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1. Document description

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2. Executive Summary

In the second year of the project most of the Observation System Experriments (OSE) and Observation System Simulation Experiments (OSSE) have entered the main production phase. A significant part of the work has been dedicated to the production of synthetic observations for OSSE experiments and the quality control of existing coastal observations. In several cases it as necessary to modify and tune models and data assimilation schemes in order to obtain the most accurate state estimates. The report shows the measured and simulated impacts of assimilating coastal fixed platforms, FerryBox observations, glider observations, observations by coastal radars and observations by fishing vessels. The impacts cover sveral European Seas in a large variety of environmental conditions.

3. Introduction

In the second year of the project most of the Observation System Experriments (OSE) and Observation System Simulation Experiments (OSSE) have entered the main production phase. A significant part of the work has been dedicated to the production of synthetic observations for OSSE experiments and the quality control of existing coastal observations. In several cases it as necessary to modify and tune models and data assimilation schemes in order to obtain the most accurate state estimates.

Section 4 is divided in seven subsections. Each subsection describes the status of OSE and OSSE experiments by a single partner. In Conclusions we summarise the main scientific results produced in the second year of the project and describe the planned developments in the third year of the project.

5. Main Report

4.1 Adriatic Sea - CMCC

Experiment set-up

OSE experiments

The first OSE experiment is a twin experiment in order to estimate the impact of existing coastal observations in the Adriatic. The experiment is performed in 2006. The observations are obtained from various projects in the Adriatic Sea like the EU project MFSTEP and the Italian project ADRICOSM. The major observational sites are the coast of Emilia-Romagna performed by the Regional Agency for Environmental Protection (ARPA), along the coast of Montenegro in the Southern Adriatic, along the coast of Dalmatia in the Middle Adriatic and along the coast of Istria in the Northern Adriatic. Fig. 4.1.1 shows the distribution of coastal observations performed in the 2006. Here we evaluate how the information from those observations impact both locally and remotely the state estimates of the Adriatic Sea. In particular it is interesting to assess the longer term impact after several months of the assimilation.

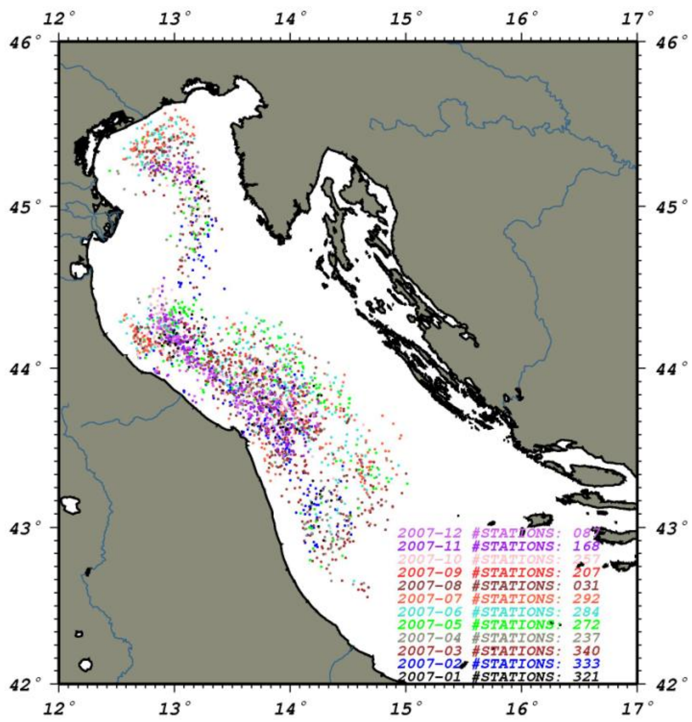

Figure 4.1.1. Positions of temperature observation by fishing vessels in different months of 2007. Observations belonging to each month are plotted by a different color.

The second OSE experiment assimilates historical temperature observations by fishing vessels in the Northern Adriatic Sea. These observations are made by the CNR in the EU project MFSTEP. In the project Jerico they are further processed and checked for quality by the CNR. The distribution of observations in 2007 is shown in Fig. 4.1.1. It can be seen that the fishing vessels made a continuous monitoring of the temperature in the Northern Adriatic. The observations were made mostly along the Italian coast and the central part of the Adriatic, because all fishing vessels originated from Italian ports.

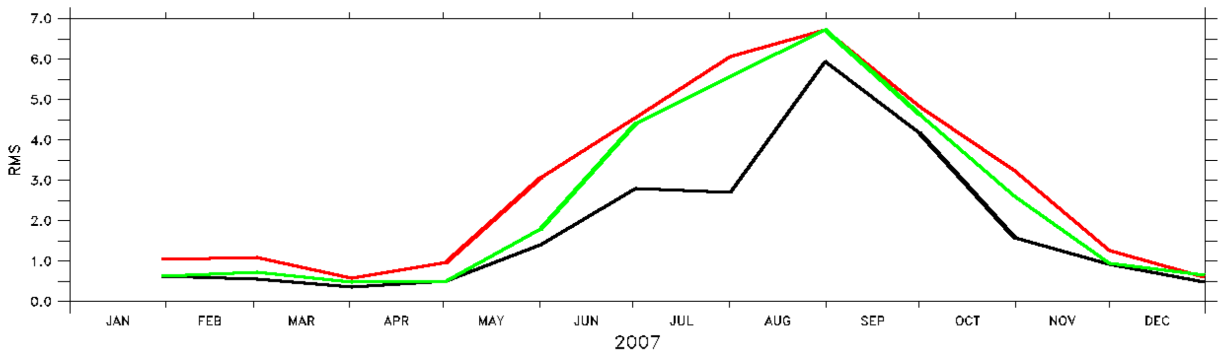

Figure 4.1.2. RMS of temperature misfits calculated by using the observations by fishing vessels in 2007. The red line is for the control experiment, the black line for the experiment with continuous assimilation, and the green line for the short term assimilation experiment. The lower RMS indicates the more accurate forecasts. The RMS is calculated only in the last 20 days of the current month in order to evaluate the long and short term impacts of observations (see text for more details).

The third OSE experiment estimates the impact of coastal observations in the Northern Adriatic Sea on the Mediterranean Forecasting System in its operational set-up. This system has a low resolution of about 6km in horizontal and 3 m thick surface layer. Nevertheless, we may expect that even in this system we may improve the accuracy of state estimates by using the coastal observations,.

OSSE experiments

The first OSSE experiment will estimate the impact of the assimilation of data from surface drifters in the Adriatic Sea. Surface drifters will be simulated in the Adriatic Sea by using the velocity forcing fields produced in an assimilation experiment. These assimilation estimates will represent the real state of the ocean. In the OSSE assimilation experiment simulated surface drifters will be assimilated with all other observations, but the initial condition and the atmospheric forcing will be pertutrbed. In the experiment we will estimate how surface drifters may improve the estimate of the surface circulation and also other physical state parameters like the temperature and salinity distribution.

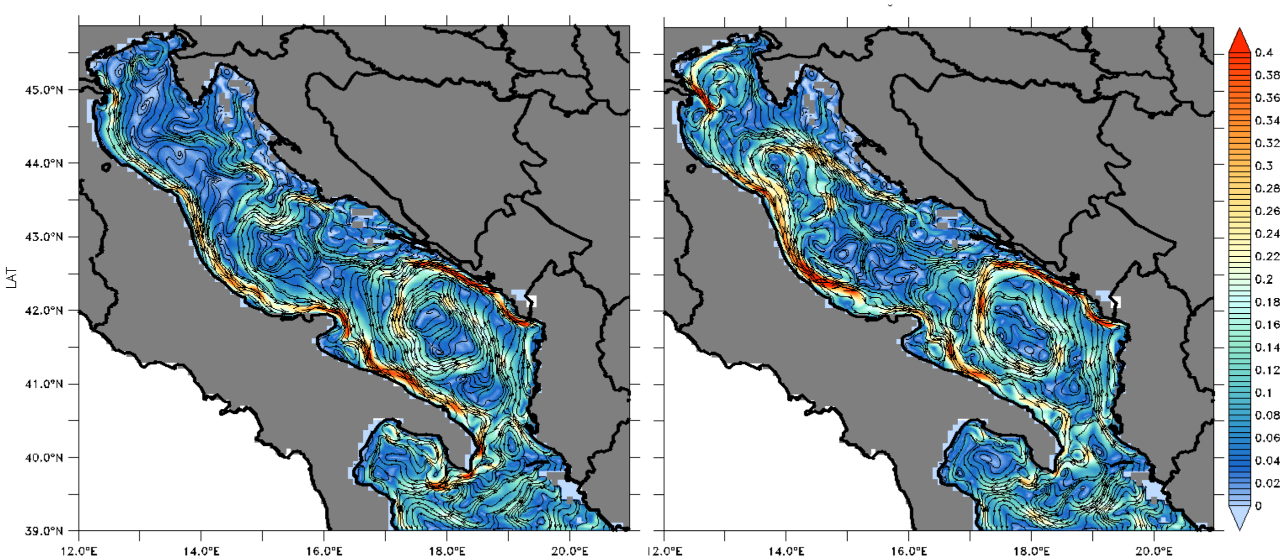

Figure 4.1.2. Intensity (m/s) and direction of surface currents in the control experiment (left) and the continuous assimilation experiment (right) estimated on 31.05.2007.

In the second OSSE experiment synthetic observations of temperature and salinity will be assimilated in order to estimate their impact on the accuracy of the analysis. These observations will have the distribution of the historical observations of temperature by fishing vessels, but they will be assumed to be more accurate and contain both temperature and salinity information. They will simulate the future more accurate instruments for measuring both temperature and salinity that soon will be deployed on the fishing vessels in the Adriatic Sea.

Ongoing development

Assimilation of coastal observations

The first experiments showed that there is a positive impact of coastal observations in areas near the observations. Furthermore, in long term their impact spreads in areas far away from the observational sites. However, due to the lack of insitu observations in remote areas it was not possible to evaluate whteher the long distance impact improves the quality of the analysis.

Assimilation of temperature observations by fishing vessels

The impact of the assimilation of temperature observations by fishing vessels was much easier to evaluate, because it was possible to use the same set of observations that every month covered a large area of the Northern Adriatic (Fig.4.1.1). Three experiments were performed. The first experiment was the control in which no fishing vessel observations were assimilated. The second experiment assimilated fishing vessel observations continuously throughout the 2007. In the third experiment fishing vessel observations were assimilated in a way that every month the analysis was restarted by using the initial condition from the control experiment. This experiment was made in order to estimate how important is the information introduced by observations from the previous month for the accuracy of the analysis in the current month.
Figure 4.1.2 shows the RMS of temperature misfits with respect to temperature observations by fishing vessels before these observations are assimilated. The time of successive passage of a fishing vessels over the same observational point ranges from several days to several weeks. Therefore, the RMS evaluates both short term impacts of several days and longer term impacts of several weeks. The control experiment has a significant increase in the RMS of misfits in summer. This increase is due to the wrong estimate of the depth of the mixed layer which in summer may be even more than 10 degrees warmer than the water below it. The continuous assimilation experiment shows lower RMS of misfits throughout the 2007. In the first half of the 2007 the RMS of misfits is about half of the control, and the difference becomes smaller only in autumn. The experiment with the reinitialization of the background fields at the beginning of each month shows a significantly larger RMS of misfits than the experiment that continuously assimilated the observations. The difference is especially large in summer.
It appears that temperature observations by fishing vessels significantly improve the analysis of the Northern Adriatic temperature in two ways. First, by observing a large area they show a much larger impact than observations localized along the coast. Second, by providing a continuous observations it brings the information on processes that hav a long term impact like the formation of the mixed layer.

Assimilation of coastal observations in the basin scale model of the Mediterranean

The experiment with the basin scale model of the Mediterranean is still in the preparation phase.

Assimilation of surface drifters

The assimilation experiment that produces data from surface drifters is under development. It will produce a long record years of synthetic surface drifter data in the Adriatic. After producing the synthetic observations we will choose the period and areas in which these observations will be assimilated.

Assimilation of synthetic observations by fishing vessels

The synthetic observations by fishing vessels are currently produced at positions where in 2007 the only temperature observations were made. In the next stage these observations will be assimilated in a twin experiment.

Expected problems

The major problem might be that by defining the period and area that are not representative for the complexity of coastal process we may overestimate the impact of observations. This problem can be especially important in OSSE experiments where synthetic observations are generated by a model and therefore do not necessarily reproduce the full signal the real observations can contain. Another important problem is that the it is not possible to increase to model resolution for the so called nature simulation, because the current resolution of the Adritaic model of 2 km is already the highest available.

