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INVITED SPEAKER

The State-of-the-art in modelling the Mediterranean-Black Sea system

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The Mediterranean-Black Sea system is characterized by significant exchanges of water through very narrow and complex passages. Through the Strait of Gibraltar, an upper flow of fresh and warm Atlantic water spreads into the Mediterranean basin, and a lower flow of colder and saltier Mediterranean water sinks in the North Atlantic. This two-way exchange is highly variable, the most intense fluctuation originating from tidal currents. The interaction between tides and the complex succession of contractions and sills that characterize the bathymetry of the Strait, hydraulically controlled, makes the Strait of Gibraltar an active element of the Mediterranean thermohaline circulation. In the same way the Turkish Straits System (TSS), composed of the Bosphorus and Dardanelles Straits and the Marmara Sea, has been found to be crucial in determining the interactions between the Mediterranean and the Black Seas.

Simulations of the Gibraltar Strait and TSS dynamics, including the effect of tides, have been performed using the MITgcm. Results will be shown, demonstrating good skill in representing such processes. An ad hoc configuration of the MITgcm, has also been used to investigate the effects of both the internal equilibrium and lateral tides incoming through the Strait of Gibraltar on the thermohaline circulation of the whole Mediterranean basin. Such version of the model is able to explicitly solve the dynamics of the strait by locally increasing the horizontal grid resolution. The results suggest that application of explicit tidal forcing in a Mediterranean model has non negligible effects on the simulated circulation in addition to the expected intensification of local mixing processes. The western basin exhibits an immediate response to the different characteristics of the inflowing AW observable in the modified deep water convection processes in the Gulf of Lion. LIW dispersal paths in the eastern basin are also affected by tides.

The results so far exposed naturally lead the way to the realization of a new integrated model of the Mediterranean and Black Sea ocean system, in which the high resolution non-uniform curvilinear orthogonal grid is extended to encompass the whole domain. The grid has an overall regular horizontal resolution, locally enhanced in the Straits in order to satisfy the minimum requirements that have been established in the high resolution dedicated simulations.

Surface Lagrangian Coherent Structures in the Gulf of Trieste

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The present work aims to detect Lagrangian transport barriers in the Gulf of Trieste by means of Lyapunov-exponent approach and tensorlines of the Cauchy-Green tensor. Lagrangian Coherent Structures (LCSs) are calculated employing 2D surface velocity fields measured by the coastal radars of the TOSCA EU research project (Tracking Oil Spills & Coastal Awareness Network). Moreover, surface drifters were deployed during the project. Comparisons between Eulerian velocity of HF-radar fields and Lagrangian velocity of drifters are carried out alongside single-particle tracking reliability. In particular, the possible influence of the data gaps in the HF-radar fields have been carefully considered. LCSs have proven to be robust against the quality of the starting HF-radar fields, leading to helpful insights in drifter positions. Indeed, after 24-hour integration the observed position of the drifter is approximately 1.5 km far from the nearest LCS, while a standard approach based on single-particle computations leads to larger errors (up to 5–7 km). However, such result must be properly interpreted taking into account the elongated nature of LCSs. A comparison between two common diagnostic tools of Lagrangian barriers is performed: Finite-Time and Finite-Size Lyapunov Exponent fields are compared in order to assess whether the patterns detected by the two measures are comparable. Finally, a joint analysis between LCSs and single-particle tracking is carried out and the results suggest that it would be desirable to couple these two approaches in real applications.

Global modelling of future extreme sea-levels using a high-resolution Global Tide and Surge Model

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The increasing sea-level and meteorological changes associated with climate change increase the flood risk in coastal cities and low lying areas. Understanding the magnitude and impact of such changes is vital to design adaptive strategies and create awareness. Such risk predictions are possible with the use of hydrodynamic models that are coupled to climate models.

In the context of the CoDEC project (Coastal Dataset for Evaluation of Climate impact), we compute the climate change induced changes on future sea-level, storm-surge, tides and waves, and the associated impacts on coastal flood risk for Europe from present date to 2100. We consider the 4.5 and 8.5 Representative Concentration Pathways (RCP), and produce extreme value statistics representing mi-century and end of century conditions. For the waterlevels, we use the Global Tide and Surge Model v3.0 (GTSMv3.0), a high resolution hydrodynamic model with global coverage. The model has a coastal resolution of 2.5km globally and 1.25km in Europe, and incorporates dynamically sea-level rise, tides and surge, and therefore calculates the non-linear interaction between them. For the meteorological forcing, we use the global EC-Earth climate model together with a European-wide high resolution climate model from the EURO-CORDEX archive. In order to assess the changes relative to present and past conditions, we perform a reanalysis of extreme sea levels using the newly available high resolution ERA5 forcing. Based on the relative changes, we design a number of indicators that provide useful information about the possible impacts of climate change globally. For Europe, a number of user cases are defined in which different industries use such indicators and global model outputs to downscale and assess impacts at a regional/local scale.

We produce output for not only global coastlines at a high resolution, but also at predefined nesting points covering the global ocean which can be used for regional downscaling anywhere in the globe.

Assessment of estuarine plume in a coastal area using high-resolution model. The Tagus mouth case.

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In coastal areas, the time and spatial scales of flow are determined by the tide, being of the order of hours. These time and space scales are important for navigation or fishing but are too small for managing nutrient loads, i.e. eutrophication. Residual circulation gives some insight on the preferential transport but does not allow its quantitative characterization because does not account for diffusion due to transient advection. In this work, it is proposed to compute long-term transport using integration control volumes. This calculation provides information about time variability of properties inside the control volume and the net fluxes of any property across its boundaries. Using several adjacent boxes this integration allows for the calculation of the effect of region inside a control volume over its neighboring regions. Using piles of control volumes one can quantify vertical fluxes - very important in upwelling areas - and compare them with horizontal transport. This is particularly important at the mouth of estuaries like the Tagus Estuary.

This strategy was used in the Tagus estuary, one of the largest estuaries in Western Europe, and adjacent coastal area. In this region, the long sea Guia submarine outfall discharges the waste water from the Costa do Estoril region with about 800 000 equivalent inhabitants. Through a downscaling approach, the three-dimensional (3D) MOHID model was run to simulate tide-generated flow, density currents, atmospheric forcing, and biogeochemical processes controlled, mainly, by vertical transport and the Tagus Estuary discharge.

The hydrodynamic model was validated using tide gauge data collected at both mouths and inside the estuary. The results of the biogeochemical model were validated using data and monitoring programs carried out in the study area. The fluxes were integrated into time and space (vertically and horizontally) using the boxes methodology implemented in the domain. The results are presented for five different river flow classes, determined from the ten-year analysis of the Tagus river flow.

Results show that the extension of the estuarine plume is determined by the river discharge and that the tidal flow associated with the estuary flood/ebb dynamics dominates the horizontal transport in the Tagus mouth vicinity. However, the vertical transport forced by the wind generated important vertical transport of nutrients from the deeper layers.

Using the integration methodology, it was easy to compare the relative importance of vertical and horizontal transport for the biogeochemical distributions at the mouth of the estuary and to compare them with the loads from the submarine outfall for different seasons, driven by the variability of the river discharge and of the upwelling regime. It was also possible to show that the submarine outfall loads are of secondary importance when compared with upwelling and river discharge.

Local time parameters use in tropical bays: Understanding of coastal hydrodynamic responses to natural and anthropic physical forcings

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Coastal modeling is nowadays widely used as it constitutes an appropriate tool to acquire valuable information on small scale coastal hydrodynamics. It allows the understanding of currents, circulation patterns, high turbulence areas, local phenomenon (eddies, downwelling or upwelling...) near the shore. This knowledge is of prime importance to tackle modern issues such as coastal erosion, siltation of bays, transport of terrigenous particles and anthropic inputs, bacterial pollution or metallic contamination, among others.

