Reprint from Ocean Community Conference '98, Proceedings, Baltimore, MD, Marine Technology Society, Nov. 15-19, 1998, p. 537-543.

A NOWCAST MODEL FOR TIDES AND TIDAL CURRENTS IN SAN FRANCISCO BAY, CALIFORNIA

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ABSTRACT

National Oceanographic and Atmospheric Administration (NOAA) installed Physical Oceanographic Real-Time System (PORTS) in San Francisco Bay, California to provide observations of tides, tidal currents, and meteorological conditions. PORTS data are used for optimizing vessel operations, increasing margin of safety for navigation, and guiding hazardous material spill prevention and response. Because tides and tidal currents in San Francisco Bay are extremely complex, limited real-time observations are insufficient to provide spatial resolution for variations of tides and tidal currents. To fill the information gaps, a high-resolution, robust, semi-implicit, finite-difference nowcast numerical model has been implemented for San Francisco Bay. The model grid and water depths are defined on coordinates based on Mercator projection so the model outputs can be directly superimposed on navigation charts. A data assimilation algorithm has been established to derive the boundary conditions for model simulations. The nowcast model is executed every hour continuously for tides and tidal currents starting from 24 hours before the present time (now) covering a total of 48 hours simulation. Forty-eight hours of nowcast model results are available to the public at all times through the World Wide Web (WWW). Users can view and download the nowcast model results for tides and tidal current distributions in San Francisco Bay for their specific applications and for further analysis.

I. Introduction

Located near the middle of California coast, San Francisco Bay is one of the most complex coastal plain estuaries on the west coast of the United States. The bay is a center of population, commerce, industry, and recreation. It is also a region of heavy shipping traffic, and is a site subject to the disposal of industrial, agricultural, and municipal wastes. Despite preventive measures, vessel traffic accidents and spills of hazardous material in the bay have occurred, and will probably occur in the future. For example, in January 1971, two Standard Oil tankers collided in Central San Francisco Bay, and spilled 26,700 barrels of crude oil (Conomos, 1975). As recent as in October 1996, more than 200 barrels of bunker oil spilled into the bay from a dry dock near Pier 70. The latest accident, although relatively minor, once again reminded the authorities that, despite extensive preventive measures, disasters related to marine vessel activities will be difficult to prevent completely. To protect this already fragile estuarine ecosystem of San Francisco Bay, all preventive measures have been heightened and coupled to a strategic plan for a rapid and effective response to minimize any damage due to accidents.

Starting from 1985, NOAA initiated Physical Oceanographic Real-Time System

(PORTS) in Tampa Bay, Florida, Houston-Galveston Harbor, Texas, and New York Harbor. In 1998, NOAA completed installation of PORTS in San Francisco Bay, California. PORTS in San Francisco Bay consists of five shore stations where water level (tides), wind speed and direction, wind gust, air temperature, and barometric pressure are reported every six minutes (Figure 1). Five acoustic Doppler current profilers (ADCPs) have been installed reporting water velocity data every six minutes (Figure 1). Since there are only a limited number of PORTS sensors, the PORTS information database is complemented by a nowcast numerical model whose results are also made available to users at near real-time. The PORTS data, data analysis, nowcasting for tides, and nowcast numerical model results constitute the San Francisco Bay marine nowcast system.

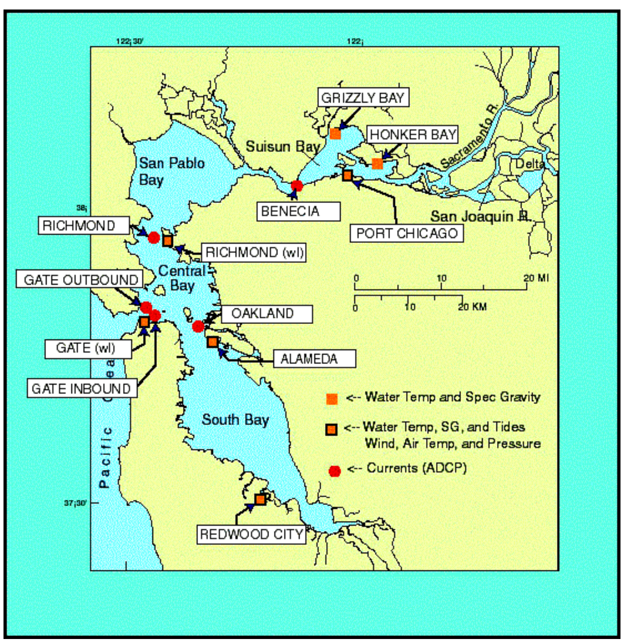

Figure 1. The San Francisco Bay estuary and PORTS sensor locations map.