4.2 North Sea – MUMM

OSE and OSSE experiment setup

Geographical area

The North Sea domain under consideration is located between 4°W to 10°E in longitude and 48.5°N to 60°N in latitude. There are three open sea boundaries: a narrow connection to the English Channel through the Dover Strait, a connection to the Baltic Sea through the Skagerrak, and a wide northern boundary. Its bathymetry varies widely, with large areas that are less than 40 meters deep (Southern and German Bights as well as the Dogger Bank) while there are deeper regions east and west of the Dogger Bank where the depths exceed 90 meters. Along the Norwegian Trench, the depth is up to 700 meters. The most important forcing mechanisms are the tides and the wind. Semi-diurnal tides are predominant at the latitude under consideration. The dominant factor governing the temperature field is the surface seasonal heating and cooling which, in the central part of the North Sea, leads to a thermal stratification of the water column in summer.

Model description

The COHERENS (Coupled Hydrodynamical-Ecological Model for Regional and Shelf Seas) model (Luyten, 2011) is a finite difference model. Simulations are performed with a horizontal resolution of 4 nautical miles in the horizontal and 20 σ -sigma levels in the vertical.

Meteorological data are supplied by the Danish Meteorological Institute (DMI) from the HIRLAM model with a temporal resolution of one hour. Tidal harmonics and daily profiles of currents, temperature, salinity and inflow/outflow conditions at the boundaries of the domain are derived from simulations with the POLCOMS (Proudman Oceanographic Laboratory) model covering a larger area. River runoffs from the Elbe, Scheldt, Rhine/Meuse, Thames, Humber, Tyne/Tees are taken into account. Baroclinic inflow/outflow conditions are imposed at the eastern boundary to include the exchange of water masses with the Baltic Sea.

Data assimilation scheme

The ensemble Kalman filter developed by Evensen (1994) combines the traditional Kalman filter with Monte-Carlo methods to generate an ensemble of states representing the model error. A square root algorithm is applied at the analysis step.

Time of integration

Simulations are carried out for September 2001, a month during which the two dynamical regimes of the North Sea coexist (well mixed and summer stratified). An initial ensemble of states is generated from the 1st of September and is integrated without data assimilation till the 11th of September. The model error is sampled once a day using 50 ensemble members. Eight temperature profiles are assimilated once a day at midnight from the 12th of September till the 28th of September.

Assimilation data sets

The data set consists of 20 temperature profiles. They are extracted at the assimilation time step from model runs generated with the same set-up but with a higher horizontal resolution of one nautical mile. Their impact on the neighboring temperature field is limited by means of an assimilation cutoff radius.

OSE experiments

Eight stations were selected amongst the existing network of stations in the North Sea. Their impact on the model forecasts is compared to that of an optimally designed network of eight stations and two variants of the existing network. Four observational networks are considered:

- the existing network,
- the existing network + 1 station,
- the existing network in which 3 stations are moved,
- the optimally designed network.

OSSE experiments

One critical issue for assimilating data in a coastal zone where temperature and salinity fronts are present is to determine the size of the influence radius of the assimilated data (referred to as assimilation radius). In order to get the largest impact from the assimilation of one observation, the assimilation radius should be as large as possible. However, as thermal fronts might be present, a data at a given location might not be correlated with points in a close neighbourhood.

When observations from fixed locations are available, their influence radius can be determined before performing the simulations. However, in the case of data from a moving platform such as a wave glider or a ferrybox, the data locations differ from one simulation to another. As a result, the influence radius of the data is to be computed during the model run.

To this aim, the spatial homogeneity of the temperature field close to the location of the available data has to be determined at the assimilation step of the model run. Given the coordinates of a data location, the model grid points located within a radius of 70km will be identified and the difference between the modelled temperature at the data location and the selected neighbouring points will be computed. If it is smaller than 1°C, then the selected grid point will be considered as spatially correlated to the data location, and the assimilation process will be applied to correct the temperature at that point. Otherwise, the influence radius of the assimilated data will be assigned to 10km (order of magnitude of the horizontal model grid spacing).

20 temperature profiles will be assimilated each day at a different location to represent the possible trajectory of a moving platform. This will allow to assess the method described above to determine the size of the influence radius of an assimilated data.

Assessment of the impact of observational networks on model forecasts

The impact of the assimilation of data from these networks on model forecasts is assessed in terms of two criteria:

- the reduction of the ensemble spread on the whole North Sea domain [Mourre et al., 2006],
- the root mean square error between the model results obtained with data assimilation and the assimilated data [Wei and Malanotte-Rizzoli, 2010].

Ongoing development

The implementation of the method for computing the assimilation radius is ongoing.

Discussion of some results

Networks description

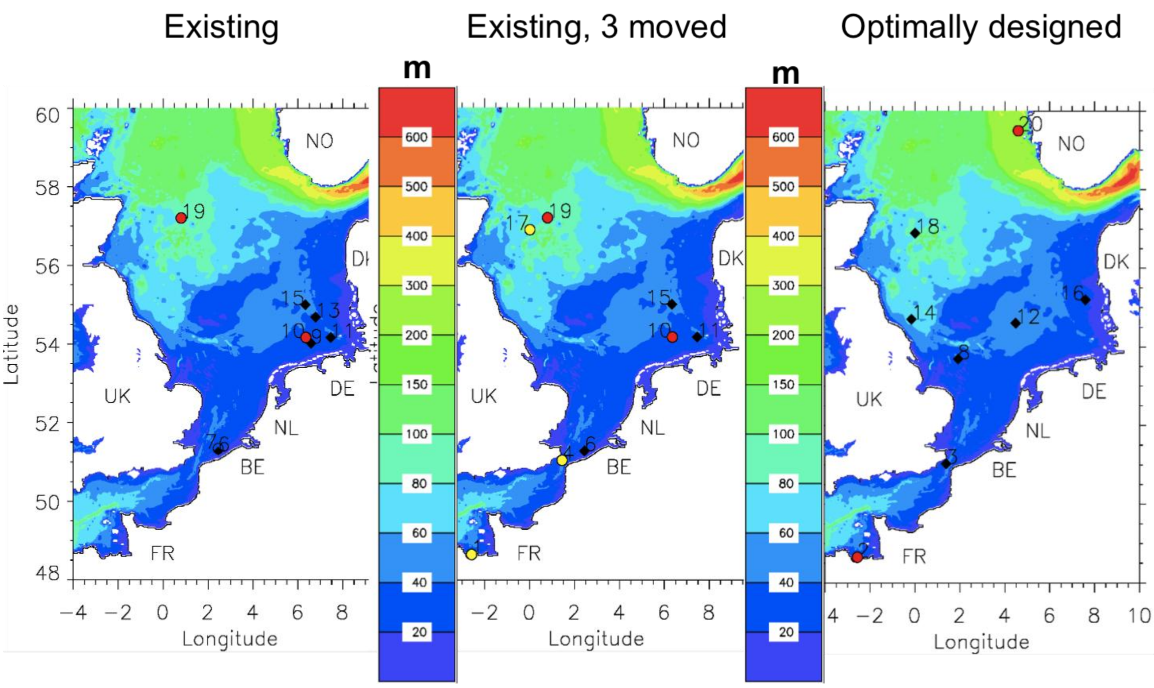

Figure 4.2.1: North Sea observational networks – Left: Existing and existing plus one (yellow dot), Center: Existing 3 stations moved, Right: Optimally designed.

Figure 4.2.1 presents the observational networks that are assessed in the framework of the OSE experiments. The existing network is characterized by an overlap between stations that are essentially located in coastal areas. The center of the panel represents the existing network in which three stations have been moved to get rid of the overlap between stations. The optimally designed network is optimal in the sense that it maximizes the number of neighbouring points to which the stations are correlated. The correlation scales were deduced from SST satellite data [She et al., 2006].

Temperature profiles

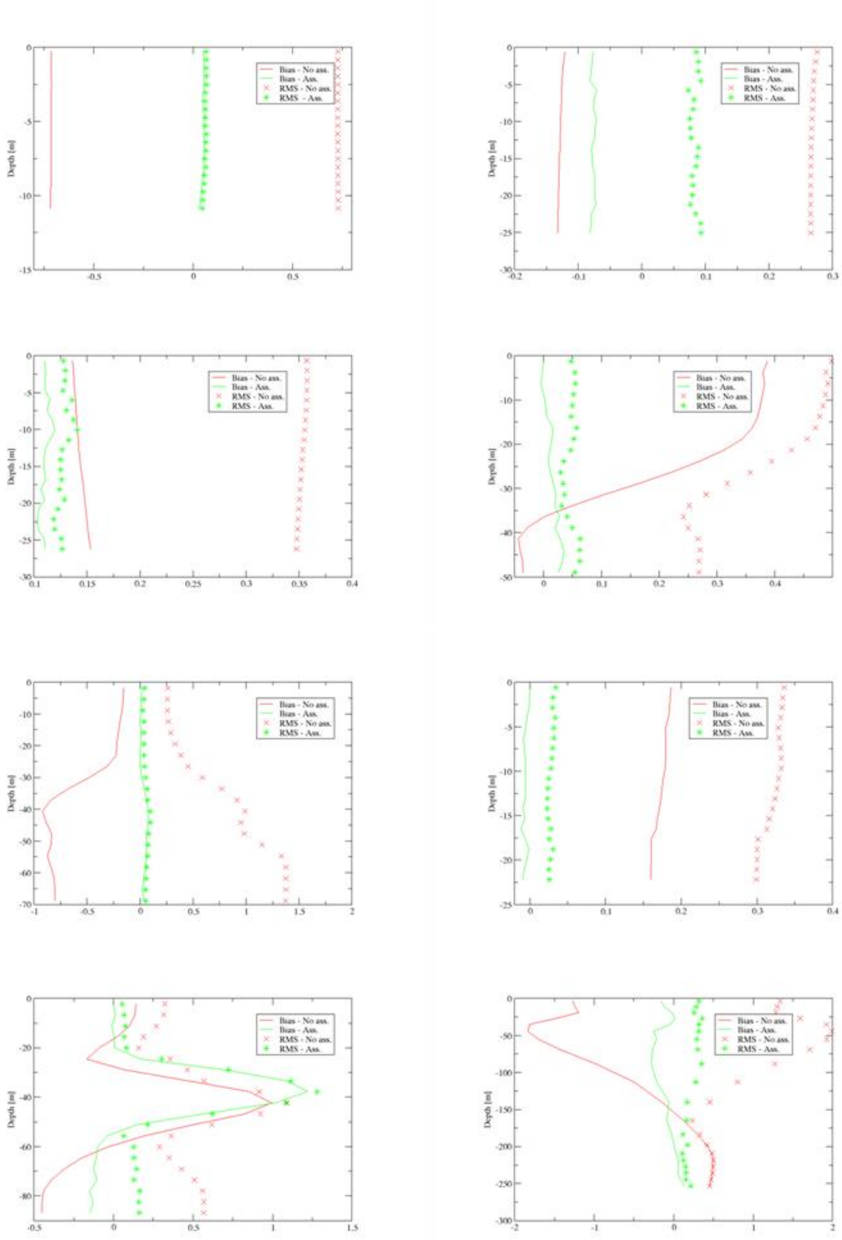

Figure 4.2.2: Root mean square error (symbols) and model bias (straight lines) between the assimilated data and the model results without (red) and with (green) data assimilation – Stations of the optimally designed network.

Figure 4.2.2 presents the root mean square error and model bias between the assimilated data and the model results without and with data assimilation for the eight stations of the optimally designed network.

At all stations, the assimilation process clearly reduces the error between the assimilated data and the model over the whole water column. This indicates that the ensemble Kalman filter is adequate for data assimilation in a North Sea model. However, at station 18, the root mean square error and bias are slightly larger at the thermocline than at the surface and bottom of the water column.

