Marine Forecasting for the New York Urban Waters and Harbor Approaches: The design and automation of NYHOPS

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MARINE FORECASTING FOR THE NEW YORK URBAN WATERS AND HARBOR APPROACHES: THE DESIGN AND AUTOMATION OF NYHOPS

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Abstract. *A new high-resolution OFS (Operational nowcast and Forecast hydrodynamic model System) for the New York/New Jersey (NY/NJ) Harbor estuary, NJ coast, Long Island Sound, and their coastal ocean has been developed. The new OFS was designed to supersede the previous NYHOPS (New York Harbor Observation and Prediction System) in providing accurate, medium term (48hr), water level, wave, 3D currents, temperature, and salinity forecasts. The new, automated system includes a) improved and updated resolution, bathymetry, forcing, and physics; b) operational, web-disseminated products geared toward marine transportation, extreme weather prediction, and search and rescue missions. The updated NYHOPS is used in a multitude of real-life environmental awareness situations, ranging from routine bulk containership schedule planning, to advising US Airways Flight 1549 response teams after the plane hit the Hudson River waters less than a mile from the Stevens campus waterfront. Examples from these situations and a description of the design and automation of NYHOPS are presented in this paper.*

1 INTRODUCTION

Marine nowcasts and forecasts are scientific predictions about the present and future states of water levels, wave conditions, currents, and other relevant oceanographic variables, such as temperature (T) and salinity (S), for waters of the open ocean or, more recently, in coastal areas. These predictions rely on a) observations from *in situ* or remote sensors and b) forecasts from numerical models of the governing physics. A nowcast may incorporate recent (and often near real-time) observed meteorological (e.g. wind and heat fluxes), oceanographic, and hydrologic (e.g. river inflow) data collected by earth observing systems. It covers the period of time from the recent past (e.g., the past few days, the hindcast period) to the present, and includes estimates of marine conditions at locations where observational data are not available due to practical/monetary constraints. A forecast may employ meteorological, oceanographic, and hydrologic computer models to make predictions for times in the future, where observational data are *de facto* not available. A forecast is usually initiated by the results of a nowcast.

The user base of coastal marine forecasts in particular comprises the general maritime community, whether it is sailors, port authorities, emergency management personnel, search and rescue teams, coastal engineers, or coastal scientists and oceanographers. The most direct usage may be that of a helmsman needing to know the currents and water level conditions *a priori* and accurately enough to plan safe passage through the waters of the simulated coastal ocean, embayments, and/or river reaches. Emergency management personnel may need to know in advance when water levels will exceed flooding levels. They, as well as search and rescue teams, may have an interest in inferring the advection and spread of hazardous substances, or the transport of buoyant apparatus and people in the water, through hydrodynamic circulation fields forecasted by a model. Regular beach goers may want to know, apart from water quality, if the waters are suitably warm for swimming. Fishermen may have an interest in predictions of nutrient-reach coastal upwelling, or the extent of salt intrusion within a river reach. The latter may affect intakes of power plants or pump stations. Therefore, a coastal marine forecast may be of interest to sewerage authorities and municipal departments of environmental protection. Even less straightforward use of an OFS model may be made by scientists interested in the understanding of ocean-atmosphere interactions, water quality conditions including sediment dynamics, underwater sound transport, beach erosion and morphology, etc.

In order to answer most of these needs a marine OFS model should be able to solve the system of equations for the following prognostic variables:

- Water level (tides, storm surge, steric fluctuations, and wave setup),
- Currents (tidal, fluvial, wind-driven, and density-driven),
- Mixing (in the form of horizontal and vertical mixing coefficients),
- T and S (based on overlying atmospheric conditions, freshwater and thermal inputs), and,
- Wave heights (distant swell and local wind-generated).

