PROJECT FINAL REPORT

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An executive summary

The research and development objectives can be summarized in four points:

- Lay the foundation for a marine core Copernicus service that includes ocean waves
- To improve wave model physics
- Improve techniques for use of earth observations in wave forecasting

The project aims was to review and propose service level and coordination requirements for a pan-European wave 'core service' complementing the MyOcean-2 project, and thus allowing end users to access a complete view of the physical marine environment, including parameters of ocean waves. This review resulted in a deliverable document, Road Map Towards a future Copernicus Service for Ocean Waves (Deliverable 6.3), from which a service provider led consortium can define and provide the service as a follow-on operational system. (this includes WP3,4 and review element of management part) . The Road Map was written in cooperation with MyOcean-2. The review report includes user consultation and demonstration exercises with respect to appropriate service quality metrics and use of probabilistic forecast techniques.

The project has improved the physics of the wave models in the aspects crucial for the atmosphere and ocean coupling and consequently the estimate of the surface exchanges. As a result after 2015 ocean modelling, Copernicus, will be able to include wave modelling into its operational activity, with an expected marked improvement not only of the underlying physics, but also of the practical results.

The project has manufacture and demonstrate techniques by which earth observation data can improve and inform the latest generation of surface wave forecasts and which enable waves to be coupled to ocean forecasts (developed recently within the GMES MyOcean project) in order to improve the skill of both systems. Outcomes from these elements of the project includes a community code that allows pull through of the research by existing wave service providers.

Summary description of project context and objectives

Summary Work package 1

The main goal ofWork Package 1 (WP1) is to improve the representation of some basic physical processes in the interaction between wind waves and atmosphere/ocean. This will improve the performance of the wave model especially in extreme circumstances where more conventional physics is likely to fail. It is also important for medium-range numerical weather prediction, as shown by the introduction of the wave effects developed in WP1 in ECMWF's new model cycle. A more realistic description of these processes is also expected to be relevant for seasonal forecasting and climate projections.

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projections.

The main focus during this has been on fully coupling the atmosphere-wave-ocean model, and on detailed studies of wave effects on the upper ocean turbulent mixing. The fully coupled global system now runs as single executable where atmospheric model (IFS) runs for one coupling time step and wind fields for the wave model (WAM), wind, pressure, radiation and evaporation minus precipitation fields for the ocean model (NEMO). WAM the runs for one coupling time step and provides updated updated surface roughness for the IFS and updated stress, Stokes drift and turbulent kinetic energy fields to NEMO. Finally, NEMO provides sea surface temperature (SST) and surface currents for IFS. The system show very promising results, in particular with respect to the results for SST.

The two way coupling of regional atmosphere-wave models are progressing. The HCMR system has recently been run for test periods and evaluated against buoys and satellite data. The ISMAR system has been upgraded and tested. The consistent overestimate of the of high winds in the uncoupled version of the COSMO atmospheric model has been reduced.

Summary Work package 2

The main goals of this work package have been to explore new methodologies in data assimilation, improve the use of near shore remote sensing data and connect large-scale forecasts to near shore forecasts.

In the framework of the MyWave project we have applied innovative data-assimilation techniques with the aim of improving near shore North Sea wave forecasts. The considered approaches were a) 3D-VAR assimilation of coastal scatterometer winds in HARMONIE; b) EnKF assimilation of wave observations in SWAN and c) Neural Network (NN) assimilation of wave observations in WAM. As reported, the results of the first trials using mainly synthetic data have led to promising results. In accordance with the project planning, we shall now move on to applying these techniques for assimilation of real wind and wave data considering a number of relevant North Sea storms.

Regional wind and wave forecasts for the considered study areas have been compared with: scatterometer winds, altimeter wave heights, wave-buoy observations and in-situ wind observations to make a realistic assessment of the accuracy of each, to identify inconsistencies and to suggest potential improvements. Special attention has been given to particularly difficult areas as the Northern Adriatic Sea. Here the surrounding mountains make the wind forecast particularly challenging, while the proximity of coastlines stresses the satellite capability.

Unstructured grids can be more easily adapted to increase resolution locally than structured grids, which makes this approach very attractive for coastal wave-forecasting. Here the unstructured-grid approach is compared to the more traditional nesting of refined local structured-grids.

Summary Work package 3

In WP3 different wave forecast ensemble systems have been implemented, assessing, for two separate and different areas, their performance and increased information with respect to a deterministic approach. The technique has been applied both at large and local scales, in the latter case for three specific harbours. Two approaches have been followed, at two different scales, North-Atlantic, with focus on the European coasts, and the Mediterranean Sea. The results have been intercompared, also with respect to the deterministic approach.

The U.K. Met Office wave ensemble prediction system (wave-EPS) for the North Atlantic 'euro-zone' comprised two models: an Atlantic wave model and a UK wave model at higher resolution. The models were driven, respectively, with winds from Global (40km resolved) and UK (1.5km resolved) wind fields. Wave ensemble variability derives from the one of the meteorological model. The used wave model is WAVEWATCH III.

The second approach in the Mediterranean Sea has been done by the Italian Meteorological Service (CNMCA). The CNMCA short-range ensemble prediction system is based on the Ensemble Kalman Filter (EnKF) approach acting on the COSMO regional model. The "sea state" EPS is based on the NETTUNO system using the WAM wave model. The corresponding spatial resolutions is 5.5 km. The NETTUNO-EPS consists of 40+1 members, that are integrated at 00 UTC up to 48 hour forecast in the Mediterranean basin.

For the validation of the ensemble model results measured data from buoys in the Atlantic and the Mediterranean Sea have been used. Data from Israel were obtained. Buoy data have been complemented with altimeter and scatterometer data. On a monthly basis, starting from July 2013, all the available data over the Mediterranean Sea were hosted on a dedicated ISMAR server.

The verification of the wave Atlantic system showed it to be biased slightly high in the Western Approaches to the UK, but biased low in the fetch limited North Sea. In comparison, the UK model was biased high in both areas. Reliability diagrams and economic value analyses, used to assess probabilistic performance, showed significant improvement once a bias correction scheme was applied.

Spread-skill relationships showed that wave-EPS can be effectively used by a forecaster in order to estimate the uncertainty associated with a given forecast. The successful verification of these systems has resulted in the Met Office committing to a further period of operational trialling and forecast systems development beyond the MyWave project.

The validation of the two, UKMO and CNMCA, Mediterranean ensemble system was based on the observations dataset which covers the six month period from July 1 to December 31, 2013. It has been found that the (de-biased) ensemble mean is generally more skilled than a (de-biased) deterministic forecast. In general the Nettuno eps forecast fits better than UKMO to decision makers who must make a protection/non-protection choice with respect to high energetic sea states, and whose costs of protection are lower than potential losses. On the contrary UKMO is in some cases more suitable for high cost/loss ratio and low energetic, early occurring events. The ensemble size influence on the differences in REV is negligible.

The PdE application of the ensemble approach to harbour wave forecast is operational since September 2013. Its main purpose is the production of categorical forecast with the highest possible accuracy and a quantitative basis for reliable and useful probability forecast. Gijon and Tenerife systems have been configured taking into account forcing files from UKMO. Barcelona application driven by ISMAR conditions runs with the same time resolution of the NETTUNO-EPS. Control and ensemble members of harbour applications have been validated with PdE buoy network.

Summary Work package 4

Beyond the MyWave project, it is anticipated that regional wave forecasts for European waters may be provided as part of a Marine Core Service. It is important that a system to provide forecasts also releases verification data. These data should enable downstream users to quantify uncertainty in wave products, when applied to their specific applications, and be aware of any impact to wave products of ongoing scientific improvements.

The availability of observed wave data to act as a baseline truth for verification is variable both globally and on a European regional basis. Therefore it is important that wave forecast verification procedures use a system of common data processing methods and metrics that can exploit both satellite and in-situ observations as comparative truths. Future increases in deployment and utilisation of ensemble prediction systems requires that the methods developed can be extended to probabilistic verification.

In light of these requirements, WP4 worked toward three key objectives. The first was to identify a set of 'compatible metrics' for verification of the core aspects of wave forecast performance using either in-situ or remote sensed observation data. Metrics were identified according to their ability to be generated using either in-situ or remote sensed data samples. These samples differ in nature since in-situ data are observed at fixed points, whilst remote sensed observations are made 'along track' of a polar orbiting satellite. The purpose of each metric was documented and presented in a project deliverable report (D4.2a). Compatibility of the verification is only possible when observation errors associated with the different observation types are accounted for. In order to ascertain whether compatibility might be feasible on a regional basis, WP4 undertook audits of available observations (D4.1), 'triple collocation' studies of significant wave height data (in order to assess regional observation errors in the North Sea and Northeast Atlantic, D4.3) and proposed methods to account for observation and sampling errors within wave verification.

The second objective was to review the metrics proposed by WP4 in light of downstream user requirements and then propose a system to deliver those metrics identified as important within a Marine Core Service wave verification system. The user consultation involved both surveys, initially issued to an identified group of nearly 70 users, and more detailed feedback discussions on specific metrics and verification methods with a small group of key respondents representing identified user types. Conclusions from the consultation process were incorporated with a review of the present MyOcean oceanographic forecast verification system, in order to propose an extension to the MyOcean system that would enable the inclusion of wave verification (D4.4).

The final work package objective was to document compatible metrics that would enable verification to be generated for ensemble prediction systems. WP4 collaborated closely with WP3 in defining a set of appropriate metrics and a method to account for the effects of regional observation errors in probabilistic verification. Metric definitions and the purpose(s) for which the metrics can be used were documented in deliverable report D4.2b. Results of this work have been used in WP3 project reports.

A description of the main S&T results/foregrounds

WP1:

Wind input under extreme conditions

The high-frequency part of the wave spectrum obeys Toba's law and is therefore proportional to the friction velocity. However, under extreme wind conditions the wave slope may exceed the usual breaking limit and one would expect that the high frequency part of the spectrum becomes saturated. This will provide a limit to drag in extreme circumstances. Extensive testing of imposing a saturation range has been carried out by MeteoF in task 1.2.2.

Wind-wave interaction in swell conditions

Experiments have been done by comparing two different mechanism for damping of swell. The experiments were done using the global coupled atmosphere-wave at ECMWF. Originally, this model system uses a swell damping term based on Janssen (private communication, 2011) in the spirit of a theory proposed by Jacobs (1987), but using a truncated eddy viscosity. This model yields a damping term for wave components traveling faster than the local wind. A second experiment uses the viscous theory by Dore (1978). The model assumes gravity waves in a two layer fluid with molecular viscosity in both air and water. Dore found an additional dissipation term for the waves due to the viscosity in the air. In these coupled simulations, the additional damping terms reduces the surface roughness that is used for calculation of the surface stress in the atmospheric model component. Hence, there is a feedback mechanism generally accelerating the surface wind in the long-wave propagating direction. In this study, three experiments have been performed. The experiments are blends of short range forecasts and analyses over three months. The first experiment is referred to as the control experiment where the damping term by Jacobs/Janssen is removed. The second experiment is a simulation with the Jacobs/Janssen damping included. The third experiment is with the Dore damping only. Both experiments with swell damping yield a small but significant damping of the swell when results are averaged over the three months simulation period. The verification when compared with satellite altimeter data shows a reduction in the bias, particularly in the tropics.

