Optimize Coastal Ocean Prediction System (COPS)

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1. Introduction

1.1 *Coastal ocean prediction*

Mooers (1999) defined "coastal ocean" to include a 200 nautical mile wide Exclusive Economic Zone (EEZ), determined by United Nations Convention on the Law of the Sea (UNCLOS). This covers a major part of the European coastal seas (Mediterranean, North Sea, Irish Sea, Baltic Sea) and part of European shelf seas. Since EEZ is also of high national interests in marine resource exploitation and environmental protection, it naturally constitutes a major focus in operational oceanography.

Prediction of physical conditions in the coastal ocean is much more mature than that of biological, chemical and ecological conditions. Parameters and ranges of the physical prediction are closely related to marine industry, environmental management, and civil and military services. Currently 48-72 hours forecasts of waves, tides, surges, ice, temperature, salinity and currents are provided in a number of European national Met-/Ocean Offices. Model resolutions ranges from 100m in local waters to 1/4 degree over shelf break.

To understand the current status and future direction of operational oceanography, predictability is a key index. Here 'predictability' means "prediction capacity of ocean phenomenon in time, space and quality", which is a more general concept than that in the weather prediction. Four major error sources influencing the coastal ocean predictability are:

- Initial error (observation error and analysis error)
- Boundary error (open boundary conditions/river inputs)
- Model error (model physics and numerics error)
- Error in weather forcing

These four error sources are generated in our Coastal Ocean Prediction System (COPS). Classic COPS includes a numerical weather forcing interface, an ocean model and computing facilities. With the development in operational oceanography in recent years, the concept of COPS now constitutes four sub-systems: weather forcing, ocean model, ocean observing and dissemination system. This change results from increasing marine user requirements to marine forecasts, scientific and technological development in ocean monitoring and ocean modeling, and the rapid developing internet technology. The weather forcing system is a coupled system with an ocean rather than just an interface. The curvature of coastline and conditions of waves, sea surface temperature and ice influence the momentum and heat fluxes of numerical weather models. The ocean model is now also a system where different models are interacted (e.g., wave-current interaction) rather than separated single models. Besides the progress in ocean modeling, ocean model coupling and ocean-atmosphere coupling, the ocean prediction errors due to in-accurate initial field, open boundary conditions, river input and bathymetry are less improved. The key to solve this problem is to implement a cost-efficient ocean observing system. Finally, real-time data delivery is becoming the top concern for ocean users, according to a survey in the ESODAE (European Shelf-Sea Ocean Data Assimilation Experiments) user workshop (Aberdeen, 2000). This indicates the importance of the data dissemination system. Furthermore, to share observations and real-time predictions from different institutes, an efficient data dissemination system or a network is essential.

European COPS is now confronted with some open questions in modeling, observation and data dissemination systems, such as

- Dozens of numerical weather and ocean models are used in European coastal ocean prediction. How to integrate the current operational models and products in order to reduce redundancy and enhance prediction quality.
- Most of the operational ocean models are not coupled. Fully coupled COPS model system is needed. ocean-atmosphere, wave-atmosphere and wave-current-water level interactions should be included in the system.
- Most of the operational ocean models use hot start rather than initialization, climatology boundary forcing rather than real-time data due to lack of observations. Existing coastal ocean observing system are not optimized. Observation redundancy and insufficiency in space and time have not been evaluated. How to evaluate and integrate existing remote sensing and in-situ observation networks for coastal ocean prediction?
- Where to put our limited resources in the observing system so that COPS model system get maximum benefit by using observations? How to design and implement a cost-efficient coastal ocean observing system in Europe?
- Existing COPS focus on increasing computing ability rather than an integrated data dissemination system, leading to "bottle neck" effects. This highly relats to duplicated operational modeling and monitoring efforts within the community. How to set up an integrated data dissemination system.
- With improving COPS sub-systems (modeling , observing and data dissemination system), the quality of coastal ocean prediction is expected to be

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greatly enhanced. On the other hand, development in weather forecasts also provides chances for the extension of coastal ocean prediction both in time and space. What is the possibility to make longer coastal ocean predictions (e.g., 10-day predictions)?

The purpose of this paper is to discuss how to optimize existing COPS to reach the maximum predictability. Section 2 describes the limits of existing coastal ocean predictability in Europe. Section 3 discusses possible extensions of the coastal ocean predictability via optimizing current European COPS.