During the course of implementing a user interface for the PORTS information delivery system of San Francisco Bay, the World Wide Web (WWW) has been adapted as an effective conduit for transmitting vast amounts of text and graphic information to users at near real-time. The marine nowcast system for San Francisco Bay combines a real-time data collection system, a nowcast numerical model, and an information dissemination scheme providing near real-time observations and nowcast model results to users through the WWW. This paper describes the implementation of a nowcast numerical model for San Francisco Bay. An overview of the San Francisco Bay PORTS is presented in Cheng et al. (1998).

II. Nowcast Numerical Model

II.1 Choice of Numerical Model

San Francisco Bay estuary is a geographically and bathymetrically complex tidal system that is characterized by broad shoals (less than 2 m deep at MLLW) and narrow channels (typically 10-20 m deep). The bay system spans between the Pacific Ocean and the confluence of Sacramento and San Joaquin Rivers, and it comprises numerous inter-connected channels, embayments, sloughs, and fragile tidal marshes. Owing to the extremely complicated geometry and bathymetry of the bay system, the tidal current pattern in San Francisco Bay varies extensively throughout different parts of the bay and changes at different phases of the tides. Because the coverage of PORTS data is not sufficient to represent temporal and spatial variability of tides and tidal currents in the bay, high-resolution numerical model has been installed as an integral part of the San Francisco Bay marine nowcast system. Since the primary objective of the nowcast numerical model is to reproduce the tides and tidal currents, a conscientious choice of an optimal model must be made before model implementation. Past modeling experience suggests that a depth averaged numerical model is sufficient for the present tasks. However, the numerical model must be computationally efficient and must be capable of resolving the complex geographical and bathymetrical features of San Francisco Bay.

A 200-m uniform finite-difference grid is used for San Francisco Bay, California. The model grid and water depths are defined on coordinates based on Mercator projection so the model outputs can be directly superimposed on navigation charts (Snyder, 1987). The region near the entrance to the bay (Golden Gate) is of great importance to navigation safety. Furthermore, the tides and tidal currents in this region are extremely complex, thus the entrance to the bay is not an appropriate location to be treated as the model boundary. Therefore, the western model boundary has been extended from the coast to the west (Pacific Ocean) by about 10 km (See Figure 4). To avoid complications in specifying salinity boundary condition near rivers, the model boundary at the eastern end is chosen to be near the confluence of Sacramento and San Joaquin Rivers about 60 km to the east of Presidio. Of the total 160,000 grid points in the model domain, about 30% are active. The 'nowcast modeling' is defined to be a model simulation that includes a hindcast for the past 24 hours and a forecast for the next 24 hours of tides and tidal currents. A nowcast numerical model must be robust, accurate and computationally efficient. Based on these modeling objectives and criteria, a robust, semi-implicit, finite-difference model known as TRIM (Cheng et al., 1993) that meets these requirements has been chosen for this application. A time integration of six-minute is used in simulations without any sign of numerical instability. Forty-eight hours of simulation requires 12 minutes of CPU time on an SGI computational server (R10000, 185 MHz CPU). The numerical algorithm of TRIM and its calibration procedures against historical field data have been reported in detail by Cheng et al. (1993). Since the model domain has been expanded in this application, the model calibration was updated; however, the model calibration procedures remain to be the same and will not be repeated here.