Improved nonlinear transfer

The nonlinear transfer in third-generation wave models has for the last 30 years been based on the Direct Interaction Approximation (DIA). The DIA has played an essential role in wave model development. Nevertheless, as it is an approximation, it is justified to ask the question whether it is possible to find efficient, improved representations of the exact nonlinear transfer. This could result in more accurate spectral shapes which might benefit the accuracy of the prediction of wave spectra and may result in narrower spectral peaks which benefits freak wave prediction. Together with Miguel Onorato (funded by ONR) work has been done to develop a fast algorithm to calculate the nonlinear transfer. The first version of this algorithm is nearly as fast as the DIA, but only gives really accurate results for broad spectra. A considerable amount of time has been spent in understanding why the present approach works. The problem is namely the following. The resonant four-wave transfer only occurs when the resonance conditions for angular frequency and wavenumber are satisfied. Because of the resonance conditions the sixdimensional integral, representing the nonlinear transfer, may be reduced to a three-dimensional integral, however, at the expense of the introduction of a singularity. In our approach we simply ignored the singularities, and just recently it has been shown numerically that this step is justified because all the singularities are only apparent as at the singularity the remainder of the integrand vanishes.

Improved wave-breaking term

The work described here concerns the improvement of the physics of the wave model MFWAM, and, in particular, the estimation of a consistent sea state dependency of the drag coefficient. The latter requires some changes which are indicated here:

1. upgrade the model MFWAM to a more recent version of the IFS-38R2 code.

2. use of better bathymetry and an improved propagation scheme.

3. implement a smoothing function (Rayleigh type) for the swell damping term induced by the air friction at sea surface. This optimizes the transition of using two parametrizations depending on the flow being laminar or turbulent at the surface.

4. adjustments of the dissipation by whitecapping in order to reduce the strong positive bias observed in the southern hemisphere in presence of high wind conditions. The sheltering and the dissipation coefficients are changed to 0.6 and $-2.8 \times 10-5$, respectively.

5. the coefficients of the non-linear interactions term (DIA) were also adjusted in the IFS-38R2 code.

Runs of the improved version of MFWAM, driven by analyzed ECMWF winds, have been performed for two Autumn seasons in 2011 and 2012. An additional 1-year run from December 2012 to November 2013 with the MFWAM model was also performed. The resulting wave heights have been validated against altimeters data (from Jason 1 & 2 and SARAL) and buoy wave observations. The comparison with altimeter wave height shows that the normalized scatter index of significant wave height is improved by roughly 5%. The statistical results in the different ocean basins shows the same trend, while a more pronounced improvement in the tropics (where swell is dominant) is seen. The bias in significant wave height in southern high latitudes region (>50◦) is significantly reduced by about 50%. Figure 1 shows the bias map of significant wave heights in comparison with altimeters for the Autumn season of 2011. The considerable reduction of the wave height bias in the southern hemisphere by the improved version of MFWAM is clearly evident.
Since the 7th of July 2014, the upgraded MFWAM was implemented in a double operational chain for global application. The verification of this pre-operational production line is entirely satisfactory, and therefore, the improved version of MFWAM will become operational in mid November of 2014. In other respects, the drag coefficient at the sea surface provided by the upgraded MFWAM shows more consistency than the one from the operational MFWAM. This clearly indicates the increase of the drag coefficient for light wind speed in sea state dominated by swell wave systems. This result allows us to start the work on coupling between the improved MFWAM with the high resolution AROME atmospheric model.

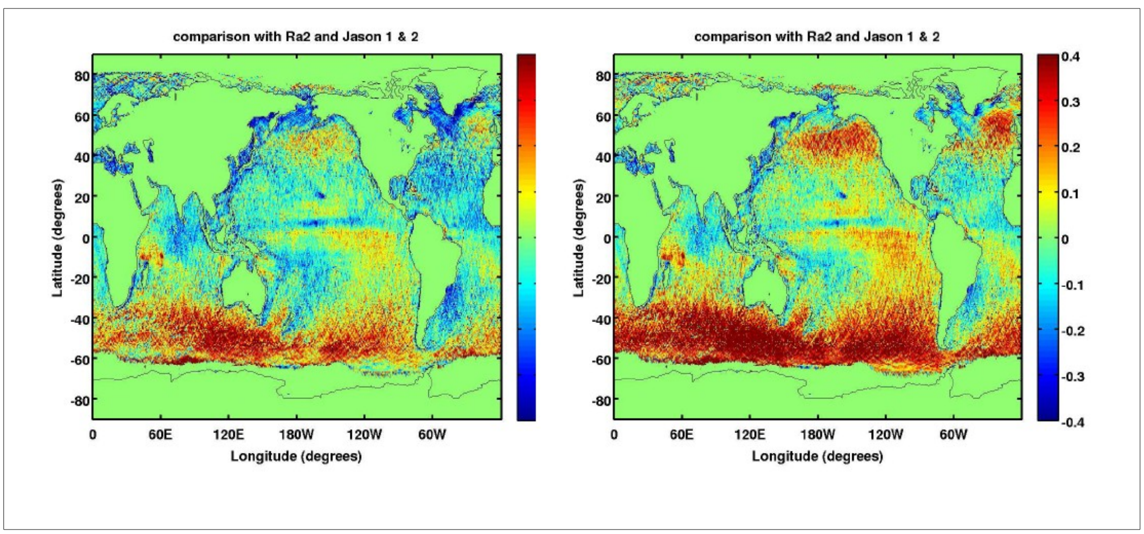

Figure 1: Mean difference between model wave height and Altimeter data from Jason 1/2 and Envisat for the Autumn of 2011. Left is the improved version of MFWAM and right is its present operational version.

Coupling to the atmosphere

Development of Italian and Greek regional coupled Atmosphere-WAM model

The coupling of ocean waves and atmosphere is an obvious and necessary step toward a unified approach in order to improve the description of atmospheric boundary layer and the forecast of ocean waves. This approach was already shown by Janssen et al. (2004) to improve both atmosphere and surface wave forecast on a global scale. In the same work it was also emphasized that with increasing spatial resolution the influence of the coupling of both systems has an increasing impact on the results for both ocean waves and atmosphere. Following this it is a logical step to couple a local high resolution meteorological and wave prediction model to account for these interactions also at a local scale.

In the two-way fully coupled mode the atmospheric model sends at each time step the near surface (10m) wind components and receives various near sea surface variables. In more details, at each time step the wave model provides the atmospheric model with consistent values of the Charnock coefficient field, friction velocity, total surface stress etc. The enhanced Charnock coefficient increases the roughness length leading to lower surface wind speed. This in turn affects the wind input and finally the estimation of the significant wave height. All the results have been verified against buoy and satellite data (Cryosat, Envisat, Jason-1, Jason-2, Altika). Two systems are reported here, the Poseidon-WAM system by HCMR and the COSMO-WAM system by the Italian Meteorological Service and ISMAR.

Contribution by HCMR

In the framework of the MyWave Project, HCMR has developed a two-way coupled system for simulating the atmospheric and sea-state conditions over the Mediterranean and Black Seas. The two-way fully coupled system (WEW) consists of two components: the atmospheric model of the Greek POSEIDON monitoring and forecasting system (Papadopoulos and Katsafados, 2009) and the WAM Cycle-4 code (Komen et al., 1994). The atmospheric model is based on an advanced version of the Eta/NCEP non-hydrostatic model (Papadopoulos et al., 2002). The WAM model uses 24 directional bins (15◦directional resolution) and 30 frequency bins (ranging between 0.05Hz and 0.793Hz) and runs in shallow water mode without depth or current refraction (Korres et al. 2011). The newly developed WEW system is fully parallelized to run efficiently on any parallel computer platform. It uses a two-dimensional scheme for partitioning grid-point space to Message Passing Interface (MPI) tasks. The Poseidon and WAM models utilize different domain projections, fundamental time integration, grid orientation and grid cell size. The current version (v0.05) of the coupled system has been configured on a very fine horizontal resolution of 1/20◦ ×1/20◦ with 493×461 E-grid points and 1001×381 regular latitudelongitude points. Gridded data from ECMWF are used as initial and boundary conditions of the atmospheric model component.

The performance of the WEW system has been statistically evaluated over sea and land areas and was compared to the standard application of the offline coupling mode (CTRL), which is currently used in the POSEIDON system forecasts. The validation of the system has been done on four recent high-impact weather and sea state events in the Mediterranean Sea. The verification exercise shows that both systems (CTRL & WEW) overestimate wind speed up to 8 ms-1 and underestimate above. However, the WEW system reduces slightly the overall bias, improves the RMSE, decreases the STD and the Mean value and improves the R2. At the same time, the WEW system leads to a substantial improvement on the estimation of the significant wave height. Despite the fact that the significant wave height from the WEW system at the buoy locations is slightly underestimated compared to the CTRL, we find improvements in almost all the other statistical scores. Similar results can be obtained from the comparison of the WEW and CTRL predictions against satellite retrievals. Namely, although the wind speed is slightly underestimated, the WEW results involve better statistical scores. This is attributed to the fact that the application of the two-way fully coupled system can overall generate and support a more realistic near sea surface circulation pattern by fully resolving air-sea interaction processes at the relevant interface, including wind speed regime and wave patterns.

Contribution by ISMAR and CNMCA

The second system has been developed at ISMAR and CNMCA, the operational branch of the Italian Meteorological Service. During the MyWave project attention has been focused on the Mediterranean Sea where the (large consortium) meteorological COSMO model and the WAM wave model (ref.cit.) have been successfully coupled. While this was one of the targets of the MyWave project, our longer term plan is to have a fully coupled atmosphericwave-circulation system, hence our actions have also been guided by this longer-term target. Therefore, all the communications between the models have been designed in such a way as to make the future introduction of the ocean circulation ROMS model a natural continuation of the present configuration. Waves are revealing themselves more and more as the crucial element conditioning all the exchanges between ocean and atmosphere (see Cavaleri et al., 2012, for an extensive discussion), and any real coupled system is expected to become a three model system involving heat exchanges at the surface (see Janssen, 2012), water vapour fluxes, spray (affecting the surface drag), and, among others, the wave generated turbulence following the work of Ardhuin and Jenkins (2006). At the present stage the COSMO and WAM models have been coupled using a novel coupling library, written in native FORTRAN, especially designed to fit the needs of both the models with respect to the parallel framework prescribed by the implementations. Therefore, the code has been formulated in such a way that the decomposition technique used in ROMS can also be easily embedded in the developed coupling library. At ECMWF the WAM wave model is tightly coupled to the local Integrated Forecast System (http://www.ecmwf.int/search/site/ifs%20ecmwf) and the COSMO-WAM coupled system in the Mediterranean Sea has been also designed in a similar spirit.

The COSMO model solves the non-hydrostatic, fully compressible hydro-thermodynamical equations in advection form. It uses a rotated geographical (lat/lon) coordinate system horizontally and a generalized terrain-following height coordinate with user defined stretching in the vertical. The numerical grid is based on an Arakawa C-grid, Lorenz vertical staggering and it uses second-order finite differences for the spatial discretization. COSMO-ME runs on a 7 km resolution grid while WAM runs on a regular 0.05◦lat-lon grid. WAM has 36 directions and 30 frequencies (These frequencies are on a logarithmic scale with relative increment of 0.1 and starting frequency f1 = 0.05 Hz). More information about the system is given in WP3 where the ensemble version of the COSMO-WAM system is fully described and analysed. The code merging strategy optimizes the operational coupling because each knot of the two grids knows since the start of the run with which knots it has to communicate.