2. Predictability in COPS: current limits

Generally there are three kinds of predictability in the coastal ocean prediction, i.e., predictability due to internal dynamics (i.e., the sensitivity of model internal dynamics to the initial error) which is also called dynamic predictability, predictability due to model imperfection (including model physics error and numerics error) and predictability due to external forcing. Relative importance of the three kinds of predictability depends on prediction scales and parameters. Dynamic predictability is more important in stratified ocean and less important in well mixed area and for surface processes such as surges and waves. Relevant prediction scales ranges from days to months in offshore areas. The predictability due to model imperfection and external forcing can be dominant in any relevant scales and parameters. In the following we discuss limits of the predictability according to subsystems in the COPS (i.e., modeling system, observing system, information dissemination system and forcing system).

2.1 *Weather forcing system*

Weather forcing is important in almost all the relevant scales in the coastal ocean prediction. Errors in the weather forcing largely restrict the coastal ocean predictability. Main error sources in surge and wave prediction by using state-of-art models are from weather forcing(Janssen, 1999). For example, She (2000) investigated a 14 months 6-hour forecasts of surface winds and waves at Danish Meteorological Institute. He found that the weather prediction error (by HIRLAM) caused an 12.6% over-estimation of the significant wave height, and is almost balanced by a model set-up error (-8%) and model physics error (-5%). Finally the forecasts of the significant wave height are almost unbiased. In storm surge forecasts, many of the ill-forecasted storm surge cases are related to ill-forecasted weather forcing, as is the case of the North Sea hurricane in Dec. 3, 1999, and North Sea storms in Dec. 25 and 27 of 1999 and in Dec. 13, 2000 etc.

The weather predictability directly influences the coastal ocean predictability both in space and time ranges. European Numerical Weather Prediction (NWP) has been developed in the way that ECMWF (European Center of Medium-range Weather Forecast) provides lateral boundary condition to regional models (e.g., HIRLAM) in member countries and the regional models are used to provide a regional prediction with higher resolution and more frequent forecast runs. In a few EU countries, regional models are nested in their own global NWP models such as in UK and Germany. Global models have longer forecasting range but lower spatial resolution. Now the best resolution in the global prediction is a 10-day forecast with horizontal resolution of about 40km. i The regional models may have higher resolutions down to 2-5km in very local areas and limited prediction ranges (e.g., 36hour). For a spatial resolution of 10-15km. the NWP has a time range of 48-72h, which means that the coastal ocean prediction can also only have a 2-3day forecast. The quality of regional models may not necessarily be better than a global model in predicting synoptic scale weather phenomenon. However recent validation studies of the HIRLAM do show better surface winds than ECMWF Global model in 48hour forecasts.

The limits of the NWP forcing on the coastal ocean predictability can be further discussed by asking: at which grid size can a global NWP model not gain further skills by reducing the grid size? Generally a better resolution produces better forecasts for hydrostatic scales (larger than 10km) because higher resolution reduces the error from sub-grid parameterization and improves the interaction among different scales. This may not be true for non-hydrostatic scales. Current global NWP models are all hydrostatic models. A reasonable limit of the hydrostatic global NWP model grid size may be 5km, considering a hydrostatic model also contributes to non-hydrostatic motions with its sub-grid parameterizations. Another constraint on the global NWP grid is the scale-dependency of dynamical predictability, i.e., small scale phenomenon have much shorter (initial) error doubling time than larger scales. The error increasing in small scales could spoil prediction in larger scales under some conditions. With sufficient computing resources, a practical predictability range of NWP in European ocean may be between 5-20km for 7day forecasts by using a global NWP model, say, ECMWF model. For the current regional models, the space limit of 5km is still applicable. However the limited regional models may not be able to provide 7day high resolution forecasts due to their poorer model physics in comparison with ECMWF model. In the future non-hydrostatic regional models used in the operational NWP could have much higher resolution, e.g., 1km. This resolution will be compatible with operational coastal ocean models.

