Project – My-Wave

Road Map Towards a Future Copernicus Service for Ocean Waves

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GLOSSARY AND ABREVIATIONS

CNMCA	Centro Nazionale di Meteorologia e Climatologia Aeronautica (Italian National Meteorological and Climatological Air Force Centre)
CNR	Consiglio Nazionale delle Ricerche (Italian National Research Council)
ECMWF	European Centre for Medium-Range Weather Forecasts
EPS	Ensemble Prediction System
IFS	Integrated Forecast System
ISMAR	Istituto di Scienze Marine (Institute of Marine Science)
JCOMM	Joint technical Commission for Oceanography and Marine Meteorology
NMS	National Meteorological Service
UKMO	United Kingdom Met Office
WAM	WAve Model

APPLICABLE AND REFERENCE DOCUMENTS

Applicable Documents

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

Reference Documents

	Ref	Title	Date / Issue
DR 1	MyWave-D4.2a	Proposal of metrics for user focused verification of deterministic wave prediction systems	02/10/2013
DR 2	MyWave-D4.3	Estimation of regional observation errors and application to MyWave metrics	23/12/2013

I INTRODUCTION

Copernicus is a system coordinated by the European Commission for monitoring the Earth surface. The main goal is to provide decision makers, industry, businesses, public authority and the general public with reliable information on the state of the planet, about atmospheric and marine forecasts for the immediate future and at longer scale, till information on climate change.

The marine service of Copernicus is provided by the EU funded project MyOcean2 (http://www.myocean.eu/), a system for ocean monitoring and forecasting at short and middle range. MyOcean provides data from in-situ and satellite observations together with forecasts, hindcasts from numerical ocean models of the structure of the ocean and its ecosystems. The MyOcean data are routinely used for planning search and rescue operations at sea and for oil spill monitoring.

Although the above information is relevant and amply used, for most of the marine activities, and certainly so for anything concerning safety, the most highly required and useful information concerns the state of the surface Crucial operations at sea (e.g., tugging of big structures), safety interventions, daily activities at oil rigs, shipping, long range routing, recreational activities, all require also detailed information about the wave conditions, at the moment and what they are going to be in the next ten days or so. So it would simply seem natural that an operational system, or system of systems, for Europe, as it was developed in MyOcean, aiming at public use and safety, includes both currents and waves. Last but not least, as more detailed in the following, there are strong reciprocal interactions between the two systems, waves and currents, none of the two being properly evaluated everywhere without full consideration of the other one.

Notwithstanding these obvious requirements, the present marine Copernicus service does not include proper and substantial wave information. There are several reasons for this discrepancy. Firstly, a rather well organized process for production and distribution of wave forecasts from national weather services was already in place when MyOcean was initiated. Secondly, given the costs involved in marine activities and how much they are affected by waves, a reliable and complete set of wave information represents a valuable commercial product. There is a substantial network of companies and institutions that provide, on a commercial basis, regular daily forecasts. On the contrary a marine core service for ocean waves under the Copernicus programme necessitates a free data policy. There is a natural resistance from interested institutions from providing all this information for free when one required practice has somehow made themselves dependent on or used to this income. On the other hand a free distribution of essential information by large organisations seems the natural way to go, possibly leaving for business the more detailed and devoted information. One of the objectives of the MyWave project is to analyse the present situation and see how to overcome the resistances opening the way to a full Copernicus service for ocean.

This document aims at making a picture of the present situation, preparing the ground for a common action leading to a single (current+waves) Copernicus ocean system, with strong connections with and coupling to atmosphere, considering, where necessary, also tidal and local wind effects.

This document is organized as follows. In section 2, the results of a survey on user needs are discussed. Section 3 discusses whether a separate wave service should exist, or whether it should be included as a part of the MyOcean service considering the conditions for distribution of information. Section 4 discusses how the collection and distribution of wind and wave observations should be organized. In section 5 the needs for global versus regional/coastal models are analysed. Section 6 discusses the basic structure for global and regional production centres. Finally, Section 7 discusses how the innovation and research results from the MyWave project could most effectively be implemented in the future Copernicus service.

