Copernicus Evolution and Applications with Sentinel Enhancements and Land Effluents for Shores and Seas

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1.- INTRODUCTION

The WP4 of CEASELESS project, led by HZG, aims to define skill and uncertainty bounds for evaluating combined satellite/model performance in coastal areas. It will build on existing/improved (assimilation in WP2 and parameterizations in WP3) modelling plus the new wealth of Sentinel information, assessing capabilities for a) sub-mesoscale/shallow water processes, b) applications to scientific/commercial uses and c) integration into operational oceanography (CMEMS). This will serve to demonstrate the added value of CEASELESS derived products and to provide documented evidence that the coastal component in Copernicus can be successful.

In this framework, this document presents a structured set of coastal products as candidates for integration into CMEMS and into the working protocol of selected users strategy for the H2020 project CEASELESS. The document is divided in three main sections corresponding to each one of the coastal products corresponding to the main geographical regions of application: Offshore wind farms (Danish Coast), Search and Rescue operations (German Bight) and Water Quality (Catalan Coast). They comprise: a) energy density fields for the renewable wind resource -DTU-, b) transport fields for calculating nutrient fluxes and concentrations in aquaculture farms –UPC-, c) trajectories for search and rescue operations –HZG-. The work will be bounded by data availability (M4.2) and will be suited to the expertise available in the partnership, matching the initial needs of users and making this type of application feasible. The resulting set of products are summarized in the present document (D4.1).
2. OFFSHORE WIND ENERGY

2.1 DEFINITIONS OF PRODUCTS

2.1.1 Wind resource maps from satellite observations

DTU is producing satellite based offshore wind atlases over the European seas based on wind fields retrieved from Sentinel-1 SAR, Envisat ASAR, and wind products from the scatterometer mission ASCAT. The wind atlases consist of different layers, most importantly maps of the mean wind speed, energy density, Weibull scale and shape parameters, and sampling uncertainties. The maps are updated continuously as new satellite observations become available for ingestion.

At present, DTU’s archive consists of 30,000+ Envisat ASAR scenes and 100,000+ Sentinel-1 SAR scenes over the European seas. The number of overlapping scenes ranges from 200 to 1800 (Fig. 2.1). The number of samples per ASCAT grid cell ranges from 2,000 to 10,000. The ASCAT sampling rate increases with latitude and the highest number of samples is therefore found over northern Europe. Fig. 2.1 shows the number of samples and the calculated mean wind speed at 10 m above the sea surface based on SAR and scatterometer observations.

![Fig. 2.1 Maps showing (left) the number of available satellite samples and (right) the mean wind speed calculated from SAR and scatterometer observations.](image)

For each grid cell within the domain of Fig. 2.1, it is possible to obtain information about the wind resource expressed through the Weibull statistics. An example is shown below for an offshore site in the North Sea (Fig. 2.2, Table 2.1, and Table 2.2).
Fig. 2.2 Example of satellite SAR based wind resource estimation for a site in the North Sea. Left: Wind rose showing the directional distribution; right: Weibull distribution and statistics based on the frequency of wind speeds.

Table 2.1 Example of the sector wise wind statistics for a site in the North Sea determined from satellite SAR data. A (m/s) and k are the Weibull scale and shape parameters, U is the mean wind speed (m/s), P (W/m²) is the wind power density, and f (%) is the frequency of occurrence.

<table>
<thead>
<tr>
<th>Sector</th>
<th>0</th>
<th>30</th>
<th>60</th>
<th>90</th>
<th>120</th>
<th>150</th>
<th>180</th>
<th>210</th>
<th>240</th>
<th>270</th>
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<tr>
<td>A</td>
<td>7.3</td>
<td>8.1</td>
<td>8.2</td>
<td>8.2</td>
<td>8.8</td>
<td>8.6</td>
<td>8.7</td>
<td>9.3</td>
<td>9.2</td>
<td>9.9</td>
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<td>8.7</td>
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<tr>
<td>k</td>
<td>2.25</td>
<td>2.25</td>
<td>2.25</td>
<td>2.25</td>
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<td>2.25</td>
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<td>7.28</td>
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<tr>
<td>P</td>
<td>283</td>
<td>387</td>
<td>404</td>
<td>399</td>
<td>502</td>
<td>464</td>
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<td>4.8</td>
<td>4.3</td>
<td>8.7</td>
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<td>5.6</td>
<td>9.7</td>
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<td>11.2</td>
<td>11.5</td>
<td>11.7</td>
<td>7.2</td>
</tr>
</tbody>
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Table 2.2 All-sector statistics for a site in the North Sea determined from satellite SAR data. A (m/s) and k are the Weibull scale and shape parameters, U is the mean wind speed (m/s), P (W/m²) is the wind power density.

<table>
<thead>
<tr>
<th></th>
<th>Weibull-A</th>
<th>Weibull-k</th>
<th>Mean speed</th>
<th>Power density</th>
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<td>Fitted</td>
<td>8.9 m/s</td>
<td>2.21</td>
<td>7.88 m/s</td>
<td>522 W/m²</td>
</tr>
<tr>
<td>Emergent</td>
<td>-</td>
<td>-</td>
<td>7.89 m/s</td>
<td>522 W/m²</td>
</tr>
<tr>
<td>Combined</td>
<td>8.9 m/s</td>
<td>2.22</td>
<td>7.89 m/s</td>
<td>522 W/m²</td>
</tr>
</tbody>
</table>

2.1.1.1 SAR wind retrieval:

SAR is an active microwave sensor capable of imaging the amount of backscattered signal per unit area - the normalized radar cross section (NRCS). NRCS depends on the size and geometry of roughness elements on the scale of the radar wavelength at the Earth surface.

Over a calm ocean surface, the returned NRCS is limited because radar pulses are reflected away from the SAR at an angle equal to the angle of incidence. As the wind picks up, roughness in the form of capillary and short-gravity waves is generated by the surface wind stress. The dominant scattering mechanism is then diffuse and known as Bragg scattering. The relation of NRCS to the local wind speed and direction and to...
the radar viewing geometry forms the key principle in ocean wind retrievals from SAR. A range of geophysical model functions (GMFs) have been developed empirically for ocean wind retrievals from radar measurements. Generally, the empirical GMFs take the following form:

\[
\sigma_0 = U^\gamma A(\theta) \left[1 + B(\theta,U) \cos \phi + C(\theta,U) \cos 2\phi \right]
\]

where \(\sigma_0\) is the normalized radar cross section (NRCS), \(U\) is wind speed at the height 10 m for a neutrally-stratified atmosphere, \(\theta\) is the local incident angle, and \(\phi\) is the wind direction with respect to the radar look direction. The coefficients \(A, B, C,\) and \(\gamma\) are functions of wind speed and the local incident angle. Empirical model functions rely on the assumption that wind speed increases logarithmically with height above the sea surface. This is normally true if the atmospheric boundary layer is neutrally stratified. Stable stratification would typically lead to an underestimation and unstable stratification to an overestimation of the 10-m wind speed.

Several parameters other than the surface wind vector or wind stress can affect the sea surface roughness and thus the NRCS. For example, mineral oil or biogenic slicks have a damping effect on Bragg waves. Oceanographic processes including fronts and eddies, internal waves, long-period surface waves, and bathymetry may also alter the NRCS.

DTU operates a processing chain for SAR wind retrieval built around the SAR Ocean Products System (SAROPS) by NOAA Center for Satellite Applications and Research (STAR), US National Ice Center and Johns Hopkins University, Applied Physics Laboratory. SAR scenes processed to level 1 (L1) are downloaded daily from the European Space Agency through Copernicus Open Access Hub (https://scihub.copernicus.eu/). The scenes are calibrated to give the Normalized Radar Cross Section and the GMF CMOD5 is then used for estimation of the Equivalent Neutral Wind speed (ENW) at 10 m above sea level.