3D Hydrodynamic modeling is currently the most commonly used device in order to realize, at lower cost and timeliness of implementation, water quality management, pollution prevention and monitoring, survey of coastal biotopes, initial state assessment and prediction of marine ecosystems health. The understanding of physical mechanisms is more intricate at the scale of a semi enclosed bay, or a lagoon, as they constitute delimited, independent zones with specific hydrodynamic, which would need to be characterized as a whole. Hydrodynamic time parameters (HTs) turn out to be convenient variables for assessing a whole water volume dynamic.

Depending on physical and meteorological forcing applied, variability of residence time of a bay/lagoon can be indicated/emphasized/highlighted. Spatial distribution and vertical gradient within the volume of interest can indicate hydrodynamic singularities and lead to the highlightening of potential stagnation/accumulation zones.

These variables are under strong influence of wind, river inputs and tides and as such must be studied in details regarding of the meteorological forcing conditions.

These issues are especially relevant within an enclosed tropical lagoon, and New Caledonia is a study site of choice for an approach of hydrodynamics via time parameters. The projected speech (or poster) will describe the comprehensive array of simulations launched within two bays at the extreme south of the Caledonian lagoon, with the 3D hydrodynamic model MARS3D developed by the IFREMER (French Institute for Marine Research and Management). It will present the methodology and analysis realized in order to assess the respective physical forcings influence on residence times. This study resulted in the clear identification of risk zones, as a function of the meteorological forcing applied and in the evaluation residence time responsiveness to forcings' variability.

Calibration of a coupled flow-wave model for Tuscany coastal areas

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The recent European Directive on the management of bathing waters (2006/7/CE), based on the Guidelines for safe recreational waters by the WHO in 2003, was received in Italy by the Legislative Decree 116/2008 and Ministerial Decree 30/3/2010. These regulations require an integrated approach with different innovative tools, such as the definition of bathing water profiles, the prediction of short term pollution events, the classification of bathing waters in four quality categories, the role of public participation. In this context, numerical models can be used to develop the bathing water profiles, to evaluate the short-term pollution and the abnormal situations. In a simplified approach, when studying the short-term microbiological pollution of bathing waters, the pollutant can be considered as a passive tracer. In this case the diffusion and transport processes of the pollutant can be solved a posteriori using the current field obtained by a hydrodynamic model. Even considering an active behaviour of contaminants which means that bacterial kinetics must be evaluated, diffusion and transport processes depend on local hydrodynamic conditions. In any case, the reliability of short-term pollution predictions depends on the quality of nearshore hydrodynamic predictions. This is usually complicated by the need of solving high-resolution (of the order of 10 m or less) wave-current coupled processes. Validation and calibration of such models is also limited by the lack of measurements close to the coast.

In this work we attempt to calibrate a coupled wave–flow model in two areas of the Northern Tuscany coast affected by bathing water pollution issues. In the area between Viareggio and Marina di Pisa wave and current data from ADCPs and buoys are used. In the second area around Livorno (between Livorno Harbour and Castello del Boccale) the current velocity data of a recently installed HF Radar are compared with the high resolution coupled model. Numerical simulations are carried out by the Delft3D Wave and Flow module. The wave and wind data of the Consorzio LaMMA (from WRF and WW3) forced the coupled wave-flow model and tidal levels were obtained by the Livorno tide gage.

Application of risk based flood forecasting in the coastal urban area of Manila Bay, Philippines to support short term decision making processes

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Recent events of hurricanes and typhoons show the importance of forecasts in the integrated process of emergency response. The identification of evacuation routes, estimated chronological appearance as well as severity of extreme weather events are only a few aspects in the interpretation of forecasts. Currently expert knowledge is required to construct the meteorological hydrological extent of present hazard. Recently efforts have been made to close this gap by shifting the output of forecasts forward, away from parameters defining the hazard, towards the occurring risk of an event. In this surrounding the risk is presented by the probability of an impact.

Manila Bay and the urban area of Manila were chosen as a site of application due to its exposure as well as its vulnerability to extreme weather events. The build forecasting system is set up to use a forecast track published by Joint Typhoon Warning Center for an historic event as an input and creates an ensemble of storm pathways with associated probabilities. Subsequent created wind profiles for every ensemble member are inserted into a Delft3D model in order to gain the spatial distribution of water depths present for every track. The translation from values for the water depths towards impacts is executed with the Flood Impact Assessment Tool (FIAT). As a final step to gain the values for risk the probabilities are multiplied with their associated impacts.

To move the forecast parameter from hazard to risk has the potential to drain more content from model-based information. Impacts can be described with certain probabilities and thus lead to a more solid decision making process for emergency response.

Looking for indicators to qualify the coastal area dispersion capability

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The water bodies which are at the land-sea interface are of prime interest and concern with respect to a wide panel of viewpoints among which the ones of various users of the coastal areas, shareholders, policy makers, people that are trying to plan and conciliate many (potentially conflicting) activities and researchers in various domain (physics, marine chemistry, biogeochemistry, ecology, ...).

This is likely why we find throughout the technical and scientific oceanographic literature such an amount of attempts to characterize these areas at a glance or with maps. For example, this was an effort perform within the preliminary studies that precedes the Water Framework Directive in the early 2000. This leads to the various and homogenous water bodies which quality have been monitored for years now. Among these indicators, we may quote residual circulation, many typical times such as the renewal, transit, flushing, e-fllushing ones, ...

First, this communication is a review of these past efforts to synthesize the capability of the coastal water bodies to move, to be renewed, to spread, to be connected between them ... Secondly, we will exhibit some additional efforts to qualify the dispersion of a given area. We will show the principle on which our approach is based, the numerical implementation of the method which is essentially lagrangian and the results obtained.

The model chosen to illustrate this approach is the bay of Brest (48°24' North / 4°29' West) ; it is partially but not fully closed. It is a macrotidal area which coast line is rather fractal, exhibiting many sheltered areas connected to a central energetic water body. It is located at mid-latitude and hence under highly variable meteorological forcings. The focus of the discussion will be on the impact of the hydrodynamics thus characterized on various benthic populations which have a pelagic stage.

An adaptable modelling approach to the management of toxic microalgal bloom events in coastal areas

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Harmful algal blooms have been increasing in frequency in recent years, and attention has shifted from describing to modeling and trying to predict these phenomena, since in many cases they pose a risk to human health and coastal activities. Predicting ecological phenomena is often time and resource consuming, since a large number of field collected data are required. The illustrated approach involves the use of a combination of high resolution atmospheric data (derived from MOLOCH Limited Area Model, operated by ARPAL) and marine data (derived from a 3D high resolution model implemented through downscaling techniques from the CMEMS Mediterranean Circulation model) as input features to predict the concentration of the toxic benthic dinoflagellate *Ostreopsis* cf. *ovata* in seawater. Ten meteomarine features were used to train a Quantile Random Forests model, which was then validated using field collected concentration data over the course of a summer sampling season.

The proposed model was able to accurately describe *Ostreopsis* abundance in the water column in response to meteorological variables. Furthermore, the predictive power of this model appears good, as indicated by the validation results, especially when the quantile for predictions is tuned to match management requirements. The Quantile Random Forests method was selected, as it allows for greater flexibility in the generated predictions, thus making this model suitable as a tool for coastal management. The model presented here was developed for a single species over a limited geographical extension, but its methodological basis appears flexible enough to be applied to the prediction of HABs in general and it could also be extended to the case of other ecological phenomena that are strongly dependent on meteomarine drivers, that can be independently modeled and potentially globally available.

Partial age: a suitable diagnosis of water exchanges between branches of a delta?

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The study of river delta dynamics (volumetric flow rate, sediment transport, morphologic changes, etc.) goes back to ancient times. The aim was and still is to understand the behaviour of deltas and their response to human modification.

Current numerical models, such as the Second generation Louvain-la-Neuve Ice-ocean Model (SLIM, www.climate.be/slim), are generally able to produce satisfactory results as to the splitting of the river discharge into the main branches, depending on their features (width, bottom roughness, ...), as well as water and suspended matter fluxes. Unfortunately, such diagnoses are unsuited to the assessment of the time-dependent exchanges between different branches, which is why a novel approach is suggested herein.