II IDENTIFY THE USER NEEDS

In order for the wave component of a marine core service to be delivered in as effective a manner as possible, it is crucial that user needs for the service are well defined. These needs can be broken down into a number of categories:

- **Requirement for observations, hindcasts** (long term datasets used for design and planning) **and forecasts** (short-medium range prediction used for weather warnings and planning of marine operations)
- **Parameters**, i.e. characteristics of sea-state that users will base decisions on
- **Configuration**, defining the domain(s) for which data are available, hindcast/forecast length, temporal and spatial resolution
- **Delivery**, defining update cycle and data format(s)
- **Metadata**, i.e. information that accompanies the service, including observation and model technical descriptions and verification data.

Observed and modelled wave data, made available through National Meteorological Services (NMSs), private companies and academia, are regularly accessed and worked with by an established set of users. This has presented the MyWave project with an opportunity to seek informed views of the value and requirements for a 'free at point of use wave service'. At this stage in the Road Map a preliminary consultation has been conducted with these known users, with a view to undertaking a follow-up consultation when the work toward a Copernicus based service will go ahead. Based on MyOcean experience, academic uptake of the service is likely to be significant and should probably be accounted for in further consultations.

II.1 Results from preliminary user consultation

At writing, a preliminary MyWave survey has been provided to 70 potential service users to assess their initial reaction to the project and the concept of a wave component of a marine service. Responses have been received from 41 users and key results are discussed below.

Questions were included that aimed to identify users based on a hypothetical user categorisation (presented in MyWave report WP4-UC). From the responses to these questions an 'in practise' breakdown of users comprises:

- **All Scales Developer-Forecasters**: these respondents said they work with wave information from data generation at both global/large regional scales and coastal scales through to provision of forecasts, and that their data and products are used both for planning and operational purposes. These users are split 70%-30% between commercial and government institutions.

- **Coastal Developer-Forecasters**: these respondents said they work with wave information from data generation at coastal scales through to provision of forecasts, and that their data and products are used both for planning and operational purposes. These users are split approximately 60%-40% between commercial and government institutions.

- **Forecasters**: these respondents said they work specifically on providing forecasts and decision aids and, across the group, undertook an even split of tasks focused on marine operations, hazard forecasting and long term planning (using past climatology). These users are split approximately 50%-50% between commercial and government institutions, with one member of the general public also falling into this category.

• **Decision Makers**: these respondents said they generally act as decision makers and, across the group, undertook an even split of tasks focused on marine operations, hazard forecasting and long term planning (using past climatology). These users are split approximately 50%-50% between commercial and government institutions.

• **Developer-Planners**: these respondents are involved in niche model development activities at various scales for planning purposes. These users are split 75%-25% between academic and government institutions.

This demographic distribution showed a similar degree of usage of in-situ observations and numerical model data (approximately 80% of respondents), with a smaller but substantial set of users (35%) accessing satellite based observations. The majority uses of data (60% plus) were stated as being for design and planning purposes (long term observation or hindcast requirement, covering a period of 10-30 years plus) and operational decision making (short range forecast requirement), with secondary requirements cited for understanding climate change, forecast warnings of extreme conditions and post-event review. Many of the users surveyed (over 50%) said they accessed wave data for the purposes of downscaling for small regional and coastal zone applications, whilst nearly 70% ran their own post processing systems on wave data in order to create forecast products or undertake consultancy. The overall picture then, is of a technically adept user base that would likely be able to access and work with any wave data provided by the service with minimal support. Availability of observation data, hindcasts and forecasts would likely be valued in equal measure.

Nearly all users expressed the need to access significant wave height, period and direction information, whilst a significant subset of users (greater than 40%) stated that they used maximum wave height, the full wave energy spectrum or its partitions. Nearly all users expected to use wind speed and direction data in conjunction with wave data, and a large proportion (60% or greater) also expected to use water level and current data. Comments were made regarding the importance of wind and wave data being consistent, e.g. offered wind model data should be from the same source as used to drive the wave model. Within the preliminary survey, no questions were asked regarding parameters that could be used to represent wave effects on ocean models, although users did cite improved integration of atmospheric, wave and ocean data as a development that would impact their work.

A majority of users (65% plus) stated that their applications of wave data were for shelf seas and coastal waters up to 10 kilometres from land, but a significant number of applications (greater than 45%) were also cited in open ocean waters and within a few hundred metres of the shoreline. This suggests that data provided at global, shelf seas and coastal scales would all have utility, although it might also be argued that supplying coastal data could impact the significant number of users that provide downscaling applications as part of their service. Aside from the user survey it should also be noted that domain selection for any future service may be heavily influenced by the existing MyOcean set-up and existing offers to the market from NMS and commercial operators. No specific questions were asked regarding lead time and temporal or spatial resolutions for products at this stage, but a significant number of users noted that the impact of the service would, in their view, be affected by lead time, spatial resolution and availability of probabilistic forecast data.