Sea surface temperature

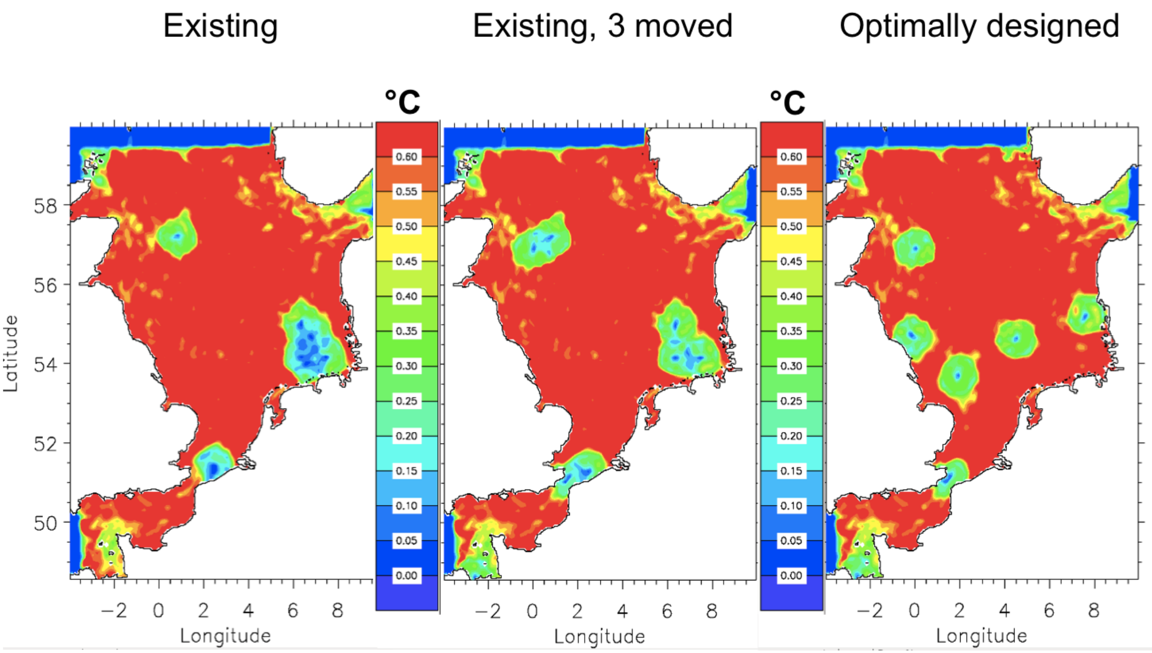

Figure 4.2.3: Standard deviation of the ensemble for the sea surface temperature - Left: Existing network, Center: Existing 3 stations moved, Right: Optimally designed.

One way to assess the impact of an observational network on the model forecasts is the reduction of the ensemble spread induced by that network, with the aim of maximizing the number of points where the ensemble spread is reduced. The ensemble spread for the sea surface temperature is presented on Figure 4.2.3. A comparison of the results for the existing network to those of the existing network in which 3 stations are moved and the optimally designed network indicates that the removal of the overlap between stations improves the observational network efficiency.

4.3 North Sea – DELTARES

Experiment set-up

In this study, the ensemble observation sensitivity technique of Sumihar and Verlaan (2010) is implemented and validated. This technique is originated from the work of Langland and Baker (2004), which provides an approximate of the OSE's method without requiring any data withdrawal experiments.
Here, the observation sensitivity technique is applied to select water level observing stations in the area of Zealand to be used for a data assimilation system for monitoring water level. The KustZuid version 3 model is used as the underlying model and 33 water level observing stations are available for the study of the observation impact (Figure 4.3.1). The observation sensitivity technique is used specifically to select a set of stations that leads to a data assimilation system which satisfies certain target accuracy at a forecast lead time of 0.5 hour. For monitoring purpose, a short lead time of 0.5 hour is considered sufficient. The experiments are done using data from the whole year of 2007.
For validation of the results, a steady state Kalman filter is implemented with the selected set of stations to provide the actual observation impact. The steady state Kalman gain is computed using a technique based on the (El Serafy and Mynett, 2008). OpenDA is used for the data assimilation experiments (www.openda.org).

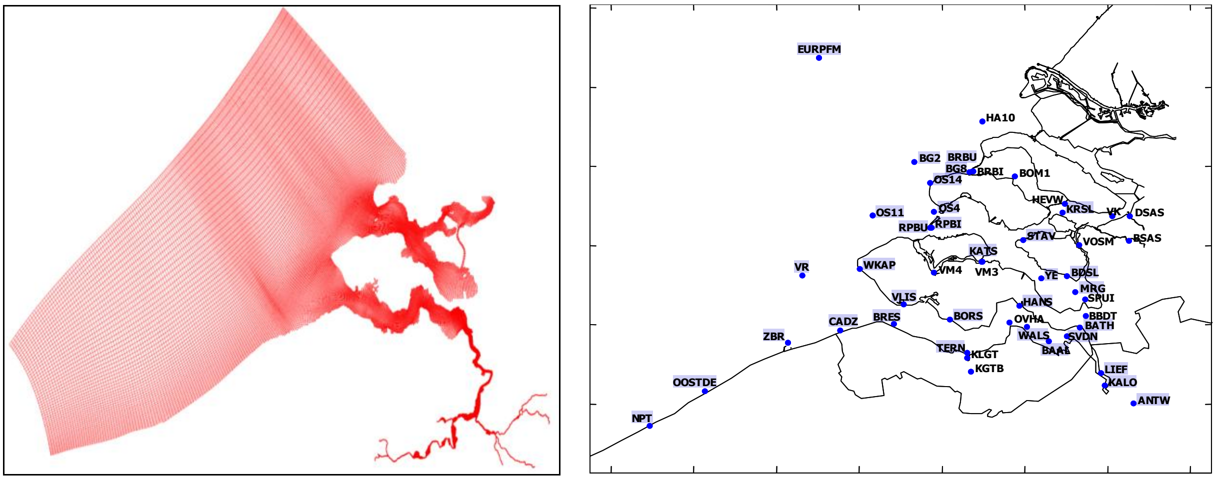

Figure 4.3.1. KustZuidv3 model schematization (left) and overview of water level observing stations in the Zealand Delta area (right). The stations used in this project are highlighted.

Ongoing development

An iterative procedure has been developed for optimalization of the observing network for data assimilation based on the observation sensitivity (Schroevers, et al, 2013). In this procedure, the observation sensitivity technique is used to indicate which observing stations will give most impact on the accuracy improvement and thus will be selected for data assimilation. An example of the observation sensitivity results is shown in Figure 4.3.2. In this study, these results are used to select the stations that will give the greatest positive impact at the forecast lead time of 0.5 hour.

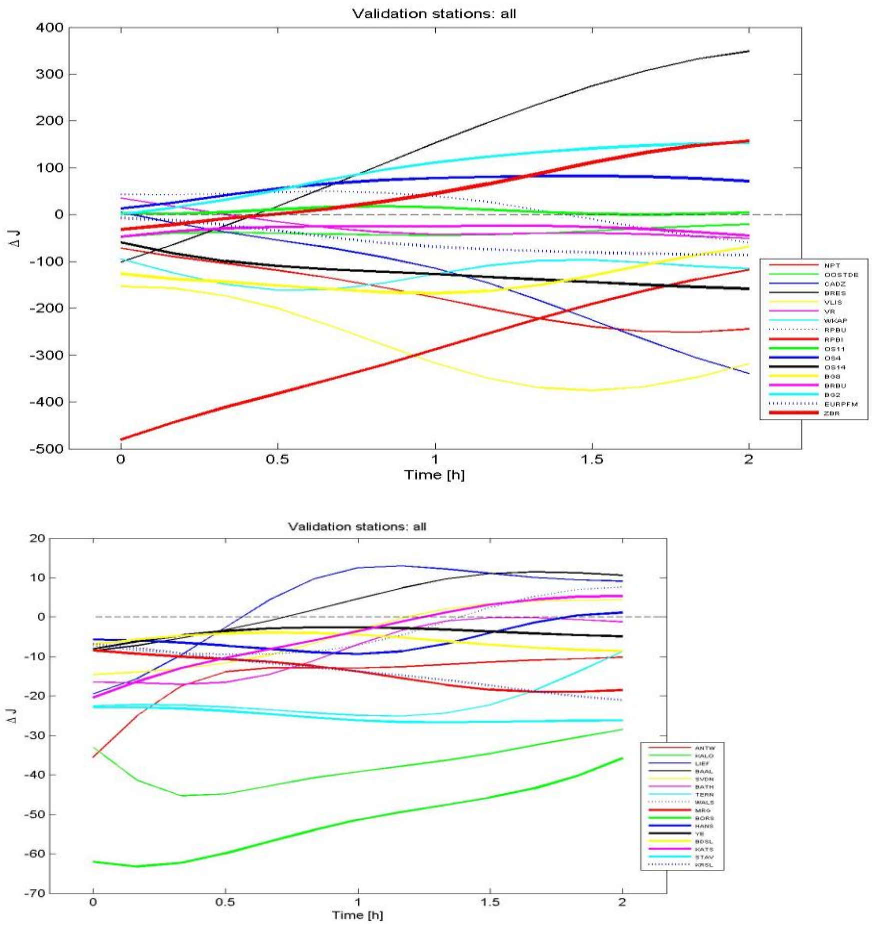

Figure *4.3.*3. Observation impact estimate obtained using the ensemble observation sensitivity technique up to forecast horizon of 2 hours: for off-shore stations (top) and for in-land stations (bottom). The observation impact is expressed in term of cost difference (ΔJ) of with and without data assimilation. Thus negative ΔJ means positive impact. The cost is computed over all the 33 stations.

Three target criteria are defined in terms of the root mean square of the model-observation residuals: 3.5, 5.6 and 10.3 cm. These numbers correspond to model output RMSE of 2.5, 5.0, and 10.0 cm, respectively, assuming that model output error is unbiased and that the observational error is unbiased, independent from model error, and has an RMSE of 2.5 cm with respect to the unknown truth. With this procedure, twelve stations are found to be required in order to satisfy the 10.0 cm criterion at all locations (Figure 4.3.3).

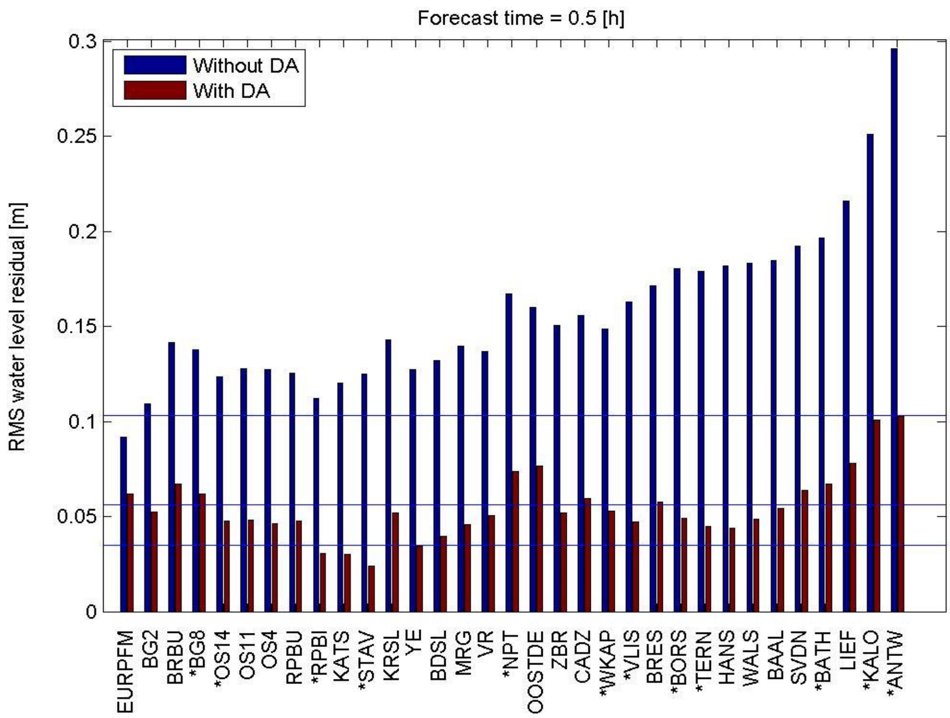

Figure 4.3.3. Estimated accuracy of model output at forecast lead time of 0.5 hour at each location of the observing stations. The blue bars represent RMSD of model output without data assimilation, while the red ones with data assimilation. The three horizontal lines represent target accuracies of model output of 2.5, 5, and 10 cm, respectively. Stations with symbol ‘*’ are assimilation stations.

Discussion on some results

Validation of the observation sensitivity technique has been done by comparing the estimated impact to the actual impact obtained by an actual implementation of a steady state Kalman filter (Figure 4.3.4). These results show that the observation-sensitivity estimated impact is rather too optimistic.

