Computers & Geosciences 89 (2016) 71–78

Contents lists available at ScienceDirect

Computers & Geosciences

journal homepage: www.elsevier.com/locate/cageo

Research paper

Development of a coastal information system for the management of Jeddah coastal waters in Saudi Arabia

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ARTICLE INFO

Article history:
Received 23 March 2015
Received in revised form
10 September 2015
Accepted 2 December 2015
Available online 7 December 2015

Keywords:
Coastal information systems
Operational models
Operational sensors
Modeling systems
Nowcasting
Forecasting

ABSTRACT

This paper presents results of the development and application of a web-based information system, Jeddah CIS, for assisting decision makers in the management of Jeddah coastal waters, in Saudi Arabia. The system will support coastal planning, management of navigation and tackle pollution due to accidents. The system was developed primarily to nowcast in quasi-real time and to deliver short-term forecasts of water levels, current velocities and waves with high spatial and temporal resolution for the area near Jeddah. Therefor it will hasten response when adverse weather conditions prevail. The Jeddah-CIS integrates sensors transmitting in real time, meteorological, oceanographic and water quality parameters and operational models for flow and waves. It also provides interactive tools using advanced visualization techniques to facilitate dissemination of information. The system relies on open source software and has been designed to facilitate the integration of additional components for enhanced information processing, data evaluation and generation of higher water level, current velocity and wave for the general public. Jeddah-CIS has been operational since 2013. Extensions of the system to speed operations and improving the accuracy of the predictions to the public are currently underway.

1. Introduction

Many coastal regions around the world have been facing threats from uncontrolled use of the resources as a result of demand from population growth and various forms of human interferences. As a consequence of climate change further damage is anticipated and is likely to worsen many of the existing problems. The sea level rise, potential enhancement of storm intensity and frequency, shoreline erosion and coastal inundation will affect the coastal areas and coastal ecosystems severely. Reclamation of land, harbor construction, exploitation of natural resources and environmental pollution can damage the sustainability of the coastal regions in the absence of careful planning and management. To improve our ability to manage coastal areas with sustainability in mind, there is an urgent need for requisite tools capable of predicting the adverse effects in order to take action.

In the past, coastal planning and management relied mainly on field observations and historical data. With the rapid development of computers, numerical methods and surveying technologies, numerical models have revolutionized our ability to understand complex interaction of coastal processes and to manage the resources of the coastal zone more effectively. As a result of the progress in oceanography, measuring and monitoring techniques, numerical modeling, remote sensing and information technology, there has been a rapid development and application of operational models. National institutes and agencies around the world have been developing global and oceanic operational models for nowcasting and forecasting of complex meteorological and hydrodynamic processes (Brasseur et al., 2005; Daniel et al., 2005; Dick and Kleine, 2007; Müller-Navarra and Knüpper, 2010, Müller-Navarra and Knüpffer, 2011). In spite of the impressive developments in global models, operational models for shallow water areas of the coastal regions require further alternatives. Recently there has been an intensification of efforts towards operational models applied to coastal areas (Schiff et al., 2002; Doong et al., 2007; Fernández and Mayerle, (2008); Wu et al., 2012; Stanev et al., 2011). The majority of them have been developed for the prediction of water levels and waves. Some works works have been done integrating model results into a more comprehensive information and management systems (Werner et al., 2009; De Kleermaeker et al., 2012).

Information concerning management systems can simply be in the form of digital maps and datasets with supplementary tables and illustrations that systematically show the coastal

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http://dx.doi.org/10.1016/j.cageo.2015.12.006
0098-3004/

environment, often with cartographic and decision support tools (O'Dea, 2007). Most useful and powerful information systems are those accessible on-line. The recent generation of information systems integrates multiple servers of data and operational models, and provides interactive tools for using the latest visualization technology. They are used to support decision-makers in the prediction of natural and human impacts on the environments and in the selection of the most adequate course of action. These information systems are also for monitoring the execution and effects of operations, for proposing adaptation strategies, for arriving at cost-effective solutions to deal with various of problems and for dissemination of information.

To enhance coastal management there is a need to develop tools for improving the understanding of the physical system. Moreover, systems should, in addition to hydrodynamics, be extended to provide predictions of sediment transport and morphodynamics. This is particularly relevant to navigation and maritime security, and also for the industry pertaining to oil, gas and offshore wind power. The capability of obtaining predictions of bed level changes in quasi-real time is becoming important and can enhance efficiency as well as reduce maintenance costs of large-scale operations.

In this paper the set-up and components of an information system developed for the coastal waters of Jeddah in Saudi Arabia are described and the results of its application are presented. Focus is given to the hindcasting, nowcasting and forecasting of water levels, current velocities and waves with high spatial and temporal resolution in the vicinity of Jeddah. The system has been tailored primarily to provide a sound scientific understanding of the dynamics of flow and transport processes due to flow in the Red Sea and to assist managers to deal with the main threats in the coastal region involving hydrodynamics.

2. Red Sea and Jeddah coastal waters

The Red Sea is an elongated basin separating the African and Asian continents. It is about 2000 km long with an average width of about 220 km (see Fig. 1). At the northern end it bifurcates into the gulfs of Suez and Aqaba. The flow through the Suez Canal is negligible; the strait of Bab el Mandeb at the southern end of the Red Sea is the only significant interface with the open ocean. The mean water depth in the Read Sea is about 190 m and can reach up to 2400 m (see Fig. 2).