Other key requirements to ensure uptake of the service related to using a standard data format, ease of data discovery, provision of technical metadata and accompanying verification (for both monitoring and intercomparison purposes). Whilst a number of users requested more information about the form and function of a future marine service, the majority said they would welcome this development and saw it as an opportunity to complement their use of existing data in the market.

II.2 Summary

At this stage the concept of a free at point of use marine service that includes wave and wind data has been generally welcomed by downstream users that include commercial, government and academic institutions. Assuming these users to be the initial target demographic for a waves service, it can be expected that their needs and methods of working with data will be broadly similar to the approach presently used with existing data in the market, and it can be also expected that the majority of users will be technically adept enough to interact with a data service similar to that presently offered by MyOcean.

Feedback from users suggests that, to obtain as wide a user base as possible, the waves service should include observations and forecasts, but also hindcasts. Key regions for data supply are open ocean waters and shelf seas and the service should ensure that supplied parameters enable downscaling modelling by users as a number of these provide such services for coastal work. Service specification should also ensure consistency in data formats, provision of technical and verification metadata and a ready method of data discovery and access.

III DISSEMINATION AND RELATION TO MYOCEAN

Weather Centres have provided the ocean wave user community with forecast wave products since the 1960's. The interaction between the user community and the weather centres was one of the driving forces to improve the quality of the wind and wave forecast. As a consequence of this long lasting interaction a well-established relation between users and data providers exists. The question therefore arises whether there are benefits of moving the ocean wave service provision from the weather centres to MyOcean.

From an operational point of view it is difficult to see benefits for moving the ocean wave forecasts to the MyOcean catalogue. However, looking at it from another angle, nowadays there are scientific reasons for inclusion of wave information in the MyOcean catalogue, since there is a strong interaction between ocean waves and upper ocean mixing and dynamics. In order to better understand the upper ocean circulation a number of sea state parameters are required. Examples are the wave breaking energy flux, the vertical shear in the Stokes drift which drives Langmuir turbulence, and the Stokes drift, important for the Stokes-Coriolis force. See Section VII.1 for more details.

Based on these considerations it is proposed to include wave information in the MyOcean catalogue. However, whether this information will be freely available depends on the related volume of information and the details of the single fields (e.g., integrated wave parameters versus spectra), and to some extent on the user requirement. Even in the USA when the user insists on the timely arrival of the forecast there is a charge. Because of the frequent preference by the users for the NOAA data, available for free, an effort should be made to highlight the quality of the ECMWF data, generally considered the world best, and of the further derived results and applications.

IV COLLECTION AND DISTRIBUTION OF IN-SITU AND SATELLITE OBSERVATIONS

Measured data, in the atmosphere, on land and on the ocean, have provided for 150 years the basic information for framing the present situation. Coupled with operational modelling, they allow the best estimate of the situation at a given time, providing also the starting point for the next forecast.

To deal with specific observations, the MyOcean project has established four Thematic Assembly Centres (TAC): Sea level, Ocean Colour, Sea Ice, and Wind and In-Situ data.

Wind waves bring with them a new set of data. Considering only instrument data, we have buoy and satellite ones (within "buoy" we include all the data measured at fixed positions). Satellite data include the ones from altimeters (same numerosity as range data). This section analyses how ocean wave observations fit into this.

For buoy data one natural option, already discussed at the joint MyOcean-MyWave meeting in August, is to include buoy observations in the existing In-Situ TAC. A relevant point to be analysed is how the related volume of information would be transferred to the MyOcean service. One possibility is to make use of the information distributed among national weather services through the Global Telecommunication System (GTS). Alternatively ECMWF is regularly receiving these data, also in connection with the JCOMM wave model intercomparison project. ECMWF could forward these data to MyOcean. However, an important issue in this respect is that usually observations received by weather centres through the GTS cannot be passed on to third parties such as an In-Situ TAC. It could be that consultation with the World Meteorological Organization (WMO) is required to resolve this issue.

