US Experience Will Advance Gulf Ecosystem Research

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Abstract. This paper addresses the vision and early steps of the cooperation between the Center for Coastal Margin Observation and Prediction (CMOP) in Oregon, United States and the emerging Gulf Ecosystems Research Center (GERC) at the American University of Sharjah, UAE. The cooperation focuses on a better understanding and ability to predict the Arabian Gulf as a complex ecosystem, and involves science, technology and training components. An ultimate goal is the development for the Gulf of a "collaboratory" inspired on the concepts of integration of observations, simulations and stakeholder needs developed by CMOP for the Columbia River coastal margin, in the Eastern North Pacific. An early phase of the cooperation addresses the development of a 3D numerical model for the Arabian Gulf water circulation. A very preliminary forecasting system has been developed at CMOP, and its skill will be systematically assessed and improved by GERC and CMOP over the next several years, with the progressive deployment of a targeted observation network. Preliminary products include the visualization of the salinity fields associated with various river plumes. The model used was SELFE (a Semi-implicit Eulerian–Lagrangian Finite-Element model for cross-scale ocean circulation), the same that is being used for the Gulf predictions. Exploratory simulations were made to assess the ability of simple grid refinement strategies and/or use of higher order numerical schemes in improving the representation of the complex dynamics of plumes, filaments (eddies) and upwelling in the continental shelf of the Eastern North Pacific, off the Columbia River. Results suggested the need for automated grid optimization strategies, which are currently in progress.

Keywords: Finite Element, Mesh Refinement, EulerianLagrangian method, River Plumes, Filaments, Eddies, Model Skill Assessment, Arabian Gulf, Columbia River.

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1 Introduction

The Arabian Gulf is a shallow (average depth 35 m) inland sea in which the water circulation is essentially closed with the exception of small opening through the Strait of Hormuz to the Gulf of Oman. It supports a rich ecosystem of coral reefs, dugongs, fisheries, and other coastal population. However, pollution resulting from desalination, wars, extensive shipping activity, oil spills, and external factors such as climate change induced sea-level rise have created major environmental stress in the Gulf, threatening its rich biodiversity [1].

Evidence of stress on the Gulf's environment comes from recent bleaching of corals and the harmful algal bloom ('red tide') that occurred in 2008-2009 [2]. Such blooms can have a potentially devastating impact; red tide may result in mass killing of fish, birds, and other marine animals, thus threatening the fisheries industry, both wild and aquacultured. It also poses a potentially catastrophic threat to the drinking water supplies of the region due to shutting down desalination plants. The Gulf region heavily depends on desalination plants that convert seawater into drinking water. During the 2008-2009 red tide, many desalination plants in the region were affected, with one plant closed for 55 days during the bloom [1].

Accurate modeling of physical circulation and transport is foundational to understanding the Arabian Gulf coastal ecosystem in its biogeochemical complexity, and to addressing a broad range of increasingly essential operational and management issues: from support to navigation and response to oil spills, to the management of desalination plants and the mitigation of red tides).

Many investigators (e.g, [3], [4]) have employed or developed hydrodynamic models to study the circulation in the Arabian Gulf. Such models predict the salinity and temperature distribution fields, fresh water intrusion from the Strait of Hormuz and river inflows (Shatt-al-Arab), and the generally counterclockwise circulation especially in the southern half of the Gulf [3]. Also, tidal and winds effects can be incorporated in the models. Typically, the surface temperature of the Gulf is about 33 ^{o}C in summer and it varies to about 22 ^{o}C near the Strait of Hormuz and about 16 ^{o}C in the up north of the Gulf. The salinity is almost constant throughout the year, but varies spatially from about 36 psu near the Strait of Hormuz to about 41 psu off the Saudi Arabian shores. The high salinity is more apparent in the southern and southwestern coasts of the Gulf [3].