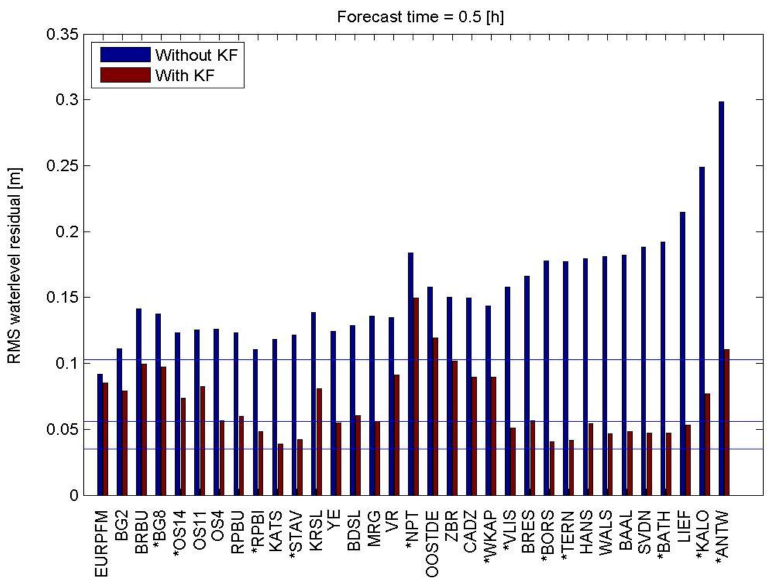

Figure 4.3.4. Actual accuracy of model output at forecast lead time of 0.5 hour at each location of the observing stations.

There are various reasons that can possibly explain these differences. The observation sensitivity method is based on two main assumptions: the underlying forecast model is assumed linear and the model and observational error statistics are assumed constant in time. In this study, the linearity assumption is not validated. However, for short lead time it is expected that the model is linear. The model performance is dependent also on weather conditions. Therefore, the assumption that model error is time invariant may not be valid. Any deviation from the two assumptions will cause the estimated observation impact to be different from the actual impact of data assimilation.

Another characteristic of this method is that the impact of data assimilation on model forecast accuracy is estimated without really running the model from the time of data assimilation until the forecast lead time of interest. Instead, it relies merely on the temporal and spatial error correlation structure as estimated from the time series of observation and model output. In other words, this method does not use the model for propagating the corrected model state in time. In reality, corrected forecast is gained by running the model from corrected initial condition at assimilation time. This difference may also cause the estimated observation impact to be different from the actual one obtained from real implementation of data assimilation.

In the observation sensitivity analysis method, the covariance structure of the model error is determined from the timeseries of observation-model differences. This provides the best estimate about the error correlation at least between the locations used in the analysis. However, in real implementation of data assimilation, error correlation structure should be specified at all grid points of the model. It is practically not possible to use observation-model difference for estimating the error covariance over the whole model area. To work around this problem, it is common in practice to simply assume certain correlation structure with a simple parameterization; this work around is used in this study for developing the actual steady state Kalman filter. This is also another factor that may lead to differences between estimated and actual observation impact.

Despite of the differences, the results show that the estimated impact has a similar spatial pattern with the actual one. This suggests that the observation impact analysis method used in this study is still useful for indicating optimal set of observing stations. However, the actual impact can only be evaluated by actually implementing a data assimilation system.

Eventual problems with experiments and plans to solve them

In these experiments, the open boundary conditions used to force the KustZuidv3 model are not very accurate. The open boundary conditions are specified as astronomical tides plus a spatially uniform surge component, while the surge component is generated by using the Dutch Continental Shelf Model (DCSMv5) at location Europlatform. Moreover, at the river boundary, a constant fresh water discharge of 250 m^3/s and a salinity of 0.3 ppt are used as the river input boundary. All these imperfections lead to an inaccurate water level representation in the model area, which data assimilation alone cannot help to satisfy a target criterion of 5.0 cm or smaller.

A new generation DCSMv6-ZUNOv4 model is currently under development. Earlier validation of this model has shown that it has a much more accurate represention of water level over the North Sea, including Zealand (Zijl, 2013). With this model, data assimilation is expected to be able increase the output accuracy to satisfy the target criterion of 5.0 cm. There is a plan to implement the observation sensitivity technique and to validate it using this model or its smaller version.

4.4 Baltic Sea - DMI

Experiment set-up

Physical model

In the Baltic Sea, DMI is running a two-way nested, free surface, hydrostatic three-dimensional (3D) circulation model called HIROBM-BOOS (HBM). The model code forms the basis of a common Baltic Sea model for providing GMES Marine Core Service since 2009. The finite difference method is adopted for its spatial discretization in which a staggered Arakawa C grid is applied on a horizontally spherical and vertically z-coordinate. The model has a horizontal resolution of about 6 nautical miles (nm) and 50 vertical layers. The top layer thickness is selected at 8 m in order to avoid tidal drying of the first layer in the English Strait. The rest of the layers in the upper 80 m have 2 m vertical resolution. In the Danish Strait, the horizontal resolution is increased to 1 nm to better resolve the complex bathymetry. A detailed description of the model can be found in Berg and Poulsen (2011).

The meteorological forcing is based on a reanalysis using the regional climate model HIRHAM through a dynamic downscaling (including a daily re-initialization) from ERA-Interim Global reanalysis. HIRHAM is a regional atmospheric climate model (RCM) based on a subset of the HIRLAM and ECHAM models, combining the dynamics of the former model with the physical parameterization schemes of the latter. The original HIRHAM model was a collaboration between DMI, the Royal Netherlands Meteorological Institute (KNMI) and MPI. A detailed description of HIRHAM Version 5 can be found in Christensen et al. (2006).

OSE Observations

The observations used in the OSE experiments consist of the ICES temperature and salinity profiles from the International Council for the Exploration of the Sea (ICES) (Figure 4.4.1) and the satellite SST. The two datasets cover a major part of in situ and satellite data in the Baltic Sea. The ICES community now encompasses all coastal states bordering the North Atlantic and the Baltic Sea. The ICES Data Centre accepts a wide variety of marine data and meta-data types into its databases from its members. The SST data is from the DMI database which provides multi-satellite and quality-controlled SST reanalysis data with the resolution of 2 km.

OSSE observations

In the OSSE experiments, we are planning to examine the impact of the simulation systems of repeated XBT lines and moored buoys in the Baltic Sea. The repeated XBT lines are designed to follow the major saline water inflows from the Danish water to the central Baltic. The moored array is set up in 40x40 km grids in the Baltic Sea. The observing system is presented in Fig. 4.4.1.

OSE Experiments

A few OSE experiments will be carried out with the HBM in the Baltic Sea to explore the relative merits of different observing systems. The integration will cover the whole year of 2009. The temperature and salinity profiles will be assimilated with 3DVAR, referred to as Exp01. The satellite SST will be assimilated with the 3DVAR (Exp02), the other conditions are the same as Exp01. Both SST and profiles are assimilated with the 3DVAR in the experiment (Exp03).

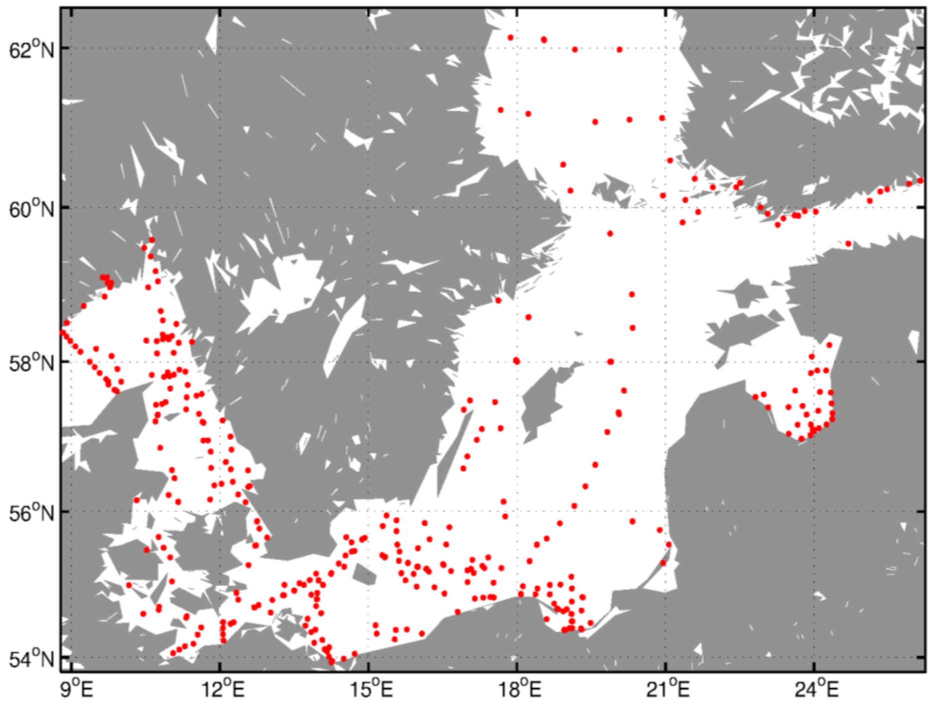

Figure 1, Spatial distribution of the temperature and salinity profiles assimilated during the precursor and inflow event period of 2006.

OSSE Experiments

OSSE with twin experiment approach provides a complete knowledge of the true ocean state and is widely used as proof-of-concept for the data assimilation methods. The OSSE experiments in the Baltic Sea are described as the following. The 'true' ocean state is generated as the unconstrained model run initiated from January 1, 2009. We consider the model boundary and flux conditions as error-free. In addition to the 'true' ocean state, a false experiment is conducted by starting the model from a false initial condition (taken from another year). The temperature and salinity profiles will be assimilated in the false experiment with the 3DVAR to reconstruct the 'true' state. The experiments assimilating the T/S profiles from XBT and moored buoy are initiated from the same initial conditions.

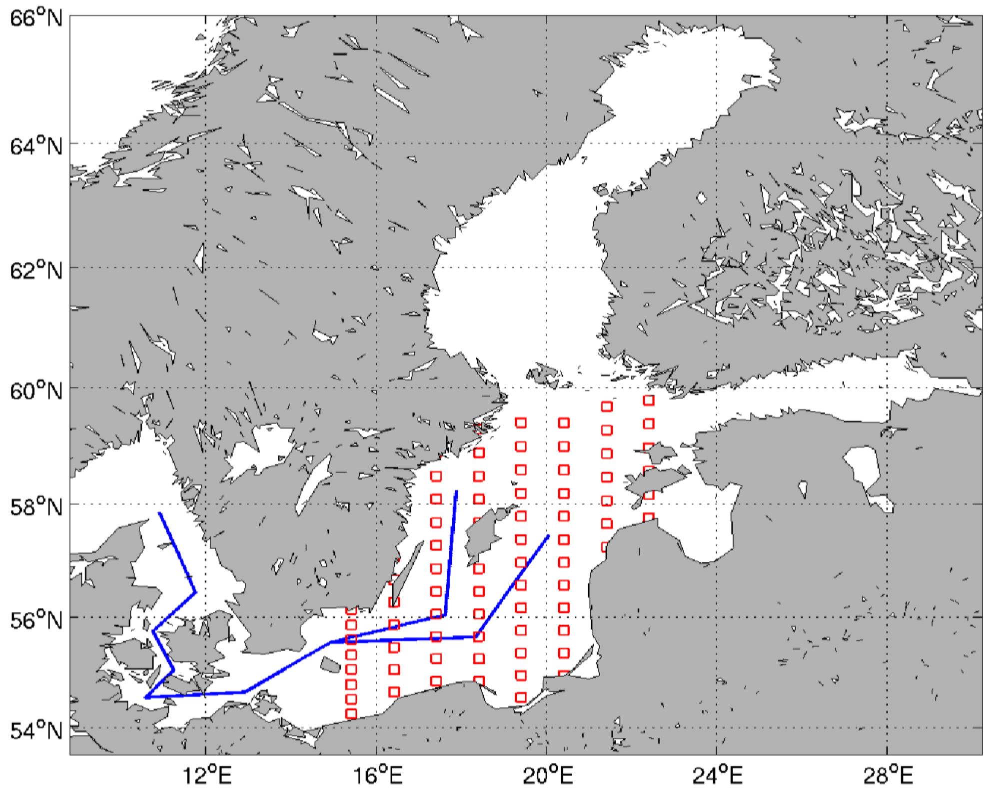

Figure 4.4.2: the observing system comprising repeated XBT lines (blue lines) and moored buoy array (red square).

Ongoing development

OSE

We are now testing the SST assimilation with the 3DVAR in the Danish water. From some preliminary results, we find that the root-mean square error (RMSE) of SST is notably reduced after the satellite data is assimilated. Fig 4.4.3 presents the evolution of the RMSE of SST from January 2 to February 5, 2009. The RMSE is generally reduced by 0.2ºC in the Danish waters. In addition, some eddies are more pronounced after the assimilation (figure not shown).