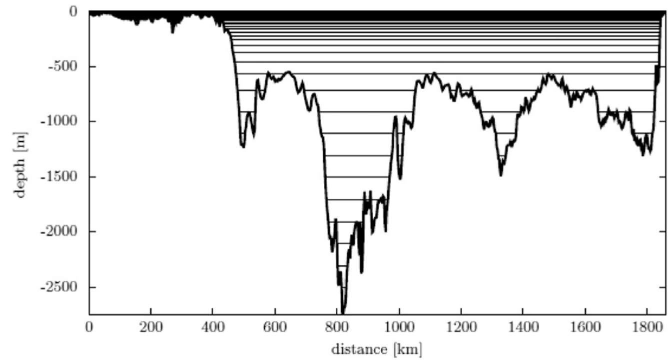

Fig. 2. Bathymetric transect of the Red Sea and grid resolution (σ-layers) over the vertical dimension.

The Red Sea and the adjacent coastal areas are among some of the least explored in the northern hemisphere. Most of the available observations are patchy and sparse, and there is a lack of understanding about the physical processes (Sofianos and Johns, 2003). In the absence of integrated process-based research and modeling for the prediction for flow and transport, coastal planning and management have become tedious and expensive. The Red Sea is a major shipping lane linking some of the world's major oceans. Navigation is facing problems and so the establishment of official traffic lanes and separation schemes to deal with the heavy ship traffic has become important. The city of Jeddah located at about the middle of the Red Sea, is the second largest city and is an important industrial centre in Saudi Arabia. During the last decades Jeddah metropolitan area has experienced significant increase of population from about 300 000 inhabitants in the early 1970's to ca. 3.4 million in 2010. It is expected that by the year 2030 over 6 million people will be living in the area (Jeddah Municipality, 2009). The Jeddah Port has expanded significantly from a few operational berths in the mid seventies to over 60 berths of international standard today. The port accounts for over

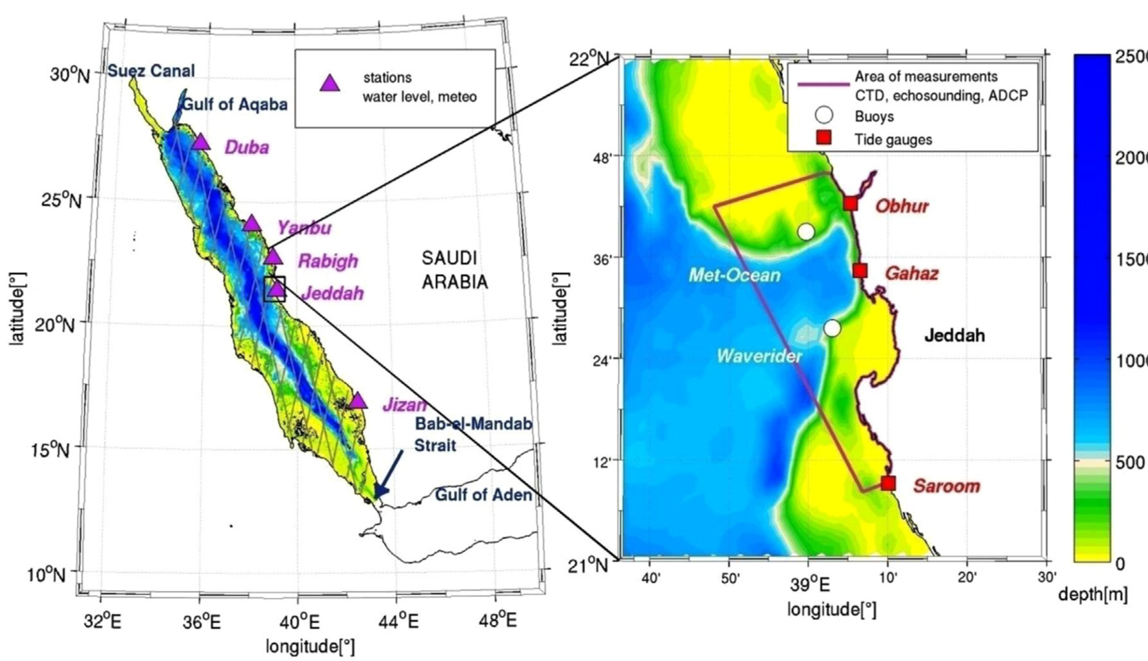

Fig. 1. Red Sea (left) and Jeddah Coastal Area (right) with details of the surveyed area and location of in-situ measuring devices.