In order to do so with sufficient accuracy, a marine OFS may use:

- An accurate description of the bottom topography, i.e., recent and accurate bathymetry,
- A good representation of that bathymetry in the form of a boundary (lateral and bottom)-resolving numerical grid,
- An established solution scheme for the equations of motion, including a turbulence submodel, and a wave module,
- observations and forecasts of the circulation drivers (e.g. meteorological conditions, river flows, tides, etc.), to force the model, and,
- observations of the model's prognostic variables for model quality control and correction.

The New York Harbor Observation and Prediction System (NYHOPS [1]) was established in 2004, through coordinated efforts from academia, local government, and the United States Navy to, by and large:

- Permit a real-time assessment of ocean, weather, environmental, and vessel traffic conditions throughout the New York Harbor and New Jersey Coast regions,
- Provide marine forecasts for the said area up to 48 hours in advance,
- Establish a continuous history of the marine conditions in and around the New York / New Jersey Harbor, and,
- Provide a test bed for environmental systems integration into situation awareness scenarios, ranging from flooding alerts to search and rescue to chemical spills.

Five years later, in 2009, a new, high-resolution, marine OFS for the NY/NJ Harbor Estuary, NJ coast, Long Island Sound, and their coastal ocean (Figure 1) has been designed at the Center for Maritime Systems of the Stevens Institute of Technology (Stevens) in Hoboken, NJ. The new OFS builds upon the older NYHOPS, providing marine conditions in a much higher resolution grid, for a larger area, based on improved representations of physics and physical constraints (such as boundary conditions), and in more formats (such as Google Earth kml files, OpenDAP/THREDDS servers, etc.). An intermediate evaluation version of the high-resolution product was first made available in early 2007. After a two-year period of continuous development, testing, and automation, the new product has become operational and publicly available under the name NYHOPS version III (www.stevens.edu/maritimeforecast), a part of the regional component of the global IOOS.

2 NYHOPS VERSION III. SYSTEM DESCRIPTION.

In brief, NYHOPS utilizes a network of sensors installed and operated by Stevens and an EDUCATE (External Data Uninterrupted Cashed Acquisition and Transfer Effectiveness) protocol that taps into external databases and federal agency forecasts, to create the input forcing to a three-dimensional hydrodynamic forecast model. The model simulates the marine environment for the next 48 hrs, in response to meteorological conditions, freshwater and thermal inflows, tides, and baroclinicity (density-driven forces) at the open boundaries. The enhancement of model accuracy is accomplished through the assimilation of observations provided in real time to the hydrodynamic model (nowcasting).