Motivated by the above considerations, a center called the Gulf Ecosystem Research Center (GERC) was established at the American University of Sharjah, UAE, to address all challenges pertinent to the Gulf ecosystem. Part of the mission of GERC will be to monitor and conduct research on ecosystems. GERC aims to offer advice on long-term solutions to a number of ecological problems. In particular, the development of Arabian Gulf circulation models would help with prediction of red tides in an attempt to prevent damage to the water processing plants filtering membranes that filter the salt water.

Collaboration between the Center for Coastal Margin Observation and Prediction (CMOP) in the United States and the emerging Gulf Ecosystems Research Center (GERC) at the American University of Sharjah, UAE, was initiated in 2011. This cooperation involves mutual exchange visits of the scholars from both institutions. The extensive experience of CMOP in modeling and monitoring the complex ecosystem of the Columbia River (CR) estuary and its continental shelf was seen as a potential starting point of such cooperation. In preparation for the cooperative maintenance and improvement of that forecast system, the first author spent a sabbatical period at CMOP, where he became familiar with SELFE and explored ways to improve the modeling of circulation of the continental shelf of the Eastern North Pacific.

2 Columbia River (CR)

The CR is the largest river entering the Eastern North Pacific Ocean (Figure 1), extending from the British Columbia coast in Canada to the Washington, Oregon, and California coasts of the United States. The CR plume exports dissolved and particulate matter hundreds of kilometers along and across the continental shelf [5, 6], which in turn influences the shelf ecosystems. Hickey and Banas[7] and Hickey et al. [8] suggested that the seaward front of CR plume likely provides a barrier to the onshore transport of harmful algal bloom in summer and early fall [9].

The CMOP research addresses biological hotspots in the CR estuary, from an integrated perspective across disciplines, observations and simulations. Of immediate interest to GERC, the CMOP studies include the characterization of the river-to-shelf circulation at various scales of spatial and temporal variability, including tidal and wind-driven baroclinic dynamics [9, 10]. Advanced modeling tools have been developed to support these studies, constituting what the “Virtual Columbia River” [11].

The Virtual Columbia River simulate the 3D baroclinic circulation in the river-to-shelf system, both retrospectively and in near real-time forecasting mode. The simulations of circulation are conducted in unstructured grids, typically with the finite element code SELFE [12] and historically also with the finite volume code ELCIRC [13]. All simulations are skill assessed ([9], [10]) against an extensive observation network maintained by CMOP and supported by strong cyber-infrastructure capabilities..

Transferring the CMOP modeling capabilities to GERC, in a form customized to the Arabian Gulf, is a priority objective, and a key step towards achieving the global vision of GERC. The transfer requires a process of workforce development and training. As a part of that process, the first author conducted an exploratory research with SELFE, in a complex yet well understood benchmark. The scientific goal was to assess the ability of simple grid refinement strategies and/or use of higher order numerical schemes to improve the representation of the complex dynamics of upwelling and circulation in the continental shelf of the Eastern North Pacific, off the Columbia River.

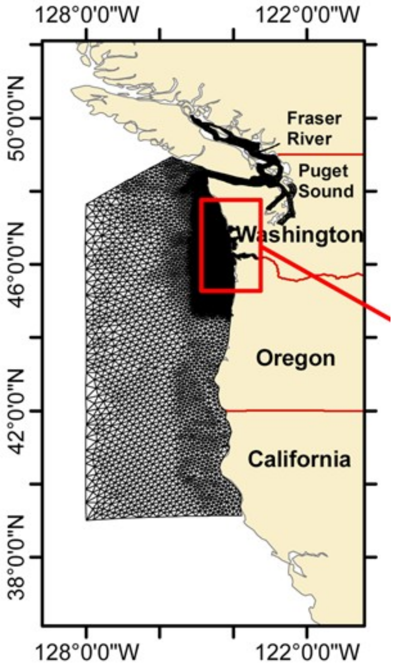


Fig. 1. Columbia River Estuary-Plume-Shelf System (inside the square zoom)

3 The SELFE Model

SELFE (Semi-implicit Eulerian–Lagrangian Finite Element; Baptista et al. 2008) is a finite element code that anchors an open-source, community-supported, interdisciplinary modeling system. It uses unstructured grids, and is designed for the effective simulation of 3D baroclinic circulation, transport and support of ecological modeling across river-to-ocean gradients and scales.