Table 1: Comparison of coupled and uncoupled wave height and wind speed results against corresponding altimeter data.

Waves/Exp	ME	AE	RMSE	CRMSE	CORR	SI	sciR
Coup	0.25	0.46	0.65	0.60	0.88	0.34	0.32
Uncoup	0.43	0.57	0.85	0.73	0.88	0.45	0.39

Wind/Exp	ME	AE	RMSE	CRMSE	CORR	SI	sciR
Coup	0.25	1.71	2.28	2.26	0.81	0.26	0.25
Uncoup	0.44	1.87	2.44	2.40	0.81	0.27	0.27

An extensive long term test has been done running the COSMO and WAM models in both one-way mode (COSMO only passes winds to WAM) and in two-way, fully interactive mode (WAMpasses information to COSMO as well). The coupled system shows the expected decrease of both wind speed and wave height. Table 1 provides summary statistics of the validation of the model results against both Mediterranean buoys and satellite (wind and wave height) data. The comparison shows that coupling leads to a substantial decrease of the model bias and a substantial improvement of the other stats for instance the CRMSE and the scatter index SI.

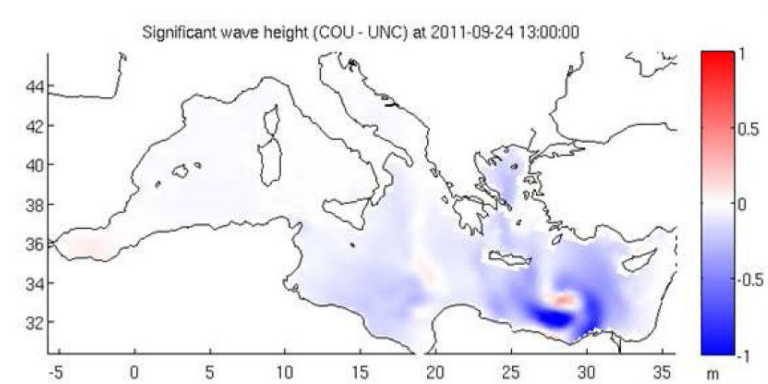

Figure 2: Differences between coupled and uncoupled results for significant wave height for a Mediterranean cyclone.

It is interesting to analyse the implications of coupling on a severe cyclonic event in the Mediterranean Sea. Fig. 2 shows the differences of significant wave height between the coupled and uncoupled runs for the considered event. A more systematic study of impact on events is beyond the scope of this compact report.

Test wave model under extreme conditions

The impact of using the limitation of air-sea momentum flux (see §1.1.1) is examined in case of waves generated by hurricanes or tropical storms. Runs of the model MFWAM during the Indian ocean cyclonic seasons are considered for 2011, 2012 and 2013. Several wind forcing from ECMWF and ALADIN were used in these runs. The impact of the limiter shows an improvement of the significant wave height at the peak by about 4%.

Extension of two-way interaction

A regional ocean wave-atmosphere 2-way coupled system has been implemented and tested. The atmospheric model used in the coupled system is a version of the non- hydrostatic HARMONIE model using AROME physics at a resolution of 2.5km. AROME is using the surface model SURFEX for calculations of the surface fluxes. The ocean wave model is a version of WAM from ECMWF. The surface roughness for heat, moisture and momentum transfer at sea surface in the original version of SURFEX are calculated from the Charnock relation using a constant Charnock parameter. The Charnock parameter provided by WAM varies and depends on the sea state following the theory of Janssen (1991). The Charnock parameter from WAM is used in SURFEX for the coupled system. The variables provided to WAM by AROME are the 10m wind and sea-ice mask. This exchange occurs every 60 seconds. The test domain, which is used for both WAM and AROME, together with significant wave height and 10m winds fields, are shown in Fig. 3.

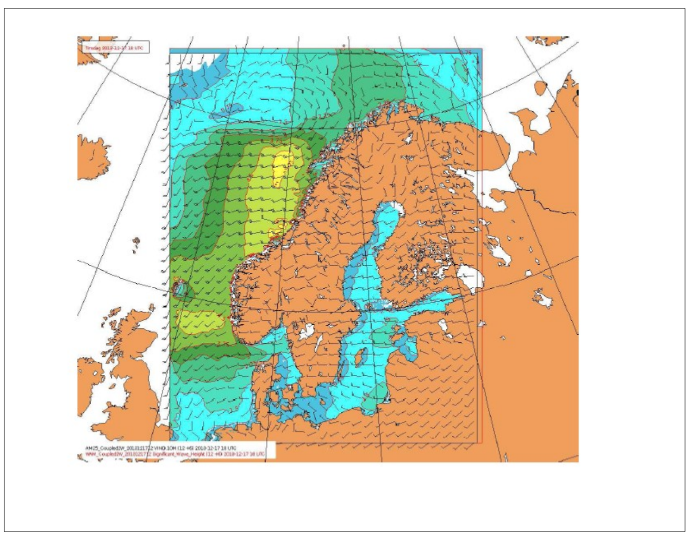

Figure 3: Metno coupling domain with significant wave height and wind field.

The model system is tested over a three month period from December 2013 to the end of February 2014. At the moment this simulation has been run for 6 weeks and the full three month runs are expected to be ready within a few weeks. The simulations comprises four daily analyses at 00, 06, 12, and 18. Every day a 48 hours forecast is then run from the 00 analyses. The forecasts are the continuously verified against synoptic weather stations from platforms and along the coast.

The quality of the 10m surface wind has been validated against observations from 33 Norwegian coastal stations. The 2-way coupled system shows, compared to the 1-way coupled system, a systematic reduction of the model bias in wind speed for the three month period.

Coupling with the Ocean

Software for processing wave-induced forcing

Sea state dependent fluxes of momentum and energy will in our operational system be calculated online in the MyWave WAM model, and we have specified output formats which are currently being implemented by HZG. The Stokes-Coriolis force, which requires the Stokes drift profile, will be calculated using the parameterisation of the Stokes drift profile presented in Breivik et al. (2014).

We have tested the impact of using sea state dependent momentum fluxes and Stokes-Coriolis force in MET's coastal ocean modeling system. Application to the drift of cod eggs and larvae in the Arctic Cod spawning grounds in Northern Norway demonstrate that the main effect is a combination of sea state dependent vertical mixing and horizontal advection by Stokes drift. Comparison of model Lagrangian velocities (combining ocean model currents with Stokes drift from wave model) with surface drifter data demonstrates the importance of using a consistent Lagrangian representation of the drift velocities, i.e. combining ocean model with wave effects and adding the Stokes drift (Röhrs et al., 2014).

Mixed layer model

Contribution by ECMWF

The NEMO general circulation ocean model has been extended to incorporate three physical processes related to ocean surface waves, namely the turbulent kinetic energy flux from breaking waves, the water-side stress (modified by growth and dissipation of the oceanic wave field), and the Stokes-Coriolis force. Experiments were run with NEMO in forced (ocean-only) and coupled mode. Ocean-only integrations were forced with fields from the ERA-Interim analysis. All three effects are noticeable in the extra-tropics, but the sea-state dependent energy flux yields the largest difference compared with a control run due to its influence on the upper ocean mixing. The biases in sea surface temperature as well as subsurface temperature are reduced, and, when wave effects are included, the total ocean heat content exhibits a trend closer to that observed in a recent ocean reanalysis (ORAS4). Seasonal integrations of the coupled atmosphere-waveocean model consisting of NEMO, the wave model ECWAM and the atmospheric model of ECMWF similarly show that the sea surface temperature biases are greatly reduced when the mixing is controlled by the sea state and properly weighted by the thickness of the uppermost level of the ocean model.

Breaking waves enhance the turbulence in the upper part of the ocean significantly. Waves absorb kinetic energy and momentum from the wind field when they grow and in turn release it when they break (Janssen, 2012). The observed dissipation rates under breaking waves are indeed much higher than anticipated by the law of the wall. This influences the temperature distribution in the upper part of the ocean, which in turn affects the temperature in the atmosphere in a coupled integration. However, it is also important to note that NEMO has already a parameterization in place for this wave-induced mixing, but that this effect has been exaggerated in the standard implementation of NEMO. We show that the proper level of mixing must be found by correctly weighting the mixing by the thickness of the model levels. Our stand-alone runs and our coupled integrations all show a marked improvement when weighting the wave-induced mixing.

As the wind increases, the wave field responds by first growing, thus storing more momentum. In this phase there is a net influx of momentum to the wave field. Then, as the waves mature and the breaking intensifies, the momentum flux from the wave field to the ocean starts to close in on the flux from the atmosphere to the waves. This is the equilibrium state where dissipation matches wind input, also referred to as fully developed windsea. Finally, as the wind dies down, there will be a net out flux of momentum from the wave field, almost all of which will go to the ocean. If wind input and dissipation in the wave field were in equilibrium, the air-side stress would be equal to the total water-side stress. However, most of the time waves are not in equilibrium (Janssen, 2012; Janssen et al., 2013), giving differences in air-side and water-side stress of the order of 5 to 10%, with occasional departures much larger in cases where the wind suddenly slackens. Likewise, in cases with sudden onset of strong winds the input from the wind field will be much larger than the dissipation to the ocean, lowering the stress to values well below 70% of the air-side stress. The water-side stress is defined as the total atmospheric stress minus the momentum absorbed by the wave field (positive) minus the momentum injected from breaking waves to the ocean.

Waves set up a Lagrangian drift in the down-wave direction known as the Stokes drift. Although its velocity decays rapidly with depth, it can be substantial near the surface (0.7 m/s). In combination with the earth's rotation it gives an additional veering to the upperocean currents known as the Stokes-Coriolis force. We have introduced this effect in NEMO (see Janssen et al, 2013; Breivik et al, 2014).

The NEMO model with wave effects has been run in forced mode with forcing from ERAInterim. The results indicate that the oceanic heat content is more in line with that of the ORAS4 reanalysis (Balmaseda et al, 2013). For a comparison of the heat budget of the default version of NEMO and a sea-state dependent version of NEM with results from ORAS4 see Fig. 4.

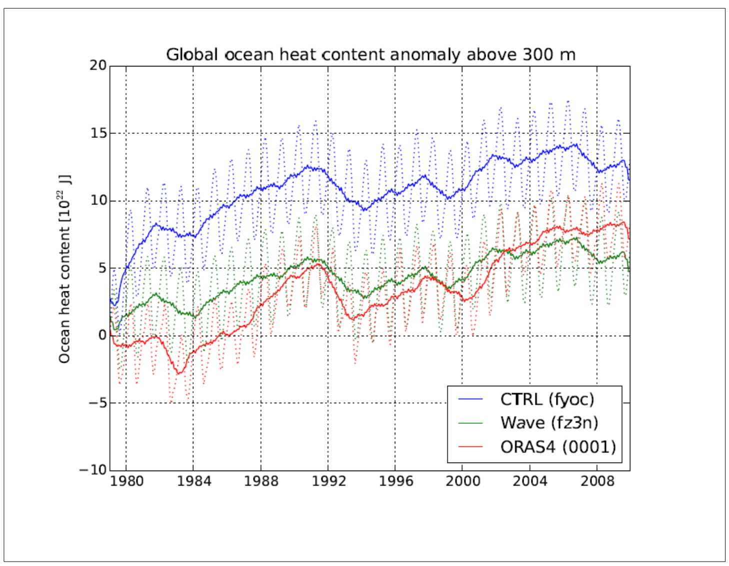

Figure 4: Comparison of upper ocean heat content (depth < 300 m) as function of time from the default version of NEMO (CTRL) and a sea-state dependent version of NEMO with results from the ocean reanalysis ORAS4.