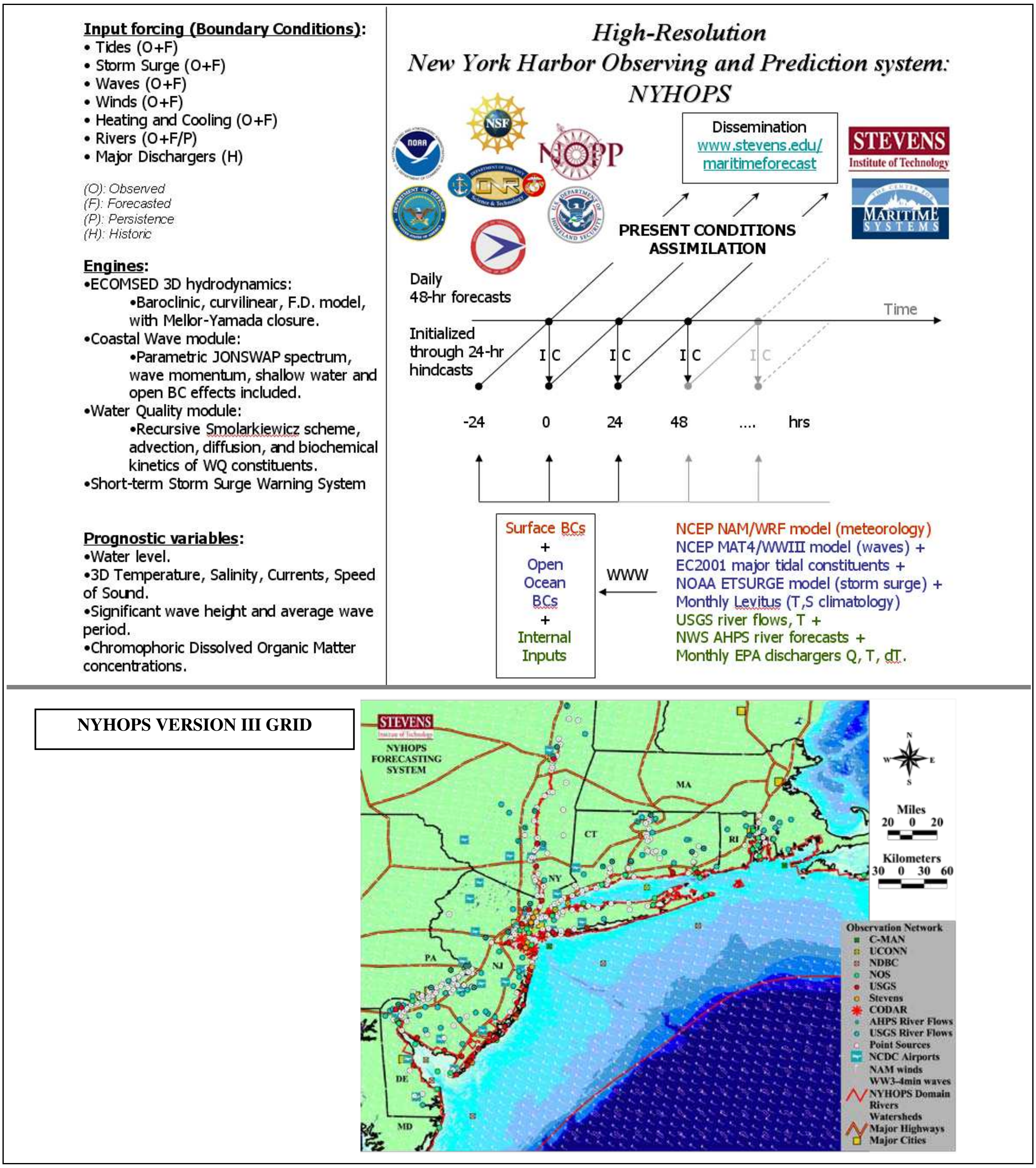

Figure 1. The latest New York Harbor Observation and Prediction System (NYHOPS version III).

NYHOPS can be viewed as a system of systems, a concept made up of various modules each working in tandem with the other exchanging information to produce their individual NYHOPS products. The NYHOPS system of systems is comprised by the following modules:

- The Stevens Oceanographic and Meteorological Data Repository (OMDR)
- The NYHOPS forecast module
- The NYHOPS website and user-tailored products (Assimilated Nowcast, Storm Surge Warning System, Google Earth ® NYHOPS viewer, Coastal Inundation Mapper, etc.)

2.1 Environmental Data Acquisition. The EDUCATE protocol and the OMDR database.

NYHOPS acquires environmental data from both Stevens and non-Stevens sources. Stevens maintains a series of hydrological and meteorological stations in New York Harbor, in local estuaries, and along the New Jersey coast (Figures 1 and 2). For observations of currents in particular, Stevens maintains a buoy with an ADCP in the Hudson River, a vertical currents profiler (ADP) on a US Coast Guard buoy in the Harbor, and one of the three HF-Radar surface current sensors shown in Figure 2. These stations transmit data periodically (typically once an hour). Some stations use internet links over either DSL or cellular modems; others transmit via a direct radio link to a receiving station located on the Stevens campus atop the Howe Center.