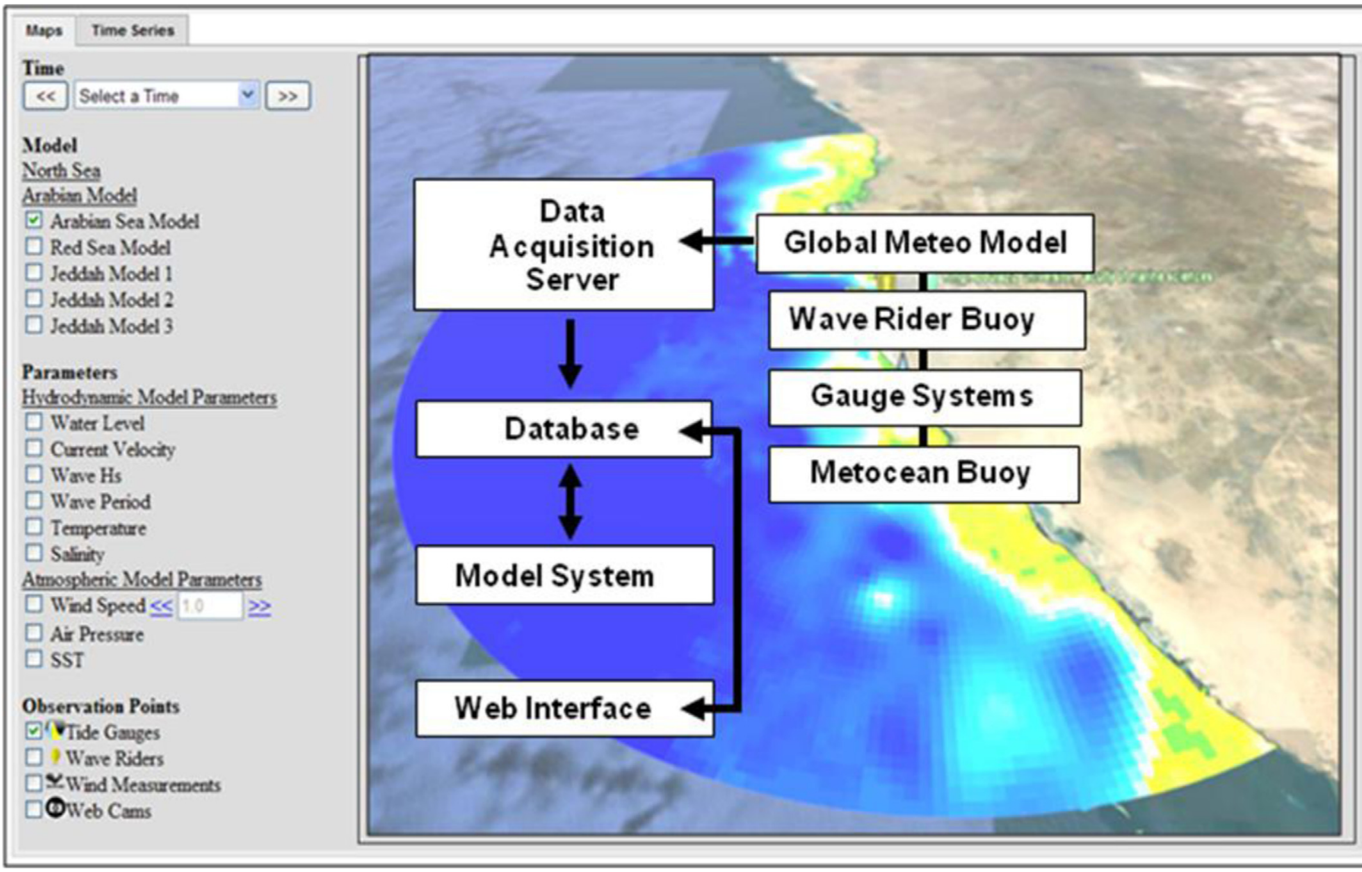

Fig. 3. Structure of the Coastal Information System with details of devices supplying real-time surveying data and external data resources.

half of the Saudi Arabia imports.

Tides range between about 0.6 m in the north near the mouth of the Gulf of Aqaba and 0.9 m in the south near the Strait of Bab el Mandeb. In the central Red Sea near Jeddah tide ranges between 0.20 m and 0.30 m. Two wind regimes dominate the Red Sea (Al-Barakati, 2004). The northern part is exposed mainly to north-western winds. In the South, western winds prevail in spring and summer, while mainly southeastern winds blow in autumn and winter. Near the city of Jeddah winds from north and northwest prevail. The wave properties in the Red Sea are strongly correlated with the wind characteristics. The growth of wind waves is limited by the dimensions of the semi-enclosed Red Sea, the narrow connection with the Indian Ocean, limits the entry of larger waves and swell. In general, mean wave heights exceed 1 m in spring while they hardly reach 0.6 m in winter (Fery et al., 2012). In the vicinity of Jeddah, dominant waves arrive from the northwest. The propagating waves refract, difract and decrease within the bay of Jeddah. The generation of synoptic wave data over a three year period shows that the mean significant wave height throughout the entire Red Sea is about 0.5 m (Fery et al., 2012). Maximum significant wave heights can be up to about 4.5 m during the same period. Sofianos and Johns, (2003) investigated the relative importance of the thermohaline and wind forcing, and their role in the circulation and stratification of the Red Sea using three-dimensional model simulations. They found out that the circulation produced by the buoyancy forcing is strong and dominates the wind-driven part of the circulation. Hence it is important to account for bouyancy effects.

Despite the weak exchange and mixing, the information available so far shows that large parts of the Red Sea are surprisingly in good environmental conditions. Recent studies (Sawall et al., 2014) also show that there is only a slight latitudinal shift in the structure of coral communities and that altered assembly structures are found only in reefs close to a source of pollution. Jeddah waste water contributes significantly to the nutrient budget and the metropolitan area contributes the major source of anthropogenic nutrient inputs into the Red Sea (Peña García et al., 2014). However are not expected to remain, because they are under serious threat from population grouth, over-exploitation of marine resources, heavy ship traffic, pollution from land and sea, and habitat destruction. Hence early action to conserve and protect the Red Sea, and the adjacent coastal areas is imperative.