Altimeter wave data are a different matter. For different reasons they do not fit into the present Sea Level and In-Situ TACs. A Space Data component will have to be added to the Marine Service. A related precursor ESA project exists, Globwave, that is however approaching the end of its funded period. Within this constraint, it has been decided to open discussions with Globwave partners. Different solutions can be considered. One would be the creation of a new Satellite TAC. However, this would partly overlap with the Sea Level one. Therefore an alternative would be to extend the current capabilities of the MyOcean Sea Level TAC whose partners offer both altimetry and SAR (wave mode) expertise and operational skills.

As far as the In Situ available information is concerned, within the MyWave project, data have been gathered from 28 buoy stations in the Mediterranean Sea, plus many more in the North Atlantic and the North Sea.

A similar question, but at a larger extent, exists for the scatterometer wind data. Three altimeters and two scatterometers are considered in MyWave. These winds are an important observation resource for wave and surge nowcasting, analysis and forecasting. A constellation of scatterometer and radiometer winds provide mesoscale wind structures. These observations are provided within the EUMETSAT OSI SAF on L2 and within MyOcean on L3. MyWave complements these observations by providing consistent wind and wave forecasts and analyses on the mesoscale.

V NEED FOR COMBINATION OF GLOBAL, REGIONAL AND COASTAL SYSTEMS

Apart from special cases of small enclosed seas, all the regional, and more so the coastal, models are run with high resolution on a bounded area. The conditions at the boundaries are a key information to be provided by a large scale model. Throughout the world the typical structure is to run a global or ocean model, with a relatively coarse resolution, and then to focus on a specific area of interest, using the global (or ocean) information as boundary conditions. This can be, and is, done for both circulation and wave modelling. In the latter case , while the information is only at one (surface) level, the number of data to be transferred increases substantially because the 2D spectra (order of 10^3 information each) are required at all the boundary points and at each time step (typically 600 or 900 s) of the integration process.

Only large operational centres can afford to run regularly global models. However, ECMWF stores (but at six hour interval) all the spectra of its global analysis and forecast runs. Therefore, albeit with some approximation related to the six hour interval, the information is in principle available for the past (at 28 km resolution with the present system and resolution). A higher resolution (11 km) version of the WAM wave model is run for the European waters, but without spectra storage.

Progressive zoomings, or higher resolution nesting in enclosed areas, are possible. As an example, in the Mediterranean the Italian Met Service CNMCA+ISMAR and UKMO pass regularly to Puertos del Estado (Spain) the spectral boundary conditions for three Spanish harbours. The harbour models are run at an extremely high resolution, with information at the borders available at one hour interval. Apart from any other consideration, the reason for not using ECMWF information is that within the MyWave project both CNMCA-ISMAR and UKMO run an ensemble forecast of the atmospheric and wave models. Based on this info, then Puertos del Estado produces corresponding ensemble harbour forecasts.

The articulated coastline and multiple sub-basins of Europe require different and specific approaches for any area. So, besides a global model, a number of regional models is required (e.g., Baltic, North Sea, Irish Sea, Mediterranean) followed by further nesting to provide the detailed coastal information where required (more on this in next section).

A strong relevant point, this too to be further discussed in the next sections, is the physical dependence between circulation and wave modelling. As illustrated in details in section VII.1, one of the main purposes of the MyWave project is to analyse in detail the physics of coupling between currents and waves. Referring to section VII.1 for the details, the relevant point is that it is highly convenient for both the models to run in a two-way coupled mode. This implies that the two models should be run, fully coupled, at the same centre, and at the resolution required for the specific problem, particularly close to coasts.

Zooming on semi-enclosed seas or on coastal areas implies an increased attention on the use and quality of the data. As mentioned above, global scale wave forecasts are very important as provider of boundary conditions for regional and coastal models. Since waves are strongly forced by surface winds at relatively short temporal scales, it is important that the wind and wave forecasts are consistent. Moreover, the surface layer schemes in meteorological and wave models are often calibrated together, which creates an interdependency between these models.

On the regional scale, e.g. MyOcean regions, most of the area still contains deep water, so additional resolution compared to the global scale does not immediately pay off, contrary to e.g. ocean models. In addition the main forcing at this scale is mostly from atmosphere to waves and then to currents and mixing. The reverse direction is much weaker. Using high resolution meso-scale atmospheric models local effects and observations can be represented in more detail to obtain better forecasts

For a proper wave modelling in coastal regions high resolution wave models forced with accurate wave boundary conditions, coastal winds and water levels are paramount. In some situations also accurate currents are needed. The resolution required for coastal wave models is much higher than at the regional scale, to resolve the large spatial gradients in wave parameters that often occur near the coast.