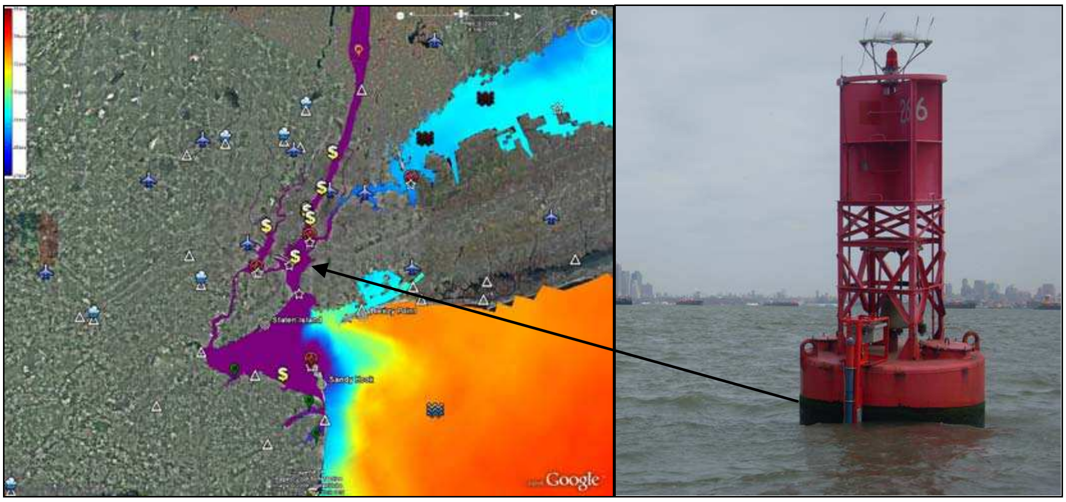

Figure 2. Distribution of NYHOPS-supporting sensor networks in and around the NY/NJ Harbor. Three, surface-current-observing, HF-Radar (CODAR) sites are named on this Figure. Icons correspond to different agencies serving observation data from fixed sensors ($ denotes Stevens-operated). The color-map underlay is a surface salinity forecast by the NYHOPS model valid Nov 6th 2008, 5pm EST similar to the currents Google Earth maps accessible in http://hudson.dl.stevens-tech.edu/maritimeforecast/google/index.shtml. The Stevens ADP mounted on a US Coast Guard ATON buoy (Aid-To-Navigation Gowanus 30) is shown on the right.

NYHOPS also retrieves data from non-Stevens sources such as NOAA, USGS, AHPS, NCDC, HRECOS, and other universities with whom we partner to share our data. Techniques for retrieving this data include 'screen-scraping' of web sites, text and XML data downloads from HTTP sources, and data file downloads from research partners. Acquisition of this data relies in a protocol we designed called EDUCATE. As Stevens is a university and is vulnerable to power disruptions, NYHOPS prefers to retrieve all data proactively to minimize any data stream loss due to service interruptions: Most data providers allow NYHOPS to specify the chronological range for which data is to be retrieved, and our software is designed to backfill missing data. Stevens-managed environmental stations are designed to retain data until it has been successfully received on campus.

All NYHOPS-supporting (or NYHOPS-generated data) are stored in the Stevens OMDR. NYHOPS utilizes dual MySQL database servers to manage both environmental and model data. They are hosted on Dell servers running Red Hat Enterprise Server Linux and include 10 terabytes of available disk storage. The database maintains environmental data dating from 2004 to the present, and model data from 2006. All data management software development is done using Perl and Java. Java programs are used to extract environmental and model data from the database and create files designed for use by FORTRAN programs. Collected observations are available in http://hudson.dl.stevens-tech.edu/maritimeforecast/PRESENT/data.shtml.

2.2 NYHOPS forecast module. The three-dimensional hydrodynamic model.

The hydrodynamic forecast model is based on the Princeton Ocean Model (POM [2]) and its shallow water derivative model, ECOMSED [3]. The NYHOPS forecast model is being run at Stevens daily, to provide a hindcast (-24hrs) and forecast (+48hrs) of the hydrodynamic circulation and wave conditions in the coastal (<200m deep), estuarine, and freshwater zones from coastal Maryland to Cape Cod, Massachusetts (Figure 1). The hydrodynamic model is initiated at 0 hrs local every day, and completes a 24hr hindcast cycle based on observed forcing followed by a 48hr forecast cycle based on forecast forcing. NYHOPS provides forecasts of water level, 3D circulation fields (currents, T, S, density, speed of sound), significant wave height and period.