The Jeddah Coastal Information System (Jeddah-CIS) has been developed primarily to nowcast in quasi-real time and to deliver short-term forecasts of water levels, current velocities and waves with high spatial and temporal resolution in the vicinity of Jeddah. It has been designed primarily to support coastal planning, to assist authorities in the management of navigation and to tackle pollution arising from marine accidents. In the case of accidents, the hasten response of the information system is expected even in adverse conditions as a result of shipping accidents or oil leaks.

3. Material and methods

Jedah-CIS integrates various sensors transmitting in-situ observations in real time and operational models for flow and waves, and incorporates interactive tools using advanced visualization techniques to facilitate dissemination of information. The set-up of the system draws on experiences obtained in the development of similar system for a coastal area on the German North Sea coast (Fernández and Mayerle, (2008)). The principal design of the system is described in detail in Fernández (2014). The system relies on open source software and has been designed to facilitate the integration of additional components for enhanced information processing, data evaluation and generation of information of higher water level, current velocity and wave for the public.

Jeddah-CIS comprises basically of four components (see Fig. 3). 1. A network of sensors for in-situ observations acquiring real time data on wind speed, water levels and waves. 2. Operational models for quasi-real time nowcasts and short-term forecasts of tides, storm surges, waves, currents, which in turn can be used for rapid scenario simulations. 3. A data base management system including the overall control and maintenance functionalities, and interfaces and 4. A web interface for visualization and dissemination of information for end-users and the general public.

3.1. Operational sensors

Several operational sensors to gather data regarding a variety of meteorological, oceanographic and water quality parameters are used. Results of flow and wave model simulations were used to address sampling locations. The location of the operational sensors near Jeddah is shown in Fig. 1. Currently three tidal gauges have been installed along the coastline (see Fig. 4a) and wave rider buoy (see Fig. 4b) and met ocean buoy (see Fig. 4c) moored offshore are integrated.

Tidal gauges equipped wind sensors are placed along the coast at three Coast Guard Stations in Saroom in the South, Gahaz close to the city center and Obhur in the North. The devices are approximately 75 km apart providing reliable information of the water level variation near Jeddah. Ultrasonic devices of the LogA_Level type manufactured by General Acoustics, Germany are used. The sensors ensure accurate measurements of water levels because they operate with a very narrow sound beam that have an angle of 30° and perform measurements in the frequency of 5 Hz. The units are equipped with sensors for monitoring the wind speed and direction, and air temperature. Fig. 1 (left) shows the supporting structure for the device installed at the coast guard in Saroom. Power supply is provided by solar panels mounted on the supporting masts. Data is transmitted continuously to the control unit at KAU via the cell phone network using GPRS.

The directional waverider buoy manufactured by Datawell, Netherlands, records and transmits wave heights, wave spectral data and wave periods. The device is moored approximately 10 km offshore of the Port of Jeddah, at the edge of the continental shelf, in a water depth of about 20 m (see Fig. 1). This location was selected since west of the buoy, the water depths increases above to over 600 m permitting observation of essentially undisturbed incoming waves from the open sea. The directional wave parameters are obtained from Global Positioning System (GPS) signals. The velocity and vertical displacement of the buoy is determined respectively from changes in the frequency of GPS signals according to the Doppler principle and time integration of the velocity (Jeans et al., 2003). The measuring accuracy for the conditions in question is approximately 1.0 cm. Wave parameters are computed for a period of 20 min and transmitted to the control unit every half an hour. Data transmission is done via cell phone network using SMS (De Vries et al., 2003).

A Fulmar Met-ocean buoy manufactured by OSIL Environmental Instruments and Systems in the UK was deployed from the shiff R/V PELAGIA at 21.46 °N 39.05 °E at a depth of about 50 m on 6 April 2012 (see Fig. 1 right). The device contains sensors for measuring meteorological parameters such as wind speed, wind direction, air pressure, air temperature, and humidity, relevant parameters such as temperature, salinity, turbidity, dissolved oxygen, and chlorophyll as well as current magnitude and direction, and waves. The buoy is powered by solar panels. Data is acquired, processed, logged and transmitted to the end user via a GSM modem.

3.2. Operational modeling system

The core of the system is the operational models for the prediction of water levels, current velocities and waves. Open source software is used to facilitate the continuing development of Jeddah-CIS. Flow and wave models based on the open source Delft3D modelling suite are adopted (Deltares, 2011a,b) The models are forced with meteorological forecasts from the Global Forecast System. The US National Weather Service runs the GFS model with a forecast horizon of 8 days. Meteorological forecasts are downloaded once a day.