2.2 *Ocean modeling system*

The coastal ocean predictability is influenced by model imperfection, i.e., errors in model physics, numerics, and in analysis. As an example, here we focus on 3D coastal ocean models. Current 3D coastal ocean models are able to simulate large scale ocean phenomenon but not mesoscale eddies and fronts. Sea surface temperature (SST), water level and large scale surface currents are best simulated while salinity and sub-surface currents have worst forecasting skills. Major errors in model imperfection are caused by errors related to parameterization (e.g., vertical mixing, numerical diffusion, bottom boundary layer), coupling mechanisms, model numerics (e.g., advection scheme, treatment of steep topography, and two-way nesting scheme) and data assimilation technic. Recently progresses have been made in improving turbulent mixing scheme by using turbulence closure scheme or K-Profile Parameterization (KPP), reducing numerical horizontal diffusion (e.g., hybrid advection scheme) and improving vertical coordinate presentation. Other error sources in model imperfection are from wave-current/water level interaction in shallow waters, bathymetry error, and low model resolution (e.g., model grid can not resolve local Rossby deformation radius) etc.

2.3 *Ocean observing system*

The predictability limits due to initial error, model imperfection and even forcing error, are all related to the coastal ocean observing system. Without sufficient observations, initial fields are normally taken from model forecasts or a climatological mean state. In the long-run, data assimilation is essential in improving operational coastal ocean prediction since the internal dynamics (baroclinic/barotropic instability and nonlinearity) dominated phenomenon (e.g., mesoscale eddies and fronts) are un-predictable without data assimilation. Observations also contribute to the model optimization with model-data comparison and process studies. The boundary forcing of 3D coastal ocean models, such as water level, temperature/ salinity profiles, river run-off etc, can also be improved by the ocean observing system.

Limits are found both in current European ocean observing system itself as well as in using the available observations. The existing observing system is not sufficient in supporting operational 3D coastal ocean data assimilation, validating and improving surface and boundary forcing. Monitoring networks are mainly designed for national and/or regional purposes based on ad hoc strategies. The in-situ observing system can not resolve major scales in shelf and coastal seas. Satellite data have large spatial and temporal gaps in comparison to COPS model grids and most of the data are not delivered in real-time. The best available near real-time (NRT) data are SST and water level in the European coastal ocean. The former has been used to make weekly SST maps with a resolution of about 20km in European coastal waters. There are not sufficient SST measurements to make daily SST maps. On the other hand, the available observations have not been used efficiently in improving operational coastal ocean prediction. In-situ data have not been shared widely among European countries but the situation will be improved in the future snice EuroGOOS data policy has been signed by many institutes. Data assimilation is only performed in 2D surge models with tidal gauge data by KNMI (The Netherlands Meteorological Institute) although data assimilation techniques and data availability in SST and water level are sufficient to make limited improvements in the prediction. COPS models have not been systematically validated against the available observations yet. These issues will be further discussed in next section.

3. COPS extensions: scientific issues

The scientific part in extending the current COPS aims to improve the the coastal ocean predictability in time, space and quality. It should be noted here that the extension is just an expectation with logical ready-go conditions for the future 5-10 years. In time, we expect 10-day coastal ocean prediction will be available. In space, the meso-scale eddy and fronts will be predicted locally but on a routine basis. Regarding the quality, the coastal ocean prediction will be steadily improved through progresses in multi-model based ensemble prediction, ocean-atmosphere coupling, wave-current-water level coupling, observing initial conditions, open boundary conditions and river inputs and data assimilation technic.

3.1 *10-day coastal ocean prediction*

Existing coastal ocean prediction range is 2-3 days, which is sufficient for warning purposes. However there are fairly large demands of longer prediction for planning work in offshore engineering, navigations, oil spill and environmental management and search-rescue activities. Since a large part of the coastal ocean predictability is due to the NWP forcing, we may expect some forecasting skills in coastal physical oceanography if the 10-day NWP products have certain skills. As mentioned in section 2, ECMWF is providing a 10-day prediction with T511 grids (about 40km grid size). Regional high resolution models generally do not make better predictions after 2 days than global models, mainly due to poorer model physics and increasing boundary influences. For the remaining 8 days, data assimilation methods (e.g., 3DVAR or simpler dynamic interpolation) can be used to retrieve hourly surface forcing from ECMWF products with a resolution compatible with the regional model. This ensures that the regional 10-day NWP forcing has a better resolution or at least a comparable quality (in general) than ECMWF model T511 products. Therefore, regional coastal ocean prediction can be made for 10 days and consequently the forecasts results can be assessed.

The 10-day coastal ocean prediction can be processed both in a national, regional, or European level. The basis for realizing the prediction is the data exchange capacity in the corresponding organizations. Current cable line capacity in the national operational centers is not sufficient to transfer the required large amount of model data (say, ECMWF T511 resolution hourly data).