Approaching the coast implies new standards on the data to be used concerning, e.g., bathymetry and water levels. Accuracy of coastal winds and currents becomes essential.

VI STRUCTURE OF THE REGIONAL AND GLOBAL PRODUCTION CENTRES

Following also what discussed in the previous section, it would seem natural to propose to follow the structure of MyOcean with one global and a number of regional production centres. However, given the present quality of the ECMWF products, for both wind and waves, also in coastal areas, it makes sense to move to local modelling only when the quality of the “local model” results is proved to be definitely better.

For the global component, we propose that an agreement should be found with ECMWF. The present approach by ECMWF for data distribution is to charge the users according to requests. This is done either by the Centre itself or by one of the Meteorological Services of the Member States, depending on whom the user refers to. The costs are limited, especially for long term and large volumes of information, but in any case this does not fit the free data policy of Copernicus. The approach by ECMWF is dictated by its Council, i.e. by Member States. We envisage that the question of cost, depending on the income provided by wave products, should be a discussion between ECMWF, its Council and EC.

Following what said in the previous section and detailed in VII-1, all regional components (MyOcean MFCs) could include operational production capabilities for wave parameters. All current regional Production Centres offer such capabilities, but specific discussions are needed for the Baltic.

An important research issue in MyWave concerns the ocean-wave coupling and use of wave dependent forcing for ocean circulation models. We believe that to best take advantage of this, it is preferable that the regional production centres for ocean waves are the same as for ocean currents. This will greatly facilitate the implementation of wave-current coupling and, wherever possible, of atmosphere-wave-current coupling. Such a system is already available at the global scale at ECMWF. Because it is not possible, or at least very complicated, for all the local users to run a full atm-wave-cur fully coupled system also at the local scale, for the nested models close to the coast, where not otherwise possible, it would be convenient to use the ECMWF atmospheric results to drive the local wave-current system. Although global, this would be acceptable because the wind will be already obtained taking full coupling into account. Obviously this point need to be discussed with ECMWF.

The future Wave service should include a R&D component, in good coordination with other R&D projects.

It is anticipated that the waves service in Copernicus will be offered within a wider marine service. In this case it will be important that user criteria regarding consistency within datasets are met. This relates principally to model data and requires that any atmospheric data released are from the same source as is used to drive both wave and ocean models.

In the long run these criteria would be best met by sourcing Copernicus data from coupled atmosphere-wave-ocean modelling systems. In the first instance consistency is best ensured by converging the wave service offer with ocean modelling systems provided by MyOcean partners and ensuring that the global and regional atmosphere-ocean modelling frameworks used are replicated in the atmosphere-wave frameworks being run. For example, in the global system the principal wave data offer should be derived using ECMWF atmospheric forcing, since this is what drives the MyOcean global forecast provided by Mercator.

Further consistency criteria, which the waves service should consider imposing, and which should improve the user experience considerably, include adopting similar grid configurations for the output wave and ocean products and provision of the wave data in a NetCDF format.

For a proper modelling of surges the wind data used to force the flow model should preferably have a temporal resolution of 1 hour. Six-hourly winds generally lead to and underestimation of the surge levels. However, the six-hour limit exists for the data of the past. ECMWF is presently issuing the forecasts at one hour interval, at least for the first days of the forecast range.

The fastest scale for waves concerns the interaction with the turbulent winds. Mesoscale winds are fastly evolving and their effect on waves can be dramatic. Wind-wave interaction on the mesoscales is an important emerging research issue, e.g., to understand seiches that can be damaging. We believe that to best take advantage of this, it is preferable that the regional production centres for ocean waves are the same as for mesoscale winds. This is in line with the global scale, where ECMWF provides winds and waves, and other centres provide MyOcean ocean services.

VII IMPLEMENTING THE RESEARCH AND INNOVATION RESULTS FROM MYWAVE

The following paragraphs describe how the innovative and research results from the MyWave project can effectively be implemented in the future Copernicus service. The aim of the MyWave project is to make long standing impact on wave research, including coupling mechanisms in the atmosphere-wave-ocean systems, wave modelling, assimilation methods for wave modelling, and the establishment of new products useful for a wider scientific community (e.g., improved wind estimates based on satellite products in nearshore areas).