While originally developed to meet specific modeling challenges for the Columbia River, SELFE has been extensively applied to study coastal margins around the world. SELFE uses a semi-implicit finite-element/volume Eulerian-Lagrangian scheme to solve the primitive form of the shallow water equations (in either hydrostatic or non-hydrostatic form). The numerical algorithm is robust, stable and computationally efficient. It also naturally incorporates wetting and drying of tidal flats.SELFE v3.1d available at CMOP [14] was used for all simulations in this study. Parallel computations were carried out in a cluster using standard Message Passing Interface (MPI).

4 Results and Discussion

One of the operational products of the Virtual Columbia River are multi-year simulation databases of circulation. One specific such database (“DB29”) was used as reference in this study, and we focused specifically on its results for April-May 2012. We modified that simulation database in various ways, each leading to a separate simulation. First, the continental shelf domain was re-discretized for a base case (run02). Refinements of the based mesh were made, leading to two additional simulations (run04 and run05). A sample mesh grid of the continental for run04 is shown in Figure 2. This grid was generated using the Surface Water Modeling System (SMS) software [15]. Table 1 summarizes the size of the grid used for the base run (run02) and the other two runs (run04 & run05). For the baseline run run02, a total of 37,146 triangles elements was used in the horizontal grid, with a higher resolution (<500 m) concentrated in the near-plume and shelf regions. The bathymetry of CR shelf was loaded onto the program.

Figure 3 shows one sample plot of surface salinity for the CR shelf from SELFE for the baseline run (run02), and runs run04 and run05, where significant refinement of the grid was applied. Furthermore, Figure 4 shows close-up comparison of the surface salinity near the plume for runs 04 and run05. Evaluation of model skill is shown in Figure 5 as a comparison of salinity for all runs with observed salinity data from SATURN-02 station at depth of 1 m. Figure 6 depicts the model skills for the temperature profile for NH10 station at a depth of 2 m.

Clearly, mesh refinement did not affect the simulation results drastically in terms of detailing plume dynamic features (upwelling, filaments, eddies, etc.). Furthermore, the SELFE model did not capture well the salinity data at the depth of 1 m and the simulation runs exhibited almost same deviation with a maximum error of -20 psu was observed. However, as the grid is more refined, it can be noticed that sharper salinity gradients become more apparent.Nevertheless, the model skills for temperature profile were more accurate as shown in Figure 6.

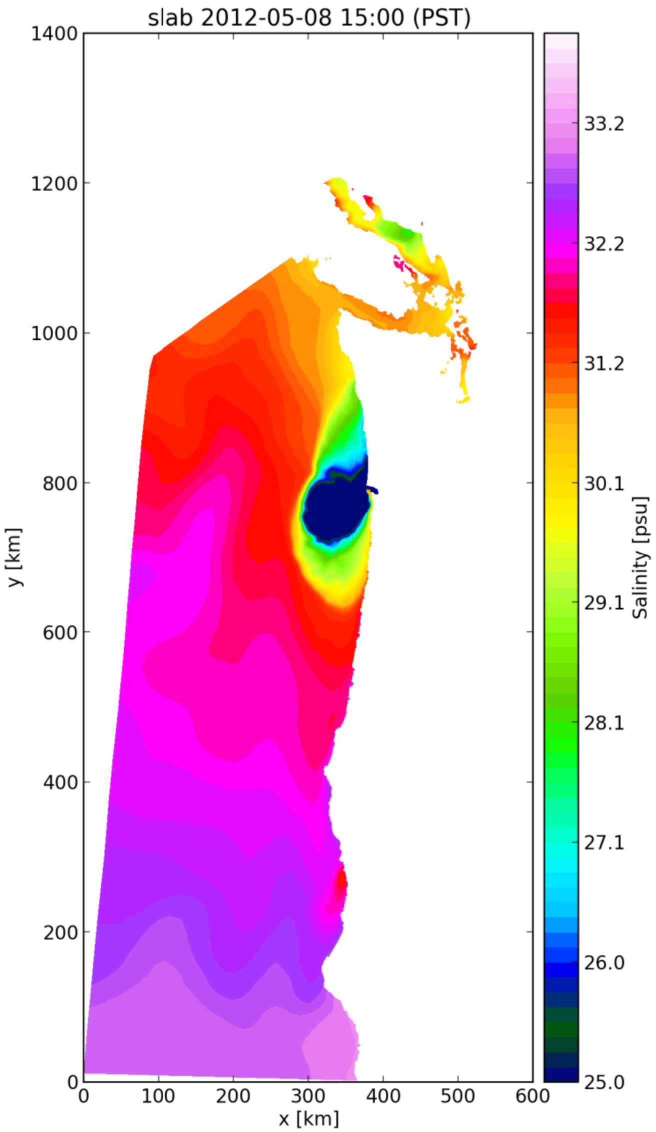
Analysis of the above simulation results triggered the need to try different numerical scheme to explore the complex dynamics of the CR shelf system. Total Variation Diminishing (TVD) transport scheme was employed in run06 and the surface salinity at one instance is shown in Figure 7. The zoomed surface salinity is shown in Figure 8. Obviously, run06 with TVD provided sharper salinity gradients in the plume area, yet eddies were not detected with this numerical scheme.