The flow model computes tide and wind induced currents and accounts for the density effects arising from distributions of salinity and temperature throughout the entire Red Sea. The effect of waves on currents is not considered. The model domain extends

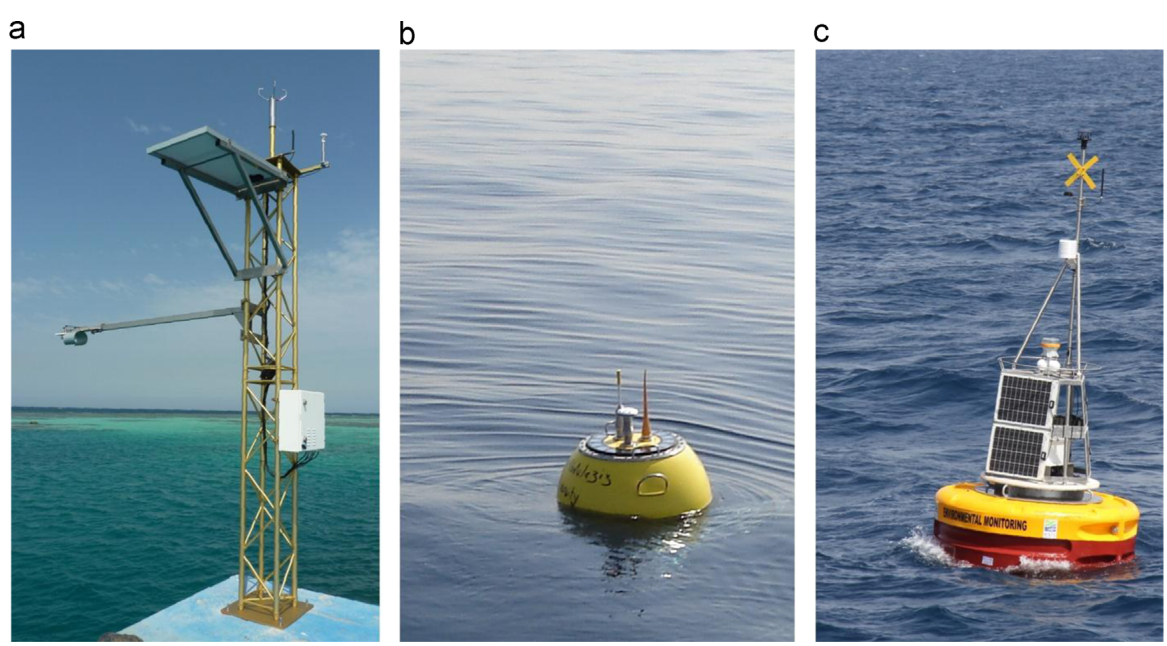

Fig. 4. Tidal gauge and wind sensor at Saroom (a). Waverider buoy (b) and met-ocean buoy (c) deployed offshore off Jeddah.

from the gulfs of Suez and Aqaba in the North to the straight of Bab-el-Mandeb in the South (Fig. 1). The model bathymetry combines GEBCO data (General Bathymetric Chart of the Oceans) with detailed bathymetrical surveys at key regions near Jeddah. A three-dimensional model approximation covering the entire Red Sea was adopted in this study (Fig. 1). The grid comprises of over 600,000 cells. Horizontal grid spacing is about 2.6 km. In the vertical 30 z-layers are adopted (Fig. 2). Closelly Spaced layers are used near the free surface to resolve the flow field well in the near coastal areas and resolve the temperature gradients. Additional layers can be added in regions with stratifications or in places with complex bathymetries and coral reefs. The open sea boundary of the model is located across the strait of Bab-el-Mandeb. Astronomical tides, sea surface height, water temperature and salinity are prescribed continuously at this boundary. Astronomical tidal constituents were obtained through an iterative procedure adopted to optimize the agreement between measured and modeled water levels at five tidal gauges along the Saudi Arabian Red Sea coast. These stations are located in Duba, Yanbu, Rabigh, Jeddah and Jizan as indicated in Fig. 1. Sea surface height, water temperature and salinity are obtained from continuous forecasts delivered by the Hybrid Coordinate Ocean Model, HYCOM (Chassignet et al., 2009). Momentum and heat exchange with the atmosphere are accounted for by prescribing at the free surface wind speed and direction, air pressure, air temperature, cloudiness and humidity from the GFS model. GFS is spectral with an approximate horizontal resolution of 27 km. In the vertical, 64 layers are used (Environmental Modeling Center, 2003). Hycom provides a forecast of seven days and is provided once per day. Flow model validation using measurements at the five tide stations (see Fig. 1) showed that water levels could be predicted with an accuracy ranging between 10 cm and 20 cm.

Waves are simulated using the open source model SWAN. SWAN is a third generation spectral wave model based on the conservation of the wave action density developed at the Technical University of Delft, the Netherlands (Booij et al., 1999; Ris et al., 1999). The model is embedded within the Delft3D modeling suite (Deltares, 2011b). Waves were computed on a radial grid with a resolution decreasing from 50 m in the bay of Jeddah to 43 km at the northwestern border area of the Red Sea. Numerical and physical parameters for the numerical modeling were selected by means of sensitivity studies (Fery et al., 2012). In order to obtain accurate results while keeping a razonable computational time, it was given attention to the choice of a computational grid, and the numerical and physical parameters. Due to the small tidal range near Jeddah the effect of the water levels on waves is found to be negligible. Therefore to speed up simulations water level variations were not accounted at this stage. Similar to the flow model, wind and pressure fields from the GFS model were used. Calibration was carried out using measurements of two meteorological buoys and one oceanographic buoy, and the operational wave-rider buoy deployed in the vicinity of Jeddah. To extend the spatial coverage, significant wave heights from the satellites Envisat and Jason-2 altimeters were also employed. The tracks followed by the two satellites are indicated in Fig. 1. The formulation of wave growth was found to have a major effect on the predictive ability of the wave model of the Red Sea. Different formulations were identified for deep and shallow water (Fery et al., 2012). It was found that the model is capable of predicting wave heights and periods in good agreement with the observations. In deep water, values of the scatter index of about 10% and 20% were obtained respectively for the mean wave period and the significant wave height. In shallow water, the scatter index resulted approximately 20% the same for the mean wave period and the significant wave height.