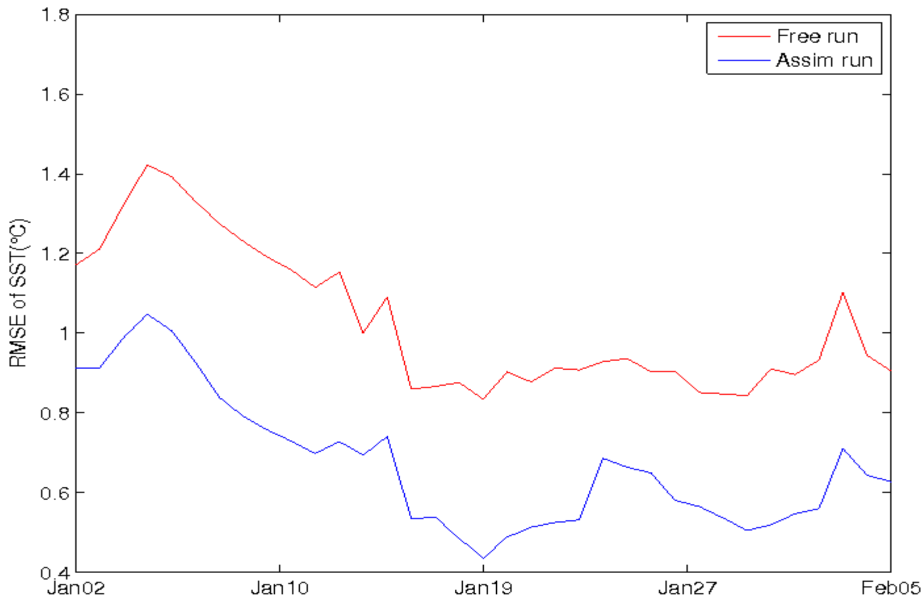

Figure 4.4.3: the Root mean square errors calculated against the satellite SST for the North-Baltic Sea.

OSSE

The ‘true’ ocean state can be generated from the current HBM with a horizontal resolution of 10 km. Twin experiments are being conducted for the time being in 2006. We are investigating the capacity of the assimilation to restore the ‘false’ model state to the ‘true’ state. A finer resolution model version (about 5 km in the horizontal) is also running in the DMI. It is an alternative to use the ‘true’ ocean state taken from the higher version of the HBM. Simulated observations are also sampled from the HBM model with the resolution of 5 km in the Baltic Sea. In addition, the design of the frequently repeated XBT lines and moored array are being tested by shifting positions/lines of the simulated routes and array

Problems and plans to solve them

Due to complicated bathymetry, the assimilation is confronted with more challenges in the Danish Water than the open seas. The background error covariance requires particular treatment to properly distribute observed information near the coastline. Guassian distribution is shown to be a poor approximation in the Danish waters (Fu et al, 2011). It is demonstrated that the assimilation could reduce the root-mean-square error of temperature and salinity. However, the sea level and barotropic velocity across the Danish Strait are only slightly improved (Fu et al, 2012). There are a few problems to be addressed to ensure a good state estimation in the Baltic Sea. Firstly, to avoid strong 'shocks' to the model state, magnitude of the innovation (model-obs) must be limited at the beginning of assimilation; Secondly, the background error covariance needs to be improved in the coastal regions. Thirdly, representative error of observations should be handled. For instance, spatial smoothing is needed for SST to filter out very small-scale eddies, which could degrade the reanalysis since the small eddies cannot be resolved with the current model configuration. The satellite observations with a resolution of 2 km contains some eddies that cannot be reproduced by the model.

Background error covariance will be defined as a non-Guassian function in the Baltic Sea as suggested by Fu et al. (2011). The spatial correlation in the coastal regions may be better represented with the new exponential function. For the SST assimilation, spatial smoothing is used and the observations are binned as ‘super-obs’ similarly as in Oke and Sakov (2008).

The central Baltic Sea is strongly stratified with a mean thermocline at the depth of about 40-60 m. In the bottom layer, the residence time of deep waters is of the order of years until the major saline water inflows occur irregularly. The current model is inadequate to resolve the major saline water inflow from the Danish Strait to the central Baltic. It is of particular interest to investigate if the designed observing network can much improve the high saline water inflow and the transport through the Danish Strait. The barotropical transport is controlled by the sea level pressure different in the North Kattegat and the east Arkona Sea. Some results show that 3DVAR slightly improve the transport by assimilating the temperature and salinity profiles (Fu et al, 2012). The transport estimation is now further explored within the OSSEs.

4.5 North Sea - HGZ

Experimental set-up

Numerical Model

The German Bight, which is dominated by tides with a typical tidal range of 2-3 m and a dominant period of 12.4 hrs, is part of the North Sea. The largest non-tidal variations are caused by atmospheric low pressure systems, either as external surges from the North Atlantic or internally generated surges. During strong storm events water levels can exceed 4 m above mean sea level. The German Bight is furthermore characterised by very shallow water with Wadden Sea areas falling dry during low tide.

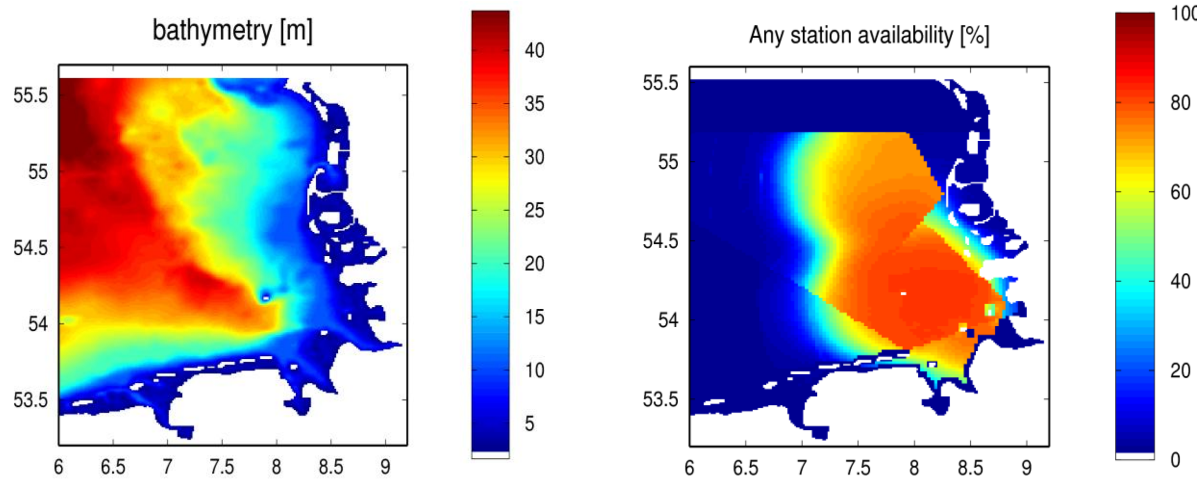

Figure 4.5.1: (left) Bathymetry of the German Bight used in the numerical model runs. (right) Availability of at least one radial component from one of the three existing HF radar stations located at Wangerooge, Buesum, and Sylt.

In JERICO the 3-D numerical model GETM (Burchard and Bolding, 2002) is used to simulate the hydrodynamic processes in the German Bight. GETM is a primitive equation model, in which the equations for the three velocity components and sea surface height, as well as the equations for turbulent kinetic energy and the eddy dissipation rate are solved. The bathymetry of the 203 km by 258 km model domain is shown in Fig. 4.5.1. The application of the model to the area of our study is described in Staneva et al. (2009). The model is run on a spherical grid with 1 km resolution. Terrain following equidistant coordinates (σ-coordinates) are used in the vertical. The water column is discretised into 21 non-intersecting layers. The model is forced by 1) atmospheric fluxes estimated by the bulk aerodynamic formula using 6-hourly ECMWF re-analysis data (wind, atmospheric temperature, relative humidity and cloud cover) and simulated by the model SST, 2) hourly river run-off data provided by the Bundesamt für Seeschifffahrt und Hydrographie (BSH), and time varying lateral boundary conditions of sea surface elevations and salinity.

OSE observations

In the framework of the COSYNA project HF radar stations were installed at the islands of Wangerooge and Sylt as well at the mainland near Büsum.

A WERA (``Wellen Radar'') system (Gurgel et al., 1999) is used. The Wangerooge station uses either 12.1 or 13.5 MHz depending on transmission and reception conditions. The corresponding radar wavelength range from 22 m to 28 m and the associated ocean wavelength λBragg relevant for the radar scattering process thus have wavelength between 11 m and 14 m. The depth of the ocean surface layer sensed by the radar can be estimated as 1/(4 pi) λBragg ≈ 1m.

Radar measurements are taken by the three stations using an integration time of 9 minutes. The integration windows are centred at 4 min 26 sec, 23 min 26 sec and 43 min 26 sec after each full hour. The range and coverage achieved by the antenna stations is illustrated in Figure 4.5.2 (right). Colors indicate the percentage of available measurements for the three stations. Figure 4.5.2 (right) shows the availability of radial current measurements from at least one station.

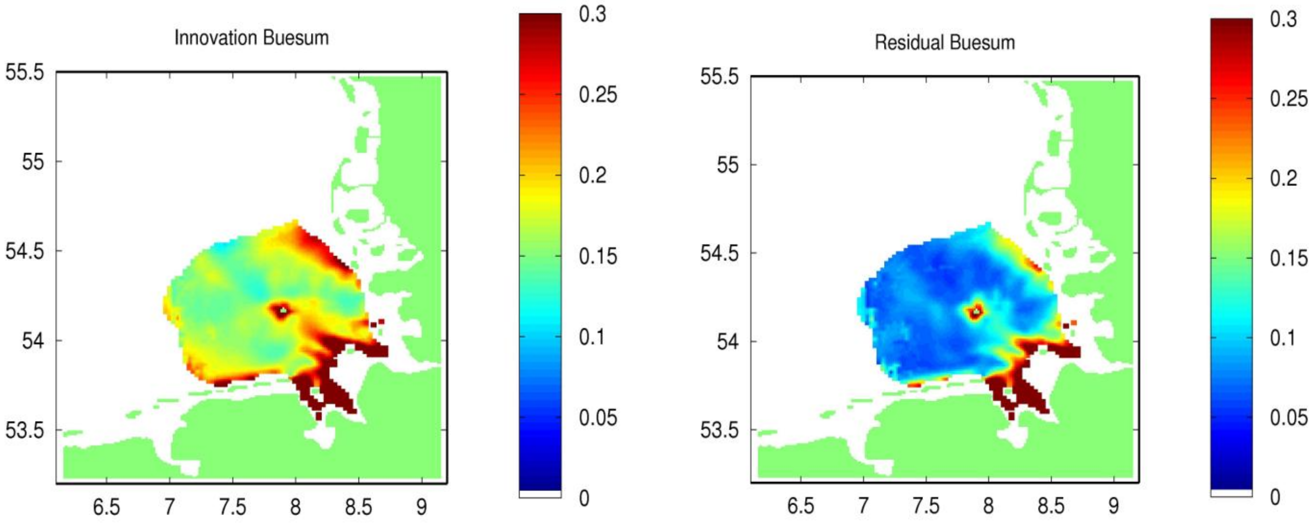

Figure 4.5.2: Innovation (left) and residual for the radial current component of the Büsum station.

OSSE observations

A FerryBox is an autonomous measurement, data logging and transmission system, which operates continuously while the carrying ship is on its way (Petersen et al., 2007). Measurements are made using devices, which are either in direct contact with or sample from a continuous flow of seawater taken from a water depth of 4-6 m. The vessel position is tracked by Global Positioning System (GPS). It is connected to a station on shore via Global System for Mobile Communications (GSM) or satellite for remote control and data transfer. The basic sensors used in this study measure turbidity, temperature, salinity, and chlorophyll a fluorescence.

The North Sea routes so far equipped with FerryBox systems are the ones between Buesum and Helgoland, Cuxhaven and Harwich, Cuxhaven and Immingham (compare Figure 4.5.3) and recently between Hamburg, Cuxhaven, Chatham, Moss and Halden. The typical cruising speed is 15 knts. The sampling rate is 10 seconds. Depending on the travel distance, the routes provide the following revisit times: Buesum-Helgoland, daily, Cuxhaven-Immingham, less than 36h, Hamburg-Cuxhaven-Chatham-Moss-Halden about 8 days. The Ferry routes do not change substantially. However, individual tracks show small deviations one from another. Therefore, to simplify the analysis we relate the data to an averaged track. The maximum deviations from the averaged track can reach 10km.