The experience acquired with this sensitivity study for the Columbia River has permitted the first author to become familiar with SELFE, and to begin exploring the application of SELFE to the Arabian Gulf. A Gulf grid was prepared as shown in Figure 9 on SMS. Then, the gulf grid along with bathymetry was used in SELFE simulations. Figure 10 shows the preliminary surface salinity of the Gulf simulated by SELFE. The early stages of development of the river plumes from Shatt-Al-Arab up north and other river plumes were captured as seen in Figure 10, whereas more work is still needed to include the observed discharge data and to spin-up the model for long enough time to obtain realistic initial conditions.

Fig. 2. SMS Grid for run04. Grids are hybrid and resolution is finest in the shelf.

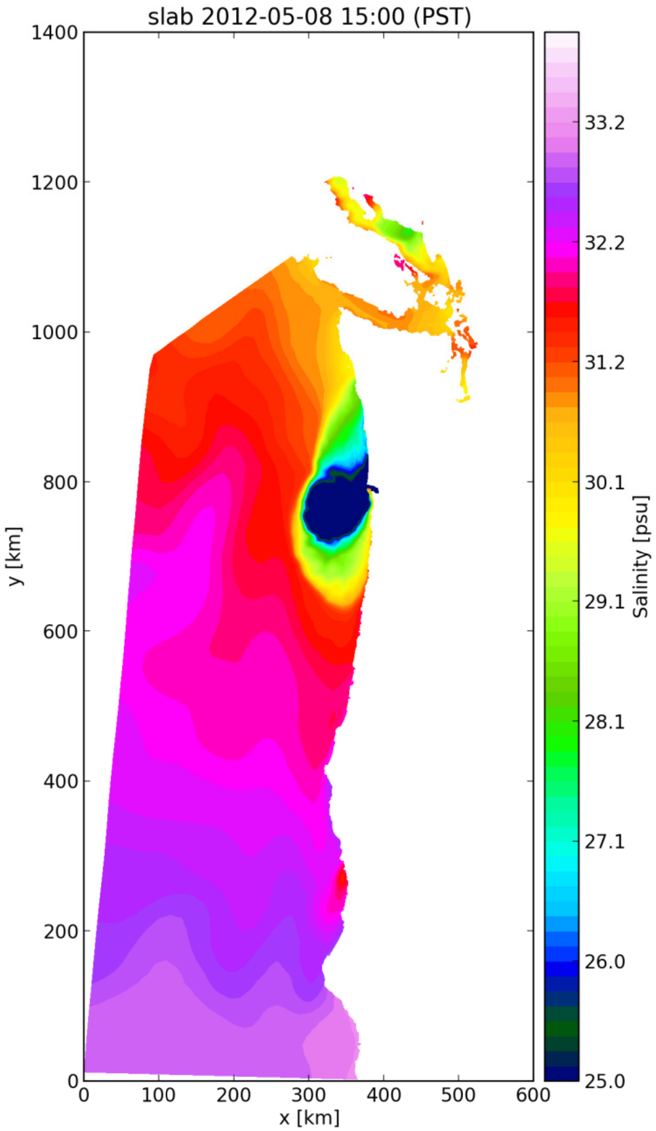
Table 1. Grid resolution and size for SELFE runs