II.2 Nowcast Modeling Procedures

In nowcast modeling mode, the relevant time scale is hours. At this time scale, the wind stress over the water surface becomes another important forcing. The wind distribution over San Francisco Bay region shows a clear diurnal pattern in the summer and is variable in the winter. To fulfill the need of wind forcing, the real-time regional wind distribution is provided by a diagnostic wind model developed by Ludwig et al., (1997). The regional wind distribution is updated every hour and is used to compute the wind stress distribution as input to

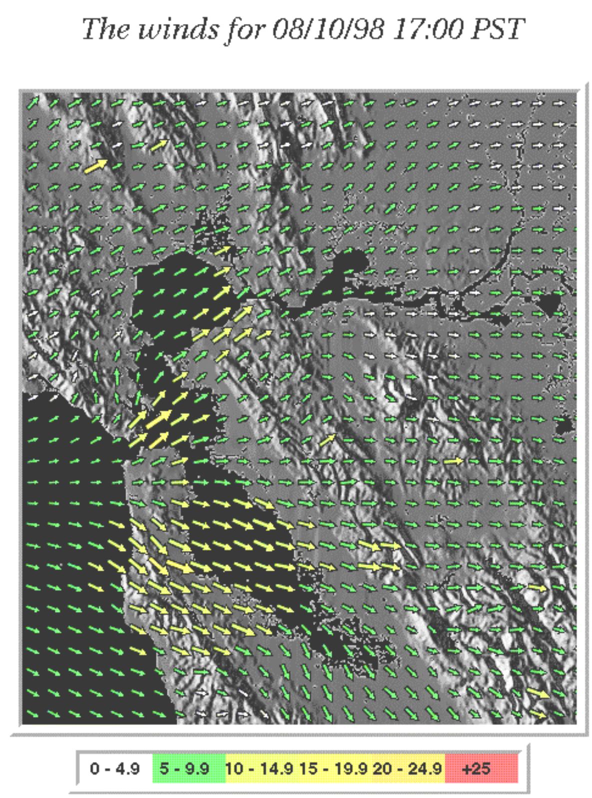

Figure 2. An example of the regional real-time wind distribution over San Francisco Bay area.

the nowcast hydrodynamic model. An example of the wind distribution over San Francisco Bay region is shown in Figure 2, (URL-wind, 1996). Clearly the wind pattern is strongly affected by the regional topography, and inland heating that generates sea-land breeze in a diurnal pattern. The wind distribution is not only an important driving force in the nowcast current model, but also provides invaluable information to aid navigation safety.

All nowcast modeling operations are cycled once an hour. Each procedure is scheduled at a fixed time within an hour and is automatically initiated and executed. At shoreline boundaries, no boundary condition is needed. At open boundaries, the salinity values and sea-levels must be specified at every time step. In this application, at the eastern open boundary, salinity is treated as freshwater, and at the western open boundary (Pacific Ocean), salinity is assumed to have an oceanic salinity value. Prescribing sea-level boundary condition is not as straightforward. Nowcast modeling mode differs from conventional modeling in that all controls and boundary conditions for a model simulation must be processed automatically. The model simulation is initiated every hour continuously to compute tides and tidal currents starting from 24 hours before the present time (now) covering a total of 48 hours simulation. Since PORTS data are not available at the model boundaries, the model boundary conditions must be estimated using data assimilation techniques. To achieve this level of operation, the nowcast modeling system needs to address both the conventional numerical modeling issues (accuracy, numerical stability, etc.) and also the issues related to interfacing PORTS data and assimilating boundary conditions automatically.

A set of boundary conditions is first estimated based on harmonic predictions using the harmonic constants derived from the nearest tide observations. Perturbations, P_i, are introduced to a boundary condition predictor to achieve a reasonable reproduction of historical observations within the model domain (model calibration). These perturbations include a shift in phase from the reference station, a modulation in amplitude, and an adjustment in the reference sea level. In principle, individual perturbations can be introduced to each open boundary point. In reality, however, only two sets of perturbations are introduced for defining the tides at the eastern and at the western model open boundaries. All dependent variables are saved in a file one hour (simulated time) after the simulation has been initiated. This file becomes the initial condition for the model simulation to commence in the next hour. The nowcast model results are saved in several ways. A complete 'snapshot' of the model results is saved every hour (simulated time). These 'snapshots' include velocity, tides, and salinity distributions in the entire domain for post-processing and broadcasting to users via WWW (Cheng, et al, 1998). Time-series of the simulated tides and velocities are saved at model grid cells corresponding to the PORTS sensor locations. Obviously, the model-generated time-series are functions of the boundary conditions. More specifically, the time-series of model simulated tides and velocities are functions of the perturbation parameters, P_i's, defining the boundary conditions. In the first 24 hours of simulation, the simulated time-series over-lap with field data at PORTS stations. To achieve a best 'hindcast' for the past 24 hours, an objective function F is defined as