NEMO has been coupled to the atmospheric, ocean-wave model as part of the ensemble suite (ENS) of the ECMWF Integrated Forecast System (IFS) since November 2013 (IFS Cycle 40R1). Preliminary results were first reported in an ECMWF newsletter in June 2013 (Breivik et al, 2013). More details of the coupled integrations were presented by Janssen et al (2013). The reduction of sea surface temperature (SST) bias has had a beneficial effect on the ensemble prediction system. Coupled seasonal integrations similar (but with the addition of the ice model LIM2) to those run operationally for the ensemble forecast system have been performed out to 7 months lead time. The results indicate that the biases are reduced, particularly in the summer extra-tropics.

Contribution by MET

Wave effects have been implemented in the General Ocean Turbulence Model (GOTM; based on the work of Umlauf and Burchard, 2003). These effects include sea state dependent fluxes of momentum and energy (e.g. Janssen, 2012), Stokes-Coriolis force, and turbulence production by Stokes drift vertical shear. The latter has been suggested as a parameterization for Langmuir turbulence (based on Large Eddy simulations; e.g. Grant and Belcher, 2009), but can also be derived as a more conventional shear production term using Lagrangian framework, e.g. that of Broström et al. (2008). In GOTM we use a two-equation system where the turbulent kinetic energy (TKE) and a second quantity related to mixing length are the dependent variables. Our first case study is the Statfjord A accident, which was a large oil spill incident at an oil drilling platform in the North Sea in December 2007. 1D-modeling of buoyant particles (simulating oil droplets) gives better results when wave effects are included (Drivdal et al., Ocean Science, in press). There is a strong dependence on particle rise velocity, which reflects the fact that wave effects become increasingly more important closer to the surface.

Validation mixed layer model against satellite data and against in-situ data

The ocean model ROMS has been tested with sea state dependent fluxes of momentum and energy (including the Stokes-Coriolis force applied as a surface stress), using validation data from in-situ, satellite, and HF radar velocity observations collected in Northern Norway during the 2013 cod stock assessment cruise of the Institute of Marine Research. The mixed layer module was based on the two-equation GLS model of Umlauf and Burchard (2003). Using wave effects yields an improvement in SST and surface velocities. Biases in hydrography and tides dominate the model errors, however, hence the improvements are small compared to the total errors. The regional model covered the Vestfjorden bay as well as the areas offshore of Vesterålen; the latter is characterized by very steep topography and strong northward currents and eddying fronts. Best results were obtained inside Vestfjorden where the residence time of the water masses is significantly longer than in the offshore areas.

Web based source code library for wave model development

During the MyWave project a new improved source code for the third generation wave model WAM has been developed in standard Fortran95 including MPI (Message Passing Interface) for parallelization purposes. This new state-of-the-art version WAM Cycle 4.5.4 meets modern standards in software design and its high-grade modular composition allows an easy replacement of individual parts of the code. To make sure that all new wave model developments will be available for all users, the software package is maintained in a web-based source code library. For this purpose the free and open source Distributed Version Control System (DVCS) GIT is used and the corresponding GIT repository has been installed on the GitHub server : mywave.github.io/WAM. Since June 2014 this repository is public and can be accessed by all users worldwide. The repository includes the source code, makefiles and a complete set up for an artificial test case (SWAMP). The web-based source code library for WAM on the GitHub server will be maintained beyond the end of MyWave by the Helmholtz-Zentrum Geesthacht (HZG).

WP2:

In the following paragraphs we first discuss the results of the individual applications before making an attempt to integrate the results:

1. Satellite observations of surface winds over water are now routinely available and generally of high quality. In MyWave the processing of the raw data was improved to provide valid data closer to the coast, which is highly relevant for coastal wave forecasting. Experiments were performed to assimilate scatterometer winds into a high-resolution HARMONIE meteorological model. These experiments encountered some technical issues that were all resolved. The assimilation of scatterometer observations did improve the accuracy of the results at analysis time, but unfortunately the impact was quickly lost during the forecast. We believe that this is caused by a more fundamental issue: the high-resolution HARMONIE model generates features at a scale comparable to or smaller than the resolution of the scatterometer, which does not lead to satisfactory results for the assimilation with the 3D-VAR method. Perhaps, spatial filtering techniques or the use of an ensemble can improve this, but clearly there is a need for further research. In addition it was found that HARMONIE is overestimating the wind speed for wind speeds exceeding 15 m/s. Data assimilation cannot resolve model biases, which strongly limits the impact of observations.

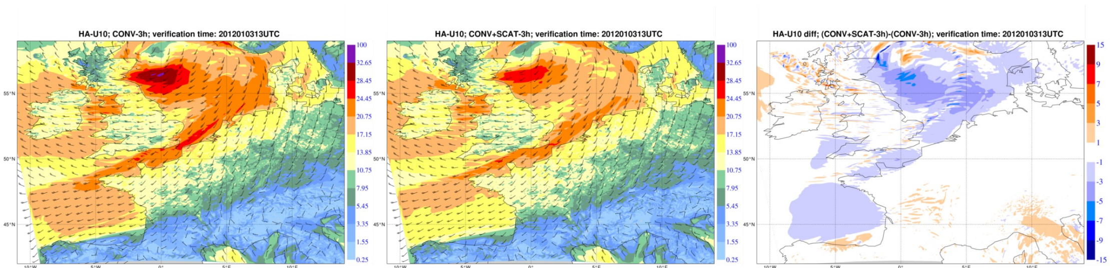

Figure 5: Case study 3 January 2012 at 13UTC. In the strong westerly flow, a cold front rapidly moved across the North Sea, passing the Dutch coast. The front was accompanied with a squall line. The coastguard ('Rijkswaterstaat') reported a so called meteo-tsunami at the coast at Ijmuiden, with a sea level change (rise and fall) of over 1.5 meters in 30 minutes. The left/middle panel show the 1-hour HARMONIE forecast of 10-m wind from the 12UTC analysis without/with using ocean surface wind data from the Indian OceanSat-2 scatterometer. The difference in the right panel shows model 10-m wind speed reductions up to 5 m/s by assimilating scatterometer winds.

2. The high-resolution HARMONIE winds were used subsequently to force a regional SWAN wave model. It was shown that assimilation of the scatterometer wind observations did improve the accuracy of the wave model runs, but the impact was not very large. The impact can probably be improved further in the future by improvements of the assimilation of scatterometer into the HARMONIE model and improvements aimed at removing the model bias.

3. In another experiment, in-situ observations of waves by wave buoys and radar were assimilated into a SWAN model of the same region. The well-known EnKF data-assimilation, here as implemented in the OpenDA toolbox, was used to perform the assimilation. In these experiments, the full 4D spectral wave energy density was corrected directly by the assimilation. A big advantage of this approach is that many more observation types, such as wind-speed and direction, wave-direction, wave-period and wave-spectra, can in principle be assimilated. Moreover, the method attempts to correct other aspects of the wave spectrum in a consistent way. It was shown for example that a higher observed wave-height also creates increments that increase the wind speeds and wave-period. Disadvantages of this approach are the need to run an ensemble of models; and the large amount of spectral data that needs to be adjusted during the analysis. These drawbacks were partially countered by the use of parallel computing and the use of a reduced spatial resolution. The results are very promising and are currently being considered for pre-operational trial runs in the wave forecasting system. Additional research is needed to study the impact of various other observation types. One interesting future experiment would be the assimilation of the scatterometer winds into the wave model instead of the meteorological model. This explicit approach may result in a greater impact than the implicit approach through the

meteorological model.

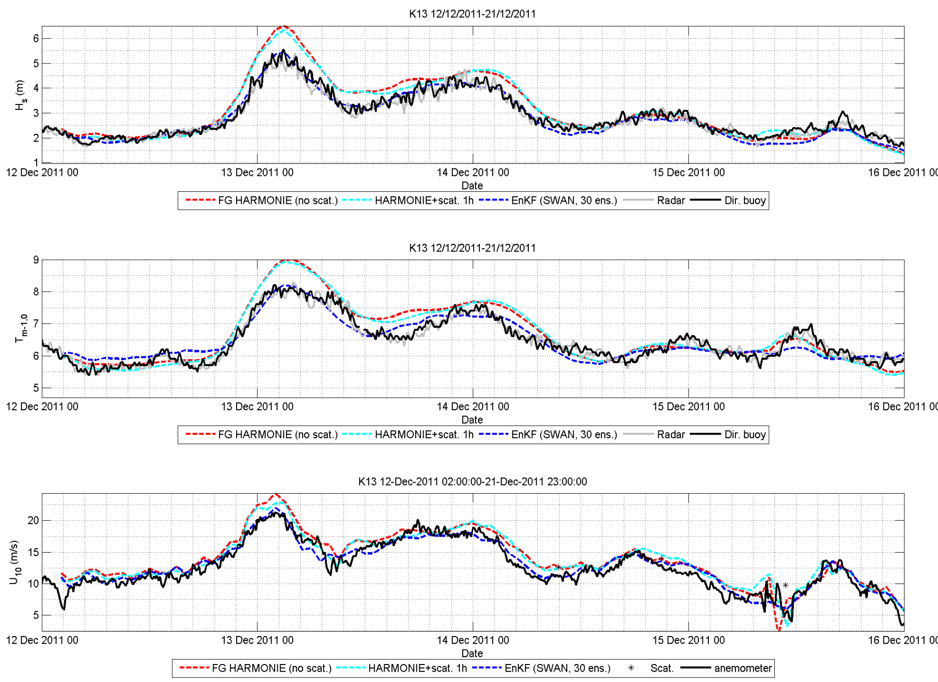

Figure 6: Case study 4. Comparisons at K13 between the observed and the modelled wind and waves using different forcing winds: First-guess HARMONIE (red); HARMONIE with 3D-VAR Scatterometer assimilation (cyan) and HARMONIE with EnKF wave height assimilation.

4. HF radar is another observation type that was studied. An innovative data-assimilation method, based on NNs, was developed. The method uses two steps. In the first step the wave observations are used to estimate the boundary condition and wind input. In the second step, the NN-model predicts the waves at the observation locations with an iterative method. Important advantages of the NN-method are that it can in principle be applied to a wide range of observations and models, that it is easy to implement and the computational efficiency during the operational phase. Disadvantages are that the operational phase needs to be preceded by a training phase containing sufficient and homogeneous data. Moreover, the training phase needs to be updated whenever one wishes to include new observations. Unfortunately, the HF-RADAR wave observations were of insufficient quality to be assimilated. It was decided to continue the experiments with synthetic observations. Clear positive impacts of the data-assimilation were shown for two stormy periods. These promising results need to be followed up by further experiments with real observations in the future, before operational use can be contemplated.