Run	# of Elements	Resolution (Max size)
02	361938	500 m
04	3179179	200 m
05	3324056	100 m



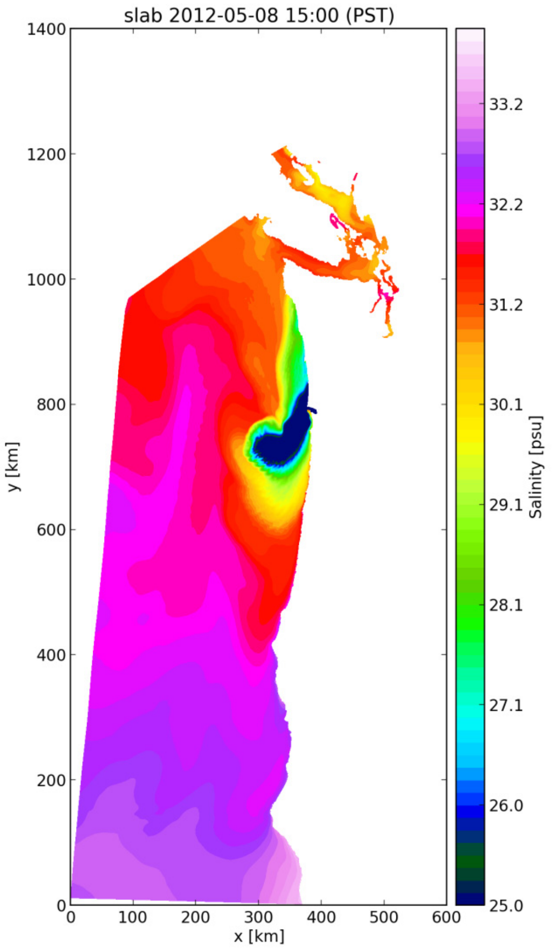
(a)

Fig. 3. Surface salinity for the three runs. (a) run02, (b) run04, (c) run05.



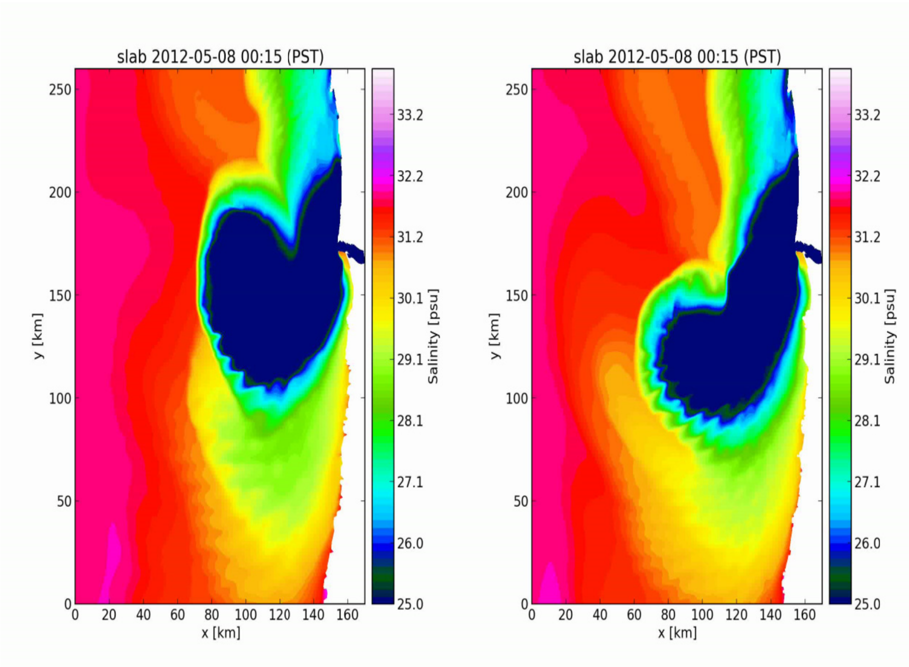
(b)