VII.1 Wave physics

The importance of waves in the coupling between atmosphere and ocean has been known for a long time. However, it is not until recently that the general improvement in atmosphere/ocean/climate systems has developed to a point where the exact details of the coupling mechanisms will make a clear difference in the accuracy of the models.

Traditionally, wind-generated surface waves have been treated as a phenomenon somewhat detached from the goings-on of the ocean beneath. That waves affect the marine boundary layer of the atmosphere by modifying the surface roughness has long been known (Janssen, 1989 and Janssen, 1991) and since 1998 ECMWF has been running a coupled forecasting system where the atmospheric component of the Integrated Forecast System (IFS) communicates with the wave model (WAM) through exchange of the Charnock parameter which determines the roughness of the sea surface (Janssen, 2004).

Waves affect the upper part of the ocean through three distinct mechanisms. First, when waves are growing they soak up momentum (and thus energy) which otherwise would have been transferred to the ocean interior (McWilliams et al, 1999, Janssen 2012). Second, as waves break they inject turbulent kinetic energy, thus enhancing the mixing, while also feeding momentum into the currents. If there were equilibrium between wind input and dissipation, the air-side stress would be equal to the total water-side stress. However, most of the time waves are not in equilibrium, giving differences in air-side and water-side stress of the order of 5-10%, which is not an inconsiderable difference. Third, waves set up a current in the down-wave direction known as the Stokes drift (see Janssen 2004 and Janssen 2012). Although this effect diminishes rapidly with depth (Breivik et al, 2013), it can be substantial near the surface (up to 0.7 m/s). In combination with the earth's rotation it adds an additional veering to the upper-ocean currents known as the Coriolis-Stokes force (see e.g. Janssen 2012 and Belcher et al 2012).

All of the above, the stress, the energy flux and the Stokes drift are already available from ECMWF WAM, both as operational forecast products (since June 2012) and in the ERA-Interim reanalysis (1979 to present, see Dee et al, 2011). To test the impact of wave information on the upper ocean we have performed experiments where wave effects are introduced in NEMO. Thirty-one year (1979-2009) stand-alone (ocean only) integrations where stress, energy flux and Stokes drift are taken from the ERA-Interim archive were compared to a control run without Stokes drift and with an energy flux based on fully developed wind sea. Therefore, the control run too includes the effect of breaking waves on upper-ocean mixing, but ignores the effect of growing and decaying wind sea on the energy and momentum fluxes (Craig and Banner, 1994). The sea-state dependent mixing gives rise to rather large temperature differences with the biggest deviations found in the summer hemisphere. This is partly due to too vigorous mixing in the control run. Whereas the temperature differences due to modified mixing are quite uniform throughout the extratropics, the differences linked to the Coriolis-Stokes effect are more localized. In sum the differences amount to more than 2K in the extratropics.

In the current setup, NEMO is updated with wave fields four times daily. However, in the new coupled model system (see Mogensen et al, 2012, Janssen et al, 2013) which was introduced in November 2013 as Cy40R1 for the ensemble prediction system, WAM, NEMO and the atmospheric model are tightly integrated and it is expected that this system will allow efficient exchange of a large number of fields at high temporal frequency. Early results with fully coupled runs indicate an impact from the coupling of WAM and NEMO also on the atmosphere, but no matter how large the wave effects in the end will turn out to be, the tight coupling under development opens up new possibilities for exchange of parameters, not just between the wave model and the ocean model, but also the other way round.

VII.2 Data assimilation

The best estimate of a given situation at a certain time, either meteorological or concerning waves and currents, is crucially dependent on measured data and on the data assimilation procedure. The chosen procedure depends fundamentally on the considered phenomenon (meteo, waves, ocean circulation). Hence different techniques, at different scales and using different volumes of information, have been devised and are in operational use. Meteorological models, with their chaotic behaviour and large amounts of observations, have developed different data-assimilation methods than ocean and wave models. In fact, not that many applications of data-assimilation exist for wave models. The size of the data in spectral wave models is difficult to handle. Moreover, there is a non-linear balance between the source terms that makes it difficult to adjust the spectra in a consistent manner. At several meteorological institutes using the WAM model a variant of the Optimal Interpolation, OI, method (Lionello et al 1992) is applied to assimilate wave-heights. This crude, but computationally very efficient, method has significantly improved forecast by assimilation of altimeter and SAR wave observations. However, this approach can currently only handle observations of wave height and may not make optimal use of the data that are assimilated.