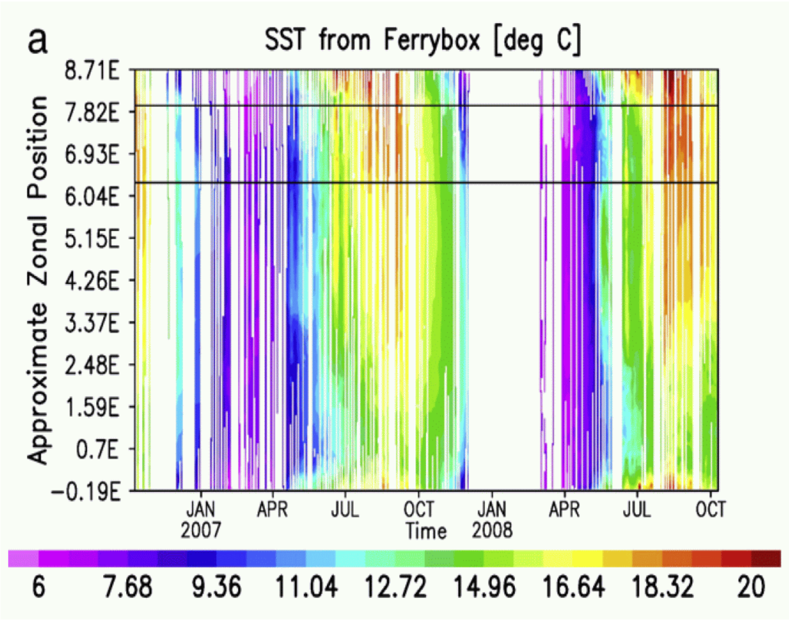

Figure 4.5.3: Example of SST data acquired by the FerryBox system operating between Cuxhaven and Immingham.

Analysis Procedure: OSE experiments

Numerical model and HF radar data were combined using a spatio/temporal optimal interpolation (STOI) technique, in which observations and model results available within a certain period typically covering one tidal or more tidal cycles are merged in a single analysis step. The method also enables the computation of short term forecasts. The statistical analysis was performed using measurements and free model runs from the year 2011. Experiments were conducted using 1) different forecast horizons 2) different assumptions about model and observation errors and 3) different length of the analysis windows.

Analysis procedure: OSSE experiments

OSSE experiments were performaned using the approaches described in Grayek et al. (2011) and Schulz-Stellenfleth and Stanev (2010). The first approach is a modified optimal interpolation technique with dayly model restarts. The second technique uses a statistical method to estimate error bars for state estimates based on model and observation errors.

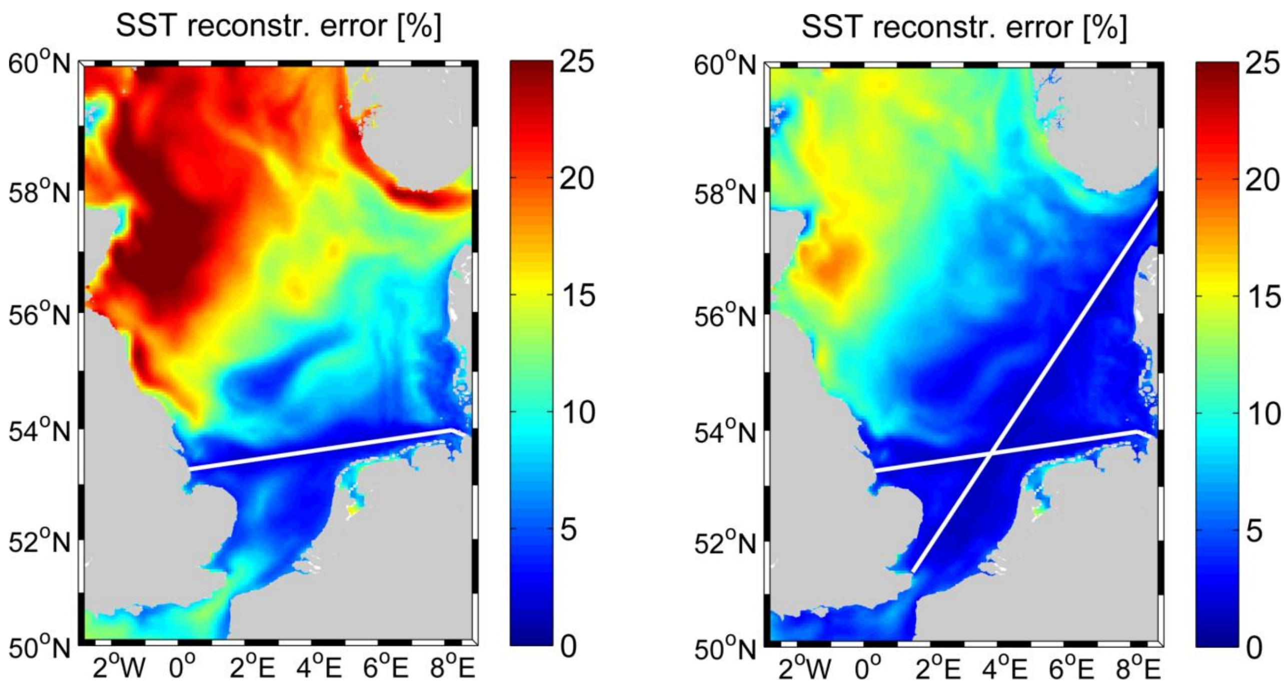

Figure 4.5.4: Relative re-construction errors for sea surface temperature using one (left) and two (right) FerryBox lines.

Discussion of some results

OSE experiments

It was demonstrated that the method is able to improve the agreement with the HF radar observation data. Figure 5.5.2 shows the respective innovations (difference between free run and observations) and the residual (difference between the analysis and the observations) for the radial current component of the Büsum station. One can see that the rms values are in fact smaller for the residual than for the innovation for the most part. Only in the very shallow water regions close to the coast where both the numerical model and the HF radar are expected to have bigger errors the reduction is not as strong. It was furthermore shown that the HF radar data are able to improve the surface current forecast over a period of at least 6 hours.

OSSE experiments

As an example Fig. 4.5.4 shows the relative errors to be expected from combined use of FerryBox and numerical model SST data. The errors are normalised, i.e. given in percent with respect to the background variance. The situation with one FerryBox line (left) is compared to a configuration with one additional line further North. One can see that the additional line has a significant impact on the SST errors.

Ongoing developments and problems

There are no basic problems with the OSE experiments. The focus of the ongoing work is on the extension of the forecast period. This requires further detailed analysis of the errors in the numerical model an their respective temporal and spatial scales. The observation and model data to perform this analysis are available and a clear strategy to do the work has been developed.

There are no significant problems with the OSSE experiments. One important issue is the additional use of satellite based SST maps (e.g. OSTIA data) in the analysis. The quantification of the benefit of FerryBox SST data in relation to these data needs some further careful analysis. The situation is different for FerryBox surface salinity observations for which no spaceborne counterpart for the coast yet exists, i.e. there are not many alternatives to the FerryBox. The analysis of SSS data is more challenging than the use of SST observations, because the correlation length are in general shorter, i.e., it is more difficuilt to spread the information provided by the observations.

4.6 Bay of Biscay and Irish Sea - IFREMER

Experiment set-up

As described in the previous report, experiments are based on the MARS3D model. MARS3D (http://wwz.ifremer.fr/mars3d) is a coastal model based on primitive equations (Lazure and Dumas, 2007; Duhaut et al., 2008). The model was designed to simulate flows in various coastal areas from the regional scale down to the inshore scale of small bays or estuaries where circulation is generally driven by a mix of processes. The spatial grid resolution is 4Km and sigma vertical coordinates (30 levels) are used.

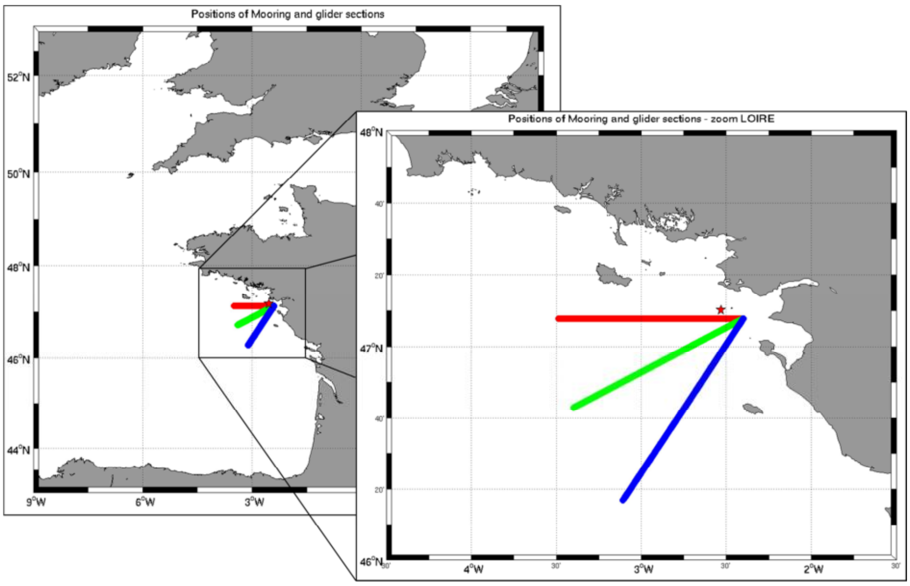

Figure 4.6.1: Design of the observation network to monitor the Loire river plume including a fixed mooring (red star) and a glider section (3 possible trajectories: East-west reference section – red, first option – green, second option – blue).

Based on this model and ensemble experiments, the Representer Matrix Spectra (RMS) method (Le Hénaff et al., 2009) has been implemented to optimize a network design without running a fully assimilated system.

The method has been applied on three observation networks:

- the RECOPESCA network, based on voluntary vessels (described in previous report)
- a local network to monitor the Loire river plume, based on glider and fixed mooring (Figure 4.6.1)
- a cross-Channel section combining Ferrybox and glider (Figure 4.6.2).

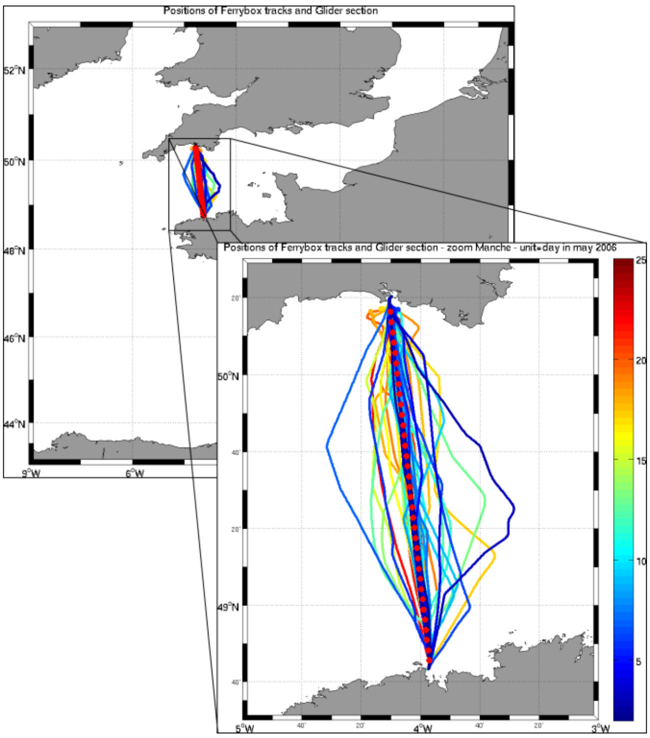

Figure 4.6.2: Design of the observation network in the western part of the Channel including Ferrybox lines (coloured lines) and a glider section (red dotted line) along the Roscoff-Plymouth transect. The colorbar displays days during May 2006.

Discussion on some results

The use of the RMS method allows exploring the model error subspace (in Temperature and Salinity) and highlighting the importance of the vertical sampling (using glider) to describe model uncertainties in coastal regions.

For the experiment close to the Loire river plume, results show that the combination of gliders with a moored station is appropriate to describe the model error subspace. As shown on the RMS spectrum (Figure 4.6.3), the combined configuration (glider + moored station) constrains a larger number of degree of freedom. However, three glider trajectories display similar efficiency to describe most of model error subspace structures. This lack of sensitivity to the glider trajectory can be generalised to the cross-shore glider trajectories starting from a point close to the river estuary. This experiment does not allow concluding using along shore or trajectories South or North of the river plume.