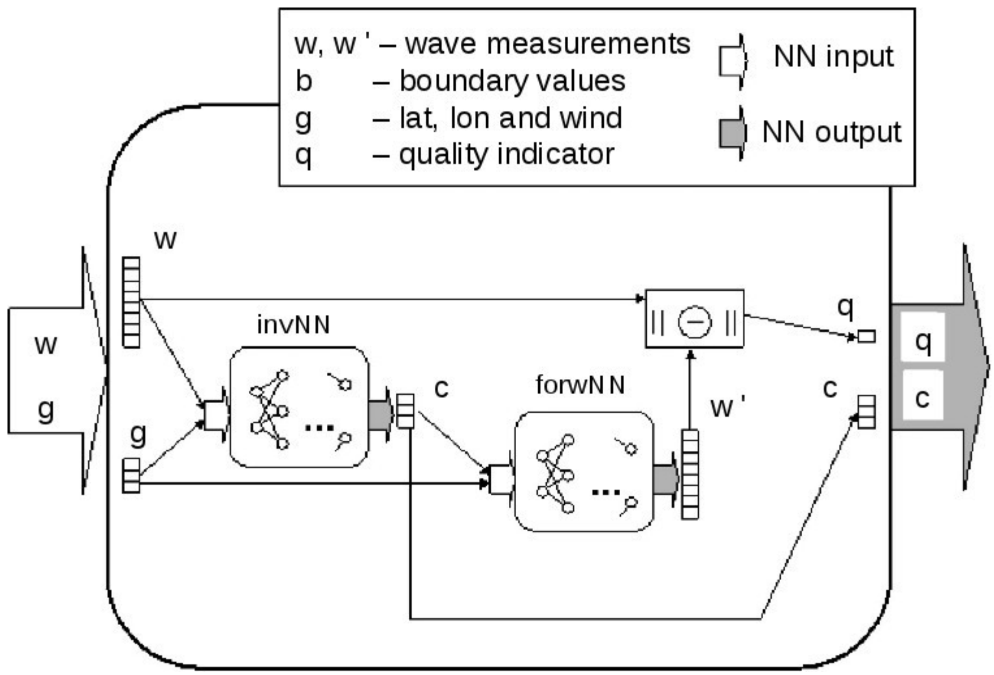

Figure 7: *Idea of the Neural Network assimilation scheme, w, w' are the wave measurements, b-boundary values, g-latitude, longitude and wind values, c-other parameters, q-quality indicator.*

5. Validation of model accuracy against more than one type of observations can provide additional information about the accuracy of model and observations. Traditionally, models are evaluated against observations that are assumed to represent the truth. However, with more and more accurate models, it is increasingly useful to account for errors in the observations. The use of multiple observation datasets can provide further insight in this. Here the triple-collocation technique was applied that assumes that the errors of the different observations and the model are uncorrelated and uncorrelated with the signal as well. Results for the Adriatic show marked differences in accuracy of significant wave height measured by different satellites, where Saral-Altika is more accurate than Jason-2 and Cryosat. Also the error estimates for in-situ observations vary per location, which larger relative errors for more sheltered locations with on average smaller wave heights. This can be explained by larger representativity errors compared to the model and satellite or by the smaller signal amplitude. Care must be taken to verify the assumption of uncorrelated errors. The altimeter wave height for example gave inconsistent results against lead-time, which is an indication that the assumptions were violated.

6. Wind waves undergo large changes when approaching the coast while the situation is much more homogeneous in the open ocean. Unstructured grids can be adapted in a more flexible manner to provide the right accuracy both near the coast as in deep water. One unstructured model was developed for the Canary Islands. Although it was possible to create an unstructured grid that had higher coastal resolution, sufficient resolution in deep water and still fewer grid-cells than the structured grid model, no increase in accuracy or computational performance was found. Some possible causes for these results are: a larger number of iterations for the unstructured solver, too large changes in size between adjacent grid-cells, or too large changes in incidence angle of the waves between adjacent grid-cells for the unstructured grid model. Further research is needed to identify the real causes and test various remedies.

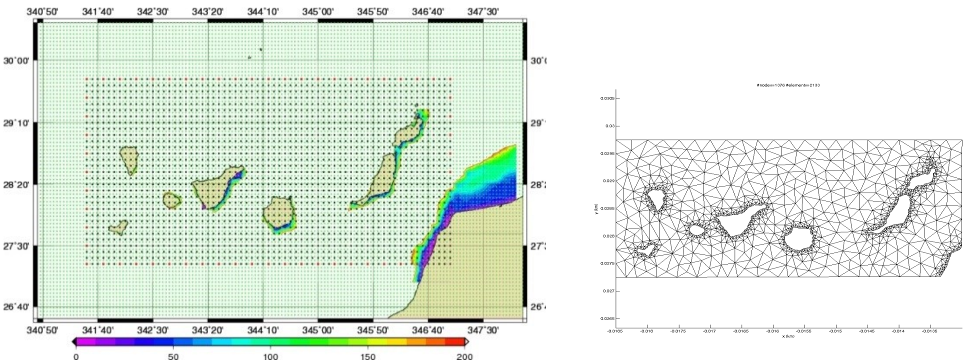

Figure 8: Nested regular (left) and unstructured (right) SWAN grid of the Canary Islands.

The experiments described above clearly show that a synthesis of a fully three-way coupled high-resolution ocean-atmosphere-wave model that can assimilate all relevant observations is not within reach. Still, progress has been made on a number of aspects working towards this synthesis. Since, it may still take considerable time to reach this fully coupled assimilative system; one also has to consider the intermediate steps towards this goal. On this path several approaches were studied to assimilate new observation types, to speed-up the assimilation process and to increase our knowledge of the errors present in todays' forecasting systems. These approaches have varying stages of maturity and are by no means exhaustive. We recommend further research to further increase our understanding and eventually design fully coupled assimilative forecasting systems.

WP3:

In WP3 different wave forecast ensemble systems have been implemented , assessing, for two separate and different areas, their performance and increased information with respect to a deterministic approach. The technique has been applied both at large and local scales, in the latter case for three specific harbours. Different approaches have been followed in producing a meteorological, hence wave, ensemble. Two approaches have been followed, at two different scales, North-Atlantic, with focus on the European coasts, and the Mediterranean Sea. The results have been intercompared, also with respect to the deterministic approach.

Specifications of the two ensemble systems

The U.K. Met Office wave ensemble prediction system (wave-EPS) for the North Atlantic 'euro-zone' comprised two models. An Atlantic wave model was formulated on a multi-resolution Spherical Multi Cell grid (SMC; Li, 2012) and a UK wave model was set-up at 8km resolution on a rotated pole grid. The models were driven, respectively, with winds from "lagged ensembles" of Global (40km resolved) and UK (1.5km resolved) wind fields (Bower et al., 2008). This enabled a comparison, for waters around the UK, of the performance of a wave-EPS in which the ensemble aimed to represent variability in synoptic scale atmospheric systems using wave physics with reasonable 'open waters' performance (Tolman and Chalikov, 1996, the Atlantic model) against an ensemble that permits variability at convective scales and used wave physics with better performance in short fetch scenarios (WAM Cycle-4, following Bidlot, 2012, for the UK model). Verification of total significant wave height and (10m) surface wind speed from the two models was made against in-situ buoy data and JASON2 altimetry for the period August 2013 to March 2014.

The MOGREPS-G ensemble comprises a control plus 44 perturbed members. The global U(nified) M(odel) 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.

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) useable levels of spread have been generated in a wave-EPS purely based on variability introduced via perturbations in wind forcing data from an atmospheric ensemble.

The wave-EPS consist of three WAVEWATCH III™ (WW3; Tolman, 2009) configurations, each run to generate 22 ensemble forecast members plus a control run. The configurations cover the following domains: the Atlantic Ocean, using a spherical multi-cell grid; the Mediterranean Sea using an 8km grid; the UK using an 8km grid with boundary conditions provided by the Atlantic configuration. The UK configuration is defined on a rotated grid with an artificial pole offset at 37.5N and 177.5E,. The UK wave model takes wave boundary conditions from the Atlantic model. The Mediterranean configuration is defined on a rotated grid using a pole at 37.5N and 177.5E.

The second approach in the Mediterranean Sea has been done by the Italian Meteorological Service (CNMCA). 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 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. 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. 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°N, -10.0°E).

A "sea state" EPS based on the NETTUNO system (Bertotti et al., 2013) and the COSMO-ME EPS has been tested and is then regularly run. Nettuno is a high resolution local scale wave forecast system operational in the Mediterranean Sea based on the COSMO-ME and WAM models with the latest advances in both meteorological and wave models. WAM (Komen et al., 1994) 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.

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

Collection and preparation of measured data for model validation

A key point in the project was the collection and distribution of in-situ and remotely sensed measured data for wave ensemble prediction system (EPS) validation. ISPRA has provided measured data from 30 buoys in the Mediterranean Sea to be used for the wave ensemble prediction systems (EPS) validation procedure. Through a specific agreement based on MyWave Project research purposes, ISMAR succeeded in obtaining the data from two stations on the coast of Israel. Buoy data over the Atlantic Ocean and the Mediterranean Sea have been complemented with selected remotely sensed altimeter and scatterometer data. An effort has also been made to provide information about all the GPS available stations for wave data measurements.

On a monthly basis, starting from July 2013, all the available data over the Mediterranean Sea provided by various institutions are hosted on a dedicated ISMAR server. This storage area has been made operationally accessible to all the interested partners, in order to perform WP3 forecast validations.

Each time-series has been and is quality checked (see MyWave D3.2) in order to guarantee the reliability of the observations. The Israel station Cameri has provided high frequency sampled wind data, which have been filtered and under-sampled on a 30 minutes basis, and 30 minutes wave spectra, from which the related spectral moments and wave parameters are derived. Full information is provided in Deliverable D3.2.

Finally, the scatterometer (wind speed and direction) data have been extracted from the KNMI Data Centre (KDC), at the address https://data.knmi.nl/. The mission considered are ASCAT-A Coastal Wind Product, ASCAT-B 25 km Wind Product, and OSCAT 50 km Wind Product.

Validation of the UKMO Atlantic ensemble system

The verification of wave climate representation and deterministic forecast performance highlighted differences in the models resulting from the choice of wind forcing and physics schemes, in particular the bias characteristics. For example, the Atlantic model was found to be biased slightly high in the Western Approaches to the UK, but biased low in the fetch limited North Sea. In comparison, the UK model was biased high in both areas. At the short ranges forecast in this study the ensemble spread is relatively small, so a significant bias (10cm or more) can have a substantial effect on probabilistic forecast skill. Reliability diagrams and economic value analyses, used to assess probabilistic performance, showed significant improvement once a bias correction scheme was applied.

Spread-skill relationships showed a strong correlation between deterministic model errors and ensemble spread, indicating that wave-EPS can be effectively used by a forecaster in order to estimate the uncertainty associated with a given forecast. Further analysis of spread also showed a very strong correlation with high wave conditions. Initial comparisons of spread against observations (via Talagrand diagrams) suggested that the wave-EPS were under-spread. However, these metrics are susceptible to effects of observational error, as discussed by Saetra et al. (2004). Once effects of model bias and observation errors were included in the verification, the spread characteristics of the models were demonstrated to be very good. The interpretation of reliability of the models also improved when observation errors were accounted for.

The successful verification of these systems has resulted in the Met Office committing to a further period of operational trialling and forecast systems development beyond the MyWave project.

Verification of the UKMO and CNMCA Mediterranean ensemble systems

The validation is based on the observations dataset reported in D3.2, which covers the six month period from July 1 to December 31, 2013. Proceeding from D4.1 and D4.2, the basic principle on which this verification is based on is that the forecasts are validated “as they are”, that is without any calibration or other kind of post processing based on the same verification scores (e.g. bias correction). This does not exclude that ensemble members are post-processed in order to account for observation uncertainty, since these are based on knowledge preceding the forecast/validation period.