At the regional and coastal scales, even fewer examples exist of data-assimilation for wave models. This is in part caused by the aforementioned difficulties, together with the shorter lead-times at which a significant impact is expected. On the other hand, there is a large amount of observations that can potentially be used to improve wave forecasts at these scales: coastal wave buoys, waves and wind measured at platforms, high-resolution scatterometer winds in addition to SAR. One coastal application, that shows the impact of advanced data-assimilation methods, is given by Voorrips (Voorrips et al 1997).

The growing intensive use of the coastal environment and the special needs of low lying lands have forced and are forcing towards also short term forecasts. Hence coastal data assimilation methods are in increasing demand. Of course this fits with the present effort to have satellite data (as the forthcoming Sentinel) closer and closer to coast.

In MyWave advanced techniques based on ensemble Kalman filters, neural networks and variational analysis have been implemented, exploiting also data sources traditionally not used, as the coastal HF radars. The developed source codes will be made publicly available. With these and other advanced data-assimilation techniques, it should be possible to assimilate more observations and make better use of them, although more research is needed to increase the computational efficiency.

Any high resolution, in space and time, modelling close to the coast, frequently in shallow water, needs a correspondingly accurate complementary information, both from the input data and from the models it is coupled to. In shallow water, or where, as in coastal areas, strong gradients are frequently possible, accurate high resolution wind fields, tides, storm-surges and current fields are a mandatory requirement.

A strong limit of the present assimilation approaches in meteorological, ocean circulation and wave modelling is that each system has its own separate approach. This is not optimal because, for instance, wind waves, highly sensitive to also small variations of the driving wind fields, carry with them substantial information about the driving winds. At a different level, this is true for all the couplings. However, currently the assimilation of wave observations does not directly affect the variables of the meteorological model and the same is true for the various meteorological-wave-current couplings. Therefore, while in the immediate future no other practical solution seems possible, the development of a fully coupled data-assimilation procedure is highly recommended for the longer term.

VII.3 Uncertainty estimates and ensemble prediction methods

Even fairly low complexity systems (see Lorenz, 1963) may show chaotic behaviour. Given the uncertainty existing in the initial conditions, a chaotic system does rapidly expand the uncertainty. If a system of this kind is used as a forecast tool, then it is clear that the final error on the prediction can be some orders of magnitude higher than the initial error. To this we must add the uncertainty associated to the physics as described in the model and to the numerics involved in the integration.

Weather forecast makes use of atmosphere numerical models which are affected by all the cited error sources. And weather itself is a chaotic system. As a consequence, it is impossible to predict the quality of a single (deterministic) weather forecast. This has led to the present feasible techniques to estimate the uncertainty of their products. In a common approach the initial conditions, which determine an ensemble of valid scenarios, must be drawn from a proper distribution, and the number of investigated states must be limited to an acceptable number. Operational Ensemble Prediction Systems (EPS) make use of dedicated techniques to generate the set of initial states which should match both needs.

In the last three decades, a number of procedures have been proposed by the weather community, and implemented in operational models of worldwide weather centres (see e.g. Buizza et al., 2005). In 1998 ECMWF started to produce EPS forecast of ocean waves (Saetra and Bidlot, 2004). In the last decade there has been a growing interest on EPS techniques among the storm surge community (see e.g. Mourre et al., 2004; de Vries, 2008; Flowerdew et al. 2010).

Well calibrated Ensemble Prediction System products present the main advantage that they estimate the uncertainties of a process accordingly to the sampled uncertainties. Thus EPS can be used to "dress" the forecasts with reliable probability of occurrence. This translates into measurable improvements in risk analysis.

One of the characteristics of the ensemble approach is to filter out the rapid fluctuations of the fields, more typical of wind than wave fields, that, although physically consistent, do not correspond to the physical truth because not guided by a sufficiently dense information (in time and space). However, it is interesting that this approach could filter out the relatively high frequency oscillations of a current field that, although present because fundamental in the physics of the overall process, do not and cannot correspond to the available accurate local measurements.

Improved predictive skill of wave models and value-added services based on probabilistic techniques are of course highly valuable for decision making for operations, more so under severe conditions While in MyWave the probabilistic (ensemble) forecast has been used for the coupled atmosphere-waves system, in the near future this might open another interesting research field by considering the same approach for fully coupled systems, although this validation would require the availability of a suitable amount of observational data for validation purposes.