The Constituent-oriented Age and Residence time Theory (CART, www.climate.be/cart) provides a general and flexible framework to evaluate the age of any water constituent and the water itself from the solution of partial differential equations.

Schematically, a clock is tied to each constituent particle and indicates the time elapsed since it was set or reset to zero. To investigate water exchanges between branches of a delta, however, the aforementioned type of age is not the best option. It is found to be desirable to have recourse to a variant of this diagnosis, namely the partial age (Mouchet et al., *Ocean Dynamics*, 66, 367-386, 2016). Accordingly, every particle is equipped with several clocks. All of them but one are at rest any time and location, which allows evaluating the time spent in every branch (or group of branches) of the delta.

This relatively novel diagnostic approach is tested in an idealised delta and is subsequently applied to the delta of the Mahakam River (Borneo Island, Indonesia), shedding a new light on the exchanges between the main channels of the delta, especially on short timescale during ebbing phases of the tides. The connectivity between the channels is estimated in a quantitative manner. These numerical results, though being of a preliminary nature, are encouraging as to the potential of the partial age. It is hoped that, in the future, it will be possible to apply such a method to suspended matter as well.

An operational oil-spill forecasting system to manage pollution emergencies for Italian oil rigs

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Oil extraction platforms at sea are potential sources of pollution due to oil spills. For this reason, an oil spill forecasting system was realized to support the management of emergencies from the oil fields in the Italian seas. The developed system, based on a multi-model approach, publishes a daily bulletin on potential oil spills able to provide a ready-to-use product to the relevant response agencies (Ministry, coast guard), and to optimize the anti-pollution resources by assessing hazard and risk related to this issue. The forecasting system covers four oil platforms in the Sicily Channel and four in the middle/low Adriatic Sea. It is composed by different numerical chains involving nested ocean and atmospheric models at different spatial scales, from basin to local. The system provides two different online services, one ordinary and a second dedicated to possible real emergencies or Civil Protection exercises on risk preparedness and response.

The ordinary service produces daily simulations of oil dispersion, transport and transformation from extraction platforms. Results, i.e. maps, animations and a properly called bulletin, are available on a dedicated web-portal. The hazard estimations are computed by performing geo-statistical analysis on the daily forecasts database. Environmental Risk is also assessed by opportunely combining hazard indexes with vulnerability layers at coast. The service for real/simulated emergencies can be activated in areas covered by the system, in near-real-time, producing oil spill simulations of 48/72 hours from the start of the numerical simulation, and producing a bulleting analogue to the one produced for the ordinary service.

Oil Spill cases in Ligurian Sea

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Accurate coastal downscaling of oceanic flow requires a dynamically coupled description of the large scale circulation dominated by largely baroclinic ocean currents, tides and wind driven circulation and detailed description of local bathymetry and forcing such as e.g. river months or lagoons.

The MIKE 3 (DHI) model is based on a flexible mesh approach and it has been developed for applications within oceanographic, coastal and estuarine environments. The spatial discretization of the equations is performed using a cell centered finite volume method, while the vertical discretization is based on a combined sigma-z approach. Together with the inclusion of the Flather boundary conditions, the model is ideal for downscaling the regional scale oceanographic models to high resolution coastal application.

The technique is applied by DHI for downscaling the MFS Mediterranean 3D model (6,5 km resolution, operated within MyOcean EU Project – Copernicus Programme) to the coast of the Ligurian Sea for ARPAL "Agenzia Regionale per la Protezione dell'Ambiente Ligure". The finest horizontal resolution is reached along the coast of Metropolitan city of Genova (50 m), while, in the remaining western and eastern Ligurian coast it is approximately 500m.

The meteorological forcing comes from MOLOCH, a LAM model operated by ARPAL. Discharges from the main rivers are also taken into account through the hydrological model DRiFt, operated by ARPAL. The model, which is operational at ARPAL, performs one run a day. Following the availability of atmospheric model forecast data, the Ligurian Sea model simulates 48 hours (-12h --> +36h).

Oil spill module is a tool for predicting fate of substance of hydrocarbon origin, covering both the transport and the changes in chemical composition. The model is developed on a Lagrangian scheme that runs decoupled from hydrodynamics. This allows to evaluate scenarios of point release (fixed spill), areal release (oil slicks) and moving release (leaking points from moving route ships) both in near-real time using the operational forecast or in studying past events, depending on request.

Recently ARPAL was involved in a real time response, activated by Coast Guard of Genova during the IPLOM accident occurred in April 2016, when crude oil was release in the Polcevera creek, flowing to the sea. Short/medium-time study of the evolution of the drift of oil spills under the effects of wind and dominant was conducted. In another case, to support investigation of the origin of wax material found on different spots in Ligurian and Tuscan beaches in the summer of 2017, ARPAL performed a continuous release of non-reactive floating material, allowing to simulate the trajectories of particles under the combined action of current and wind to evaluate its probable source.

Merging observations and numerical models to assess pollutant distribution in the North-Western Mediterranean Sea

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Numerical models aimed at forecasting pollution at sea normally are able to predict the evolution of active or passive tracers, from point to non-point sources. The reliability of such predictions is strongly dependent on the quality of the hydrodynamic data used to force transport/diffusion models.

At the regional/coastal scales of main interest, it is important to solve processes with spatial variability of the order of a few kilometers, and time variability of the order of a few hours, in particular as regards mesoscale eddies and marine fronts.

In these cases, model resolution plays an important role, and therefore it is important to have the ability to nest local scale models on the operational products available today at basin scale, such as the Copernicus marine products (CMEMS).

This work shows some applications of the operational models currently available at the LaMMA Consortium for the solution of operational oceanography problems, such as emergencies related to oil spills and other surface pollutants, in particular Plastic Marine Litter (PML).

With regard to the latter, quantitative simulations are particularly complicated by the fact that PML is a form of diffuse pollution that is critically affected by the dynamics of marine currents on time scales ranging from days to months/years.

Recently, numerical models for Marine Litter (ML) distribution have been mainly employed: 1) to evaluate large scale distributions, at global or enclosed basin scales, as in the Mediterranean sea (van Sebille et al., 2015; Lebreton et al., 2012; Mansui et al., 2015); 2) to understand long period trends; 3) for forward/back-tracking analysis in order to find connections between sources of ML and accumulation areas (Liubarsteva et a., 2016; Aliani et al., 2017).

These approaches do not consider some aspects. For example, the fact that the circulation in the Mediterranean basin shows high seasonal or sub-seasonal variability, or that, surface debris distribution can significantly overlap with feeding areas of important marine species, since they have similar dynamic features and temporal variability.

In this work, concentrations of PML in the North-Western Mediterranean Sea, and, in particular, in the area corresponding to the Pelagos Sanctuary, computed by numerical models, were statistically compared with observations, and some significant correlations were found. Modelling of pollutant sources is a particularly challenging problem to be

addressed, as its better characterization will allow the development of better estimation methods for floating litter concentrations, and hence will provide qualitatively and quantitatively more correct interpretation on the observed PML data.
The availability of observations (eg HF radar), combined with satellite data, also contributes to a better assessment of the uncertainty of the hydrodynamic models, and it gives also benefits to the modelling of both point-source and diffuse pollution.

Applications of the Oslofjord model

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In order to receive funding for studies involving ocean modelling, applications for the downstream users have to be defined. In the research project FjordOs some of the end users was included throughout the project. This caused some challenges in communication of complex modelling issues, but also some benefits. The end users now knows more how model results may and, more importantly, may not be applied, and the modellers got input on how the results could be presented in order to be understood better by the end users. A few applications was defined at the beginning of the project. As the project evolved, more applications lined up as the end users saw more possibilities.
We will present how the challenges in communication was solved in the project together with examples on how the results from the model have already been applied in other research projects.