$$F=\sum_{i=1}^{M}\int_{t_o}^{t_o+24}\left[\varsigma_i^m(t,P_1,P_2,P_3,,,,P_k)-\varsigma_i^o(t)\right]^2 dt+\sum_{j=1}^{N}\int_{t_o}^{t_o+24}\left[V_j^m(t,P_1,P_2,P_3,,,,P_k)-V_j^o(t)\right]^2 dt \quad (1)$$

where

t_o = starting time of simulation;

$\varsigma_i^m,\varsigma_i^o$ = simulated and observed sea-level at the i-th station, respectively;

V_j^m,V_j^o = simulated and observed velocity at the j-th station, respectively;

P_1, P_2, P_3,,,,P_k = Perturbations in the boundary condition predictor;

M = total number of sea-level observations in PORTS;

N = total number of ADCP observations.

The objective function is a measure of how well does the nowcast numerical model reproduce observations at the PORTS data stations for the immediate past 24 hours. For a perfect simulation, F approaches to zero. Treating (1) as an optimization problem, a best achievable simulation is attained by maintaining F to a minimum. Therefore, the perturbation parameters can be determined from

$$\frac{\partial F}{\partial P_k} = 0; \quad k=1,2,3,,,,,,K; \qquad (2)$$

where (2) is a system of K number of equations for solving the K perturbation parameters in the open boundary conditions. The optimization problem, (2), is solved for K perturbation parameters after each simulation. They are used to generate the open boundary conditions for the simulation to commence in the next hour.

Model results of past simulations are not saved or archived. Instead, the model initial and boundary conditions are archived once a day. Since the numerical model is computationally very efficient, past tides and tidal current distributions can be reproduced easily by a simulation starting from an appropriate archived initial and boundary conditions.

III. Nowcast Model Results

During the course of development and implementation of the San Francisco marine nowcast system, it was clear that the sea conditions, weather conditions, and nowcast model results must be made available to users as close to real-time as possible. Recent advances in internet technologies and the explosion in WWW usage have made it obvious that WWW is ideal for this marine nowcast system. Vast amount of real-time and nowcast data can be transmitted to users with minimal time delay. This approach was successfully tested by making available the real-time regional diagnostic wind distribution over the San Francisco Bay region on the WWW for public use since February 1996 (Ludwig et al., 1997). User feedback provides further reassurance that the user interface for the San Francisco Bay marine nowcast system should be an internet based system in order to achieve an effective deliverance of PORTS data and nowcast results to a broad spectrum of potential users. The integration of a nowcast numerical hydrodynamic model, real-time observations, and delivering the real-time data and nowcast results (both observations and model results) on the WWW makes the San Francisco Bay marine nowcast system a very unique and extremely powerful system. An overview of the San Francisco Bay marine nowcast system is described in Cheng et al. (1998).

The results of the nowcast numerical model can be divided into two categories: 1) Time-series data and 2) Tidal current maps. These results can be obtained from San Francisco Bay PORTS site on WWW (URL-sfports, 1998). The home-site of San Francisco Bay marine nowcast system has a