Whereas scatterometers can deliver simultaneous wind speed and direction retrievals, wind speed retrievals from SAR rely on a priori information about the wind direction. Wind directions are here obtained from global models. Envisat scenes from 2002-10 are processed using wind directions from the Climate Forecast System Reanalysis data set (CFSR, available at http://nomads.ncdc.noaa.gov/data.php?name=access#cfs-reanal-data). Envisat scenes from 2011-12 are processed using wind directions from the Global Forecast System (GFS) at 0.50° resolution (available at http://nomads.ncdc.noaa.gov/data/gfsanl). Sentinel-1 scenes from 2014 are also processed using wind directions from GFS but at 0.25° resolution (available at ftp://ftp.ncep.noaa.gov/pub/data/nccf/com/gfs/prod/). Land and ice covered surfaces are eliminated through masking with data from the IMS Daily Northern Hemisphere Snow and Ice Analysis at 4-km Resolution by the U.S. National Ice Center (http://nsidc.org/data/docs/noaa/g02156_ims_snow_ice_analysis/).

For each SAR wind field, two types of outputs are made available for download via the web interface https://satwinds.windenergy.dtu.dk. An image file in .png format shows a display of the wind field with a standard color scaling. A NetCDF (.nc) file holds the wind speed data together with various ancillary data used for the wind processing and metadata describing the product. Fig. 2.3 shows the web interface for DTU’s SAR wind archive. Users can view all data and obtain free access to download upon registration.

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2.1.1.2 Scatterometer winds

The ASCAT product used, is the re-processed 2007-2016 12.5 km, stress-equivalent coastal winds available from the Copernicus Marine Environmental Monitoring Service (CMEMS, http://marine.copernicus.eu/). For the period 2007-2012 the WIND_GLO_WIND_L3_REP_OBSERVATIONS_012_005 product was used, while from 2013 the WIND_GLO_WIND_L3_NRT_OBSERVATIONS_012_002 product is available.

2.1.2 Extreme wind and wave atlas data from modeling:

The 50-year extreme winds at various heights as well as the 50-year extreme significant wave height have been calculated for the water areas around Denmark through wind and wave coupled modeling systems (see section 3.4).

The calculation has been prepared using the selective dynamical downscaling method \(^3\) and hence only storms during 1994 and 2016 that contributed to the extreme wind and extreme wave samples are modeled. Briefly, three groups of model output are available:

1. 429 storm days that contributed to the extreme wind atlas around Denmark using the WRF-WBLM-SWAN model system. The stored data include
   a. Atmospheric parameters on 52 vertical model levels: Wind Speed, Wind Direction, Pressure, Temperature, Humidity (with the lowest level at about 10 m, and a vertical interval of 10 m up to 100 m)
   b. Atmospheric parameters at 10 m above ground level: Wind Speed, Wind Direction, Friction Velocity and Roughness Length
   c. Wave parameters: Significant Wave Height, Wave Length at Peak Frequency, Wave Direction and Wave Period at Peak Frequency.

2. 1080 storm days that contributed to the Extreme Significant Wave Height around Denmark using the WRF-WBLM-SWAN model. The stored parameters are the same as the first group.

---

3. 932 storm days that contributed to the Extreme Significant Wave Height around Denmark using the WRF-MIKE 21 SW model. The stored parameters include: Significant Wave Height, Peak Wave Period, Wave Period (T₀₁ and T₀₂), Peak Wave Direction, Mean Wave Direction.

From the raw model output data, the following variables are calculated:
1. Annual Maximum Wind Speed and corresponding Wind Directions at 10 m, 50 m and 100 m at each grid points of domain III (WRF-WBLM-SWAN model).
2. The 50-year winds at 10 m, 50 m and 100 m at each grid points of domain III (WRF-WBLM-SWAN model).
3. Atlases of the 50-year winds at 10 m, 50 m and 100 m over all water grids of domain III (WRF-WBLM-SWAN model).
4. Atlases of the 50-year Significant Wave Height for all grid elements around Denmark (WRF-MIKE 21 SW model).

The modeled data have a spatial resolution of 2 km.

Figure 2.4 and 2.5 are examples of two products, the 50-year wind at 100 m from WRF-WBLM-SWAN modeling and the 50-year significant wave height from WRF-MIKE modeling where varying water depth was taken into consideration 4.

Fig. 2.4. The 50-year wind at 100 m over water, from WRF-WBLM-SWAN modeling 4.
Fig. 2.5. The 50-year significant wave height from WRF-MIKE 21 SW (Larsén et al. 2012)\(^5\).

2.2 SUPPORT FOR VERIFICATION

2.2.1 Ocean buoy observations

CMEMS offers easy access to met-ocean observations from an extensive network of ocean buoys. The maps in Fig 2.6 show the stations, which provide wind speed, in the North Sea/German Bight/Baltic Sea and in the Mediterranean. Observations from these buoys have been downloaded and prepared for systematic comparisons with the satellite winds.

\(^5\) Larsén X. G., Bolaños R., Du J., Mark Kelly; Henrik Koføed-Hansen; Søren Larsen; Ioanna Karagali; Merete Badger; Andrea Hahmann; Marc Imberger; Jacob T. Sørensen; Sara Jackson; Patrick Volker; Ole Svenstrup Petersen; Alastair Jenkins; Angus Graham. Final report for X-WiWa project: Extreme winds and waves for offshore turbines. Report DTU Wind Energy E-0154, ISBN: 978-87-93549-22-7, 2017
Fig. 2.6. Maps showing the locations of ocean buoys available through CMEMS for (top right) the North Sea and German Bight and (bottom) the Mediterranean Sea. A picture of an ocean buoy is shown at the top left.

2.2.2 Mast observations

Wind observations from offshore and coastal masts will be used for comparisons with the satellite winds in line with previous studies (e.g. Hasager et al 2011)\(^6\). Offshore observations are available from the Fino platforms 1, 2, and 3 albeit the data needs to be filtered to eliminate effects of nearby wind turbines. Fino 1 is almost completely surrounded by wind turbines whereas Fino 2 and 3 still provide measurements of the freestream wind speed within some directional sectors. The coastal mast Høvsøre in Denmark provides wind measurements, amongst other meteorological observations, at different levels up to 116.5 m. The mast is positioned 2 km from the coastline and measurements at the highest levels represent wind conditions of the

marine boundary layer (Peña et al. 2016). Fig. 2.7 shows the mast and two examples of comparisons between SAR winds and mast observations from the 100-m level extrapolated to 10 m.

Fig. 2.7 A picture of the Høvsøre mast in Denmark is shown together with examples of scatter plots comparing wind retrievals from SAR and mast observations. Left plot: Envisat; right plot: Sentinel-1.

2.2.3 LiDAR observations

DTU has access to LiDAR observations, which can give information about the spatial variability of the wind speed either vertically (profiling LiDAR), horizontally (scanning LiDAR), or in all three dimensions. An extensive LiDAR campaign has been carried out on the Danish North Sea coast in 2015. During the campaign, different LiDAR instruments were mounted near the coastline with a scanning configuration that gives coverage of the first 0-5 km from the coastline and offshore (Ahsbahs et al. 2017). Comparisons of SAR and LiDAR wind speeds along transects perpendicular to the coastline are shown in Fig. 2.8. The left plot shows comparisons with dual Doppler LiDAR observations, which are obtained at different heights and extrapolated to 10 m. The right plot shows comparisons with LiDAR sector scans obtained at a constant height of 50 m and extrapolated to 10 m. The different scanning configurations could be the reason for differences in the relative wind speed.

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2.3 METRICS

2.3.1 Wind speed comparisons

Wind speeds retrieved from satellite observations will be compared to the in situ observations listed above. The comparisons will take the form of scatter plots and associated statistical metrics such as the correlation coefficient (R2), the Mean Absolute Error (MAE), the Root Mean Square Error (RMSE) and biases (see Fig. 2.7 for an example). Time series analysis will be performed in order to examine and visualize the bias per observation. Some examples are shown in Fig. 2.9 for the station Lleo in the Balearic Sea.
2.3.2 Mean wind speed comparisons

In order to analyze the accuracy of the spatial wind speed variability given by satellite winds, comparisons with other data sources will include considerations of the spatial positioning of observations. An example using LiDAR observations along transects was given in Fig. 2.8. Another example is shown in Fig. 2.10 where metrics such as the bias, MAE, RMSE and correlation coefficient are given as a function of distance to the coastline.