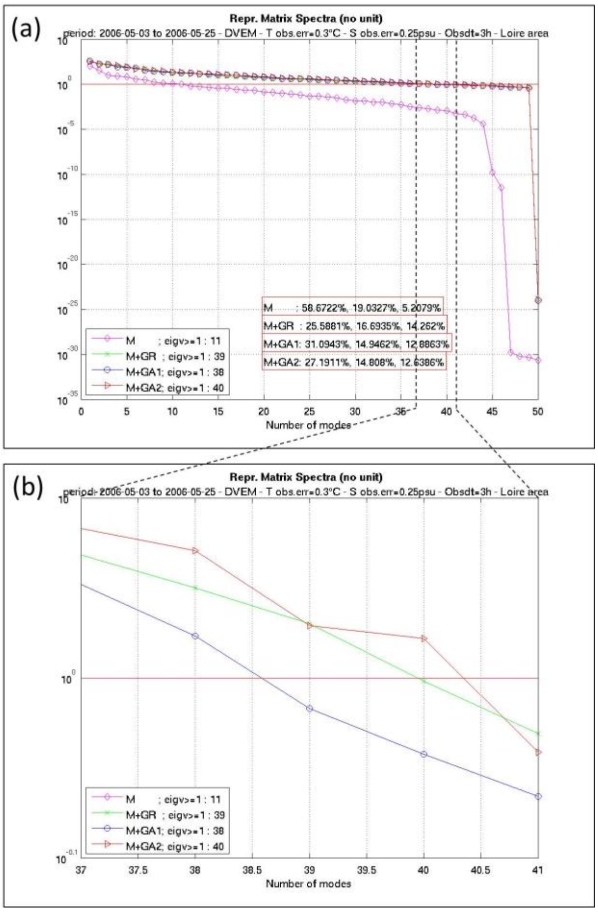

Figure 4.6.3: (a) RMS spectra, computed for the three combined network (glider + mooring), and for the moored buoy only. Period : 03/05/2006 – 25/05/2006. (b) Zoom on the area wher curves cross the threshold equal to 1.

In the western Channel, both in situ observation networks are analysed along a Roscoff-Plymouth transect. The first network includes the FerryBox (with subsurface temperature and salinity measurements) and the second network combines this FerryBox with a glider section (similar to those proposed in the Loire river region).

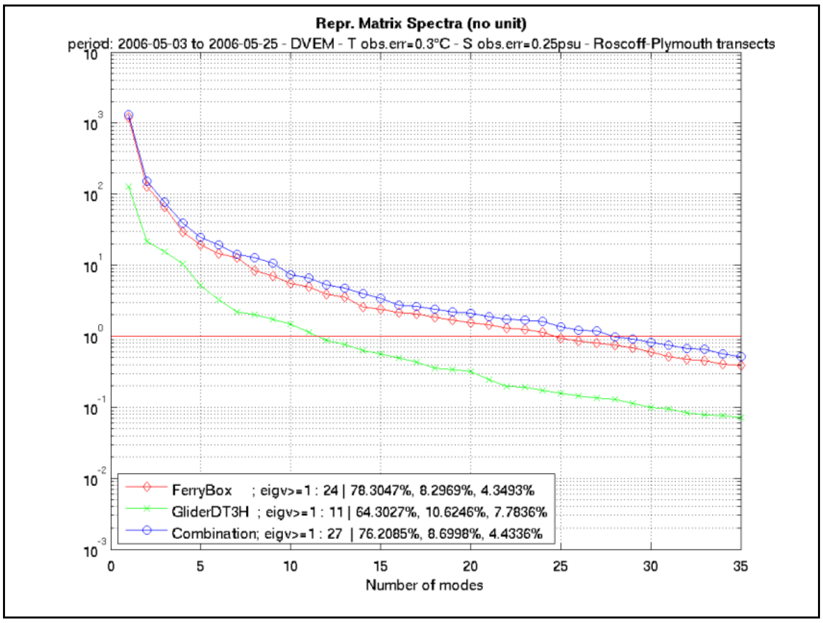

Figure 4.6.4 : Representer Matrix Spectrum for the three networks in the Channel : FerryBox only (red), glider only (green), and FerryBox + glider (blue).

This RMS analysis highlights the efficiency of the FerryBox only to describe the model error subspace even if it collects only surface measurements. Indeed, due to the high frequency spatio-temporal sampling (the FerryBox cross the Channel until twice a day when the glider needs several days to flow on the same distance), this network displays better performances than the glider (Figure 4.6.4). However, these two platforms appears as complementary with a larger of degree of freedom described by the combined network (glider + FerryBox).

This study needs further investigation to quantify the role of the glider to detect model error at depth as expected from this vertical profiling platform.

Eventual problems with experiments and plans to solve them

These experiments allowed first evaluation of observation coastal networks in the Bay of Biscay and the Channel. However the size of ensemble (50 members) is a limiting factor in the study. Further investigations, beyond the scope of the present work, would need the generation of ensemble with a large number of members.

4.7 Aegean Sea - HCMR

Experiment set-up

Numerical model

The Aegean Sea model is based on the Princeton Ocean model (POM) and was developed as part of the Poseidon system. The model domain covers the geographical area 19.5^{o}E – 30^{o}E and 30.4^{o}N – 41^{o}N with a horizontal resolution of 1/30^{o} and 25 sigma layers along the vertical with a logarithmic distribution near the surface and the bottom. The model is forced with hourly surface fluxes of momentum, heat and water provided by the Poseidon - ETA high resolution (1/10^{o}) regional atmospheric model [1] issuing forecasts for 72 hours ahead.

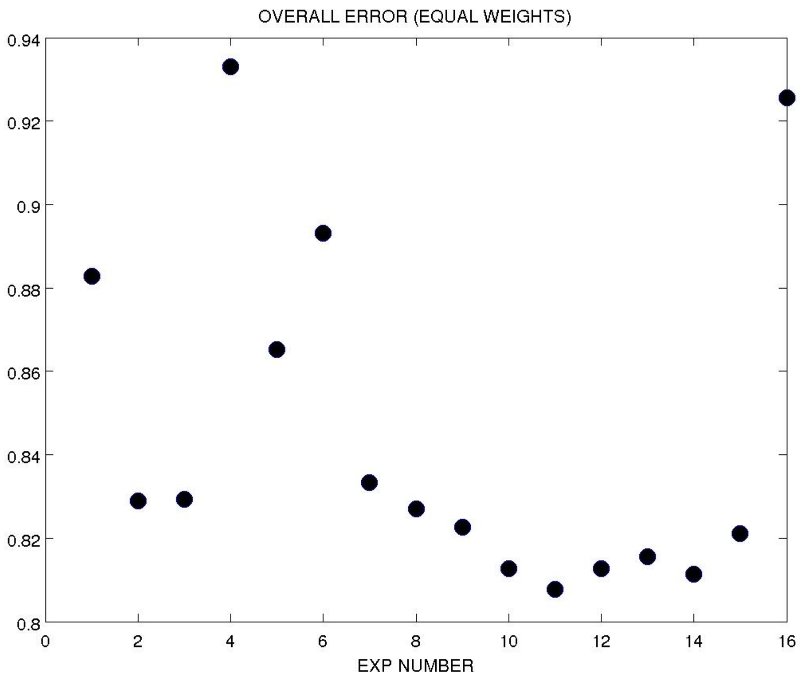

Figure 4.7.1: Combined model error (with respect to SSH, SST and HF Radar current measurements) for a series of 16 experiments performed over year 2010. Error minimization is achieved of EXP11.

In the Aegean Sea model the Dardanelles inflow/outflow is parameterized as an open boundary where a two layer system is explicitly prescribed with inflow of fresh Black Sea Water (BSW) in the upper layer and outflow of saline Aegean waters below.

The inflow/outflow transports follow a seasonal cycle with maximum values of inflow to the Aegean during mid-June (0.01 Sv) and minimum during mid-November (0.005 Sv). The salinity of the upper layer is set to 28.3 psu with a seasonal variation of 2 psu while the interface depth is kept fixed to 25m. The inflow/outflow transport values at the Dardanelles exit and the time of the occurrence of their maximum/minimum values that have been used in the model experiments described in this work differ from the standard version of the Aegean Sea model. In order to choose the optimal values of the above parameters, a series of sensitivity hindcasting experiments have been performed where the criterion of the minimization of the model error with respect to different sets of observations over the North Aegean Sea area has been used. In Figure 4.7.1 we present the combined model error with respect to the three sets of observations (gridded satellite SSH & SST and HF Radar surface current measurements) over the North Aegean Sea for year 2010 and the series of 16 experiments. Error minimization is achieved for the experiment where maximum inflow of 0.01 Sv to the Aegean is assumed at the end of May.

Table 4.7.1: Description of the different experiments performed with the Aegean Sea model

Experiment	Period of model integration	Observations	Frequency of data assimilation
EXP0	05.04.10 – 31.12.10	Satellite SSH-SST and T/S ARGO profiles	Weekly
EXP1	05.04.10 – 31.12.10	Satellite SSH-SST and T/S ARGO profiles. Zonal and meridional surface velocity components from HF Radar	Weekly
EXP2	05.04.10 – 31.12.10	Satellite SSH-SST and T/S ARGO profiles. Zonal surface velocity components from HF Radar	Weekly
EXP3	05.04.10 – 31.12.10	Satellite SSH-SST and T/S ARGO profiles. Meridional surface velocity components from HF Radar	Weekly

Assimilation system

The assimilation scheme used by the Aegean Sea forecasting system, is based on the Singular Evolutive Extended Kalman (SEEK) filter which is an error subspace extended Kalman filter that operates with low-rank error covariance matrices as a way to reduce the prohibitive computational burden of the extended Kalman filter (Pham et al., 1997). The filter is additionally implemented with covariance localization and partial evolution of the correction directions.

Observations

The standard assimilation system for the Aegean Sea model inserts on a weekly basis AVISO gridded (1/8^o) absolute dynamic topography (ADT) observations for the Aegean Sea area, gridded (1/16^o) AVHRR SST data, T/S ARGO profiles and temperature profiles from any available XBTs over the area, using the time evolving filter statistics and the model forecasts in order to estimate the innovations. The AVISO gridded maps of absolute dynamic topography are produced by merging all available satellites into one regional product available at near real time for the Mediterranean Sea. Additionally daily averaged surface currents over year 2010 from the WERA HF radar system installed at the eastern coast of the island of Lemnos are used in order to examine their effect to the estimation of the hydrodynamic state of the Aegean Sea.

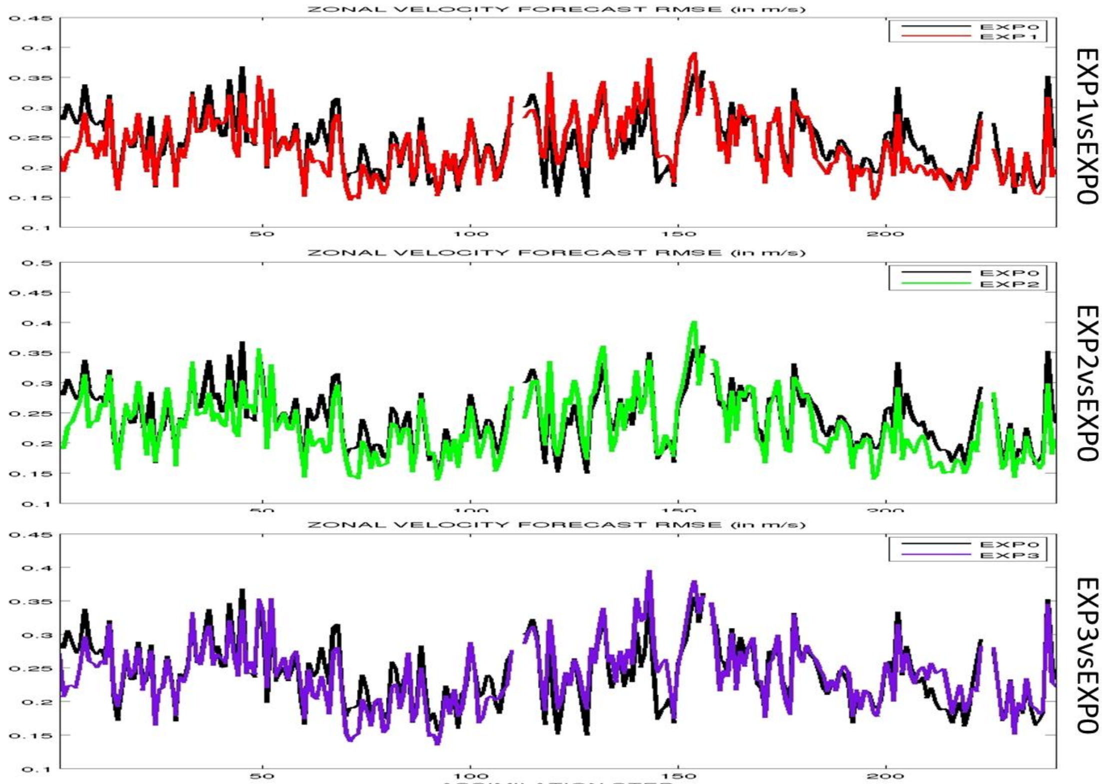

Figure 4.7.2: RMS error (in m/s) with respect to daily averaged zonal velocity for the period 4 May – 31 Dec 20120. Upper panel: EXP1 (red) vs EXP0 (black), Middle panel: EXP2 (green) vs EXP0 (black) and Lower panel: EXP3 (blue) vs EXP0 (black)

The method of processing High Frequency (HF) radar measurements from the WERA radar site in Lemnos Island, Greece, is the Open-boundary Modal Analysis, or OMA. We applied this technique to half-hourly total current data for the entire 2010 and then the data were daily-averaged. The OMA method follows the procedure described in [2].