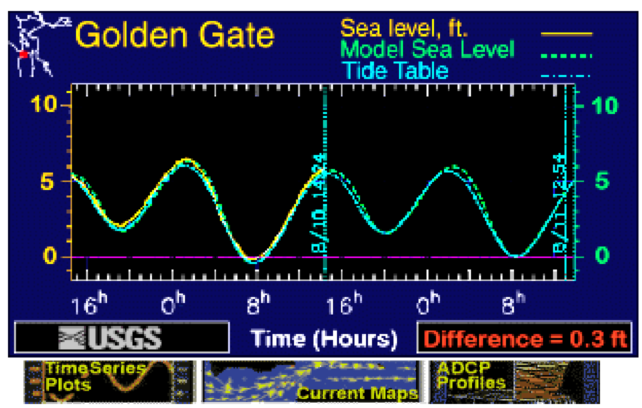

Figure 3. Twenty-four hours of observed (yellow), forty-eight hours of nowcast modeled sea-level (green), and forty-eight hours of NOAA tide table prediction (blue) of tides at Presidio Station (9414290).

left panel and a main panel. The left panel shows the menu and options. Selected results are shown in the main panel. Figure 3 shows an example of the model simulated water-level time-series near

Golden Gate (Station 9414290) when compared with observations and with tide-table prediction published by NOAA. Similar results can be found for other PORTS stations.

The second category is the simulated tidal current distributions superimposed on a navigation chart. Starting from the home-page, an index for the current map can be found by selecting "current map" from the left panel, Figure 4. The color background is an index of water depth. By pointing-and-clicking at a region of interest, the index map can be zoomed into Suisun Bay, San Pablo Bay, Central Bay, or South Bay. At this level, an areal velocity distribution is also shown, Figure 5.

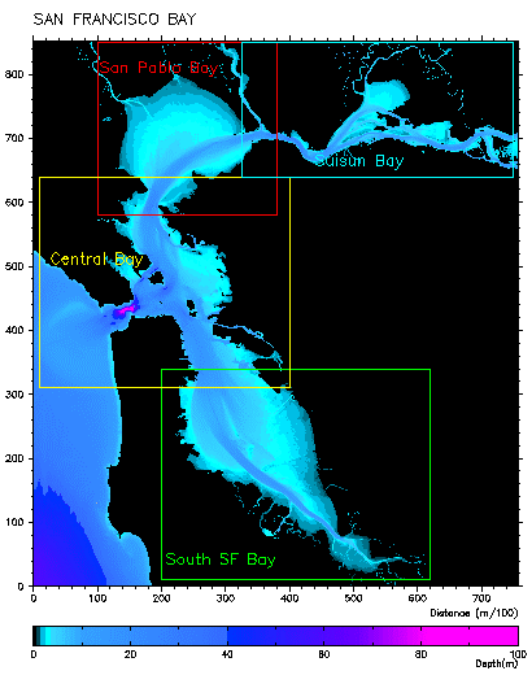

Figure 4. Index map of the San Francisco Bay nowcast numerical model domain. The color background is an index of the water depth.

Ideally, a velocity map should have the capability of continuous zooming and panning. Technically this approach is possible, but the response time to user requests is too slow because of high computing demand. As a compromise, the regional velocity map is

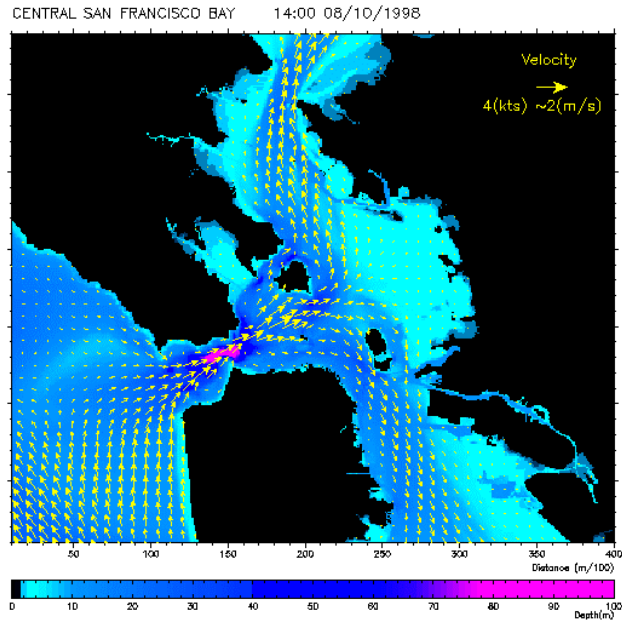

Figure 5. An areal velocity distribution in Central Bay showing flooding in Central Bay. Detailed velocity distribution can be obtained by zooming into the next level.