![Fig. 2.10 Wind speed statistics shown as a function of distance from the coastline using buoy stations in the Balearic Sea](image)

2.3.3 Storm winds and extreme wind

The modeled winds from the hundreds of storms are validated using measurements from all sites in the innermost model domain. The results are shown as time series in Fig. 2.11 as well as scatter plot in Fig. 2.12. The estimate of the 50-year wind is validated with measurements from fewer sites, since it requires relatively long time series for the calculation of the 50-year wind. The results are shown in Fig. 2.13 for WRF-WBLM-SWAN in comparison with the not-coupled, WRF alone, modeling.
Fig. 2.11. Comparison of measured and WRF-WBLM-SWAN modeled wind speed at measurement heights of all days when measurements are available. The sites are (from above to below): Horns Rev M2, M8, FINO 1, FINO 3, RUNE and Anholt (Larsén et al. 2012).
Fig. 2.12. Same data as in Fig. 2.11 but as scatter plot at the six sites. The color bars show the number of points at one coordinate (Larsén et al. 2012).

Fig. 2.13. Comparison of the 50-year wind U50 at 5 stations (FINO 1, 2, 3, Høvsøre (at 100 m) and Horns Rev M2 (at 62 m)), measured vs. modeled. (left) using entire modeled data (right) using modeled data from the period overlapping with measurements (Larsén et al. 2012).
2.3.4 Storm waves and extreme significant wave height

The modelled wave parameters have also been validated with measurements from several sites. Fig. 2.14 and Fig. 2.15 show the comparison between the measured and WRF-WBLM-SWAN modelled significant wave height at 7 sites, in time series and in scatter plot, respectively. Similar validation has been done to the WRF-MIKE 21 SW modelling and Fig. 2.16 shows the scatter plot of the comparison of significant wave height.

Fig. 2.14 Comparison of significant wave height time series from all storms simulated where measurements are available at 7 stations, from WRF-WBLM-SWAN modeling (Larsén et al. 2012).
Fig. 2.15 Same data as in Fig. 2.14 but scatter plot of the measured and modeled significant wave height. The color bars show the number of data at one coordinate, from WRF-WBLM-SWAN modeling (Larsén et al. 2012).
Fig. 2.16. Scatter plot of the measured and modeled significant wave height. The color bars show the number of data at one coordinate, from WRF-MIKE 21 SW modeling (Larsen et al. 2012).

2.4 COMBINING DATA AND MODELS

2.4.1 Comparisons with model wind speeds

Wind direction information for routine SAR wind speed retrieval is typically obtained from a Numerical Weather Prediction (NWP) model, which delivers outputs at regular temporal and spatial intervals all over the globe. Since the model data is prepared and re-gridded to match the SAR scenes, it is convenient to compare the retrieved SAR wind speeds to the model wind speeds. Fig. 2.17 shows an example where SAR winds are compared to model data from the Global Forecast System (GFS). The wind speeds are binned into intervals of 1 m s$^{-1}$ and at moderate wind speeds up to 20 m s$^{-1}$ the error bars are very small due to the large amount of available samples. Higher wind speeds show much larger error bars as the results are based on relatively few samples.

An important issue to keep in mind when comparing satellite and model wind speeds is the effect of atmospheric stability. The satellite winds described in previous sections are retrieved as Equivalent Neutral Winds (ENW). Wind speeds from NWP models are expressed as real winds, in contrast, meaning that stability effects are included. Model outputs of temperatures and heat fluxes are unfortunately too uncertain to be used for stability correction (Peña and Hahmann, 2012).

---

2.4.2 SAR wind retrievals using model wind directions

In coastal seas adjacent to mountainous terrain, it is essential to resolve the smaller-scale variability of the wind direction in order to retrieve the wind speed correctly. As stated above, SAR wind retrievals are often initiated using wind directions from a global model to ensure coverage everywhere. The spatial and temporal resolution of global modeling systems is somewhat limited. In the case of GFS, hourly outputs are available and the spatial resolution is 0.25-0.50° latitude / longitude depending on the data set chosen. A much higher spatial resolution can be achieved with regional model runs as demonstrated in Fig. 2.19 with the WRF model. The example illustrates how the wind speed is affected by a higher-resolution wind direction input from WRF.
2.4.3 Vertical wind extrapolation using models

Extrapolation of the 10-m mean winds retrieved from satellites to higher levels in the atmosphere where wind turbines operate requires information about the atmospheric stability from a different source – in this case from the Weather Research and Forecasting (WRF) model. Previous work has shown that a correction of the vertical wind profile for atmospheric stability effects can be done on the basis of WRF data if the long-term average rather than the instant effect of atmospheric stability is considered (Peña and Hahmann, 2012). Our approach is therefore to combine the 10-m mean wind speed from satellite data with a long-term average stability correction based on WRF simulations in order to calculate profiles of the mean wind speed up to 100 m.

Our calculation of the long-term atmospheric stability correction follows the method described by (Badger et al. 2016). Once the stability correction parameter, $\Psi'$ is known, the wind profile is calculated as follows:

$$\left(\kappa \frac{u(z)}{u_z}\right) = \ln\left(\frac{z}{z_0}\right) - \langle u'_{10} \rangle$$

where $u$ is wind speed, $u_z$ is friction velocity, $\kappa$ is von Karman’s constant, $z$ is the height, and $z_0$ the aerodynamic roughness length. The brackets denote long-term mean values. Example profiles of the stability correction and the mean wind speed are shown in Fig. 2.20.

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Fig. 2.20. Left: Profile of the long-term stability correction, $\Psi$ from 0 m to 100 m calculated from WRF data for an example site in the Baltic Sea. The plot shows slightly unstable conditions (positive $\Psi$) near the surface and stable conditions (negative $\Psi$) higher in the atmosphere. Right: Mean wind profile from 0 m to 100 m calculated from the combined SAR and WRF data set. Stability dependent winds (SDW) are slightly higher than equivalent neutral winds (ENW) at the highest levels. The difference between the two plots shows the effect of including stability information in the wind profile description.

Fig. 2.21 shows examples of mean wind speed maps for the height 100 m calculated with the method described above. Calculations based on SAR (left) and scatterometer (right) data give similar spatial variations of the wind speed but the absolute values show a difference of up to 1.5 m/s between the two data sets. Comparisons against in situ observations from the sources described above will be used to assess the accuracy of mean wind speed maps at both 10 m and 100 m.

Fig. 2.21 Mean wind speed maps over the European Seas after extrapolation from 10 m to 100 m. The maps are updated regularly and the latest version can be found at http://science.globalwindatlas.info/science.html.
Satellite based maps of the mean wind speed over the European Seas are currently published at the web site http://science.globalwindatlas.info/science.html together with a model based wind atlas called the ‘Global Wind Atlas’. We envision that the same type of dataset could be made available via CMEMS once thorough validation of the satellite winds and resource maps as well as the model wind profiles been undertaken. CEASELESS will contribute to this validation effort.

Fig. 2.22 The current web interface for viewing and downloading of SAR-based wind resource maps at http://science.globalwindatlas.info/science.html.

2.4.4 The wind-wave coupled modeling

2.4.4.1 The WRF-WBLM-SWAN modeling System

The modeling system consists of the atmospheric model mesoscale Weather Research and Forecasting (WRF) model and the Spectral Wave model Nearshore (SWAN), and the interface the Wave Boundary Layer Model (WBLM) (Du et al. 2017)\(^\text{12}\). The WBLM was implemented in SWAN, with the purpose to improve the third-generation ocean wave model SWAN under fetch-limited conditions on wave simulation and stress estimation. SWAN and WBLM share the same wind-input source function from Janssen (1991)\(^\text{13}\).

WRF and SWAN are coupled through WBLM using online two-way coupling approach. We use the framework of the COAWST, where the technical interface is the Model Coupling Tool (MCT). WRF sends the wind-components to SWAN and SWAN sends back the stress calculation. The time step for SWAN and the coupling to WRF is 5 minutes. In the wave modeling, the EmodNET bathymetry data from http://www.emodnet.eu/new-year-and-new-phase-emodnet are used. The modeling system has been used explicitly to examine the wind simulation for two conditions: (1) storm wind conditions and (2) coastal zones.