INVITED SPEAKER

The role of numerical modeling in coastal zone management

G. Umgiesser

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Numerical modeling has become an important tool in the environmental sciences. Modeling can be used to integrate observations interpolate these data in the spatial and temporal dimension. However, modeling can also be used for forecasting and "what-if" predictions.

Modeling in transitional areas such as lagoons and coastal zone show big differences with respect to the open sea. The strong influence of land based inputs, the relative importance of sediments and the atmosphere, and men made influences to the water bodies distinguish these areas from open waters and ask for different techniques in modeling. Especially the use of unstructured numerical grids allows a faithful reproduction of the spatial complexity found in the transitional areas.

Integration of different models is needed to describe the complexity of processes that are occurring in lagoons and the coastal zone. Special attention is dedicated to make these models work smoothly together.

Here we show how numerical modeling can be useful in the coastal zone. Applications to various water bodies are presented. Hydrodynamic studies in the coastal zone, as well as transitional waters and their interaction with the sea are discussed. In this contest the water residence time is one of the important parameters that can help estimating the state of health of the water body on a purely hydrodynamic based parameter. Other applications are the study of pollution and the connectivity of transitional basins with the open sea.

Fifty years of shallow flow modelling in The Netherlands and the transition from structured to unstructured grid modelling

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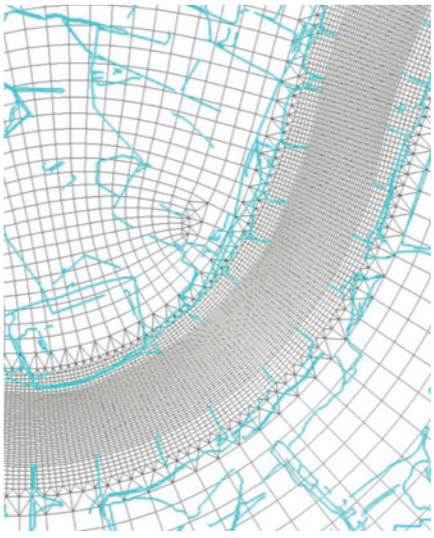
The publication of Leendertse in 1967 can be seen as the starting point of two-dimensional numerical modelling of shallow water flows in The Netherlands. He introduced the Alternating Direction Implicit (ADI) method that was used for practical applications in The Netherlands. This WAQUA software was applied in the Dutch 'Delta works' project, which was initiated after the February 1953 flood disaster in The Netherlands in which 1836 people died. Next to the numerical modelling physical scale models were used in the Delta works' project. In the late 1980s, three-dimensional shallow water modelling became possible due of the advance in computing power. In this period, the hydrodynamic modules Delft3D-FLOW and TRIWAQ were developed for 3-D modelling, which are part of the Delft3D and Simona model suites, respectively.

At many JONSMOD conferences model results for either Delft3D or Simona have been presented, in particular for modelling the North Sea Continental Shelf. In literature, a lot of applications of Delft3D for coastal, river and estuarine areas have been published (6000+ papers). However, in none of these papers is explained why the hydrodynamic modelling with Simona and Delft3D has been so successful. In this presentation we will summarize the key features of the underlying numerical method, which has resulted into an excellent performance with respect to robustness, accuracy and computational efficiency. The Delft3D and Simona software suites have been successful during many decades and still are, both nationally and internationally with thousands of users.



In 2011, a transition started in The Netherlands towards unstructured grid modelling for shallow water flows. To that purpose the Delft3D Flexible Mesh model suite is being developed. It is foreseen that in the coming decade the Dutch operational hydrodynamic models, which are currently based on a structured grid, will be replaced by models with an unstructured grid. In case of unstructured grid modelling it is common practice to only use triangles. However, we follow a different approach in which a combination of 'structured' curvilinear grid cells and unstructured grid cells (triangles, pentagons and hexagons) is used. This offers extra flexibility for the user. The pros and cons of different grid approaches for unstructured grid modelling with D-Flow Flexible Mesh will be presented.

Advances in the CROCO project

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CROCO (Coastal and Regional Ocean Community model) is a new oceanic modeling system built upon ROMS and SNH non-Boussinesq kernel. CROCO is gradually including algorithms from MARS (MUSTANG sediment model) and HYCOM (vertical coordinates) and is increasingly sharing libraries with NEMO (AGRIF grid refinement, OASIS coupler, XIOS I/O server, PISCES ecosystem model). CROCO is designed for solving fine-scale processes from the nearshore zone to the regional ocean with capabilities for LES-type simulations in realistic configurations, including coupling with the atmosphere, waves, sediments and ecosystems. Particular attention is given to numerical accuracy, high-performance computing (optimization, scalability), portability and easy access (http://www.croco-ocean.org).

This communication will present a quick overview of CROCO and produce examples to underline some of its original developments:

- *Kernel*: a non-Boussinesq approach for non-hydrostatic dynamics will be presented with one application to internal nonlinear waves in the Gibraltar Strait of the Mediterranean Sea. Another type of application is surface gravity waves propagation and breaking on the shore. We will expose the model dynamics, show its novel capabilities (e.g., nesting between hydrostatic and non-hydrosta tic domains) and quickly discuss advantages of a non-Boussinesq approach against the more traditional anelastic approximation where acoustic waves are filtered (well-posedness, performance, scalability).
- *Methods*: numerical methods are selected or developed around the notion of effective resolution. We will present examples of spurious dynamics generated by numerical errors in jet and vortex simulations and we will discuss cost versus accuracy, relevant choices from regional modeling to Large Eddy Simulations, and interaction with turbulence closure schemes.
- *Coupling*: we will present the main coupling procedures and some applications to nearshore and offshore problems. Examples will illustrate the benefit of a full 3D approach to wave-current, hydro-morphodynamic and air-sea interactions.

Recent improvements of the Oslofjord model

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During JONSMOD 2016 we presented a new high resolution ocean model for the Oslofjord, in southeastern Norway. The model is based on the open source community model ROMS, and has a horizontal resolution of between 50 and 400 meters. For the last two years, this model has been run semi-operational at MET Norway, and has also been used in multiple research projects.

There is an ongoing follow-up project to improve the model, and make it available to stakeholders like e.g. the Norwegian Coastal Administration for use in events like possible oil spill and other areas of interest.

In order to increase the overall quality of the forecasts for the Oslofjord, we have performed multiple experiments to improve the vertical structure of the water masses. The main focus has been on the vertical resolution of the model, and tuning of the parameterization of the vertical mixing schemes used, mainly the GLS scheme. The bias in the upper part of the water column is significantly reduced and a more accurate description of the vertical structure of temperature and salinity is achieved. The model now produce more accurate forecasts of the hydrography in the upper layers, especially during the summer season. This has many implications for downstream users, especially within biological applications. We will present the current setup and state of the model, an overview of the performed experiments, and comparisons with observations to show the improvements.

Evaluation of the performance of the new coupled wave-ocean forecasting model for the Adriatic Sea at Arpae-SIMC, Emilia-Romagna, Italy

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The Emilia Romagna region meteo, marine and coastal forecasting system is managed by Arpae-SIMC and is composed by a several units that run in cascade, i.e. meteorological, oceanographic, wave and coastal numerical models. The weather and marine forecasts of this regional modelling system is used by the regional Civil Protection Department to issue weather and marine warnings. For marine and coastal warnings, the key variables to be evaluated are mainly sea level and waves along the coasts.

The actual operational system is composed by two independent models, AdriaROMS and SWAN (Simulating Waves Nearshore), the former for the forecast of sea level in whole Adriatic basin, and the latter for waves prediction. SWAN is run in a sequence of nested domains at increasing horizontal resolution, from the Mediterranean to the Italian and finally to high resolution regional domains . The ocean model AdriaROMS instead is an implementation of the Regional Ocean Modeling System (ROMS) and, in addition to the sea level forecast, it computes temperature, salinity and currents.