3.2 *Improve Met-ocean service in extreme weathers*

Hurricanes and extra-tropical storms cause severe economic losses in European coastal ocean and continent. Current Met-ocean (METOC) service in extreme weather conditions is mainly made on single regional model products, i.e., deterministic prediction. In many cases, however, only part of the NWP models give reasonable predictions while others fail due to the complexity in nonlinearity, internal dynamic instability and model, initial and forcing errors. For example, ECMWF and German NWP models made better predictions of hurricane in Dec. 3 than HIRLAM models; for the Christmas storms in Dec. 25 and 27, 1999, only Danish and Mexican HIRLAM gave good predictions; In a storm passing the North Sea in Dec. 13, 2000, ECMWF missed the strong wind zone in the North Sea while DMI HIRLAM and UKLAM caught the feature quite well. At the time of prediction, the quality of different NWP models is unknown due to two reasons: one is lack of accessing to the products from all models (i.e., model data exchange) and the other is the lack of NRT model quality assessment system. Therefore the deterministic prediction made by individual national centers may miss the best NWP products available. This leads to a failure in storm weather forecasts and subsequently ill-predicted surges, waves and other ocean elements.

How can we improve this situation? Note the following facts that:

- In storm cases, model error fields at the early forecasting stage (3 or 6h) will propagate to the rest of the forecasting period
- NWP and ocean model skills (weights) can be estimated by using model error fields against observations at the early forecasting stage.
- Ensemble prediction can be made by using forecasts from different NWP and ocean models and their skills (weights)

A system is proposed to fulfill above processes, which includes a data exchange network, a model-data comparison system in NRT and an ensemble prediction system. The data exchange network consists of three components: a weather model data exchange network (W-MODANET) exchanging surface components of NWP products such as surface winds, stress, 2m air temperature, cloud cover and humidity etc; an ocean model data exchange network (O-MODANET) exchanging ocean model prediction and a NRT ocean observation exchange network (OBSNET). This data exchange network should be much faster than the current data dissemination systems in European national weather centers. These data are integrated into model-data comparison system, which analyzes NWP and ocean model qualities at a early stage of prediction and sets weights for the models. With model weights and model products, forecasting samples can be created and the ensemble forecasts can be made for METOC services.

3.3 *Cost-efficient ocean observing system*

It has been recognized in the community that a cost-efficient ocean observing system is a key for the success of future operational oceanography (Prandle et al, 2001). The coming EU 6th Framework Program (R&D) will continuously support European component in the global observing system. The currently funded EU 5th Framework program such as EDIAS and MAMA aim to configure and network the existing ocean observing system in Europe. A natural development in the European ocean observing system is the assessment, optimal design and implementation as necessary of the system.

3.3.1 Assessment of existing coastal ocean observing system

Evaluation of the existing observing system provides information such as spatial-temporal distribution of data redundancy/insufficiency, data usefulness in data assimilation and the physical phenomenon that the system can resolve. This is the premise for integrating and optimizing the observing system. Currently an assessment of the European coastal ocean observing system is not available. Here we briefly describe the principles and methods used in the observing system evaluation. Generally three kinds of approaches can be used: statistical evaluation, dynamical evaluation and semi-empirical evaluation. Statistical evaluation can be conducted by using sampling error analysis, optimal interpolation (OI) and scale analysis. She [1996] evaluated the ENSO observing system which includes TAO buoy array, VOS XBT network and TRITON buoy array. The study gave the spatial-temporal distribution of the sampling error and reconstruction error which clearly demonstrated the distribution of data redundancy and insufficiency in the ENSO observing system. Dynamical evaluation uses Observing System Simulation Experiment (OSSE) which is a sort of sensitivity study to demonstrate the influence of different sampling schemes on the prediction errors caused by, say, initial error and boundary forcing error etc. Only a few examples have been reported by using simplified 3D ocean models [Le Traon et al., 1999]. Semi-empirical methods use ad hoc integrated indicators to evaluate the existing system. One example is given by Bailey et al. [1999]. There are several points that previous studies have not touched. One is the assessment of mixed in-situ and remote sensing networks. Another is that important coupling processes have not been involved in the observing system evaluation quantitatively. Current in-situ ocean observing system aims at observing ocean elements rather than systematic ocean phenomenon. These aspects should be included in the assessment of European ocean observing system.