The SAR wind data have been used to validate the modeled wind speed. The SAR radar backscatter data have been used to identify the coastal features, help selecting the study cases as well as validating the different approaches for modeling the coastal wave conditions (Du, J. 2017).

2.4.4.2 The WRF-MIKE modeling system

The modeling system consists of the WRF model and the spectral wave model MIKE 21 SW. Here one-way offline coupling approach is used, meaning that we only use WRF wind field as input to the MIKE 21 SW model, but there is no feedback from the wave model to WRF. The frequency of feeding in the wind to MIKE 21 SW is once in an hour.

The boundary conditions for the wave modeling is from DHI’s global model and water levels are from DHI’s hydrodynamic model. EmodNET bathymetry data are used.

2.5 APPLICATIONS AND GENERAL APPLICABILITY

The maps and results generated in CEASELESS are useful for many different applications in the context of offshore wind energy since in situ wind observations at sea are extremely costly and sparse. Satellite based wind resource maps are useful in the early planning phase of wind farm projects where no other measurements are available. They can be used to assess the wind power production itself, or to validate model predictions of the wind resource. Satellite based maps are very suitable for characterizing spatial wind variability caused by different meteorological phenomena such as island and mountain wakes, mountain lee waves, gap flows, and synoptic fronts (Young and Winstead, 2005). At existing wind farm sites, the satellite based wind maps can be used to analyze the impact of wind farm wake effects on the surroundings and to assess the impact on the environment or on neighboring wind farms.

2.6 INTERACTIONS WITH COPERNICUS AND OTHER USERS

The products proposed in connection with offshore wind energy applications build upon data sets already available through Copernicus and/or CMEMS. At present, wind fields from SAR and scatterometer data can be downloaded via Copernicus but Level 4 products tailored to wind energy applications are not offered. The proposed satellite-based wind resource maps covering the European seas will be valuable for model validation, primarily for the wind energy community but also for other CMEMS users who are interested in wind conditions and in validation of modelled winds against the satellite wind retrievals.

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3. SEARCH AND RESCUE OPERATIONS (drift calculations)

3.1 DEFINITIONS OF PRODUCTS

The General Objective of this derived product is to develop a hydrodynamic model coupled to an ocean wave model as an innovative forecasting system to be applied for drift calculations. The model system will provide drifter trajectories released at a certain point and time with specific properties like the aerodynamic drag coefficient. The area is of high complexity concerning drift estimates, because of the strong impact of bottom friction and ocean surface waves.

The forecasting model system will be developed and tested in the German Bight, which is an intensely used and ecological sensitive area. Of particular concern is the dense ship traffic with increased risks of pollution events and man overboard accidents. Pollution is a potential threat to the coast with busy touristic areas and to the Wadden Sea National Parks of Schleswig-Holstein, Hamburg, and Lower Saxonia. Another factor of growing importance is offshore wind-farming, which involves additional ship traffic for maintenance and construction activities.

3.2 SUPPORT FOR VERIFICATION

A set of met-ocean instrumentation are used to calibrate and validate the numerical models and the downscaling scheme. Moreover, these observations would allow validating some of the products that are already available in the CMEMS (e.g. NWS-MFC) and Sentinel data (available through CMEMS TAC).

3.2.1. Open Sea Oceanographic Data

The analyses focuses on the joint analysis of numerical model data and observations from both satellites and in-situ instruments. A particular emphasize was on SENTINEL data and their potential for improving state estimates near the coast.

Fig. 3.1 Topography of the North Sea and buoy locations used in this study. Water depth above 180 m is marked with dark blue. The red circles correspond to wave measurement stations and red squares to water level measurement stations. The blue dashed line marks the zonal transect, where vertical profiles of velocity was analysed. Station BSH03 also corresponds to station “Elbe”
3.2.1.1 Wave In-situ data

Ocean wave information is important to estimate the Stokes component of the surface drift, which is an important factor in particular in the shallow and sensitive near coastal areas. The wave in-situ data are taken from the WMO’s Global Telecommunication System (GTS), which presents “communications and data management component that allows the World Weather Watch (WWW) to operate through the collection and distribution of information critical to its processes”. It is implemented and operated by National Meteorological Services of WMO Members and International Organizations. The names and locations of the wave buoys are shown on Fig. 3.1. The data have been through an automated quality check upon retrieval. Additional in situ wave data are taken from the wave-buoy observational network operated in the North and Baltic Seas by the BSH (http://www.bsh.de/de/Meeresdaten/Beobachtungen).

A novel WP4 study based on wave height information from the SENTINEL-3 altimeter, the numerical model WAM and GTS in-situ stations is presented in the following. The data set to be used are from April 2016 and concentrates on the North Sea area. Fig. 3.2 (left) shows the SENTINEL-3 ground tracks in the North Sea. The exact repeat cycle for these tracks is 28 days. Locations of available GTS stations are indicated by red dots in Fig. 3.2 (left). The number of resulting triple colocations over the considered period of one year is shown in Fig. 3.2 (right). Data sets were considered comparable if the time gap was less than 1 hour and the spatial distance was less than 10 km.

![Fig 3.2: (left) SENTINEL-1 altimeter tracks in the North Sea. The exact repeat cycle for these tracks is 28 days. Red dots indicated the locations of GTS stations. (Right) Number of triple colocations between numerical model, GTS stations and SENTINEL-3 altimeter for a period of one year](image)

3.2.2 High Frequency Radar:

As part of the COSYNA (www.cosyna.de) system three HF radars have been installed on the island of Wangerooge, at Büsum, and on the island of Sylt to monitor ocean currents and waves in the German Bight. (Schulz-Stellenfleth 2016\textsuperscript{16}, Stanev et al., 2015\textsuperscript{17}). These systems cover the eastern part of the German Bight.

and are Wellen Radar (WERA)-type radars operated in the 10.8-MHz (Büsum and Sylt) and 12.1-MHz (Wangerooge) frequency range. Spatial resolution is 1.5km in range and 38 in azimuth. Because of the working frequency, the radar couples to 12.5-m-long (12.1MHz) and 13.9-m-long (10.8MHz) ocean waves by Bragg scattering and the radar echoes provide information on ocean currents within a surface layer of about 1m. The working range of the WERAs mainly depends on salinity, sea state, working frequency, and electromagnetic noise [radio frequency interference (RFI), background noise, and ionospheric reflections. The COSYNA WERAs use electromagnetic ground wave propagation and reach out to 120km off the coast.

3.2.3 Sea Surface Elevation

The tide gauge observations from the eSurge project (www.esurge.org) are used. An overview of the existing operational tide gauges in the North Sea and Baltic Sea regions are available at the webpages of the EuroGOOS regions NOOS (North West Shelf Operational Oceanographic System) and BOOS (Baltic Operational Oceanographic System), respectively, www.noos.cc and www.boos.org. The water level data are acquired through the NOOS ftp server. Sea surface elevation data are also obtained from the Sea Level Thematic Center (SL TAC).

3.2.4 ADCP Data

Acoustic Doppler Current Profilers (ADCPs) at the FINO-1 and FINO-3 research platforms (see Fig. 3.1 for their location) measure the current direction and velocity profiles at 15 depth levels. All data are collected continuously on the platform and are transferred hourly to shore for further processing and presentation on the FINO website. The research platform FINO-1 was erected in the German Bight in 2003 as a basis for the construction and operation of an offshore wind farm. The main goal of the FINO-1 measurement project is the determination of the prevailing marine conditions (physical, hydrological, chemical and biological) in this offshore region. The type of ADCP used (Nortek Acoustic Wave and Current Meter, AWAC) is designed to measure current profiles and wave parameters.