The 3D hydrodynamic code includes significant features not included in the original POM, such as wetting-and-drying (W&D) and thin-dam formulations, data assimilation, as well as coupled wave and fully-2D atmospheric modules [4,5]. A high-resolution curvilinear model grid is used to encompass the entire Hudson-Raritan (New York/New Jersey Harbor) Estuary, the Long Island Sound, and the New Jersey and Long Island coastal ocean (Figure 1). The resolution of the grid ranges from approximately 7.5km at the open ocean boundary to less than 50m in several parts of the NY/NJ Harbor Estuary. The current vertical resolution of the grid is 10 sigma (bottom-following) layers. The 72hr NYHOPS version III daily run (W&D hydrodynamics with coupled waves and 2D atmospherics) runs on a Dell Nehalem computer with eight 2.93GHz cores (2 quads with hyper-threading) in about 1.5hrs with a 1sec barortopic (2D) and a 10sec baroclinic (3D) timestep.

The NYHOPS version III model has been extensively validated against water level, wave, T, S, and current observations during a 2-year validation period. For example, long term (2007/02/01-2009/02/01) mean root-mean-square-error (RMSE) for the 0-24hr forecast period is 9.8cm and 10.8cm at Atlantic City and Sandy Hook, NJ respectively. Within that 2-year evaluation period, the NYHOPS version III model driven by the 2D NCEP NAM (North-American Mesoscale WRF) meteorological forecasts explains 82% and 74% of the surge variability (R^2 value), respectively – similar skill is obtained for wave-heights. Even for the 48th hour of the forecast, the NYHOPS RMS error for water level predicted at Atlantic City is maintained below 13cm. For comparison, the mean astronomical tidal range at Atlantic City is 122cm (an extra 15% of the total water level variance is from storm surge). With regard to temperatures, the model skill (long-term RMSE close to 1ºC) in sea-surface-temperature (SST) prediction has proven to be comparable with remote satellite observation skill [5,6].

The code that automatically collects and QA/QC's the model forcing data from the Stevens OMDR, sets up the model run based on the latest available information consistent with the EDUCATE protocol, executes the daily simulation, stores, plots, and posts the model results on the web is cron-tabbed on a computer running Red Hat Enterprise Linux. The master code is a combination of many smaller pieces written in Linux shell, perl, matlab, FORTRAN, and Java. A snippet of the master code is shown on Figure 3.

Finally, all NYHOPS model native NetCDF output conforms with the latest Climate and Forecast (CF version 1.4) metadata conventions and canonical units. Packing (integer scaling) of data is used to reduce output size to approximately 3GB of output data per day (10-min averages for 72 hrs).