3.3. Data base management system

The data base management system controls the subsystems of Jeddah-CIS including the sensing devices and the operational modelling systems. In the design of the database, attention was paid to the integration of components for enhanced information processing, data evaluation and generation of data products. The database management system MySQL was used here. It was selected as it is open source and particularly suited for the development of cost-effective and scalable web-based applications. MySQL is relational, does not require much computational resources and is well integrated with other tools in the development of web solutions. The sets of data storing the measurements and the model results are organized in tables in the database. The easy interchange of information among the various Jeddah-CIS subsystems to provide a uniform interface played also a major role. As all the components interact directly with the database, the addition of modules and replacement of existing ones are facilitated leading to improved scalability.

3.4. User interface for visualization and dissemination of information

A graphical user interface based on web infrastructure was setup for locating, accessing, downloading and viewing measured data and the results of the operational modelling system. On the client side a combination of Hyper Text Markup Language (HTML), Cascading Style Sheets (CSS) and JavaScript written specifically for this interface is used. Some external JavaScript for the interaction of menus (the jQuery and its plugin Sidr) and Bootstrap for calendars are used to pick up the desired times. Both jQuery and Bootstrap and the used plugins are available under the MIT licence. In the server side scripts made in Python and PHP were created. The user interface is composed of maps using different layers that are combined with Scalable Vector Graphics (SVG). On the server side, an Apache server enables data retrieval from the database and displays the results. The web interface was designed primarily to facilitate the dissemination of information using advanced visualization techniques. The interface consists basically of an expandable menu on the left hand side of the screen for selection of the information and a main window for visualization.

4. System operation and results

The system delivers continuous, quasi-real time nowcasts and forecasts with a forecast horizon of 48 h. There are two controlling units integrating the facilities and for maintenance operations: one is located at the Research and Technology Centre of the University of Kiel (CAU) in Germany and the other is in Jeddah at the King Abdulaziz University (KAU) in Saudi Arabia.

Once per hour scripts made in Python are checking for the availability of wind information from GFS and ocean parameters from HYCOM. If new data is available it is downloaded and made available for the hydrodynamic models. Other independent scripts are also looking for the local availability of both data sources and when possible they prepare all the input files and start the calculation of the models. To speed up the post-processing and visualization of the results, a forecast of 6 h is made each time. Thus a forecast of 48 h is done in 8 simulations. Once a block of hydrodynamic results is obtained, selected outputs (i.e. water level, currents, water temperature, salinity, wave information and wind fields) are stored in the database in a compressed format which can be accessed by other components of the system. As soon as new results are available the post-processing can be started. In this module maps for the selected parameters are created offline and stored in the database for the use in the web interface. The maps are generated with Python using among others the library Matplotlib.

Once the raw data from the operational sensors reaches the control unit, the information is processed and stored in the database for further use. Datasets are created, compressed and stored in files for external backup. Tools for calculating key parameters are started and the relevant data is created and properly organized. The information from the tidal gauges is made available as a plain text in a serial port by the software delivered by the manufacturer. At this point it was required to develop an in-house program written in Python. This program reads the information, prepare and store it in the database. For the wave rider the information obtained in an SMS was also decoded and stored with Python.

The results can be displayed as a time series at given locations or maps covering different regions of the model domain. Time series is generated on demand whereas the dedicated maps are generated during post-processing. Although Python has been used for the offline figures, the Integration of Matplotlib with Apache server created compatibility conflicts. For time series the figures are created with a PHP script that uses the PHPlot class available under the LGPLv2 license. Rendering maps requires data interpolation and creates a delay in the server response to the browser. To speed up such operations, figures are pre-calculated offline at the post-processing time and stored in the database. Figures are stored in PNG format to reduce the amount of transmitted data and to enable a balance between quality of graphics and compression.

Typical displays are shown in Figs. 5 and 6. Fig. 5 shows a map of the water levels computed for the entire Red Sea as well as the expandable menu in the left to select the desired information. In box is displayed a comparison of time series of measured water levels from one of the sensors and the results of flow model simulations at the Station Obhur. In Fig. 6a map for currents and time series of wave heights recorded with the wave rider near Jeddah are shown. Extensions of the interface to enable retrieval of information at any given location within the model domain and the development of tools for facilitating comparisons and analysis of the results are currently in preparation. Public access to parts of the system is available in the site http://nowcasting.corelab.uni-kiel.de

With a computational time step of one minute for the flow and 15 min for the wave, the forecast of 48 h takes about one hour using eight cores of Intel Xeon E5-2690 processor. Moreover the pre-processing of the meteorological model data and enhancements in the performance of interpolations shall increase the net forecast further. As the user interface is web-based, delivering fast results is of great relevance to provide a pleasant experience to the final user and to reduce time-out disconnections. Time-outs are mainly due to slow network connection between the server and the client, large amount of data transmitted or the long time for the server to process the requests. Rendering maps requires data interpolation and creates a delay in the server response to the browser. To speed up such operations, figures are pre-calculated offline at the post-processing time and stored in the database. Figures are stored in PNG format to reduce the amount of transmitted data and to enable a balance between quality of graphics and compression.