3.2.5 COPERNICUS SAR Products

The CryoSat-2, launched in April 2010 carries the Synthetic Aperture Radar (SAR) Interferometric radar Altimeter (SIRAL) and is the first space borne altimeter instrument with SAR capabilities. Compared to conventional pulse-limited (or Conventional) Altimetry (CA), SAR altimetry, is pulse-limited along-track and beam-limited across-track and has therefore the potential to provide a better along-track resolution and a higher Signal-to-Noise ratio (SNR). The SIRAL instrument operates in one of three modes: SAR mode, interferometric (SARIn) mode and Low Rate Mode (LRM) following a geographical mask which is regularly updated. On the North Eastern Atlantic CryoSat-2 operates in SAR, SARIn and LRM mode depending on the mask. Data collected in SAR and SARIn mode can be processed in a similar way as data collected in low resolution model, in this case they are called Reduced SAR (RDSAR). We use CryoSat-2 RDSAR data (C2-RDSARRADS-1Hz) from RADS database and SAR products available from the grid processing on demand (GPOD) service at ESRIN (C2-SARGPOD-1Hz) (https://gpod.eo.esa.int). Data are also available as RDSAR products. For out studies we use the official Sentinel-3 SAR (S3a-SARNTC-1Hz) and RDSAR products (S3a-RDSARNTC-1Hz), which are made available directly via Copernicus (https://sentinels.copernicus.eu/). The same data are available from RADS. Significant wave height data from S3a and JASON-3 will be also available by the Sea Level Thematic Center (SL TAC).

3.3 METRICS

The S&R product validations and analyses can be presented with scatter plots that show measured against modelled values (e.g. of the significant wave heights for each of the satellites). These diagrams also illustrate overplotting (as there are hundreds of thousands pairs of measured and modelled data) by estimating the bivariate probability density through evaluating a 2d-gaussian kernel on a square grid in the variable space (Venables and Ripley, 2002)\(^{18}\). The size of the grid cells (for e.g. significant wave height) is in the order of \(10^{-5}\, \text{m}^2\). Furthermore, the plots can include summary statistics, such as the mean value and standard deviation, and statistics that describe the model skill to simulate the different variables (e.g. velocity or significant wave heights at certain period).

The skill scores used are Pearson’s product-moment correlation coefficient, the root mean squared error RMSE, the bias, the scatter index SI (e.g. Chawla et al., 2013)\(^{19}\), and the reduction of variance RV. The scores read as follows, where o and m stand for observed and modelled data. An overbar over a variable denotes the average value derived from the sample of length n.

\[
\text{Correlation} = \frac{1}{n-1} \sum_{i=1}^{n} (o_i - \bar{o})(m_i - \bar{m}) \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (o_i - \bar{o})^2} \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (m_i - \bar{m})^2}
\]

\[
\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (m_i - o_i)^2}
\]

\[
\text{BIAS} = \frac{1}{n} \sum_{i=1}^{n} (m_i - o_i)
\]

\[
\text{SI} = \frac{\hat{\sigma}}{\sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (m_i - o_i - \text{BIAS})^2}}
\]

\[
\text{RV} = 1 - \frac{\sum_{i=1}^{n} (m_i - o_i)^2}{\sum_{i=1}^{n} (o_i - \bar{o})^2}
\]

One of the general assumptions for the correlation coefficient is that variables follow a normal distribution, which is not the case for the significant wave height. It might be advisable to use another measure to gauge the monotonic relation between modelled and observed significant wave heights, such as the rank correlation. However, we use Pearson’s correlation coefficient as it is a quasi-standard for evaluating numerical models.

The scatter plots also show the least-squares linear fit without including any intercept between measurements and modelling results. Ideally, such a fit would be close to the straight line dividing the scatter plot at an angle of 45°, which is included as a reference. Last, we also show pairs of quantiles of the measured and modelled significant wave heights. The quantiles are estimated from the empirical cumulative density function at specific percentiles 0.4 % apart from each other. The highest quantile shown corresponds to the sampled maximum value, which translates to the 100\(^{th}\) percentile of the empirical distribution.


Figure 3.3: QQ-Scatter plots of measured significant wave height - in-situ-GTS vs. remote sensing data of: (left) Sentinel-3A SAR, and (right) Jason-2 from June to November 2016: QQ-plot (black crosses), reference line (blue line) and least squares best fit line (red line).

Following CMEMS PQ recommendations, model parameters, re-gridded to a common standard grid can be intercompared to allow consistency, quality and performance assessments. Quality and performance assessments will be carried out if the “observed ocean truth” can be co-located on the common grid domain. Instantaneous model velocity fields regridded on the standard grid could be compared to interpolated value of HF-radar on this grid, in order to allow quality or performance assessment. Additionally, available regridded HF-radar velocity fields will also be considered: model velocity values should be interpolated and collocated to these data, and allow validation.

3.4 TRAJECTORY /DRIFTER ANALYSES

Model runs for the S&R will be validated against drifter data. The drifter trajectories that are modelled can be also used to understand to the importance of, e.g., wave effects on search and rescue, e.g. for SAR applications. In addition, the model robustness in different meteorological conditions can be considered using different data sources. The velocity of the drifters can be calculated by taking the distance between each drifter position and its time difference. The velocity is located in the middle between the two positions. The model velocities are interpolated to the drifter velocity positions and times ((lat, lon, time). This is done component-wise for $u, v$ and with the velocity magnitude $U = \sqrt{u^2 + v^2}$. To compare the model and drifter velocities, the root mean square error (RMS) and the linear correlation coefficient (COR) are calculated.
As a measure of the modelled trajectories the skill score $ss$ as proposed by Liu and Weisberg (2011)$^{20}$ is chosen (De Dominicis et al., 2013)$^{21}$. First an index $s$ with:

$$s = \frac{\sum_{i=1}^{N} d_i / \sum_{i=1}^{N} l_{oi}}{N}$$

where $N$ = total number of time steps, $d_i$ = distance of real and modelled drifter at time step $i$ and $l_{oi}$ the total length of the trajectory of the real drifter at time step $i$ is calculated. This index is used to calculate $ss$ with

$$ss = \begin{cases} 
1 - \frac{s}{n}, & (s \leq n) \\
0, & (s > n)
\end{cases}$$

where $n$ = tolerance threshold = 1 as proposed by Liu and Weisberg (2011)$^{20}$ what means that the cumulative separation distance is not larger than the cumulative trajectory length. That is, if $s$ and $ss$ is close to 1 the modelled trajectory is close to the observed trajectory.

### 3.4.1 Calculation of the distance between a real and a simulated drifter:

For the German Bight, the available drifter observations have a temporal resolution between 20 min and 1 h. The simulated drifters have a fixed time spacing of $\Delta t=10$ min to be above the lowest Nyquist frequency. At each time step of the real drifters, the closest position (in time) of the simulated drifters is detected and saved for the calculation of their distance. Tests with the used Runge-Kutta method have shown that smaller time steps do not yield better results and 10 min were found to be a good compromise between numerical efficiency and accuracy. For the calculation of the distance, a Haversine Formula is used which calculates the length of the great circle arcs of two points on the surface of a sphere.

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3.5 COMBINING DATA AND MODELS

3.5.1 GALATON data assimilation

Classical assimilation filters, where an analysis is performed based on observations and model data at a certain time step are not optimal for the areas like the German Bight, which are strongly dominated by tides and where the predictions are also needed at intra-tidal time scales. In the following, we will shortly present a novel method which appears appropriate to carry out the blending of models and HF radar observations in an efficient and dynamically consistent way. We remind that the assimilation of HF radar data is not a trivial task because of irregular data gaps in time and space, inhomogeneous observation errors, and inconsistency between boundary forcing and observations (Breivik and Sætra, 2001).²²

The STOI method (Schulz-Stellenfleth et al. 2016)²³ applied to the German Bight uses a spatiotemporal optimal interpolation (STOI) filter to improve short-term hindcasts and forecasts of surface currents will be applied. An example of an analyzed current field together with the free model run and the HF radar measurements is shown in Fig. 3.5. The plot shows an outflow situation during Storm Xavier on 05 of December, 2013 at 03:00 UTC with current speeds approaching 1 m/s in some areas. The high variability of currents is mostly due to the combination between the strong tidal forcing and specific bathymetric features in the very shallow area. The green arrows represent the HF radar measurement, the blue arrows are the free model run and the red arrows are the analysis.