3.3.2 Integration of existing ocean observing system

For a European coastal ocean observing system, an integration of the existing monitoring resources can be made based on the assessment of the system, as discussed above. Monitoring efforts should focus on high quality operational NRT products, such as daily SST maps, water level, surface wind, wave products and boundary conditions for semi-closed seas. According to in-situ and satellite observation availability, daily SST maps can be derived by mixing measurements from NOAA AVHRR, Meteosat data, VOS, Ferry boxes, platforms, mooring and drifting buoys in European coastal ocean. This kind of SST maps can be further assimilated into the 3D ocean models. 2D surge models can provide water level maps by assimilating tidal gauge and altimeter data. Assimilating SST and water level into 3D coastal ocean models can resolve scales larger than coastal eddies and fronts. In some cases (clear sky), meso-scale features can also be partly resolved. NRT surface winds and wave products can be obtained by mixing in-situ and satellite measurements. They are very useful in checking NWP and wave model NRT quality. T/S Profiles and current measurements in European coastal waters are non-systematic, very sparse and most of them are not in NRT, and can therefore not be used properly in the coastal ocean data assimilation. Do they help coastal ocean prediction and how? The profile measurements should be made along informative sections, i.e., sections containing important physical processes in regional sea level, such as a section crossing the North Sea around 59°N and sections crossing the sills into the Baltic sub-basins. With less resources, the observing system can improve models more efficiently. All these ideas should be quantitatively tested by using OSSE and optimal design theory.

3.3.3 Optimal Observing System Design (OOSD)

OOSD has been a major concern in operational oceanography and climate change studies, such as GOOS, WOCE (World Ocean Circulation Experiment) and OOPC (Ocean Observation Panel of Climate). However, only a few preliminary studies have been conducted, due to the lack of quantitative methods and mature research consortiums. The study needs experts of system evaluation and design, data assimilation, error analysis, information theory, marine monitoring, together with an interested funding agency.

A major reason that we can optimize an in-situ network is that the ocean system has statistically stable inhomogeneous structures, which have different scientific and practical implications, and they should be monitored by using different strategies (sampling density) and instruments. The information content varies with locations. The characteristic scales, spectrum and spatial pattern are statistical basis for optimum observing system design. Sampling density closely depends on these statistics. A comprehensive diagnosis on these indicis are needed before the optimal design can be conducted.

Optimal observing system design (OOSD) means the design is optimal in a cost-efficient sense. Scientifically, a cost-efficient observing system means the minimum system reconstruction uncertainty and maximum system effective information for given amount of resources; economically, a cost-efficient observing system means the minimum investment for given scientific requirements for the system quality. The most challenging work is to form the cost-efficient observing system design into a quantitative framework.

"Cost" means the financial support for the observing system including in-situ and remote sensing components, which may be approximately estimated by summing the total costs of different kinds of instruments and their operational budget, i.e.,

$$C = \Sigma_{i=1}^{i=I} C_i N_i + \Sigma_{j=1}^{j=J} C_j^s N_j^s \qquad (1.1)$$

where C is the cost of the whole observing system, C_i the cost of one i^{th} category in-situ instruments including average cost of production, maintenance and operation etc., and N_i the number of i^{th} category instruments, I is the total number of instrument categories. C_j^s, N_j^s and J are similar with C_i, N_i and I except for satellite sensors. For an in-situ monitoring network, N_i can be further described as:

$$N_i = \int\int_S \frac{1}{L_i(x,y)M_i(x,y)} dxdy \qquad (1.2)$$

where S is the monitoring area, L_i and M_i zonal and meridional sampling distances of i^{th} category of instruments, which are locally dependent.

"Efficiency" means that the observing system should be efficient in making benefits. The benefits mainly depend on the quality of the datasets derived from the observing system and their relevant products, i.e., how useful is the observing system in guiding human activities. Note that the benefits may be different for applying the same datasets on different purposes and with different data dissemination system. This indicates that the benefits also depend on how the information derived from the observing system is used. However, for the simplicity we assume that the data will be used in a way as efficient as possible.

