave model. *J. Phys. Oceanogr.*, **26**, p 2497–2518.

Tolman, H. L., (2009) User manual and system documentation of WAVEWATCH III version 3.14. NOAA / NWS / NCEP / MMAB Technical Note 276, 194 pp

Toth, Z., Kalnay, E. (1993) Ensemble forecasting at the NMC: the generation of perturbations. *Bull. Am. Meterolol. Soc.* **74**. 2317 – 2330

WAMDI Group: Hasselmann, S., Hasselmann, K., Bauer, E., Janssen, P.A.E.M., Komen, G.J., Bertotti, L., Lionello, P., Guillaume, A., Cardone, V.C., Greenwood, J.A., Reistad, M., Zambresky, L., & Ewing, J.A. (1988) The WAM model - a third generation ocean wave prediction model. *J. Phys. Oceanogr.*, 18, 1775-1810

Wang, X. G., Bishop, C. H., Julier, S. J. (2004) Which is better, an ensemble of positive-negative pairs of a centred spherical simplex ensemble? *Mon. Weather Rev.* **132**. 1590 – 1605