![Figure 3.5: Surface currents in the German Bight. (a) De-tided currents as seen by the HF radars during the period when storm “Xavier” was over the German Bight. The positions of the arrows illustrate the area covered by HF radar observations. This area is smaller than the model area. (b) Simulated and observed surface currents. The green arrows represent the HF radar measurements (not over the entire model area), the blue arrows are based on the free model run, and the red arrows are the analysis. The positions of the three HF radar stations are given with the triangle symbols; the diamond shows the position of the FINO-3 station.](image)

Table 3.1 shows innovations and analysis residuals for the radial components of all three HF radars averaged over a period of 3 month. Innovation is defined as the RMS difference between observations and free model run. The analysis residual is the RMS difference between observations and the analysis. The percentage

reduction (RED) shows that the STOI scheme is able to achieve an improved agreement with the HF radar observations with regard to all measured velocity components.

<table>
<thead>
<tr>
<th>Radar Station</th>
<th>IN [m/s]</th>
<th>AR [m/s]</th>
<th>RED [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sylt</td>
<td>0.098</td>
<td>0.068</td>
<td>31</td>
</tr>
<tr>
<td>Büsum</td>
<td>0.176</td>
<td>0.139</td>
<td>21</td>
</tr>
<tr>
<td>Wangerooge</td>
<td>0.168</td>
<td>0.126</td>
<td>25</td>
</tr>
</tbody>
</table>

Table 3.1: Spatially and temporally averaged innovations (IN; m/s), analysis residuals (AR; m/s), and percentage reduction (RED) in the radial component differences after analysis with respect to the three radar stations.

<table>
<thead>
<tr>
<th></th>
<th>Free Run</th>
<th>Analysis</th>
<th>RED [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMS u [m/s]</td>
<td>0.122</td>
<td>0.097</td>
<td>20</td>
</tr>
<tr>
<td>RMS v [m/s]</td>
<td>0.126</td>
<td>0.103</td>
<td>18</td>
</tr>
</tbody>
</table>

Table 3.2: Comparison of the meridional and zonal surface current component of free run and analysis with respect to FINO-3 ADCP measurements (m/s). The last column is the achieved reduction (RED) in percent.

The skill of data assimilation estimated using independent ADCP data is demonstrated in Table 3.2. Here, the RMS differences with respect to ADCP measurements taken at the FINO-3 platform (see Fig. 3.5b for its position) are given with the first and second column referring to the free model and analysis, while the last column is the achieved reduction in percent. The rms values represent averages computed for a period of 3 month. The reduction values demonstrate that the analysis leads to an improvement of surface current estimates with regard to independent measurements, which were not used in the assimilation procedure. It is worth mentioning that the above demonstration of skill is valid for the specific area. Further applications of the proposed method to different regions (e.g., regions dominated by pronounced baroclinicity) need additional analysis.

3.5.2 Particle tracking: Enhancement of search and rescue by using HF-Radar surface currents

Maritime safety, management of marine resources, protecting coastal and marine environment, forecasting coastal weather, monitoring and seasonal and longer-term forecasting of coastal climate requires the integration of existing and newly emerging technologies with the aim to provide the society with the best estimates, including the quantitative information of errors. In the following part we will give one example of useful application of coastal forecasting using COSYNA surface currents. Two experiments have been carried out using as an input the model data described in section 3.2.1 (see also Fig. 3.5). In total 33746 Lagrangian particles (this number equals the number of wet model points) have been released every day starting from 00:00 on September 1, 2011 at the surface in the center of every grid cell and were 2-D tracked with a Lagrangian model. Trajectories were computed over three days using hourly model output from either analysis or free model run. The trajectory simulations for the same initial positions of particles have been restarted every day for the same integration time of three days. The Lagrangian model output consisted of 33746x30x24 individual positions. In Fig. 3.6a the monthly averaged distance between positions of particles in the two runs 24 hours after the release is shown. Release locations from where particles reached the model boundary were excluded from the statistical analysis.
This map gives an idea about the expected success of search and rescue if data from HF radar are used or not used. In the latter case the positioning of a lost object would be 3-6 km wrong after one day. Errors could be particularly big if the release is in the proximity of barrier islands or close to the northern model boundary. The complicated mesoscale currents around the Helgoland Island could pose problems in the model and observations and explain larger spatial variability of the error pattern. The trajectories from the two runs in 6 exemplary locations during three days of integration starting on September 5, which are also shown on the same figure give an idea about the dominating propagation patterns, as well as an illustration that the coherence of tidal oscillations is lost relatively soon after the release. This illustrates the need for intra-tidal information from measurements to correct model trajectories. The temporal evolution of the distance between particles released at the same positions (Fig. 3.6b) demonstrates the rapid increase of the distances between trajectories in the two runs. The averaged positioning error plotted by the dashed line gives an overall idea about accuracy in the search and rescue operations using output from the free run. The reduction of the error of positioning of an object due to the use of HF radar data during three days is about 10 km on average. It is obvious that using the HF radar data could provide a useful enhancement of the quality of surface currents’ products in search and rescue applications.
3.6 APPLICATIONS AND GENERAL APPLICABILITY

As an example, results on the particle transport model simulations and validations as well as its sensitivity on wave-induced processes in the forecasting coupled model system are analysed below. The available drifter data are from the cruise HE 445 that was performed from 18 May to 1 June 2015. The FS Heincke deployed 9 Albatros drifters (see Fig. 3.7) corresponding to two different models MD03i (Drifters 1 to 6) and ODi (drifters 7 to 9). The drifters provided the current position by Global Positioning System (GPS), which were transmitted to the FS Heincke via Iridium (bidirectional satellite communication network). A sail (0.5 m length and diameter) was attached to every drifter to enhance the drag below the water surface. The sail was 0.5 meters under the water surface. Due to the very small aerodynamic drag of the drifter, the drifter’s paths represent the current in the upper meter of the water column.

![Figure 3.7 Left: Deployment of HZG drifters; Right: HZG Drifter trajectories in the North Sea.](image)

OpenDrift (Dagestad et al., 2018) is a freely available open-source off-line Lagrangian model developed by MET Norway. The model consists of several modules for the advection of e.g. oil spills, larvae and passive tracers. For this study the passive tracer module is used, which advects tracers only due to currents and winds. The sea and wind currents input is described in the next section. The patterns with time series of the distance between the observed and model drifter #5 trajectories and the trajectories of the different experiments (Fig. 3.8) demonstrate clearly the improvements of the particle transport model predictions by the coupling between wave and circulation models compared to the stand-alone circulation model.

![Figure 3.8: Left: Time series of the distance (km) between the observed and model drifter #5 trajectories. Middle:](image)

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Drifter#5 trajectories: observed (black line) and modelled (the colors of the different experiments are given in the legend on the left panel; the name of the model experiments in the legend is explained in the Table on the right hand side.

![Image of velocity graphs and wind direction](image)

Fig. 3.9: Velocity from Drifters and Model runs (upper panels) and wind speed and direction (lower panels).

In the real ocean, the waves play also the role of a reservoir for momentum and energy because different amounts of the momentum flux from the atmosphere is taken up by the waves. In the coupled model system the momentum transferred into the ocean model is estimated as the fraction of the total flux that goes directly to the currents plus the momentum lost from wave dissipation. Additionally, we demonstrate that the wave-induced Stokes–Coriolis force leads to a deflection of the current (Fig. 3.9). During the extreme events the Stokes velocity is comparable in magnitude to the current velocity. The resulting wave-induced drift is crucial for the transport of particles in the upper ocean. The performed sensitivity analyses demonstrate that the model skill depends on the chosen processes. The results are validated using surface drifters, ADCP, HF radar data and other in-situ measurements in different regions of the North Sea with a focus on the coastal areas. The using of a coupled model system reveals that the newly introduced wave effects are important for the drift-model performance, especially during extremes. Those effects cannot be neglected by search and rescue, oil-spill, transport of biological material, or larva drift modelling.