Generally, we have two ways to measure the quality of the datasets and their relevant products. One is to use the integrated error of the observation system, which can be chosen as observation error (including sampling error and instrumental error), noise-signal ratio, analyzed or assimilated initial field error, forecasting error or some weighted summation of these errors. The other is to use "effective information" resolving relevant scales in the observing system. The above two ways are corresponding to the following two categories of OOSD problems. One is for operational prediction and modeling usages and the other is for understanding the important physical processes in the atmospheric and oceanic systems. In the first case, the observing system should have sufficient resolution and accuracy because the error of input datasets is one of the most essential factor to decide the error of modeling and prediction results. Its quality can be measured by an error function, such as measurement error and sampling error for raw datasets, analysis error in objective analysis and/or data assimilation and forecasting errors. This gives rise to two issues for the operational OOSD. One is to design an observation system with the highest data quality (i.e., the system has minimum errors) for a given cost of the system. The other is to design an observing system with the minimum cost for an accepted error. These two OOSD problems can be written as

$$(\mathrm{I})\begin{cases} \min\limits_{L,M}(\int\int_S F(L(\mathbf{r}),M(\mathbf{r}))d^2\mathbf{r}) \\ \Sigma_{i=1}^{i=I}C_iN_i+\Sigma_{j=1}^{j=J}C_j^sN_j^s=constant \end{cases}$$

$$(\mathrm{II})\begin{cases} \int\int_S F(\mathbf{r})d^2\mathbf{r}=constant \\ \min\limits_{L,M}(\Sigma_{i=1}^{i=I}C_iN_i+\Sigma_{j=1}^{j=J}C_j^sN_j^s) \end{cases}$$

where F is an error function.

If one observing system can satisfy the needs of operational prediction, it can be used to study many important physical processes owing to its high data quality. However, this may not be true in opposite. Many observation systems in the ocean do not have as high resolution as required in the operational prediction. The main purpose for designing such sparse sampling ocean observing systems is to extract the information of interesting scales as much as possible with the constraint of the limited costs. One difficulty for this sparse OOSD problem is that we do not know what the real ocean is and the sampling error or noise of the system can not be estimated with enough accuracy by using low resolution datasets. An alternative way is proposed here by only focusing on the effective information but not error at all. Similar to the case of the operational OOSD, two sorts of sparse sampling system designs can be written as follows:

$$(\mathrm{III})\begin{cases} \max\limits_{D}(Inf(D)) \\ C=constant \end{cases}$$

$$(\mathrm{IV})\begin{cases} \min\limits_{D} C(D) \\ Inf(D)=constant \end{cases}$$

where $Inf(D)$ is an information function of the design D, such as variance or physical information (signal) with interesting scales in the ocean. OOSD problem (III) is to design an observing system with maximum useful information of the system for a given cost while (IV) is to design an observing system with minimum cost for a given amount of information of the system.

In OOSD problems (I) – (IV), function $Inf(D)$ and the integration of F are for the whole system and we say that these designs are globally optimal. Observing systems can also be designed in a sense of locally optimal. The global design problem can be solved by simplifying it into many local designs for homogeneous sub-regions under the local homogeneous assumption. The error function F can be estimated optimally by different statistical or dynamical methods, such as sampling error theory, noise-signal ration analysis, optimal analysis and OSSE. She and Nakamoto [1996] showed an example to determine the distribution of the optimal sampling distances in the tropical Pacific for a given sampling error criterion, i.e., the problem I. The study was based on sampling error analysis and optimal design methods. It should be noted that the studies of functions F and $Inf(D)$ for real ocean observing system are very rare. This is an obstacle for further OOSD studies.

3.4 *Pilot experiment: optimal design, field experiment and data assimilation*

Data assimilation has rarely been performed in the 3D operational coastal ocean models due to model imperfection in maintaining energy of meso-scale eddies and short of observations. Without wide data assimilation studies, major benefits from the ocean observing system (i.e., to improve ocean prediction) can not be identified. Optimal observing system design, field experiment and data assimilation experiment are highly related. A pilot experiment group consisting the three components is foreseen as a necessary step to the success of operational oceanography in Europe. Evaluation/integration of the existing ocean observing system and the optimal design study can provide guidance to the field experiment, i.e., the most efficient sampling locations and distances Field experiment and existing ocean observing system construct a new rationalized ocean observing system and can provide data flow to the data assimilation system. Data assimilation in turn proves the value of the new ocean observing system and improved coastal ocean prediction.