Nowadays, a new model "Adriac" is running in pre-operational mode. The new model Adriac is an implementation of the Coupled-Ocean-Atmosphere-Wave-Sediment Transport Modeling System (COAWST), which couples ROMS with the wave model SWAN.

In addition to run the two models coupled, the new model refines the horizontal resolution, from 2km to 1 km, and the vertical resolution, from 20 to 30 σ levels (terrain following). The rivers climatology used to force river sources has been updated with more recent hydrological data: it takes into account of 49 rivers along the Adriatic basin with their climatology, and it is forced by quasi-real time flow rate data for the Po river, whose delta is considered as divided into 11 branches.

Adriac is driven at the southern boundary by the hourly sea level, currents, temperature and salinity fields provided by the Copernicus Marine environment monitoring service (CMEMS) and it is forced at the sea surface by the fields of the atmospheric model COSMO-I5 and COSMO-I2. The tidal forcing includes 8 astronomical tidal components interpolated using OTIS Software: K2, S2, M2, N2, K1, P1, O1, Q1.

The results of the verification of the new model Adriac are presented together with a comparison of its performance against the previous marine operational models.

A North Sea-Baltic Sea regional model: coupling of ocean and atmosphere through a dynamic wave interface

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The coupling of models is a commonly used approach when addressing the complex interactions between different components of the earth system. In climate and forecasting research and activities, advanced models are needed and there is an urge towards the use of coupled modelling. This study presents the development of a new, high-resolution, coupled atmosphere, ocean and wave model system for the North Sea and the Baltic Sea, which is part of the Geestacht COAstal model SysTem GCOAST. We focus on the nonlinear feedback between strong tidal currents and wind-waves, which can no longer be ignored, in particular in the coastal zone, where its role seems to be dominant. The proposed coupling parameterizations account for the feedback between of the upper ocean on the atmospheric circulation by accounting for the effects of sea surface temperature and the sea surface roughness. Several sensitivity experiments are performed to estimate the individual and collective effects of different coupling components. The performance of the coupled modelling system is illustrated for the cases of several extreme events. For example, the inclusion of wave coupling leads to a decrease of strong winds through wave dependent surface roughness or changing sea surface temperature, associated with mixing and ocean circulation. This leads to better agreement with in-situ and satellite measurements. Comparisons with available atmospheric and oceanic observations showed that the use of the fully coupled system reduces the errors, especially under severe storm conditions.

This justifies the further developments and implementation of the coupled model systems, (i.e. including the land, biogeochemical, fishery, etc. components) for both, operational and climate, research and development activities.

Modelling Wave-Current Interaction in the Lofoten Maelstrom

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The Lofoten Maelstrom is an extremely intense tidal current on the southern tip of the Lofoten peninsula in Northern Norway. The maximum current strength during the tidal cycle is estimated to be around 3 m/s, which makes this one of the strongest regular currents observed in open ocean waters. The strength of the currents and its dangerous whirlpools has sometimes reached mythical proportions, such as the old tale of the magical millstone on the bottom of the sea, continuously grinding salt and making eddies on the ocean above. There is also an abundance of references to it in literature. Examples are Edgar Allan Poes A Descent into the Maelstrom and in Jules Vernes *Twenty Thousand Leagues Under the Sea*.

The area of the Maelstrom is located on the eastern borders of the norwegian Sea and is exposed to predominating south-westerly winds and waves. For this reason, the tidal current is often subject to waves with the opposite direction, causing steeper waves, wave breaking and a complicated and dangerous situation to navigate in. To improve the predictability of the environmental conditions of the area, MET Norway is introducing wave-current interaction in its high-resolution coastal forecasting system. This system consists of a wave model (WAM) and a ocean circulation model (ROMS), both with an approximate horizontal resolution of 850 m, covering the whole coast of Norway.

Observations from the optical sensors at Sentinel-1 satellite show very consistent patterns of white bands during ebb and flood tide. From the model simulations these bands coincide with the location of a strong convergence area at the front of the tidal current maxima. We propose that these white bands are caused by the formation of foam in the convergence zone.

The results from numerical experiments with and without active wave-current interaction will be presented and discussed. Also comparison with recent optical observations from Sentinel-2 and SAR observation from Sentinel-1 will presented.

Two-way nesting technique applied on MOHID modelling system

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A bidirectional method is under development for the MOHID modeling system and in this communication the first results of the ongoing work are presented. MOHID is a finite volume 3D hydrodynamic and biogeochemical model with hydrostatic and boussinesq approximations, developed at Maretec center (Instituto Superior Técnico) for the last 3 decades. Typical coastal applications with MOHID model involve the use of a downscaling one-way nesting system in order to better represent near shore bathymetric features. One-way nesting using a downscaling methodology implies good agreement of coarser (parent) and finer (child) grid solutions near their boundary to avoid errors reflections and propagation. Therefore, finer grid open boundaries need to be set at a place with weak hydrodynamic features and smooth bathymetry where local features do not diverge from regional ones, which often occurs far from the application focus area. An ever increasing methodology comes from the assumption that a higher resolution child domain holds more accurate hydrodynamic solution, and should, thus, feedback finer grid results to the coarser grid solution – Two-Way nesting – by adding the effect of local features into regional domains. This technique also opens the door for smaller area finer grids while still providing good hydrodynamic nearshore solutions. Another advantage of this methodology is the improvement of regional applications which do not consider fresh water discharges, with local high resolution estuarine applications. These local applications feedback the influence of a river plume into the regional application, instead of discharging the river flow directly in only a few numerical coarser grid cells. There are several different two-way methods, with different ways to address conservation and noise problems at the boundaries. For the MOHID case, a nudging scheme will be used for the entire overlapped area with the exception of a sponge area near the border to avoid destructing regional features entering the child domain. Nudging will consider a time decay that can be adjusted by a user, and will address velocities, temperature and salinity fields, leaving the water level undisturbed to be computed by the parent domain after the feedback. This methodology is expected to be of use not only to renewables studies with underwater turbines, but also for narrow straits and watershed and agricultural applications. The methodology and some results obtained for a schematic case as well as a real case for the Tagus estuary will be presented.

A high-resolution, tide-including model of the Mediterranean Sea-Black Sea system

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E. Napolitano, G. Pisacane, G. Sannino, M. V. Struglia

ENEA, C.R. Casaccia, SSPT-MET-CLIM, Rome, Italy

A new three-dimensional, primitive equation model of the circulation of the Mediterranean Sea-Black Sea system has been developed, which includes the effects of the main astronomical tides. The model is based on the MITgcm (Massachusetts Institute of Technology general circulation model), in its hydrostatic version. The model domain is discretized using 100 vertical z-levels, and a horizontal computational grid of 2500 x 750 points, with a uniform resolution of 1/48° (about 2km) over most of the domain, except in the regions of the Straits of Gibraltar, Dardanelles and Bosphorus, where higher resolutions (down to a few hundred meters) are needed to correctly resolve the dynamics. The model has a single open boundary, to the west of the Gibraltar Strait, where boundary conditions are taken from the NEMO operational model. Surface forcing (hourly wind stress, heat and fresh water fluxes) is derived from the regional atmospheric high-resolution (5 km) SKIRON model.

A first physical validation has been performed, comparing the results of a 40 days run (19 March-30 April 2018) with available satellite observations (sea height, sea surface temperature, turbidity). After one month of simulation, during which no assimilation or relaxation was performed, the model circulation and the sea surface temperature distribution were still found to be in good agreement with the satellite observations, showing the capability of the model to follow the evolution of the system in a period (beginning of spring) that is characterized by complex dynamics and significant changes in the surface heat fluxes.

The tidal dynamics of the model has been validated through comparison with the results of a tidal inversion software (OTIS), with reference experimental data, and with tide gauge measurements covering the simulation period. The tides have been found to provide an important modulation of the transport across the Gibraltar Strait and the Sicily Channel (which was expected), but also across the Corsica Channel and the Otranto Strait (which was less expected). The tides also have significant effects on the local circulation; this is particularly evident in the Sicily Channel, where the streams of Atlantic water crossing the channel are strongly altered by the tidal cycle. In this region, and also in other parts of the domain, evidence has been found of nonlinear effects due to the presence of the tides.