### 3.7 INTERACTIONS WITH COPERNICUS AND OTHER USERS

According to the CMEMS evolution strategy, the CMEMS is currently designed to deliver products to users in four main domains of application:

1. marine safety, which requires information at very high resolution in focused areas all over the globe to support marine operations, marine weather forecasting, sea ice forecasting, combating oil spill, informing ship routing and search and rescue operations, and all activities requesting offshore operations
2. marine resources, with applications to the sustainable management of living marine resources, through fisheries and aquaculture
3. coastal and marine environment, with applications that require good knowledge of environmental status in coastal areas in terms of physical, chemical and biological components and their variability
4. weather, seasonal forecasting and climate, with needs for accurate information near the surface and sub-surface ocean, on a daily or shorter time basis, in real time and delayed mode
Improved circulation and better representation of upper-ocean hydrography as well as improved water level forecasts, address all four areas of the evolution strategy above, but we believe that the contribution we can make to improve circulation and hydrography will be particularly valuable for those who want to use the currents for oil fate modelling (Jones et al, 2016) and search and rescue (Breivik et al, 2013). The coupled waves-circulation system and increased synergy between the newly available data and models will also demonstrate to what extent the improved model physics and methodology will add to the predictability. Finally, the coastal and marine environment and marine safety rely on accurate water level forecasts, which are known to depend on the atmospheric and wave forcing (Staneva et al, 2017).

We address the following topics that are considered as a short-term CMEMS priority:

1. Predictability studies to assess the feasibility of developing open ocean and coastal/regional seas’ forecasts with lead-time of a few days to weeks, together with assessment of likely prediction skill;
2. Improved methods for analyzing and predicting upper ocean currents;

Specifically, the predictability of upper ocean currents will be assessed by using current measurements on all scales from the high resolution model domain covering the North Sea, where Acoustic Doppler Current Profilers (ADCP), drifters and high-frequency (HF) radar data from the German bight will be used to assess the performance of the model (Staneva et al, 2017). This is again very relevant for the drift of oil and suspended matter in the upper ocean (Jones et al, 2016) as well as for search and rescue (Breivik et al, 2013).

The new implementations will demonstrate the added value in improving the open ocean and coastal/regional seas’ forecasts together with assessment of likely prediction skill and will be delivered and integrated into the CMEMS Forecasting Centers. The verification methods will cope with the existing CMEMS protocols and the Marine Core Service structure. New methodologies for validation of surface waves and coastal ocean currents data sets (incl. Lagrangian likes products) can be further implemented into the CMEMS PQ documents-QUIDs, and will be of high added-value for MFC and TACs.

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4. WATER QUALITY (Concentrations and residence times)

4.1.- DEFINITIONS OF PRODUCTS

The General Objective of this derived product is to develop an hydrodynamic model as an innovative forecasting system to be applied for early warning, prevention, mitigation and implementation of management measures for water quality issues. This tool will help aquaculture competitiveness, while preserving marine resources and ecosystems in the Mediterranean.

The forecasting model system will be developed and tested in Fangar Bay (Ebro Delta, NW Mediterranean Sea), chosen as an example of a protected Mediterranean coastal area (NATURA 2000 and Biosphere Reserve) in which the sustainability of human activities (tourism, fisheries, aquaculture) will benefit from a tool that will improve the management and decision-making process for the key players.

The Ebro Delta Bays is a relevant natural area of great ecological interest. Furthermore, Alfacs and Fangar bays are the scenario of relevant socio-economical activities for the region such as Shellfish Aquaculture, Fishing and Tourism. However, those activities as well as the ecological equilibrium can be affected by the proliferation of invasive species; harmful phytoplankton blooms (HABs), as well as shellfish massive mortality outbreaks due to environmental parameters (i.e. water temperature). In that sense, bay hydrodynamics play a relevant role in the distribution and persistence of such affections. For this reason, the knowledge related to Fangar Bay hydrodynamics, currently poorly know, will allow key information to better explain such events, as well as, the development of new tools for early warn detection and further management.

On the other hand, water mass transport in marine systems has been demonstrated to be a decisive factor controlling the behavior of chemical and biological variables of the ecosystem. In this sense, water renewal and substances dispersion are highly related to the evolution of the ecological status in bays. Wind or wave induced re-suspension processes also may affect the ecological status inducing the vertical transport of substances from the sea bottom to the inner water column. The derived product considers the role that water circulation patterns play, re-suspension processes and residence times on the ecosystem dynamics of Fangar Bay.

4.2.- SUPPORT FOR VERIFICATION

A set of met-ocean instrumentation are used to calibrate and validate the numerical models and the downscaling scheme. Moreover, these observations would allow validating some of the products that are already available in the CMEMS like numerical models (IBI and MED systems) and Sentinel data (winds, waves, SST).

4.2.1. Open Sea Oceanographic Data

The field data obtained during the field campaigns would provide the optimum framework to calibrate and validate the numerical model and the Sentinel data. The instrumentation available on the open sea region (shelf) covers a wide variety of sensors that allow the validation of variables such water currents (HF Tarragona Radar and Coastal Buoy of Puertos del Estado –PdE hereafter-) and Winds (PdE coastal buoy). These observations are used to validate the coastal domain of the nested modelling system. Moreover, the wind data is used to validate the accuracy of the Sentinel 2 Level-1 Ocean (OWI) data in the area. Below is a more detailed description for both observation systems:

4.2.1.1. High Frequency Radar:
A CODAR SeaSonde standard-range High Frequency (HF) radar system was deployed at the Ebro delta in December 2013 within the framework of the RIADE (Redes de Indicadores Ambientales del Delta del Ebro)
project. The HF radar network consists of an array of three remote shore-based sites: Salou, Vinaroz and Alfacada. Each site is operating at a nominal frequency of 13.5 MHz with a 90 KHz bandwidth, providing hourly radial measurements with a cut-off filter of 100 cm s\(^{-1}\) and representative of current velocities in the upper first meter of the water column. The System have been intensively calibrated and validated (Lorente et al. 2015)\(^{28}\).

4.2.1.2. Coastal Moorings:
The meteo-oceanographic data set REDEXT includes all the observations from the buoy network in deep waters from the PdE. These buoys are moored far from the coast and in water depths greater than 200m. In the area of interest, there is one buoy: Tarragona Coastal Buoy. This buoy provides information about ocean currents (i.e Figure 4.1 shows the water current speeds for year 2014), water temperature, salinity, and wind speed and direction.

![Figure 4.1. From top to bottom: water current speeds, salinity and water temperature measured in the Tarragona Coastal Buoy.](image)

4.2.2. Coastal Zone Oceanographic Data

The internal dynamics of the Fangar Bay are characterized through the data analysis of the meteorological and oceanographic data collected in the bay in two field campaigns conducted during summer and autumn of 2017. In both field campaigns, two buoys (one in the bay mouth and another inside the bay) have been moored. Each one is equipped with an ADCP (Aquadopp current meter) at the bottom that measures the water currents above them (at the entire water column), the bottom water temperature, bottom pressure and the waves. Moreover, each mooring was complemented with an OBS (Optical Buckscatter system), which would allow to study the re-suspension events. Figure 4.2 shows the schematics of the summer field campaign.

During autumn campaign, a meteorological station was also deployed in the bay (measuring wind intensity and direction, humidity and air temperature). Moreover, and coinciding with the deployment and recovery of the moorings, a set of Lagrangian buoys were launched and tracked into the bay mouth for around 3-4 hours. Finally, during the period in which the buoys where moored, various CTD (plus water sampling in order to study the Chla-a) campaigns sampling more than 15 points along the bay where performed. A set of sediment samples were also obtained in order to be able to characterize the bottom of the bay (important for the numerical model calibration).

The analysis of these data and the comparison with the numerical models would allow performing a set of model calibration and validations.

4.2.3. Sentinel Data

Data from Sentinel 1 Level-2 Ocean Product (OWI, winds) will be used in order to validate the atmospheric models used in the Coastal and Bay Domains.
Data from Sentinel 1 Level-2 Ocean product (OSW) will be used in order to validate the coupled wave model and their performance considering the land-coast effects.

Data from Sentinel 2 are expected to be calibrated with in-situ data from field campaigns and be enough to be able to characterize the spatial distribution of Total Suspended Matter and Chl-a along the bay.

Data from Sentinel 2 are expected to provide high-resolution bathymetries (due to the shallowness of the area). These new and updated bathymetries will be used to improve the modelling results.