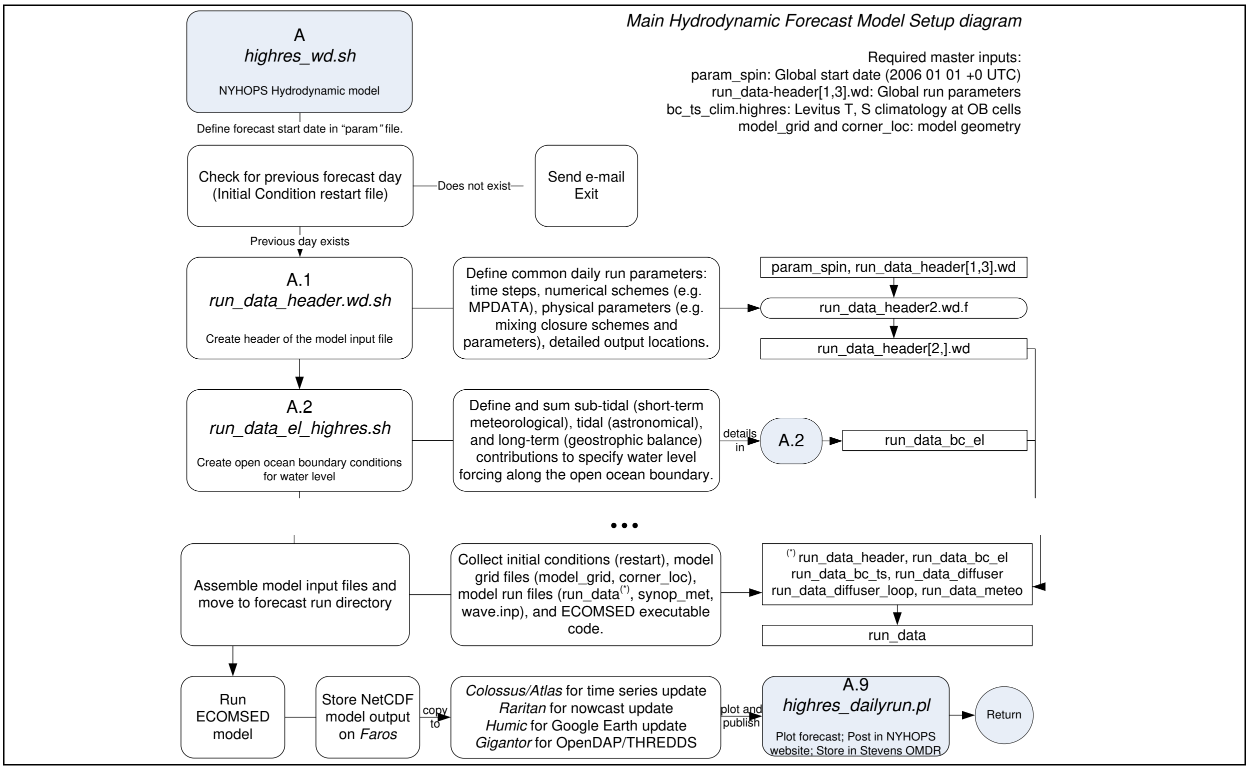

Figure 3. A snippet of NYHOPS automation. The NYHOPS flow diagram for hydrodynamic model setup.

2.3 NYHOPS website.

The NYHOPS web site provides access to the following areas:

Nowcast Environmental Data: The NYHOPS Present Conditions (Nowcast) site (http://hudson.dl.stevens-tech.edu/maritimeforecast/PRESENT/index.shtml) provides maps for two areas within the model region, Manhattan Waters and the New Jersey Coast. The graphic display combines near-real-time forecasts and environmental data using a Laplacian assimilation step [7]. The user may then navigate to the Present Conditions Time Series and Download page, which allows the user to plot and/or download environmental data stored in the Stevens OMDR. The user may specify a date range, select a time zone, and select English or SI units. This page uses the Google Maps API to display the location of each of the stations. An example is provided in Figure 4.