Seamless and cross-scale modelling of the ocean: from regional to shelf-coastal and harbour scale

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The present work shows the development and implementation of 3D-thermo-hydrodynamic fully-baroclinic modelling systems, based on the unstructured-grid finite-element SHYFEM model (Umgiesser et al., 2004; Ferrarin et al., 2018) and solving with appropriate and variable resolution different oceanographic scales.

The first implementation is UMEDBS (Unstructured-grid MEDiterranean and Black Sea), covering the entire Mediterranean and Black Sea with a unique continuum grid, and focused both on the regional and shelf-coastal scale. The model domain extends in a large Atlantic box (similar to the one described in Oddo et al., 2009) with a lateral open boundary nested into high-resolution global ocean model (GOFS16, Global Ocean Forecast System, Iovino et al., 2016). The horizontal resolution is optimized on the local bathymetry, coastline and expected solutions (relevant dynamics and coastal scale features), and ranges from 4-5 km in open-ocean to 1km-500m in overall shelf-coastal seas to 50-60m in narrow straits (Dardanelles and Bosphorus). The model has been run in hindcast and free-active mode for 4 months (Jan-Apr2017) and compared with satellite observations and in-situ coastal observations showing good agreement. Furthermore, model inter-comparison has been performed with GOFS16 and MFS-CMEMS (Mediterranean Forecast System) analysis. The impact of straits (Gibraltar, Sicily, Otranto, Dardanelles, Bosphorus, Kerch) on the dynamics and exchanges of interconnected basins (e.g. Black Sea, Marmara Sea end Eastern Mediterranean Sea) have been investigated.

The second implementation is SANIFS (Southern Adriatic Northern Ionian coastal Forecasting System, Federico et al., 2017) focused on the coastal-harbour scale of the Apulia region and based on downscaling approach from the new MFS-CMEMS operational products (1/24 horizontal resolution). SANIFS has been enhanced in terms of horizontal resolution, up to 100 and 20 m in coastal and harbor areas, respectively. SANIFS outputs have been validated at the coastal scale, both with short-term and long-term runs. In particular, the long-term run (4 years: 2013-2016) has been carried out adopting a procedure based on re-initialization from parent model.

Improvements in turbulence model realisability for enhanced stability of ocean forecast and its importance for downstream components

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The numerical stability of ocean circulation models is of high significance in operational forecasting. A substantial improvement in numerical stability of the 3D-ocean model HBM could be achieved by the implementation of new realisability criteria in the turbulence closure scheme. Realisability criteria which were already well documented for closure functions without double diffusion were therefore extended to those using double diffusion. A purely technical validation method called ε-test which is suitable for the detection of numerical stability problems is presented and the effect of the development in turbulence model is demonstrated under severe weather conditions during extreme storm events. Evaluation of statistics of longer simulations indicate that instabilities appeared only locally and temporary, nevertheless a significant impact on drift products relying on the current forecasts could be demonstrated, which underlines the importance of realisability in turbulence closure schemes in comprehensive operational model systems including ocean circulation and downstream drift components.

A multi-scale strategy towards numerical simulation of coastal erosion

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In the present work the development of a strategy towards the numerical simulation of coastal erosion has been described. This strategy is based on the coupling between an open-source software, Delft3D, which is used to simulate flow and wave dynamics on large areas, in this specific case corresponding roughly to the entire gulf of Cagliari, and a proprietary code, Shallowbox, used for more detailed simulations in a smaller area of interest.

The code ShallowBox is able to deal with hydro-morphodynamics phenomena. It is based on a shallow-water approach coupled with the Exner equation, which expresses the conservation of the sediment volume. In the Exner equation the solid transport discharge is provided by a closure model. The Meyer-Peter Müller model is used for sediment transport and the action of the shear between the fluid and the solid surfaces is taken into account through a source friction term in the momentum equations.

A treatment of wetting-drying interface permits to deal with the coastline evolution. Finally, the effects of the possible presence of seagrass meadows, which are known to have a non negligible impact on sediment transport, are introduced in the model.

The numerical formulation is based on a well-balanced finite-volume discretization for unstructured grids. The proprietary code ShallowBox has a few positive features. The first one is related to the use of unstructured grids which allows to efficiently take into account in the simulations the presence of natural or engineering solid elements of complex geometry, and, hence, to investigate, for instance, the impact of human interventions. Furthermore, the dry/wet treatment implemented within the project permits to explicitly obtain the evolution of the coastal line.

Applications of the whole computational strategy to the simulation of a 2km × 1.5km area in the Gulf of Cagliari are. The effects of modeling aspects have been investigated as well as the impact of the presence in the area of a pier. Lines of further developments of ShallowBox and future applications of the multi-scale simulation strategy are discussed.

Tidal Modulations of Surface Gravity Waves in the Gulf of Maine

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Analysis of observational data demonstrates significant semidiurnal tidal modulations in the mean wave variables in the Gulf of Maine (GoM). The observed tidal modulation features significant spatial-temporal variabilities, with large magnitudes near the mouth of the GoM particularly in fall. In this study a coupled wave-circulation model is used to examine the tidal modulation of surface gravity waves in the GoM. The coupled wave-circulation model successfully reproduces the observed tidal modulation and associated spatial-temporal variabilities. Model results demonstrate that the favorable conditions for the tidal modulation in the region are swell-dominated waves associated with relatively stable wave propagating directions. The large tidal modulation in the wave height occurs at several different tidal phases, indicating the effect of nonlocal tidal currents. Process-oriented numerical experiments demonstrate that the observed tidal modulation is associated with the current-induced advection, refraction, and wavenumber shift. Model results also demonstrate that the accumulated effects of nonlocal tidal currents across Georges Bank (GB) determine the observed unusual timing of the maximum tidal modulation in the wave height behind GB in the following tidal currents. As a result, both amplitude and phase of the tidal modulation behind GB are indirectly controlled by the strong tidal currents on GB. The amplitude could reach ~0.4 m over areas just behind GB, and the phase propagates towards the inner GoM with a wavelength of ~40 km.

Modelled diurnal oscillations propagating around Saint Pierre and Miquelon

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The archipelago Saint Pierre and Miquelon (SPM) is a group of islands, located (47°N, 56°W), southwestard off Newfoundland islands, with hydrological conditions poorly known.

The regional sea level tide around SPM is semi diurnal. Diurnal oscillations on the bottom temperature have been observed, with an amplitude which could reach 10°C, with an unexpected O1 tidal component (~26h). It was found that the barotropic tidal current has a strong diurnal component at the edge of Newfoundland continental shelf and Grand Banks (GB), which has already been described. The diurnal tide component has also an impact on SPM dynamics. At 47°N, these diurnal oscillations are sub-inertial and according to the theory are trapped by the topography during stratified period and propagate clockwise around the archipelago.

The aim of this study is to investigate the characteristics of these diurnal oscillations using new observations performed around SPM. The new dataset of summer 2016 consists of: records of bottom temperature (at 60 m depth), currents time series and few weeks records of temperature profiles around SPM (from 10 m to 80 m).

A 3D model has been implemented on the area, with a uniform schematic stratification corresponding to summer period (averaged of the temperature profiles measured in 2016), with tidal forcing. Phases deduced from the harmonic analysis, performed on modelled and observed data, demonstrate the ability of the model to reproduce a Coastal Trapped Wave (CTW) which propagates around SPM. These first results will allow us to give a description of the diurnal oscillations and give a better identification of the characteristics of its propagation around SPM.

Rapid decline in tidal amplitude along the Dutch coast since 2007

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As the astronomical forces that drive tides are constant, tides are generally considered to be stationary. However, they can be altered due to various reasons ranging from global change in sea level and ocean stratification to local changes in bathymetry, outflow of rivers and geomorphology.