The general idea of OMA is to generate a set of modes for a given domain which can be used to approximate any current field on that domain. These modes are generated by solving two Laplacian eigenvalue problems on the domain with Dirichlet and Neumann boundary conditions and adding a set of boundary modes to account for flow across open boundaries. Any current field in the domain can be described using a combination of these modes.

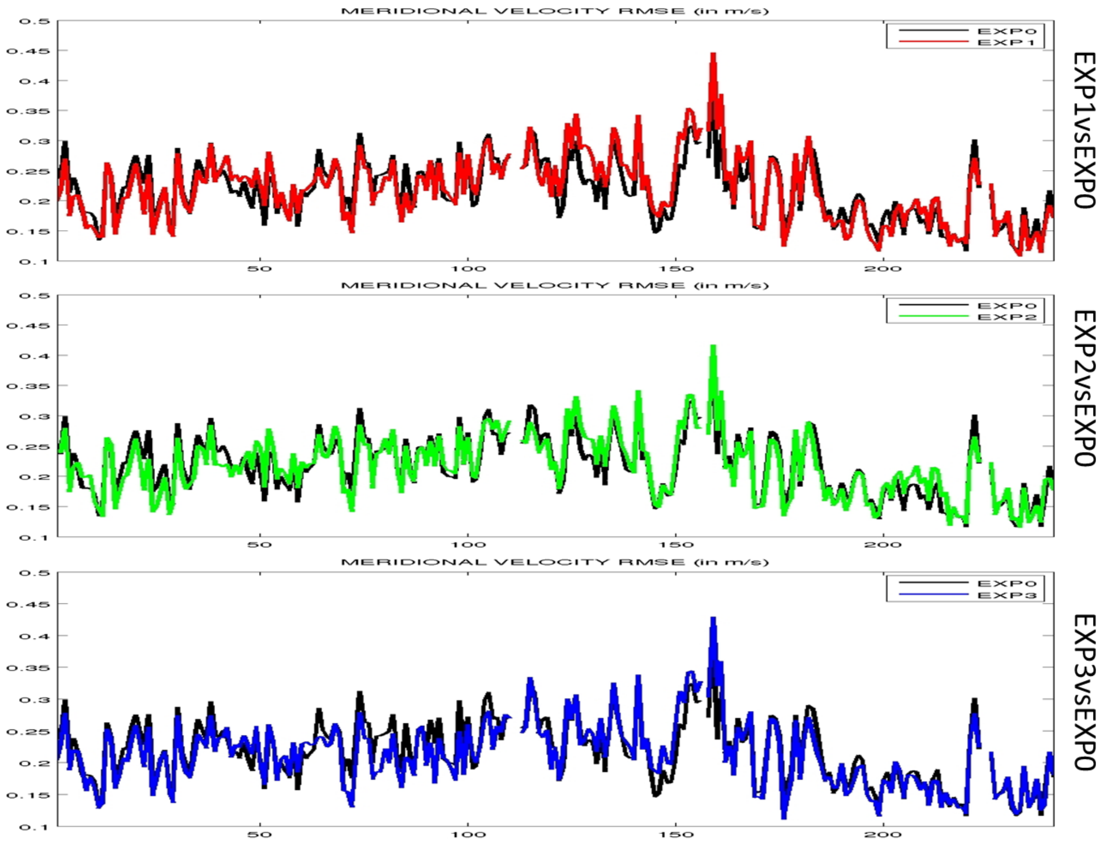

Figure 4.7.3: RMS error (in m/s) with respect to daily averaged meridional velocity for the period 4 May – 31 Dec 20120. Upper panel: EXP1 (red) vs EXP0 (black), Middle panel: EXP2 (green) vs EXP0 (black) and Lower panel: EXP3 (blue) vs EXP0 (black)

We implemented the OMA algorithm using the code for Matlab from http://www.ucsc.edu/~dmk/software/openMA. The code has two tunable parameters: the modal cutoff length scale L and the regularization weighting constant k. In our case a modal cutoff length scale of 5km was chosen (L=5km) and a value of 10^{-3} was used for the regularization coefficient (k=10^{-3}).

Ongoing development - Discussion on some results

As this study primarily focuses on the effect of the assimilation of surface currents data in the area in front of Dardanelles Straits on the model state we hierarchically started with a set of sensitivity experiments (briefly discussed in 1.2) which have been performed over year 2010 in order to choose the best values for inflow/outflow at the Dardanalles Straits. The data assimilation study is focused on the period May – December 2010 and uses the model characteristics corresponding to S-EXP11 of the previous set of sensitivity experiments. In order to assess the impact of the surface current measurements from the HF Radar system, we have performed four sets of experiments as shown in Table 4.7.1. EXP0 refers to the standard integration of the Aegean Sea model over the period May – December 2010. In this setup the model assimilates on a weekly basis gridded satellite data of SSH & SST and all available ARGO T/S profiles. Standard model performance is discussed in [4]. In EXP1, the model additionally to the standard set of observations of EXP0 assimilates every week the daily averaged zonal and meridional surface velocity components measured by the HF Radar System. EXP2 considers only the zonal component of the surface currents while EXP3 assimilates only the meridional component. The performance of the assimilation system is assessed by the standard statistic of the RMS error with respect to SSH, SST and the daily averaged surface velocity fields (in the area between the Lemnos island and Dardanelles). On a weekly basis as we consider the model RMS error with respect to observations just before their insertion into the system (forecast RMS error) these observations can be considered as quasi-independent. This is done for the sea surface height. For the surface velocity data the RMS error is calculated on a daily basis and for those dates coinciding with assimilation days the error is calculated before their insertion into the model. Thus the surface velocity can be considered as an independent set for model validation.

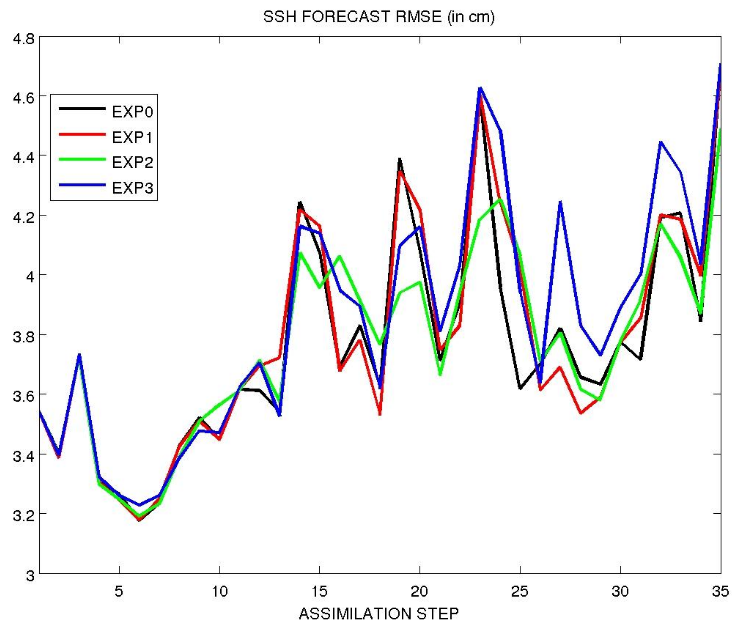

Figure 4.7.4: SSH forecast RMS error (in cm) calculated on a weekly basis (i.e. at each assimilation time step) for the four experiments.

Figure 4.7.2 presents the temporal evolution of the RMS error (on daily basis) of the zonal surface velocity component for experiments EXP0, EXP1, EXP2 and EXP3. The results obtained in EXP1 and EXP2 clearly show that the introduction of the total or the zonal component of the velocity field between Lemnos and Dardanelles exit leads to a a net reduction of the RMS error with respect to the control experiment (EXP0). During the period from mid-August up to the end of September 2010 the insertion of total or zonal velocity data seems in many cases to increase the error with respect to the standard run of the model. On the other hand the assimilation of the meridional component of the surface current (EXP3) improves marginally the RMS error from the beginning of the experiment up to mid-August 2010.

In Figure 4.7.3 we show the temporal evolution of the RMS error with respect to the daily averaged meridional component of the surface current. The assimilation of both components of the surface currents from the HF Radar increases slightly the RMS error for the late summer – early autumn period with respect to the control run. As can be seen by the RMS error corresponding to EXP2 and EXP3 (middle and lower panel of Fig. 4.7.3) this is mainly due to the assimilation of the meridional component itself which seems to be dynamically incompatible with what the model predicts at the surface especially during the late summer period.

Finally in Figure 4.7.4 we examine the effect of the assimilation of surface velocity components to the forecast RMS error of the sea surface height over the whole model domain. It is very encouraging that EXP2 (additional assimilation of the HF Radar zonal surface component) implies noticeable changes to the SSH RMS error behavior with respect to the control run (EXP0). This error reduction can be explained on the fact that the correction of the Dardanelles outflow introduced by the assimilation of the HF Radar surface currents data into the model induces changes to the surface circulation field in the North Aegean and secondarily to the rest of the Aegean Sea. These changes are then depicted into the SSH field leading to a decrease of 1 – 1.5 cm for certain periods. For the other two experiments, EXP1 shows some marginal improvement with respect to EXP0 while EXP3 (assimilation of the meridional component) deteriorates the behaviour of the SSH error from assimilation step 27 onwards.

5. Conclusions

In the second year of the project most of the partners have made an important progress in the production of scientific results. We can define two general methodologies to estimate the impact of existing and future observational platforms. The first method makes twin experiments with and without the assimilation of selected observational platforms. This method is applied by the CMCC, DMI, HGZ and HCMR. The method is very general, because it can be easily applied with non-linear processes. It can be further used to estimate the long term impacts from observations. A problem with this method is that it can evaluate observational impacts only in the observational space and requires a large number of accurate independent observations. The second method, applied by the IFREMER, MUMM and DELTARES, estimates the impact by the projection of observational contribution on the background error covariances approximated by ensembles of model simulations. Obviously the advantage of this method is that it does not require a large number of independent observations. A disadvantage is that it is based on the underlying linear theory and in the presence of large non-linearities it can evaluate only the short term observational impacts.

Two sets of twin experiments are finished in the Adriatic Sea. In the first set of experiments the impact of near coastal observations is is evaluated by including and excluding the observations near coasts of Istria and Emilia-Romagna. It was shown that the information introduced by these observations improves the state estimates near the observational points. It also spreads over the whole Adriatic Sea. However, it was not possible to quantify the improvement in remote estimates due to the lack of independent observations in remote areas. In the second set of experiments the impact of temperature observations by fishing vessels in the Northern Adriatic is evaluated in three experiments. They estimated both the short and the long term impacts of these observations. It as shown that these observations have both short and long term positive effects, but the long term effect becomes extremely important in summer in order to correctly estimate the depth of the mixed layer.

The OSE and OSSE experiments with in situ observations in the North Sea indicate that all existing stations improve the accuracy of the state estimate, but just by moving a single observational site the accuracy is significantly improved. Furthermore an optimal design is made in which the increase of accuracy is spread over the largest area.

Another set of OSSE experiments in the North Sea is performed by the method called observation sensitivity technique. This method indentified the areas in the North Sea in which the positioning of observational platforms would most significantly improve the accuracy of the state estimates.

In the Baltic Sea a set of experiments has shown an important impact of the satellite SST assimilation. The results and methodologies used for these experiments will be used in the next set of OSE and OSSE experiments with in situ coastal observing platforms.

OSE experiments with the coastal radar in the German Bight show that is able to significantly improve the analysis of the surface currents and the sea level. The technique for OSSE experiments for the estimate of the impact of different future FerryBox lines in the North Sea has been developed and is based on the estimate of the reduction of uncertainties in the model space.

Several OSSE experiments are performed in the Bay of Biscay and the Irish Sea. They evaluate the impact of the fishing vessels, combination of glider and fixed platforms, and combining Ferrybox and glider observations. The experiments performed during this year showed that a glider combined with the fixed observational platforms is sufficient to monitor the Loire river plume. The RMS analysis in teh Irish Sea show that the FerryBox is very efficient in improving the accuracy of the analysis.

A series of OSE experiments in teh Aegean Sea are performed in order to estimate the impact of a coastal radar. The results of these experiments show that teh radar has an important impact on the reduction of uncertainties in the analysis of surface velocities and the sea level.

All OSE and OSSE experiments proceed according to the planned production of results. We expect that all of the planned experiments will finish during the third project year.

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