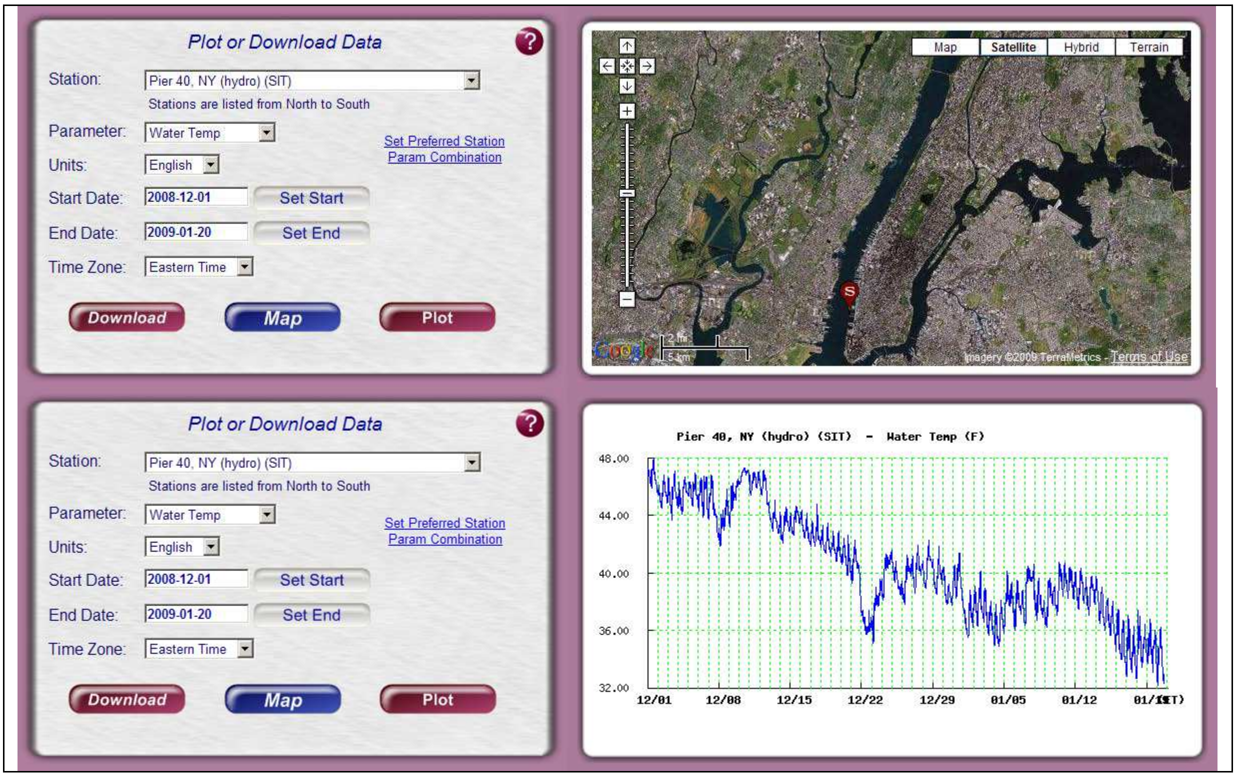

Figure 4. Online interface to the Stevens OMDR. Example of a water temperature record request (in local eastern US standard time, and English units) from the Stevens-maintained Pier 40, NY station between 2008-12-01 and 2009-01-20. Upper panel shows the beginning of the Excel® file available for "Download". The middle panel shows a Google® "Map" of the sensor location. The bottom panel shows a time series "Plot" of the data.

NYHOPS Hydrodynamic Forecasts: This section of the website (http://hudson.dl.stevens-tech.edu/maritimeforecast/maincontrol.shtml) presents forecasts for 48 hours, along with hindcasts for 24 hours. The NYHOPS region is presented as a series of sub-regions, which may overlap and encapsulate one another. Forecasts are currently displayed hourly (every 10-minutes, as stored, in the future), and the user may opt to 'animate' the display such that the server will display 48hrs worth of forecast for a given region and parameter.

The model graphic includes markers for each station for which 10-minute time series are available. By clicking on a station marker the user can view these time series which include up-to-now comparisons (including RMSE) between model forecasts and observations acting as "ground truth" for the forecast. Time series are available for approximately 88 stations. The Hudson River waterfront of the Stevens campus, and several of the Stevens river-borne observation stations are located less than 1km away from the site of the Jan 16, 2009 US Airways Flight 1549 "landing" on the River. Thus, direct real-time observations and ground-truthed model forecasts were immediately available to inform responders to the accident of the present *and future* environmental conditions in the River (www.dhs.gov/xres/programs/gc_1235499372408.shtm).

Because NYHOPS is a university product, and limited bandwidth must be shared with an entire campus, it was important that the website be optimized for data transmission efficiency. There are two major ways in which this was done:

1) To avoid unnecessary interaction between the browser and web server, all user interaction is handled client-side through Javascript. Once the page is loaded, the only access to the web server is to download additional graphics.
2) The model forecast graphics include a great deal of land. Because the background maps are more graphically complex, they are not incorporated into each graphic. Instead, one background image is downloaded for each region, and the model graphics are transparent where there is land. This allows placing the model image on top of the map. Further efficiencies are gained through the use of Indexed PNG files for model graphics.