In this presentation, we will present an analysis of tidal records along the North Sea coasts of The Netherlands. The data are analysed with a mixed statistical-deterministic modelling approach using a high-resolution hydrodynamic model to remove natural tidal variability, including the nodal cycle, from the observed time series. This offers a methodological advantage compared to a statistical removal of the nodal cycle from observations and also offers the opportunity to perform numerical experiments exploring potential causes of change in the tidal record.

Analysis of M2 amplitude shows considerable interannual variability, but little or no trend prior to 2006-2007 in the Dutch coastal stations. However, from 2007 onwards we observe a relatively strong decline in M2 amplitude in many of the stations assessed. In some stations, we observe a cumulative decline in tidal amplitude over the period 2007-2017 of up to 5%. The strongest relative decline occurred at tide gauge station Petten located at the Holland coast, with a decrease of 0.46 % per year (i.e. 3.2 mm/year). The decline in tidal amplitude shows a strong spatial coherence, with a gradually decreasing rate of M2 amplitude change to the north and south of this station.

Finally, we will present results from an evaluation, using model experiments and literature, of various physical mechanisms for their ability to cause the observed changes in tidal amplitude, without affecting the tidal phase.

High resolution numerical analysis of bathing water hydrodynamics around the Adige River mouth (Northern Adriatic Sea)

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CADEAU is a Copernicus Marine Environment Monitoring Service (CMEMS) downstream coastal service devoted to operationally deliver a bulletin based on the Copernicus Marine Service derived products to quantify nutrient dynamics, eutrophication and bathing water quality in coastal areas in support of the application of the EU Directives related to coastal and marine environment (Water Framework Directive – WFD, Urban Waste Water Treatment Directive – UWWTD, Bathing Water Directive – BWD, Marine Strategy Framework Directive – MSFD). The CADEAU products were designed to provide information on the space-time distribution of the major parameters related to water quality in the coastal areas of the Northern Adriatic region. Further project outcomes were developed to identify the impacts and to track the potential sources of bacterial pollution that can affect coastal areas and bathing waters.

In the framework of this activity, we implemented a high resolution numerical model to investigate the wave-current interaction in the shallow flow at the Adige River mouth. The model, developed at ISPRA (Lalli et al., 2016), is based on a finite difference scheme with a complete wave current coupling in the time domain. It explicitly solves the processes of wave refraction due to currents and sloping bottom, as well as wave reflection/diffraction around marine structures. Furthermore, the model allows to reproduce the bacterial dispersion and decay downstream of the discharge points.

The model was used in the 2D shallow water version, the spatial domain was discretized by a staggered grid (elements size 10m x 10 m) and the discrete equations were solved step by step by means of a 3rd order Runge-Kutta time marching scheme.

The simulations were carried out by using different boundary conditions, including river flow discharge, littoral currents and waves. The coastal current input was provided by the coupled MITgcm-BFM model (Cossarini et al., 2017) developed for the CADEAU project goals.

Several scenarios were simulated in order to evaluate the coastal hydrodynamic circulation due to the Adige River-Adriatic Sea interaction, and to estimate the impact of bacterial pollution on the bathing waters.

Introduction of the effects of a barrier reef in the CROCO model for the modeling of lagoon hydrodynamic circulation: Example of the Toliara Lagoon (Madagascar)

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In the channel lagoons of tropical islands, the coral reef constrained the hydrodynamics exchanges between lagoon and ocean and also plays a crucial role on the hydrodynamic circulation, the residence time as well as the age of water. The coral reef is an atypical boundary for the lagoon dynamic. It is characterized by its ability to be alternately submerged at high tide and almost emerged at low tide. The high roughness of coral generates high bottom friction on the flows above the reef, whereas this reef is also affected by the wave breaking which generates a cross-reef flux. These multiple effects drive a particular and complex water masses dynamic.

The physical interconnections imposed by the reef on the "Grand Récif de Tuléar" (GRT) reeflagoon system will be analyzed by combining the results of in situ observations and 3D numerical modeling with the Coastal and Regional Ocean Community (CROCO) model. This model is implemented by specifying the harmonic components (amplitudes and phases) of the dominant semi-diurnal tidal waves (M2 and S2) at the open ocean boundary which opened at the Mozambique channel. Along the reef barrier, the cross-reef flow is introduced through the use of the term of radiation stress which varies with both the water level and also with the significant height of the swell. The validation of the model was carried out by comparing simulated elevations and currents to datasets of in-situ measurements obtained from Acoustic Doppler Current Profilers (ADCP) deployed during two field campaigns in 2007 and 2008 in the Toliara lagoon. Generally, results of the model show a fairly good agreement with measured water levels and currents but these results improves with the implementation of the wave effect on the cross-reef fluxes.

Furthermore, a realistic simulation of 2 months underlines the major role of the cross-reef flux in the lagoon water dynamics. Indeed, at this time scale,almost 92.6% of the lagoon water is incoming i the lagoon because of fluxes associate to oceanic wave breaking. In the same way, we also highlight that the lagoon water age depends upon the height of the waves breaking on the reef.

INVITED SPEAKER

Variational assimilation of satellite and in situ observations in the Copernicus Services

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Short term ocean forecasting uncertainties are associated to initial conditions inaccuracies and atmospheric forcing uncertainties. The initial condition uncertainties are connected to low representativeness of observations, model inadequacies and data assimilation approximations. In this talk we will overview the specifics of the variational assimilation system, so-called 3Dvar, for the Copernicus Marine Environment Monitoring Service (CMEMS) analyses of the Mediterranean and Black Sea.

CMEMS has developed in the last 20 years a 3Dvar data assimilation system for the Mediterranean and Black Sea that uses satellite altimetry and sea surface temperatures, subsurface ARGO floats, gliders and ship of opportunity XBTs. Analysis quality indices will be presented and some key factors for the future development of the new data assimilation schemes will be discussed.

The Mediterranean analysis and forecasting physical system for the Copernicus Marine Service: description and skill assessment

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The Mediterranean Analysis and Forecasting System is a numerical ocean prediction system that operationally produces analyses and 10 days forecasts of the main physical parameters for the entire Mediterranean Sea and its Atlantic Ocean adjacent areas.
The system is composed by the hydrodynamic model NEMO (Nucleus for European Modelling of the Ocean) 2-way coupled with the third-generation wave model WW3 (WaveWatchIII) and forced by ECMWF (European Centre for Medium-range Weather Forecasts) atmospheric fields. The forecast initial conditions are produced by a 3D variational data assimilation system which considers a daily assimilation cycle of Sea Level Anomaly, vertical profiles of Temperature and Salinity from ARGO and ship CTDs and heat flux corrections with satellite SST.
The system has been recently upgraded in the framework of the Copernicus Marine Environment Monitoring Service (CMEMS) by increasing the grid resolution from 1/16 to 1/24 degree in the horizontal, thus becoming fully mesoscale resolving and from 72 to 141 vertical levels, by increasing the number of fresh water river inputs and by updating the data assimilation scheme. The model has a non-linear explicit free surface and the forecast is forced by surface pressure, interactive heat, momentum and water fluxes at the air-sea interface.
The focus of this work is to present the latest modeling system upgrades and the related improvements achieved by showing the model skill assessment including comparison with independent (insitu coastal moorings) and quasi-independent (insitu vertical profiles and satellite) datasets.