5.3.- METRICS

The hydrodynamic models are validated using all the available observational data. Basic statistics (correlation factor and bias) and skill score -- skill assessment index SK (Wilmott, 1981)\(^{29}\) and cost function \(\chi\) (Holt et al., 2005)\(^{30}\) between observations and modeling results are used to validate the numerical model. SK equals 1 when a perfect agreement between model and observations occurs and decreases to 0 for a complete disagreement. The cost function \(\chi\) is defined as a measure of the ratio of model error to the observed variance. For \(\chi\), an acceptable predictive skill of the model is related to values lower than 1 (root mean square error (RMSE) smaller than the standard deviation from observations), and a well-modeled variable threshold is situated at 0.4.

In all the following formulas \(o\) represents observational data, \(m\) modelling results and \(n\) for the total amount of observational data used, and the over bar (—) denotes all data length mean values.

**Correlation factor:** Correlation factor quantifies the strength of a linear relationship between two variables, and is defined as standardized covariance. Values close to one indicates strong linear correlation (positive or negative depending on the sign), while 0 indicates no linear relationship:

\[
 r(o, m) = \frac{\sum_{i=1}^{n}(m_i - \overline{m}) \cdot (o_i - \overline{o})}{n \cdot STD_o \cdot STD_m}
\]  

(1)

**Skill score (SK):** In this case values close to one indicates good agreement and equal to 0 indicates complete disagreement.

\[
 SK = 1 - \frac{\sum_{i=1}^{n}(m_i - o_i)^2}{\sum_{i=1}^{n}(|m_i - \overline{m}| + |o_i - \overline{o}|)^2}
\]  

(2)

In the cost function \(\chi\) \(\sigma^2\) is the variance of observations (square of standard deviation):

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Some of the validation results would be aggregated using Taylor Diagrams. In this kind of diagram, the comparison between observations and the model are shown in terms of correlation, the centered root mean square difference (CRMSD) and the standard deviations. In order to compare in the same figure different vertical layers against observations, the standard deviations and CRMSD are normalized over the standard deviation of the corresponding observations (Grifoll et al., 2013). In the diagram, the model skill improves as the points get closer to the observation reference point.

Normalized Standard deviation (normalized over the deviation of the observations)

$$\text{STD}_{(m,o)} = \left( \frac{\sum_{i=1}^{n}(m_i - \bar{m})^2}{n \cdot \sigma_o} \right)$$

Normalized root mean square error:

$$\text{CRMSE}(m,o) = \sqrt{\frac{\sum_{i=1}^{n}[(o_i - \bar{o}) - (m_i - \bar{m})]^2}{n \cdot \sigma_o}}$$

4.4.- COMBINING DATA AND MODELS

The three-dimensional model used is the COAWST Modeling System (Warner et al. 2008). This system considers the coupling between the hydrodynamic model Regional Ocean Modeling System (ROMS), the wave model SWAN and the sediment model CSMT. Previous implementation for the hydrodynamic model in Alfacs Bay did prove good skill assessment compared with currents, sea level and water temperature variables (Cerralbo et al. 2016). For the hydrodynamic model, the application consists of two nested regular grids with spatial resolution of ~350 m and ~70 m for the coarser (Delta) and finer domains (Fangar Bay) respectively. The nesting ratio (~5) between coastal and bay domains is defined to get enough resolution to reproduce the circulation due to bay coastline allowing the transference of large-scale dynamics into the nested domain. The chosen vertical discretization consists in 20 and 15 sigma levels for the coastal and bay domains respectively. Bathymetry of the coastal system is built using a combination of bathymetric data from GEBCO (www.gebco.net) and from specific local high-resolution sources (including a transition zone

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33 Cerralbo, P., Espino, M., Grifoll, M. Modeling circulation patterns induced by spatial cross-shore wind variability in a small-size coastal embayment, Ocean Modelling, Volume 104, August 2016, Pages 84-98
of ~2 km to keep consistency the transports associated to the MFC-IBI boundary conditions). The bathymetries in both domains are smoothed using a Shapiro filter with an r-factor criterion below 0.25. The initial and boundary conditions (Sea level, water velocities, Temperature and Salinity) are obtained from MFC-IBI (Sotillo et al. 2015) daily forecasts. On the other hand, SWAN model are implemented considering different options: a downscaling nesting from the solution of the CMEMS Mediterranean products and without nesting (using a set of downscaling meshes and also testing an unstructured grid for the entire NW Mediterranean Sea). The sediment capabilities are only applied in the finer domain (Fangar Bay).

The validated and calibrated hydrodynamic numerical model would be configured to run daily with horizon forecast of 48-72h (design of operational system). This would allow the forecasting of hydrodynamic variables such water sea level, currents, waves, temperature and salinity. The analysis of these variables would allow the knowledge of possible bottom sediment re-suspension events, episodes with high water temperatures and the water flushing times of the Fangar Bay under each situation.

4.5.- APPLICATIONS AND GENERAL APPLICABILITY

Previous studies in similar environments (Alfacs Bay) revealed different mechanisms that are able to mix the entire water column -break the stratification and mix the warmer and fresher upper layers with the cooler and saltier waters-: co-oscillating waves with periods around 1-3h (called seiches) that under some circumstances become very energetic (velocities higher than 50 cm s-1) and strong winds (Cerralbo et al. 2015). On the other hand, similar forcings (seiches and winds) have been related to re-suspension events (Grifoll et al. 2016).

In the Fangar Bay, the analysis of the prognostic variables would allow the forecasting of possible bottom sediment re-suspension events, episodes with high water temperatures and determination of areas with low residence times. The comparison of these scenarios with the previous analysis of historic scenarios would allow us to pilot an early warning system in Fangar Bay based on probability analysis.

The knowledge acquired would allow to describe a conceptual model of the bay linking the physics (atmosphere and ocean), biogeochemical processes and land effects in the region. Finally, with these tools and knowledge, a set of different natural solutions for the bay problematics are expected to be studied. For instance, the results of similar numerical tests in Alfacs Bay (Cerralbo et al. in prep) revealed how the modification of the freshwater flows from the surrounding rice fields and the opening of a sea connecting channel through the inner area of the bay are able to reduce the water flushing times (Figure 4.3).

Figure 4.3. Water local e-flushing times computed for different numerical experiments: a) C (Control Simulation); b) B1 (Bar Breaching 1); c) B2 (Bar Breaching 2); d) B3 (Bar Breaching 3); e) R1 (Freshwater 1) and f) R2( Freshwater 2). The colors represent the local e-flushing times in days.

4.6.- INTERACTIONS WITH COPERNICUS AND OTHER USERS

According to the CMEMS evolution strategy, the CMEMS aims to deliver products to users in four main domains of application:

1. marine safety, which requires information at very high resolution in focused areas all over the globe to support marine operations, marine weather forecasting, sea ice forecasting, combating oil spill, informing ship routing and search and rescue operations, and all activities requesting offshore operations
2. marine resources, with applications to the sustainable management of living marine resources, through fisheries and aquaculture
3. coastal and marine environment, with applications that require good knowledge of environmental status in coastal areas in terms of physical, chemical and biological components and their variability
4. weather, seasonal forecasting and climate, with needs for accurate information near the surface and sub-surface ocean, on a daily or shorter time basis, in real time and delayed mode

Improved water circulation in coastal areas (such coastal lagoons, estuaries and ports) address all four areas of the evolution strategy above. In this sense, we believe that with this contribution we can create and improve the products that will be particularly valuable for those who want to use the hydrodynamic
knowledge (water currents, sea level, temperature and salinity) for water quality and management issues. Moreover, the aforementioned operational system would be entirely based on the downscaling of the CMEMS models (MFC-IBI and MCF-MED). The new implementations will demonstrate the added value in improving the coastal regions forecasts together with assessment of likely prediction skill and will be delivered and integrated into the CMEMS Forecasting Centers. The verification methods will cope with the existing CMEMS protocols and the Marine Core Service structure.

The final users of these early warning systems are expected to be the:
- Primary producers of the Fangar Bay (mussels and fish farmers)
- Local and Regional Authorities (Water quality programs and Beaches water quality)