3.5 *Fully coupled COPS modeling system*

A fully coupled COPS modeling system includes: a NWP model with compatible resolution, a 3D coastal ocean model (including ice), a 3D shelf model providing boundary conditions for the 3D coastal model, a surge model, a wave model and a drift-dispersion model. The coupling interface consists: ocean-ice-atmosphere coupling, wave-current-water level coupling and wave-atmosphere coupling. The fully coupled COPS modeling system also provides a solid modeling basis for biological, ecosystem modeling and coastal zone change modeling. Recommended research areas include: a consistent surface stress in wave-atmosphere model coupling; impact of breaking waves (droplets) on the surface heat flux in the high sea; ocean-ice-atmosphere model coupling and validation; wave-currents-water level coupling in shallow waters.

4. COPS extensions: technology issues

Besides scientific part of the COPS extension, technology integration and necessary infrastructure are required to ensure the implementation of the extensions.

4.1 *Technology integration*

Existing monitoring technology effectively covers most of sea surface physical variables in operational oceanography. By optimally mixing the existing in-situ observations with satellite observations and rationalize existing monitoring networks, the surface variables can be assimilated into operational models. Previous results exhibited positive effects of the data assimilation in water level, wave and SST. Existing ferry-box technology can provide SST and sea surface salinity in a very high resolution. Satellite remote sensing of surface salinity will come true in the recent couple of years. For assimilation purposes in coastal/shelf seas, a certain mount of in-situ salinity locations will be needed to supplement the low resolution satellite measurements. Surface current can be monitored by HF radar and in-situ sensors. Technology for assimilating surface currents in 3D ocean models has been developed in EuroROSE (a EU MAST-III project). However, it is still far from assimilating surface currents in operational models since the operational surface currents monitoring in a large area has not been available. There are no sub-surface monitoring tools to provide sufficient data for assimilation in the operational 3D ocean models in coastal/shelf seas. The ferry-box technology is currently only feasible for measurements near surface. Moorings ARGO profile drifters are only suitable for deep waters (2000-3000m). There is a urgent need for the community to develop cost-efficient technologies for shallow water sub-surface monitoring.

An approach consisting in an adaption of existing profilers to shallow waters could be an attractive solution. There are two type of Lagrangian profiler: surface drifting and bottom drifting profilers. The former is suitable to be used in the offshore area where surface currents are weak and the latter in the area with solid sea bottom. Currently both kinds of profilers are used only in deep ocean but is possible to be modified for shallow waters. The modified shallow water Lagrangian profiler will provide CTD profiles at regular times (e.g., once or twice a day) at the price of the order of 12K USD per profiler. Its autonomy is of the order of 100 cycles and can be optimized by adding more battery load. The possibility of re-using after recovery and re-furnishment is much larger than the deep ocean profilers. An other kind of profiler is bottom-moored, which can be used in muddy bottom and is efficient in providing open boundary conditions. The cost of the bottom-moored profiler is similar as the Lagrangian profiler. It is still in the development phase. These three kinds of profilers all use ARGOS satellite to transmit data. The low cost of the drifter makes it possible to deploy them in a higher resolution than any other existing in-situ monitoring technologies. The observations will make 3D T/S assimilation and subsequently eddy/front prediction come true in operational prediction.

4.2 *Information dissemination system*

By "information dissemination system" we mean a system for NRT data exchange and value-added post-processing among operational meteorology and oceanography institutes. Data dissemination and value-added processes are also important in users' group but is beyond the scope of this paper. Information dissemination system proposes another limit for the coastal ocean predictability. This is especially the case in Europe, where many NWP models and ocean models are running for operational forecasts and the coastal ocean is monitored by many countries. Data assimilation can not be successful by using observations from a single country. It is essential to share observations in assimilation and model validation. Storms and hurricanes over Europe are governed by complicated mechanisms such as baroclinic instability, nonlinear interactions among different scales and air-sea interaction etc. It is impossible to predict them all correctly with one model. Different models have different skills in forecasting these cases. It is possible to provide a better forecast for extreme weathers by using forecasts from different countries. Coastal ocean numerical prediction is in the same situation which can be improved by sharing model products from different countries. An efficient information dissemination system is needed for member countries to share increasing observations and model predictions.

Due to extreme large amount of data exchanged in the system (up to 1GB/day), existing operational data exchange methods such as GTS and ISDN will not be sufficient. The only possible way is using ftp. Many European Met. Offices have not upgraded their ftp server for years. The speed of the ftp server in most of the Met. Offices is slower than 16MB/second. Hence the information dissemination system should have its member institutes' ftp server upgraded in a compatible level. In addition to this, ensemble prediction based on multi-model products (see section 3.2) needs a central server (or a virtue oceanographic center) to handle the data dissemination and value-added post-processing.

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