It has been found that the (de-biased) ensemble mean is generally more skilled than a (de-biased) deterministic forecast, if the EPS is built with the same model grid resolution. However, the analysis of both wave model input and output bias shows that the EMs are more energetic than the control members, and this is partly due to the way in which the results are post-processed to get the EPS statistics (see Figure 9). In deterministic sense, we have observed that UKMO has a better ability to mimic the overall climatology distribution, and Nettuno tends to overestimate the distribution upper tail. On the other hand, Nettuno is better correlated with the observations than UKMO, and this aspect compensates the skill gap due to the higher variability.

UKMO spread is generally higher than the Nettuno one, but the latter tends to develop faster than the former and, at least for wind speed, to reach it after 48 forecast hours (Figure 10). The spread information takes time to be transmitted from input (wind) to output (wave magnitudes), therefore the Nettuno waves spread remains lower than the UKMO one for the first 48 forecast hours. It is expected that the two ES would reach each other between 72 and 80 forecast hours. Even if substantial difference exists in the EPS width, both systems predicted significant wave height distributions result under-spread. A detailed analysis shows that both systems are under-spread where they should mimic low forecast uncertainty (with UKMO slightly more under-spread than Nettuno), and generally over-spread where the uncertainty is higher. In the high uncertainty region UKMO is more over-spread than Nettuno, and the behaviour of the latter is sometimes in line with the deterministic error distribution.

Both the average UKMO reliability, and the one evaluated for a number of discrete cases, is generally lower (better) than Nettuno one. The differences mainly depend on the observations sub-sample (Figure 11). On the other hand, Nettuno resolution is superior to UKMO one. In particular, the latter lacks in ability to discriminate occurrence/non-occurrence of high energetic events, especially at buoy locations (mainly distributed close to coastal regions). Nettuno eps forecast generally fits better than UKMO to decision makers who must make a protection/non-protection choice with respect to high energetic sea states, and whose costs of protection are lower than potential losses. On the contrary UKMO is in some cases more suitable for high cost/loss ratio and low energetic, early occurring events. The ensemble size influence on the differences in REV is negligible.

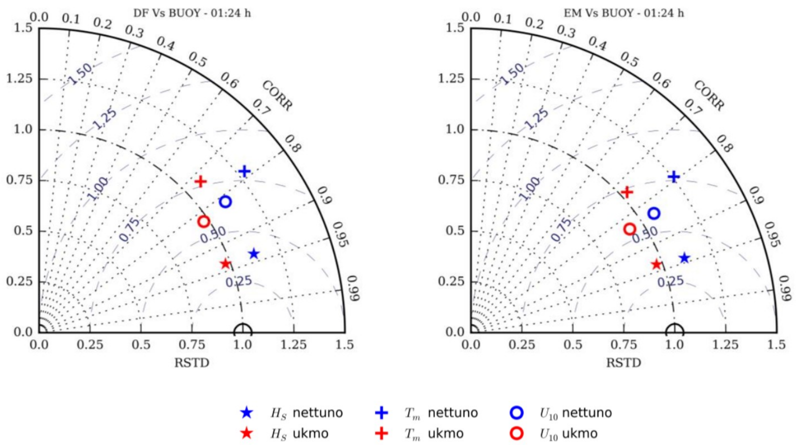

Figure 9: Taylor diagram for control member (left) and ensemble mean (right) referred to buoy measurements. Comparison for the first 24 forecast hours. Standard deviation and centred pattern RMS are normalized with respect to reference. Time window: 1/7 to 31/12 2013. Coverage: Mediterranean Sea.

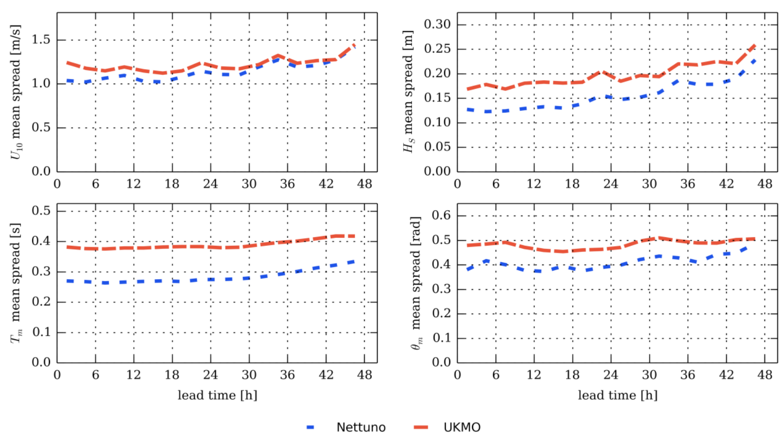

Figure 10: EPS spread climate for U10 (top left), HS (top right), Tm (bottom left) and θm (bottom right). Spread is averaged (RMS) each 3h of forecast lead time. Time window: 1/7 to 31/12 2013. Coverage: Mediterranean Sea. Estimations made accounting for co-located forecasts only.

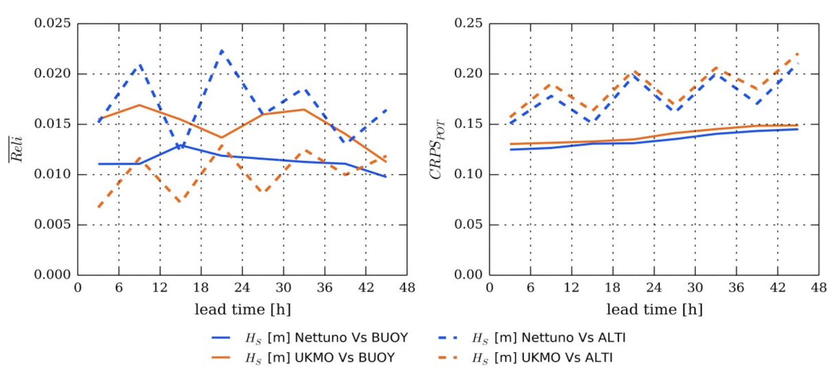

Figure 11: Breakdown of CRPS for significant wave height. Left: reliability; right: potential CRPS. Dashed lines: altimeter; continuous lines: buoy. Time windows: 1st July to 31st December 2013. Coverage: Mediterranean Sea.

Application of ensemble systems to harbour forecast

The Wave-EPs local models are operational from September 2013 with the main purpose of providing categorical forecast with the highest possible accuracy and a quantitative basis for reliable and useful probability forecast.

Gijon and Tenerife systems have been configured taking into account forcing files from UKMO. Therefore they run with the same time resolution as UKMO wave-EPS is defined: 4 runs (0z/6z/12z/18z), and control member +22 members. At 0z/12z members 1-11 run out to full forecast, 12-22 perform short update cycle, and at 6z/18z members 2-22 run out to full 72h forecast, 1-11 perform short update cycle. The restart dumps are produced at T+6. The full 22 member ensemble product can then be generated using overlapping full forecast members from the last two runs.

Barcelona application driven by ISMAR conditions runs with the same time resolution as NETTUNO-EPS is defined; it consists of 40+1 members, integrated at 00 UTC up to 48 hours forecast. The ensemble is run once a day at 00 UTC.

Control members of harbour applications have been validated with PdE buoy network.

In the operational models there are also added routines that generate EPSgrams, probability and spread maps (Figure 9, top, centre and bottom panels). The EPSgram gives the ensemble information at an individual grid –point location, which indicates the time evolution of the given parameter. In the case of harbour applications the relevant parameters are the significant wave height and the mean direction. The spread is indicated by the range of forecast values. 50% of the members are distributed evenly around the median to define a vertical rectangle. The remaining members define the extreme 25 % spikes. The box-epsgram thus provides a discrete probability information in the intervals 0-25%, 25-50% and 75-100%. The deterministic member (control member) is included as a reference. The continue-epsgram gives hourly information that is the time resolution of the model.

If the purpose of the EPS were to produce accurate categorical forecasts, then a lower number of members would suffice for an estimate of the ensemble mean. The reason why the EPS has so many members is the need to accurate probabilistic estimates of the risk of extreme and rare events. The probability maps are an important tool to add to the alert system that the harbours already have with their deterministic forecast.

Although Wave-EPS local models could produce more outputs for the commercial ports, the epsgrams with the wave direction or the significant wave height and the probability maps are the most useful tools to start to introduce the predictability to the users, adding a categorical forecast to the deterministic information.

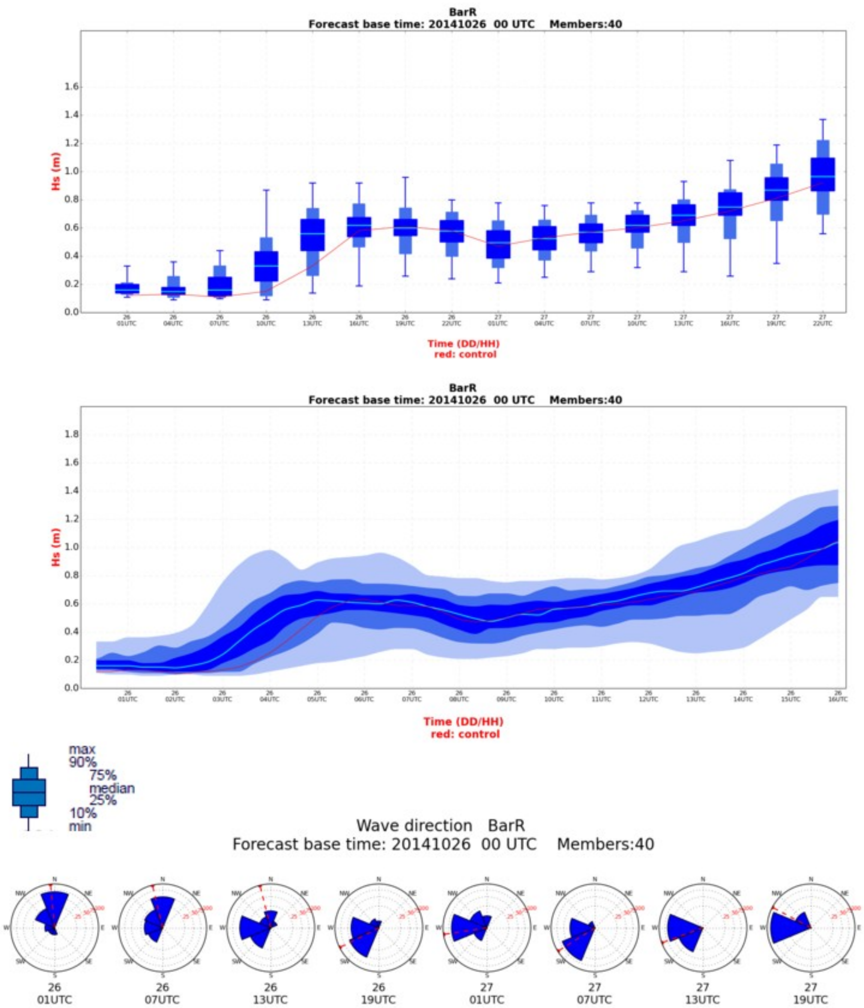

Figure 12: EPSgram Barcelona-CNMCA application. Run:2014102600. Lead time +48h

WP4:

Identification of compatible metrics using remote sensed and in-situ wave measurement baselines

It is expected that wave verification within a Marine Core Service should be available and robust for all regional systems. However, the availability and quality of observed wind and wave data to act as a baseline truth for verification is variable both globally and in different European regional seas. Work in this task was aimed at establishing procedures under which regionally consistent wave verification can be carried out, through optimally exploiting both satellite and in-situ observations as comparative truths for wave model forecasts. 'In-situ data' describes any form of observation (e.g. using a heave sensor, laser altimeter) made from sea-borne platforms that are fixed in space and sample at regular short intervals in time. 'Satellite data' describes remote sensed observations made by instruments (e.g. altimeter, Advanced Synthetic Aperture Radar) mounted on low orbit space vehicles. These observations are made along tracks following the satellite's (polar) orbit of the earth. This leads to a data sample that is spatially dense along-track but temporally sparse at fixed points.