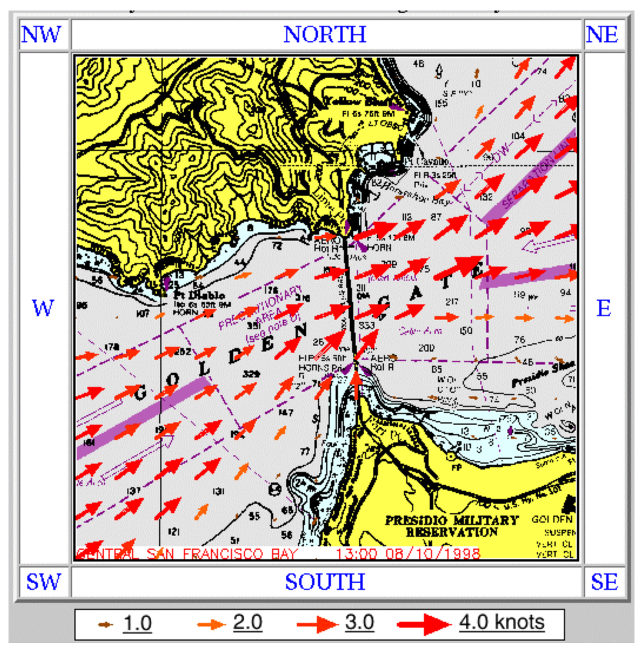

Figure 6. An example of tidal current distribution near Golden Gate Bridge, entrance to San Francisco Bay from the Pacific Ocean.

divided into consecutive tiles. A detailed and a quantitative velocity distribution map can be obtained by pointing-and-clicking at the location of interest. The nowcast model velocity vectors are plotted on a tile of a navigation chart published by NOAA, Figure 6. The velocity maps in the eight neighboring tiles (NORTH, NE, E, SE, SOUTH, SW, W, and NW) can be visualized by pointing-and-clicking at the edge of the tile. This format is used for the nowcast model results because the navigation chart is a format familiar to users in the maritime community. If a wireless modem is available, then the real-time tides and tidal currents can be made available to ship operators when the vessel is under way. These real-time and nowcast information of tides, tidal currents, and weather conditions are extremely useful in all maritime activities. Since the concept and the installation of the marine nowcast system are quite new, the true usefulness of the present system is difficult to quantify. It is clear, however, that an accurate forecast of water-level (tides) would improve the margin of navigation safety. The usefulness of the present system is subject to continuing evaluation, particularly after the present system has logged sufficient hours of user exposure.

IV. Summary and Conclusion

NOAA installed Physical Oceanography Real-Time System (PORTS) in San Francisco Bay, California to provide real-time observations of tides, tidal currents, salinity, and meteorological conditions. The installation of PORTS in San Francisco Bay presents an opportunity for the development of a comprehensive marine nowcast system for optimizing vessel operations and for improving marine navigation safety. A nowcast numerical model has been successfully installed and has become an integral part of the San Francisco Bay marine nowcast system. Nowcast modeling procedures differ from conventional modeling in that all controls and boundary conditions for a model simulation must be processed auto-matically. All nowcast modeling operations are cycled once an hour. Each procedure is scheduled at a fixed time within an hour and is automatically initiated and executed. Since PORTS data are not available at the model boundaries, a data assimilation algorithm has been developed and successfully tested for defining open boundary conditions of the nowcast model. The nowcast model results along with the PORTS data are disseminated via the WWW. The real-time information of tides, tidal currents, and weather conditions can be used in all maritime activities. Archived model initial and boundary conditions allow a rapid reproduction of tides and tidal currents in the bay for a previous date if those results are needed. Furthermore, archived field data are invaluable to scientists conducting studies of the San Francisco Bay ecosystem.

Acknowledgement

This research effort is jointly funded by the U. S. Geological Survey and NOAA through the San Francisco Bay PORTS project partnership.

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