4DVAR assimilation of surface current and water level measurements in a 3D barotropic circulation model of the German Bight

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Because of the shallow water, the tidal dominated circulation in the German Bight is a challenge for numerical models. There are a lot of uncertainties about the bathymetry, as well as the bottom roughness, and the dynamics is complicated by strong nonlinear mechanism, like the generation of overtides. At the same time, the German Bight is a very busy region with a lot shipping and offshore
activities resulting in strong demands for accurate information on currents and water levels, i.e., in the context of Search and Rescue (SAR) operations.
In this study a combination of tide gauge observations and measurements from three HF radar stations in the German Bight are assimilated into a 3D circulation model with 1 km resolution and 7 vertical layers in order to improve estimates for water levels and currents. The horizontal grid and bathymetry as well as the open boundary and meteo forcing is indentical to the setup used at the Hydrographic Federal Maritime and Hydrographic Agency (BSH). A 4DVAR technique is used, which is based on an adjoint model to compute the gradient of a cost function, which penalizes deviations between the observations and the model results.
The analysis is performed in two steps, where systematic model errors like bottom roughness, internal friction related to turbulence and meteo drag coefficients are treated first. For this purpose, the system is run in a hindcast mode over a certain tuning period. Subsequently, stochastic error components relevant in an operational forecast setup, like errors in the open bo undary forcing and the meteo forcing are reduced. This is done in a forecast configuration where a 12 hour forecast is launched based on a 12 hour hindcast. The results are compared to the operational output of the BSH system as well as to drifter data acquired in 2015. The achieved improvements, as well as remaining residuals between model and observations are discussed. Particular focus is put on the spatial distribution of remaining systematic errors and strategies to further reduce these. The results are put into the general context of coastal data assimilation, which is of growing interest in particular with the accelerating activities on the modelling of the European Seas within the Copernicus program.

Integration of the Italian water quality dataset and a model downscaling of the Mediterranean CMEMS: the CADEAU coastal service

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CADEAU is a pre-operational service in support of the application of the EU Directives for coastal marine environment. It is based on an integrated model downscaling of the regional Mediterranean Copernicus Marine Environment Monitoring Service (CMEMS) to produce daily forecasts and an annual bulletin reporting the marine environmental state and the water quality in the Adriatic Sea. The service is applied to the northern Adriatic coastal area, where eutrophication and marine resources exploitation both influence and depend on the quality of the ecosystem.

CADEAU is based on the high-resolution (1/128°), coupled MITgcm-BFM modeling system, which is initialized and driven by the downscaling of the CMEMS Mediterranean products. The MITgcm (Massachusetts Institute of Technology general circulation model) and the BFM (Biogeochemical Flux Model) are widely used models for geophysical fluid dynamics and for ocean biogeochemistry, respectively. The coupled system integrates in-situ datasets managed by ISPRA (Italian Institute for Environmental Protection and Research), hydrological and meteorological data, and CMEMS satellite maps of sea surface temperature and chlorophyll. ISPRA experimental data include physical, biological and chemical parameters, and urban wastewater treatment plants (UWWTP) discharges.

The integrated modelling system, which adopts multivariate data assimilation, has been tested successfully. The numerical results reproduce the seasonal and interannual variability of the main hydrodynamic and biogeochemical properties of the northern Adriatic Sea, consistently with both the experimental data (when and where available) and the up-to-date knowledge provided by literature and current climatologies.

The CADEAU service supplies several derived products, such as ocean current variability, concentration and dynamics of biogeochemical variables (nutrients, chlorophyll, dissolved oxygen), and dispersion of pollutants in proximity to the discharge points (rivers and UWWTP outfalls).

Potential service outcomes are the evaluation of the spatial-temporal variability of the biogeochemical conditions, the analysis of the UWWTP impact and the assessment of Good Environmental Status in the Adriatic Sea to meet the requirements of the EU Directives.

On the computation of LAT-grids

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Following the guidelines of the IHO, most countries display depths in their nautical charts relative to a Chart Datum (CD) based on the Lowest Astronomical Tide (LAT). However, for many applications such as hydrodynamic modelling, we require data relative to a different vertical reference. Although, accurate conversion is not a simple task, hydrodynamic models can play an important role in this process. In this presentation, we will present a number of recent developments for the accurate computation of LAT using hydrodynamic models.

For the North Sea region, we studied the use of a Kalman filter to assimilate tidal data at tide gauges into a 2D tide model of the North West Continental Shelf. This can significantly increase the accuracy, but requires careful consideration of the consistency. Special attention is needed for intertidal areas, where LAT is not defined and where straightforward computation results in unusable results.

In addition, we will present results for the LAT computations for Europe with the Global Tide Surge Model (GTSM v3.0). We refined the computational grid to 1.25km in Europe and studied several non-gravitational aspects of tides in more detail. In the next release of the EMODnet bathymetry users will be able to download the data relative to Mean Sea Level, based on this conversion.

Singular value decomposition and correlation analysis to optimize in-situ observation networks

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In deciding the configuration of an observation network aimed at improving the reliability of an ocean forecasting system through data assimilation, the choice of the kind of measurements devices, their number and installation positions is central but still not clear. Ocean observation networks and in particular in-situ networks are expensive and the choice of sensors, number and their positioning require careful assessment in order to optimize the investments in terms of forecast reliability. This study highlights the impact of the positioning of a fixed numbers of ADCPs in a simplified ocean model (double-gyre). The network design criteria proposed here, is based on two elements: 1) the singular value decomposition (SVD) of the tangent propagator of the model which identifies areas where maximum error growth occurs, within which sampling gives particular advantages; and 2) the correlation between points, since the information observed on neighboring points can be redundant.

The SVD has many advantages, especially when we dispose of a variational assimilation method like the 4D-Var, also because the calculation of Singular Vectors and Singular Values is linked to the availability of tangent linear and adjoint models.

The criteria adopted is easily replicable in practical applications and requires rather standard studies to obtain prior information (i.e. climatological and correlation studies), to be carried out in order to properly design observation networks. The sampling strategy we present is a preliminary tool to understand the observation needs for real analysis and forecasting systems.

Adaptive Ensemble Optimal Interpolation for efficient data assimilation in the Red Sea

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Ensemble optimal interpolation (EnOI) have been introduced to drastically reduce the computational cost of the ensemble Kalman filter (EnKF). The idea is to use a static (pre-selected) ensemble to parameterize the background covariance matrix, which avoids the costly integration step of the ensemble members with the dynamical model. To better represent the strong variability of the Red Sea circulation, we propose new adaptive EnOI schemes in which the ensemble members are adaptively selected at every assimilation cycle from a large dictionary of ocean states describing the variability of the Red Sea system. Those members would account for the strong eddy and seasonal variability of the Red Sea circulation and enforce climatological smoothness in the filter update.

We implement and test different schemes to adaptively choose the ensemble members based on (i) the similarity to the forecast, or (ii) an Orthogonal Matching Pursuit (OMP) algorithm. Results of numerical experiments assimilating remote sensing data into a high resolution MIT general circulation model (MITgcm) of the Red Sea will be presented to demonstrate the efficiency of the proposed approach.

Bayesian Inference of Spatially-Varying Manning's n Coefficients in the Coastal Ocean Using a Generalized Karhunen–Loève Expansion and Polynomial Chaos

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Bayesian inference with coordinate transformations and polynomial chaos for a Gaussian process with parametrized prior covariance model was introduced in [1] to enable uncertainties in the parameterized prior field. The feasibility of the proposed method has been successfully demonstrated on a simple transient diffusion equation. In this work, we adopt a similar approach to infer a spatially-varying Manning's n field in a coastal ocean model. The idea is to view the prior Manning's n field as a stochastic Gaussian field expressed through a covariance function with uncertain hyper-parameters.

A generalized Karhunen–Loève (KL) expansion, which incorporates the construction of a reference basis of spatial modes and coordinate transformation, is then applied to reduce the dimension of the parameters space. A Polynomial Chaos (PC) expansion with similar coordinate transformation is next exploited to build a cheap surrogate of the large-scale numerical model ADCIRC, which is used to accelerate the Bayesian inference process using a Markov Chain Monte Carlo (MCMC) algorithm. Water elevation data are inverted within an Observing System Simulation Experiments (OSSEs) framework based on a realistic ADvanced CIRCulation model to infer the KL modes and the hyper-parameters of a reference 2D Manning's field. Our results demonstrate the efficiency of the proposed approach and suggest that including the hyper-parameters uncertainty greatly helps enhancing the inferred posterior compared to the case with fixed hyper-parameters.

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