The study aimed to identify 'compatible metrics' for verification of wave forecast performance using either in-situ or satellite observation data. Compatibility was defined as the ability to inter-compare or combine results from verification using in-situ and remote sensed baselines. This can only be achieved by accounting for uncertainties introduced to the verification due to sample size and errors associated with the different observation types.

Sampling issues were identified via an assessment of observation data availability, both globally and in selected European regions. For example, a review of a 3 month sample of data from the North Sea indicated close to 20000 (6-hourly) in-situ measurements being made and just over 400 satellite passes (D4.1). Whilst these numbers seem large, wave parameters are well correlated on temporal scales of 6-12 hours and spatial scales of 50-300km (dependent on location). Since verification statistics assume a sample of independent data, correlation between observed values reduces the effective size of a data sample significantly. A test in which strict temporal and spatial independence criteria were applied to the North Sea observations reduced the verification data sample by a factor of 20 (D4.2a Appendix B). Comparing independent data sample sizes with estimates of the sample size required to achieve specific confidence levels in the verification statistics led the study to conclude that, for regional wave model verification, issuing regional verification results based on (minimum) 3 month data samples is necessary (D4.2a). Sample size limitations also suggested that the use of statistical re-sampling techniques (e.g. the bootstrap method, Efron and Gong, 1983) would be a valuable tool to assess the quality of operational verification.

Observation errors were assessed via a triple collocation study (D4.3). Triple collocation is an established technique in which three independent estimates of a condition can be inter-compared in order to derive the systematic and random errors associated with each estimator (Stoffelen, 1998). Previous studies have generally been focused on global networks, but the MyWave project sought to assess observation error characteristics in European regional seas. The study concentrated on two areas with differing wave climates and a high density of in-situ observations, namely the North European Atlantic Margin (NEAM) and the North Sea, and applied the triple collocation method of Janssen et al. (2007). Rolling 12 month data samples were analysed for the period 2010-2011 (e.g. Figure 13), based on collocation match-up criteria that assumed the same condition was measured by satellite and in-situ measurements made within 50km and 1 hour of each other.

The study demonstrated that robust and consistent estimates (within +/-1%) of both in-situ and satellite altimeter errors could be generated from the regional data samples. Low sample size introduced a degree of sensitivity, for example a susceptibility of the results to outlying data (from poor in-situ observations), changes in the in-situ network and, at the scales analysed, subjective control of altimeter observation errors by choosing to aggregate successive soundings ('super-observation'). Relatively stable estimates of in-situ and altimeter errors were obtained despite the model data used being inhomogeneous in time. Estimates of random observing errors for both NEAM and North Sea were consistent within 1-2%, at close to the 10-12% level for the in-situ data and 5-7% level for the satellite data. However, the linear calibration factor used to measure systematic errors between satellite and in-situ data (as the reference) was more variable between the sea areas (1.02-1.04 in the NEAM and 1.06 in the North Sea). This result suggests that regional variability in observation errors exists and should be accounted for. The variations that were introduced by changes to the in-situ network over time suggest that, if observation errors are to be applied in a quantitative sense in operational verification, regular review of triple collocation results with contemporary observation data need to be made. Conversely, regular monitoring of triple collocation data may help detect issues in the observing network.

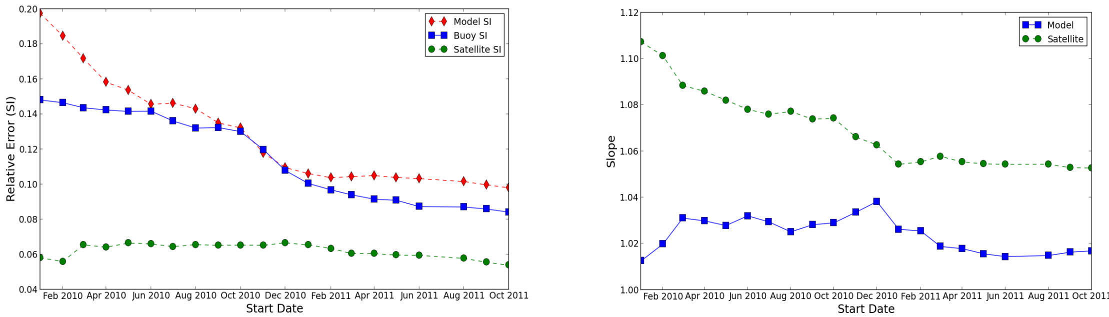

Figure 13. Time-series of rolling 12 month sample error estimates for model, in-situ platform (labelled buoy) and satellite Scatter Index (left panel) and Slope (right panel) for the North Sea. Samples were determined based on all available Envisat, Jason-1 and Jason-2 altimeter data with 3 soundings in each super-observation; the in-situ data provided the reference 'truth' for the slope estimate.

A method to apply both sampling and observation errors to the verification was developed and presented in deliverable report D4.3. Following user feedback, the approach retains a direct comparison between the forecast model and observations (i.e. no attempt is made to remove observation errors from the verification). The sample size effect on variability of the metric is assessed through re-sampling. The re-sampling step provides an opportunity for the effect of observation errors (measured using the triple collocation technique) to be assessed within the verification scheme. For each re-sampled instance of the forecast-observation data, a further instance of 'pseudo-observation' data can be generated, by combining the forecast sample with a simulated set of observation errors. Multiple instances of pseudo-observation data are used in order to compensate for a lack of phase information to accompany the observation error estimates. Verification of forecasts against the pseudo-observations generates results equivalent to a scenario in which the model had estimated the truth perfectly and all the errors were observational. The idealised verification score therefore provides an upper bound to the performance levels that the forecast can reasonably be expected to achieve. The study also examined the use of a naive comparison (based on random sampling of the model climatology) to give a lower reference bound and a method to directly inter-compare verification performed against in-situ and satellite baselines.

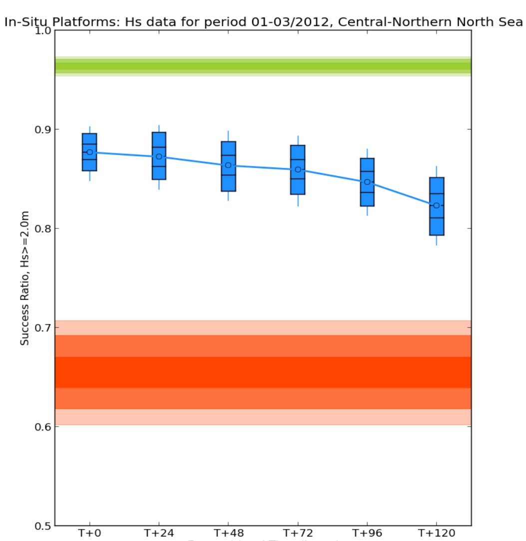

Figure 14. Success Ratio (SR) for forecasts of Hs greater than 2m versus lead time for model against in-situ data. Box and whiskers symbols show the direct model-observation comparison (marker at bootstrap ensemble mean, inner box lines at

25-75% range, outer box lines at 5-95% range and flyers at 1-99% range), the green plume shows idealised SR (same ranges) and the orange plume shows the naive prediction SR (same ranges).

Because the technique generates verification data samples, rather than correcting a pre-calculated verification score, the data produced can be applied to any of the metrics described by the MyWave project. A number of examples are given in deliverable report 4.3 and Appendix A of report 4.4. Figure 14 illustrates the application of the technique to a Success Ratio (SR) metric, which measures how often an event will be observed, having been forecast (with a maximum score of 1.0 and minimum score of 0.0). In the figure, the blue circles and line show the mean forecast-observation SR values derived for each forecast lead time. The box and whiskers symbols denote the variability in the SR results, due to sample size, and indicate that at short lead times the variability is large compared to the change in SR. The green shaded region shows idealised SR values, indicating that observation errors would restrict a verification score to approximately 0.96. The shaded orange region shows the naive prediction score, i.e. the score that can be achieved purely by using random guesses. SR scores are heavily influenced by the background climate in terms of the proportion of the sample that contributes to the score. In this case a relatively high number of forecasts are well above the 2m threshold and even the naive predictions score highly. However, by comparing the direct forecast-observation scores with the idealised and naive values, it can be seen that the predictions are skilful even for a forecast with lead time of 120 hours, and that the forecasts also have significant scope for improvement throughout the forecast range.

Assessing the verification in this relative manner enables a degree of compatibility between the in-situ and satellite based verification.

Identification of user focused metrics and proposal of a Marine Core Service wave verification system

A successful verification scheme will provide uncertainty and performance data that is relevant to a variety of marine users and which can be clearly portrayed and simply discovered. Work was undertaken in this task, in parallel to the description of compatible metrics, in order to identify a subset of metrics that are likely to be most relevant to users of operational wave forecasts. This information was subsequently combined with a review of an existing operational oceanographic forecast verification system, provided through MyOcean, in order to propose a wave verification procedure that might be successfully integrated with that service whilst delivering wave users key requirements.

Documentation of metrics

Definitions of a range of metrics, that could be generated by comparing forecasts against either in-situ or satellite observations, were presented in deliverable report D4.2a. Each metric describes a different aspect of forecast performance, so a key part of the definition process was to identify the purpose for which each metric could be used. In order to easily associate the purpose of the metrics with users requirements for verification, five overarching purpose categories were defined:

1. Climatology tests (for example quantile-quantile plots) determine the ability of the prediction system to replicate the reference climate. The outcomes may be used to determine systematic errors and specific process representation issues.
2. Measures of prediction uncertainty in parameter space (for example Mean Absolute Error) describe forecast accuracy from samples of forecast-reference errors.
3. Measures of prediction accuracy and resolution in probability space (for example Hit and False Alarm rates) describe the ability of the prediction system to successfully identify reference conditions. These data can also be used to evaluate the long term benefits of using the model

predictions, i.e. whether more gains than losses will be made through basing decisions on prediction data.

4. Measures of performance through the parameter range assess reliability of the forecast based on the conditions being forecast.
5. Extreme statistics analysing performance of the model specifically at the tail(s) of the distribution of conditions.

19 'tests', comprising one or more metrics evaluating a specific aspect of system performance, were documented and examples of 16 of these were provided to users for consultation purposes.

User consultation

The user consultation followed a two-stage process. In the first stage surveys, initially sent to 68 users, were carried out to obtain a high level view of user expectations and requirements for verification data. The surveys concentrated on the purposes for which users would review verification data, key wave parameters needing to be verified, format and preferred methods for accessing verification results. In the second stage, key representatives of different user communities were presented with a number of verification metrics (the set provided to users is replicated in D4.4 Appendix A) and asked for feedback.