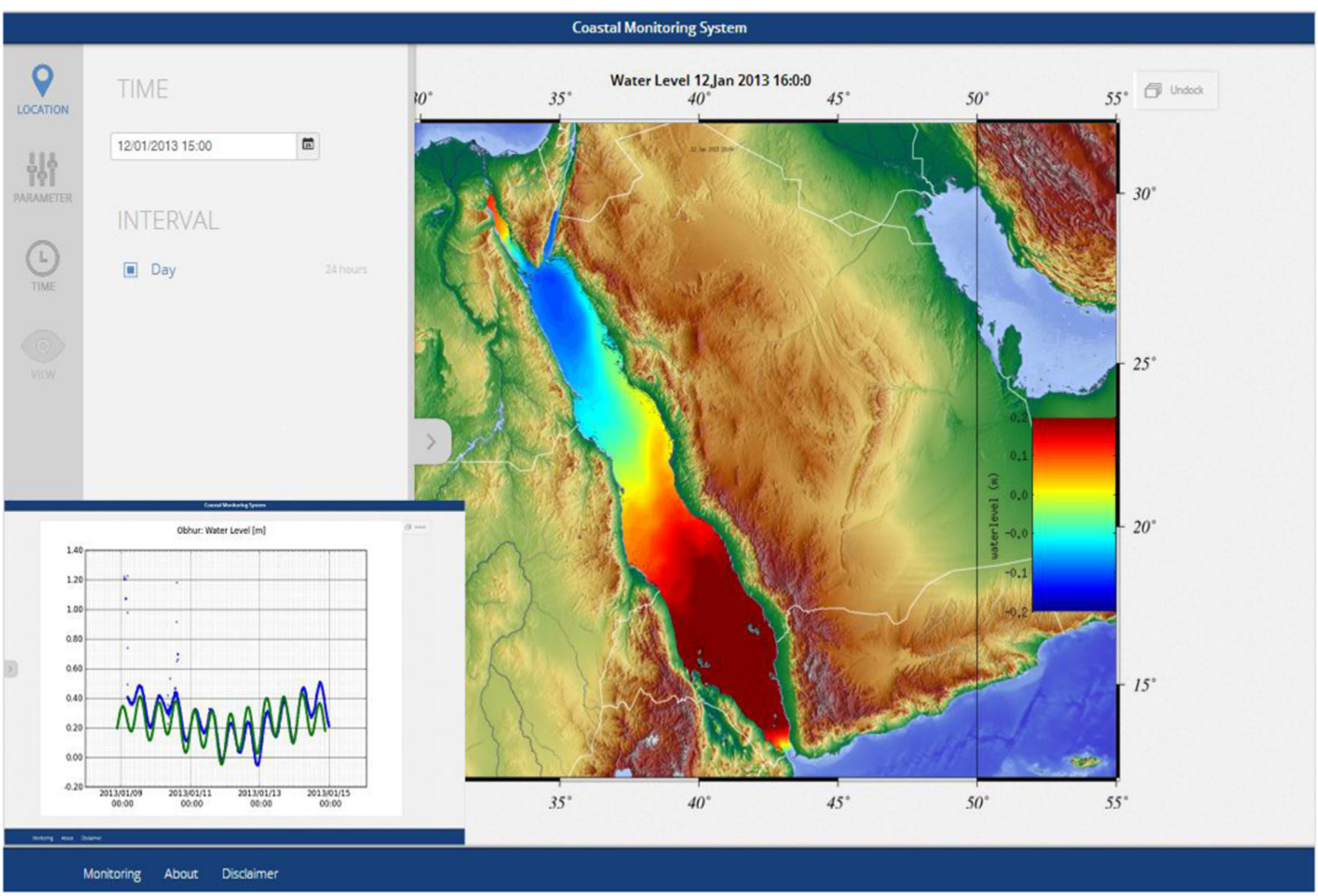

Fig. 5. Predicted water levels over the entire Red Sea. In box time series of measured (blue) versus modeled (green) water levels at the Station Obhur are displayed. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