Fig. 3. (*Continued*)



(c)

Fig. 3. (*Continued*)



(a) (b)

Fig. 4. Zoomed surface salinity for run04 and run05

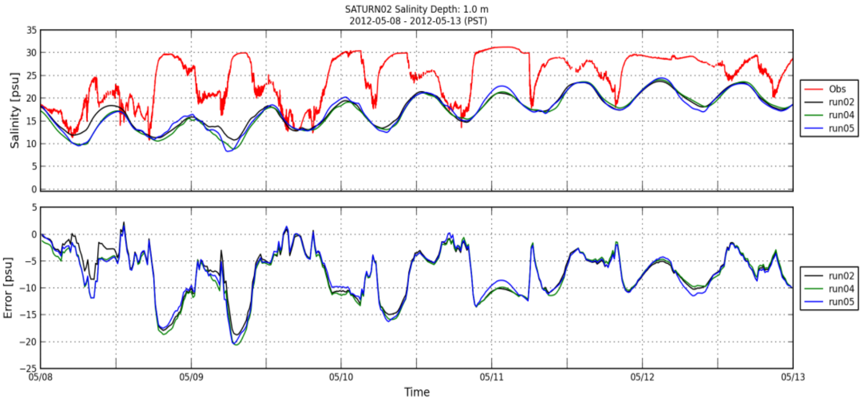


Fig. 5. Comparison of observed and simulated surface salinity at Saturn-02 station