It is expected that elements of the developments within the MyWave project will be at least incorporated within the operational wave modelling systems run at European National Met Services and environmental consultancies over a post project period. The impacts of these developments could be felt by all existing users of wave data from relevant institutions, and will therefore reach a substancial user community and members of the general public affected by waves.

The anticipated implementation path for this system beyond MyWave will comprise a period of limited operational use by experienced marine and flood forecasters within the office in order to establish best working practises with the forecast data, a period of wider integration within the MyWave institutions and trial external customers and, finally, a public roll out using operational delivery infrastructure. As an estimate, this process will take 1-2 years to complete following the end of the MyWave project. The provision of dedicated short range wave ensemble data for the North and West of Europe and the Mediterranean Sea could be viable after this period.

Within MyWave the Met Office is trialling and demonstrating the utility of a high-resolution short range ensemble wave forecast in the Atlantic and UK waters out to 3 days ahead. Still within MyWave both the Met Office and the Italian Met Service in cooperation with ISMAR are running a meteorological and wave model ensemble in the Mediterranean Sea. The evaluation of these data is in progress and a careful tuning of the ensemble spreading is presently one of the key points of study. A report on the obtained results is in progress.

VII.4 Metrics for uncertainty and forecast quality

Tasks in MyWave Work Package 4 have focused on defining verification for model wave forecast data that might be delivered within Copernicus. Work has been based on the assumption that the verification system must make optimal use of available satellite and in-situ wave observations in order to enable consistent comparisons between forecasts and an observed 'truth' in any area of the globe. Also that the metrics used should provide information that not only measures wave forecast skill, but allows the impacts of the forecast to be understood by users of the service.

Within the work package a survey of interested users included the following key system requirements for verification:

- The main requirements for verification data related to review and intercomparison tasks rather than use in downstream intervention strategies.
- A majority of users would be interested in near-real time monitoring data and downloadable match-up information in addition to review statistics.
- Interactive webpages were considered the best method to deliver verification data.
- Overall wave height, period and direction were considered the most important parameters to verify by all users. A 50-50 split in user requirement was found for verification of more detailed parameters.
- Users considered verification of accompanying wind data as a high priority.
- Quantitative measures of parameter errors were considered to be generally more important than measures of performance in predicting given events, with the exception of high energy storms.
- Users expressed a preference to see verification statistics referenced against raw observations (i.e. without accounting for observation errors), a distinction made between in-situ and satellite data verification and an effort made to account for sampling and temporal variations within the verification's presentation.
- Metadata describing metrics, observed data used as a reference and quality control procedures should accompany the verification.

Based on these findings, the MyWave project is working toward developing verification methods that will meet these requirements and delivering a description of the system that may provide this verification operationally. For example, a common approach to verification using either in-situ or satellite data has been described and a set of user focused metrics to be tested in consultation with users has been identified within deliverable report MyWave-D4.2a. An observation error assessment for two European regional sea areas (the North Sea and North European Atlantic Margin), based on a triple co-location method, has been conducted and enables the effects of these errors to be considered within a proposed verification scheme. The verification methodology, which has been developed to meet user requirements following feedback from a survey, has been described and illustrated in deliverable report MyWave-D4.3 and will be further tested in consultation with users during the remainder of the project. Innovations which are applicable to, but which do not fall into, the present MyOcean verification scheme can be shared if the services are integrated.

It is envisaged that the delivery method for wave verification should follow the existing MyOcean template. Specifically, production centres will generate model-observation match-up data and an agreed set of verification metric data on a regular basis, and then supply this data to a central ‘verification centre’. The verification centre takes responsibility for final quality and control and visualization of production centre verification in order that results are presented in a consistent fashion from system to system. The present MyOcean system does not have a dependency on quality controlled observation data delivery via TACs, and adopting a similarly relaxed procedure is also likely to benefit timely delivery of verification data for the wave service. One item of note is that the wave forecasting community has thus far invested significant resource in model intercomparison schemes (e.g. via JCOMM and GlobWave) and the proposed MyWave verification plan should be considerate of any efficiencies that might exist through establishing formal links with these programmes.

An important addition to the verification service that has been identified by waves users is the facility to access raw model-observation match-up data in order that third parties can carry out their own analyses. It is strongly recommended that this facility is considered for integration into both the wave and ocean aspects of the Copernicus service.

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