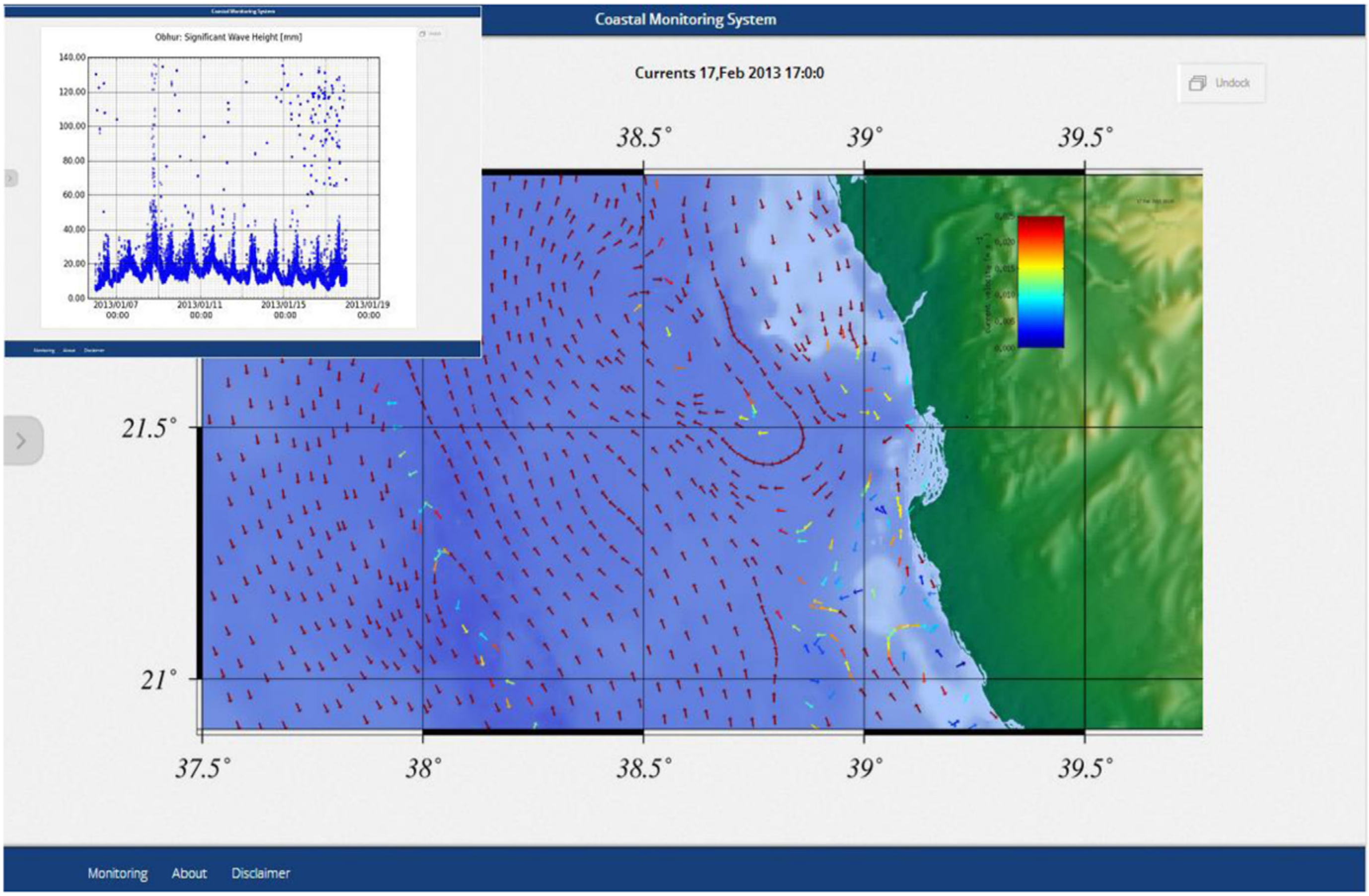

Fig. 6. Predicted current velocities near Jeddah. In box measured wave heights near Jeddah Port are displayed.

5. Concluding remarks

In this paper results of the successful development and application of a web-based coastal information system for the Jeddah coastal areas are presented. The near real-time information provides stakeholders with additional resources to address compliance issues in the area. The data can be used for early warning during extreme events, in rescue operations and to support coastal planning. It can also assist in the management of navigation and support maritime operations, to tackle pollution due to accidents, and to hasten response during adverse conditions as a result of shipping accidents or oil leaks.

Jeddah-CIS has been operational since 2013. The system has been used in the assessment of water quality and in the identification of the main sources of pollution near Jeddah (Pena-Garcia et al., 2014). As the knowledge about the flow and transport processes in the Jeddah coastal areas is limited, the generation of synoptic data covering several years has proved quite helpful in the improvement of understanding of the physical system thus helping in the efficient management of coastal areas and ecosystems.

To enhance sustainable environmental management in the whole Red Sea, there is a need to adapt and extend the existing system with fully operational capabilities. To further increase the accuracy of the predictions data assimilation techniques shall be implemented. Existing stations managed by the Saudi Arabian Government needs to be embedded. In particular, real time observations from weather stations, oceanographic moorings and satellite remote sensing shall be integrated.

Since the existing sensors are relatively few located mainly near Jeddah, it is envisaged to deploy several high frequency radars along the coast of the Red Sea for measurements of free surface currents and waves over wider areas. Moreover, the installation of additional tidal gauges in the vicinity of the strait of Bab-el-Mandeb is contemplated in order to improve the prescription of conditions at the open sea boundary leading to higher accuracy of predictions.

The proposed extensions are in line with our view for the development of a National Coastal Information System reaping benefits from the recent progress in digital processing and communication technologies. This would extend the applicability of the system to other fields such as the management and conservation of the sensitive coral reef system, management of fish farming operations, and preparedness and response to tackle oil spill accidents. Maritime security as well as quick emergency response during accidents and adverse weather conditions can also be improved.

Acknowledgement

Jeddah-CIS was developed in the framework of the research project “Jeddah Transect” funded by the government of Saudi Arabia from 2011 to 2013. The Research and Technology Centre Westcoast of Kiel University (CAU) in Kiel, Germany and the Faculty of Marine Sciences of the King Abdulaziz University (KAU) in Jeddah, Saudi Arabia jointly coordinated the project. The authors wish to thank the government of Saudi Arabia for funding the project under Grant Nr. T-065/430- DSR. The support and cooperation of the Saudi Arabian Coast Guard is highly appreciated. We also acknowledge the support from the technicians and engineers from the Faculty of Marine Sciences of KAU and the

Research and Technology Centre Westcoast of CAU.

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