The results of the consultations were distilled into the following recommendations for a user focused verification system (presented in more detail in D4.4):

- Verification data should focus on a direct comparison between prediction and reference observation, but should retain separation of metrics measured against different observed references (e.g. in-situ and satellite data).
- The primary parameters to be verified are significant wave height and, where possible, wave period and direction. Accompanying wind speed and direction statistics should also be provided where available.
- The metrics should quantify the verification in real terms (e.g. quantified error, probability of forecast success/failure) rather than as an abstracted skill score.
- Published verification should concentrate on simple metrics requiring minimal explanation.
- Web based publication of verification is the most convenient form for users.
- Verification data should be archived so that long term performance changes can also be identified.
- Issuing verification that focuses on the performance of forecasts in high energy storms would be considered a useful extension to the system.
- Other potentially valuable extensions to the system would include verifying the 'consistency' of forecasts, providing mapped views of verification data. A number of users expressed an interest in making forecast-observation match-up data available for download by users with an interest in carrying out their own verification.

Proposal of an operational wave verification system

In addition to assessing user requirements, the study reviewed the system for delivery of verification adopted by the MyOcean project (MYO2-PQ-CVGWP). This work was based on the assumption that future delivery of wave data within a Marine Core Service is likely to be in coordination with existing MyOcean services, under the Copernicus programme. The assumption provided a major driver for the form of the proposal, since the most efficient way to provide consistent ocean and wave verification would be for the wave verification programme to adopt a number of the existing MyOcean procedures. The focus of the proposal (given in detail in D4.4.) was on the necessary structures and procedures for delivery of an initial (V0) operational verification scheme for deterministic wave forecasts.

The proposal suggests a division of responsibilities for verification data production made along the same lines as for the MyOcean process. Production centres creating the wave forecasts (PCs) should also be responsible for model-reference match-up and generation and quarterly release of statistics files, with a central verification team (potentially the existing MyOcean team) responsible for further data aggregation and publishing of the verification. PCs will be responsible for detailed verification of new models or science upgrades provided within product Quality Information Documents (QuIDs). One proposed option that departs significantly from the MyOcean role assignment, but which is more suited to the wave community (where data assimilation is not a standard practise), would be to place responsibility for observation data acquisition and quality control in the hands of a Thematic Assembly Centre(s) in order to provide a centralised resource for these data.

In terms of operational metrics, user feedback (in particular the requirement for simplicity) suggests that only a limited extension to the types of metrics presently published by MyOcean is required. The suggested core metrics for wave data at V0 are:

- Bias, Root Mean Square Error, Mean Absolute Error, Scatter Index and 'Probability error within x' metrics, to be generated as daily values based on 3 month rolling data samples.
- Quantile-quantile data based on quarterly updated 12 month rolling data samples.
- Bias, Root Mean Square Error and, Mean Absolute Error stratified by condition, based on quarterly updated 12 month rolling data samples.

In addition, establishing long term series of core metric results was proposed, in order to provide users with a long term view of progress in improving product accuracy. Other metrics and data processing methods, studied during the course of the MyWave project, are expected to be best suited to verification carried out for the QuIDs. Future developments of the operational verification system are anticipated to include adopting methods associated with re-sampling the verification data and extending the verification to ensemble forecasts.

It is anticipated that most wave PCs have a level of infrastructure in place which can be adapted to meet the requirements of this proposal. Some (best endeavours) architecture for global wave model verification already exists and is used by a number of European centres. Nevertheless it is expected that specific resourcing will be needed, to meet the level of detail and standardisation required, in order to integrate wave verification into a Marine Core Service infrastructure. These resources would be needed for set-up and ongoing support.

Identification of metrics for ensemble prediction system verification

It is envisaged that the future development of wave forecasting will see increased deployment and utilisation of ensemble prediction systems (EPS) providing probabilistic forecast information. The final work package objective was to define the methods required in order to extend operational wave verification to probabilistic forecasts.

WP4 collaborated closely with WP3 in defining appropriate data sampling, metrics and a method to account for the effects of observation errors in probabilistic verification. The audit of available observation data suggested that, in order to calculate ensemble forecast statistics with a reasonable level of accuracy, at least 3 month samples of the most common observed parameters would be required for basic verification from European regional seas and that the data sampling period would need to be increased to at least 6 month or 12 month periods when more complicated metrics, such as reliability diagrams, are to be produced.

Metric definitions and the purpose(s) for which the metrics can be used were documented in deliverable report D4.2b. 19 'tests' were identified within four overarching purpose categories, according to the aspect of model performance being tested, and reviewed as an extension of deterministic forecast verification to probabilistic forecasts:

- Climatology tests determine the ability of the prediction system to replicate the reference climate. In the context of an EPS, these tests are used to assess the representivity of the underpinning model and statistically derived predictors (e.g. the ensemble mean).
- Measures of prediction uncertainty in parameter space (e.g. Mean Absolute Error). In the EPS context these tests can be extended to assess the relationship between EPS spread and deterministic forecast uncertainty and to summarize probability errors and reliability.
- Measures of prediction uncertainty in probability space. For an EPS these tests are extended to assess the value of event probability prediction data in decision making.
- Assessment of performance in forecasting extreme conditions.

The identified metrics were communicated to WP3 and used within assessment of ensemble prediction systems developed in the MyWave project.

In addition, WP3 work with Atlantic 'euro-zone' models included the application of a method, developed in WP4, to account for observation errors within ensemble verification. The method built on work by Saetra et al. (2004) and followed a similar principle to the one defined for deterministic verification, i.e. creating an idealised verification score based on an assumption that the EPS represents the true probability distribution function of observed conditions and the application of a representative distribution of observed errors. Observed errors were calculated based on results from the WP4 triple collocation study. An example of application of the method is given in Figure 15. The figure shows a rank histogram, which is used to determine whether an EPS has sufficient spread in its forecasts. In these diagrams a U-shaped form indicates under-spread, however the shape is influenced by observation errors. Generating the idealised verification allows the form of the direct forecast-observation data to be compared with the shape that would be achieved in the circumstance where model spread was perfect (indicated by the dashed black line). Figure 15 indicates that, once model bias is accounted for, the EPS is only slightly under-spread in the tails of the probability distribution function.

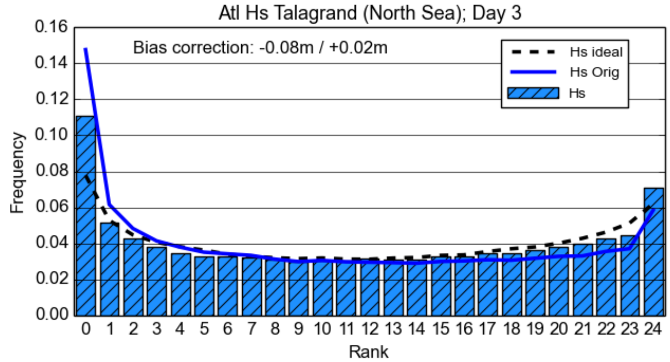

Figure 15. Rank histogram (Talagrand diagram) of significant wave height for the North Sea, for Day 3 forecasts from the Met Office Atlantic 'euro-zone' wave model. The solid blue line shows results before bias correction, the columns show results including bias correction and the dashed black line shows ideal performance using pseudo-observations;.

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Potential Impact

Providing accurate wind and wave forecasts constitutes the most important meteorological service for day-to-day management of offshore and coastal operations, and is a key component in coastal flood warning systems. Value-adding services, for instance model based wave climate studies, are frequently used by industry and authorities in the development of marine installations, planning of shipping routes, harbour management, coastal defence engineering, and so on. The air-sea fluxes of momentum and energy are sea state dependent and the forecasts of marine winds are demonstrably improved by coupling atmosphere and wave models. Ocean circulation model skill can also be improved through coupling to wave models, but although the basic theory for this coupling is in principle known it has not yet been adopted by operational institutions.

At the end of the project period an improved wave model community code base and documented evidence of impacts has been made available for assessment by National Met Services and integration into operational services as an upgrade to those presently provided to European users. In addition to the intrinsic value of accurate wave forecasts for industry and authorities, we also expect that the project will have a significant scientific impact. Uncertainties in current earth system/climate models will be reduced by using a direct physical coupling between the waves and the ocean. It is anticipated that the evidence base and potential value-add resulting from an integrated approach to wave-ocean system modelling and observation will provide the necessary stimulus for properly adding waves to the Coperenicus marine service within a follow-on project.

A major outcome is to have identified methods by which verification statistics can be enhanced through use of re-sampling strategies, in order to understand confidence limits in the verification results, and application of observation error data, in order to better understand high performance limits that can be achieved by forecast models. The re-sampling techniques are particularly valuable for understanding verification data in regions where observations, which can be expensive to gather, are sparse. The use of re-sampling in model verification may therefore be seen as one method by which we can understand whether 'enough' observations are being made to help monitor the natural environment in tandem with numerical models.

It is believed that MyWave WP4 reports D4.2a and D4.2b will provide useful references for modellers and forecasters aiming to measure and communicate uncertainties in the guidance they issue to users. The reports are both freely and publicly available via the project website.

Finally, the project has provided a proposal for a verification system that could be set up to accompany delivery of wave forecasts via a Marine Core Service. The proposal focuses on the most likely future scenario, in which wave data are delivered alongside oceanographic information within the Copernicus programme. In particular, the proposal has set out working procedures, data formats and governance that will be compatible with the existing MyOcean verification system that will transfer into the Copernicus programme. The impact of doing this groundwork will be to save costs, within a wave service implementation project, by having an initial plan available.

A study determining wave correlation length-scales in the North Sea and Northeast Atlantic (Palmer and Saulter, 2013) has been published as a Met Office Technical Report. Results of the triple collocation study have been presented at the 7th EuroGOOS conference "Operational Oceanography for Sustainable Blue Growth", Lisbon 2014, and it is anticipated that peer reviewed publications will be written on both the triple collocation work and the application of re-sampling and idealised scores in wave verification. It is anticipated that the proposal for operational wave verification will be communicated beyond the MyWave project as part of future work to incorporate waves into a Marine

Core Service.

Results of the triple collocation study and verification methods developed in MyWave have already been embedded within Met Office operational wave model verification systems. Running this pilot system will help enable us to understand the value of the documented metrics and analysis method. Verification developed to evaluate the Met Office wave ensemble prediction systems has been successfully used in creating a “user case” for implementing the models in an operational setting. In another example, metrics demonstrating wave model performance in predicting oil rig evacuation and helicopter no-fly criteria over the 2013-14 winter storms in the North Sea have been shared with representatives of the UK oil and gas industry and the Civil Aviation Authority. Code used to generate WP4 metrics have been written in Python and are informally available to other project partners and potential collaborators. It is anticipated that the main exploitation of work within MyWave will be realised in the event of wave forecast data being delivered as part of an operational Marine Core Service.

The wave model WAM was developed during the 1980s by a European group of scientists. The last publially available version of this code was WAM cycle 4, which was released in 1994. Since then, the WAM development has been done within separate organizations without any particular coordination. It has been an objective of MyWave to coordinate the efforts on model development into a new public ally available version of the code. For this purpose the free and open source Distributed Version Control System (DVCS) GIT is used and the corresponding GIT repository has been installed on the GitHub server : mywave.github.io/WAM. Since June 2014 this repository is public and can be accessed by all users worldwide. The web-based source code library for WAM on the GitHub server will be maintained beyond the end of MyWave by the Helmholtz-Zentrum Geesthacht (HZG).