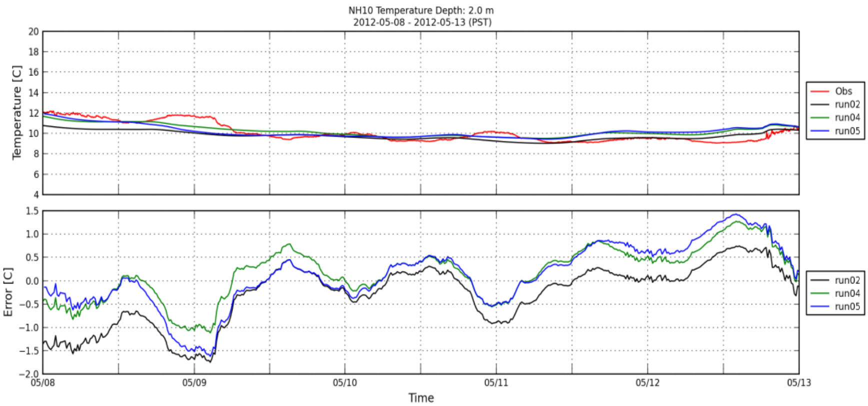


Fig. 6. Comparison of observed and simulated surface temperature at NH10 station

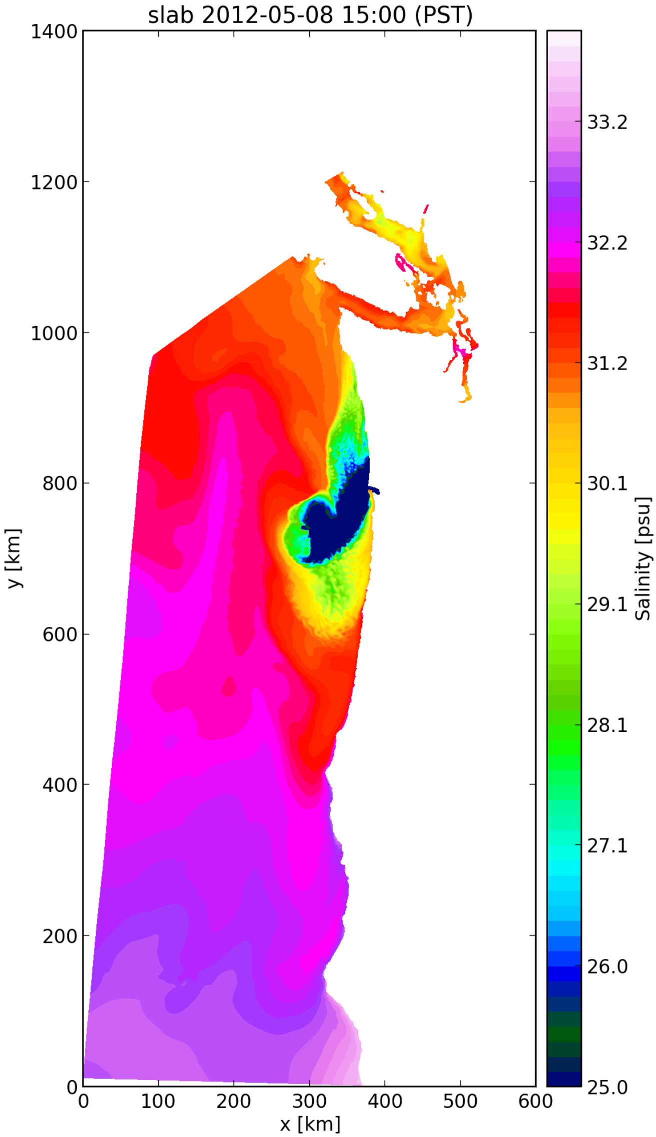


Fig. 7. Surface salinity for run06

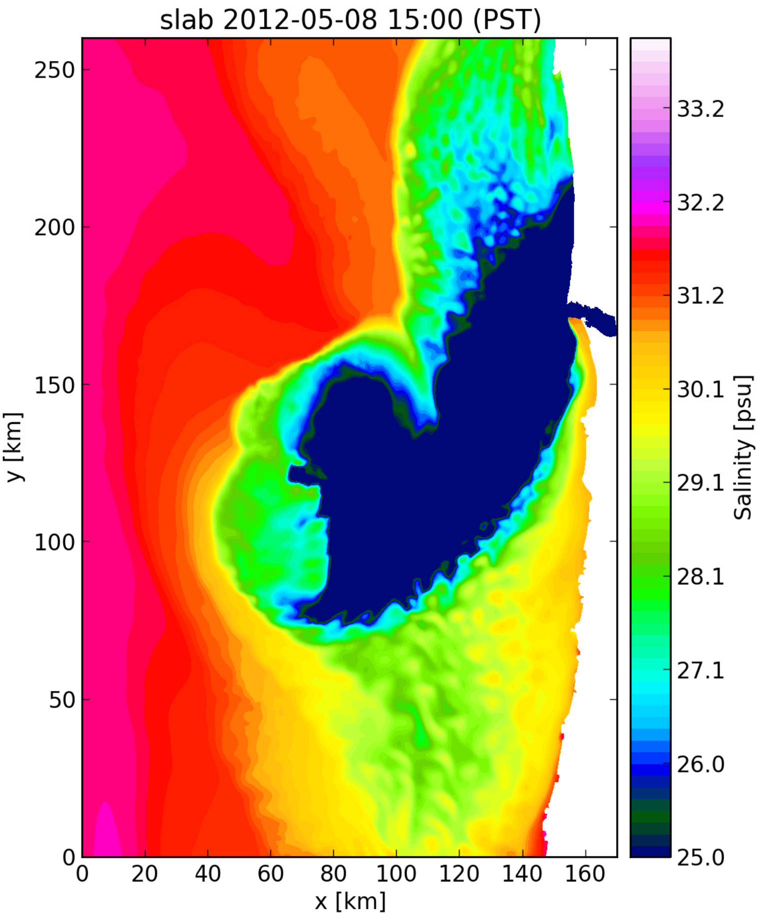


Fig. 8. Zoomed surface salinity for run06

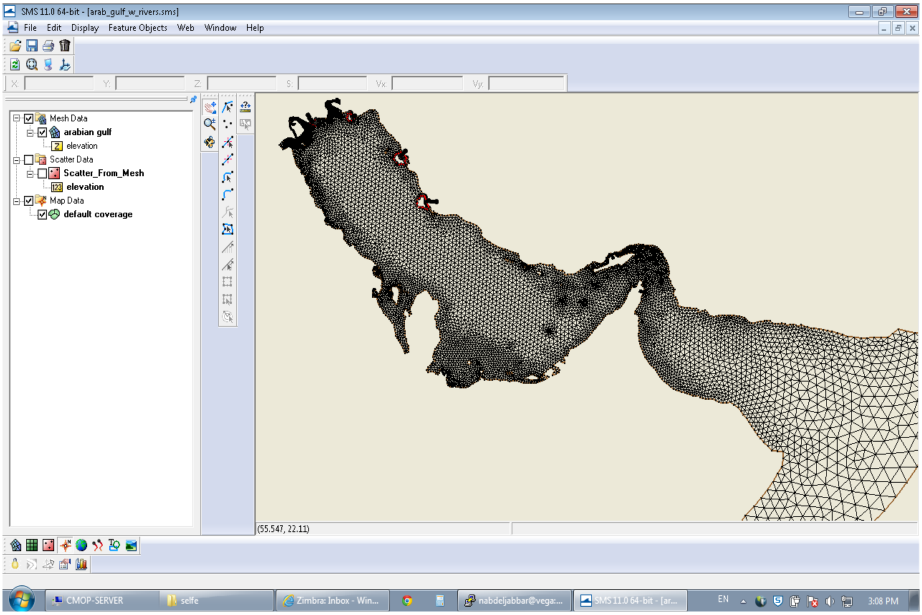


Fig. 9. A mesh for the Arabian Gulf

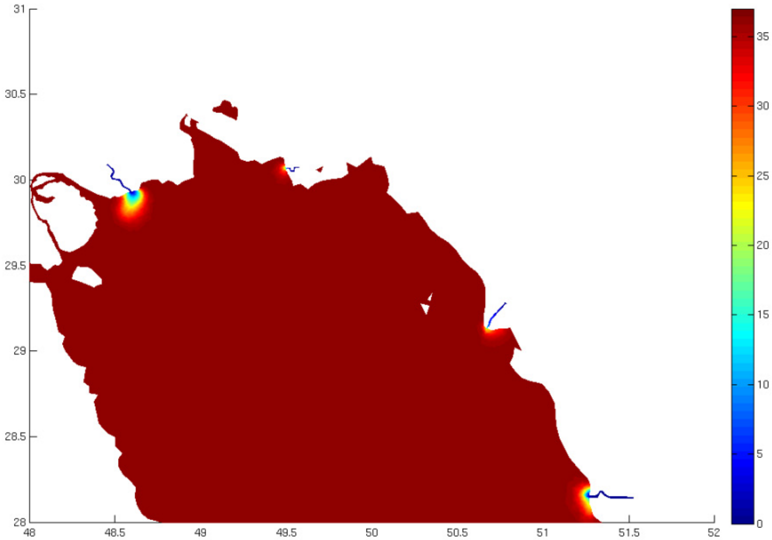


Fig. 10. Arabian Gulf surface salinity as simulated by SELFE

5 Conclusion

This paper emphasizes the vision and early steps of the cooperation between the Center for Coastal Margin Observation and Prediction (CMOP) in the United States and the emerging Gulf Ecosystems Research Center (GERC) at the American University of Sharjah, UAE.

An early phase on the cooperation focuses on the development of a 3D numerical model for the circulation in the Arabian Gulf. A very preliminary forecasting system has been developed at CMOP, and its skill will be systematically assessed and improved by GERC and CMOP over the next several years, with the progressive deployment of a targeted observation network.

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