3 USER-TAILORED APPLICATIONS OF NYHOPS.

Some uses of a marine OFS such as NYHOPS were mentioned earlier. A few more presently available or under development NYHOPS applications that have arisen based on user needs are described next. NYHOPS-optimized floatable trash controls, bacteria tracking for beach closure forecasts, etc., are further examples.

3.1 Storm Surge Warning System (SSWS) and Map of Inland and Coastal Inundation (MICI)

The Storm Surge Warning System (SSWS [8], http://hudson.dl.stevens-tech.edu/SSWS) has been designed to automatically inform local officials of the probability of impending coastal flooding in their area. Water levels are checked against specific flood levels (minor, moderate, and severe) as tabulated by the PHI (Mount Holly, NJ) NWS Forecast Office for the local area serviced by NOS reference sensors. If a flood level is predicted to be exceeded by the forecast water level, SSWS automatically accesses an electronic database of registered users (e.g. emergency management, local police, fire department officers) who are then automatically contacted via a “flooding alert” e-mail message sent out to pagers, cell phones, and computer servers. The text message indicates the anticipated time of flooding, station location, and flood warning level, and provides a link to that station’s time series page so that he/she can assess the accuracy, duration, and severity of the forecast event that triggered the alert, and decide on appropriate action. The passive and autonomous nature of the system removes the need for emergency management staff to continuously monitor coastal water level data, freeing up personnel for pre-event preparation and planning. The map on the SSWS website shows SSWS station location markers color-coded by their real-time observed and NYHOPS forecast flood level. Clicking on a marker or station name brings up time series of water levels at that station. A control box can be used to select a different SSWS station, define the start and end date to be displayed, change vertical datum to accommodate level reference to the one used by the user’s agency, change units and time zone, and query the observations.

The Map of Inland and Coastal Inundation (MICI) is an exciting new tool under development among Stevens and partner institutions (simple demo at: http://penguin.dl.stevens-tech.edu/wpdemo) that is expected to bridge the gap between predictions of coastal and inland flooding. The NYHOPS ocean hydrodynamic model will be linked to inland flood models (HES-RAS and HEC-HMS) to calculate simulated “areal-photography-like” flood maps as nowcast or forecast by the coupled models for underway flooding events due to both inland rainfall and coastal storm surge. Inundation maps, evacuation routes, and real-time observations of inland flood levels will be included and continuously updated as Google kmz files on the Google-API-based site.

3.2 NY/NJ Harbor NAvigation and Vessel SAFEty Support System (NAVSAFE) and NYHOPS OpenDAP/THREDDS server

Commercial and recreational boaters in the Harbor (including bulk container schedulers, sail boat racing pilots, and kayakers) form one of the most consistent user groups of NYHOPS products. Boaters are generally interested in water levels (grounding avoidance, bridge clearance, cargo optimization), surface currents, waves, and wind [9]. The present NYHOPS suite of websites includes a lot of information that this user group has found useful in the past. Boaters use the site to get information and download the NYHOPS geo-referenced images (of currents or winds for example) to on-board applications that can display them *en route*.

Yet, user needs evolve with technology improvements. Under renewed funding from the NJ Department of Transportation, NYHOPS will be placed into an operational Navigation and Vessel Safety Support System for the NY/NJ Harbor. Stevens is developing a path planning algorithm that will provide ocean and weather conditions along a transportation route chosen by the port pilots. PC-based and/or Internet served application interfaces, such as iPhone® and Blackberry® applications, will be developed to efficiently generate, distribute, and display NYHOPS forecasts and path simulations. Through clickable color maps and time series plots the user will be able to determine the current and water level values at a particular location and time in the Harbor.

Finally, it is possible that, even with such direct and diverse product offerings as aforementioned, the needs of a particular user might not be satisfied. Many people have asked for direct access to the NYHOPS forecast output data so that they can develop particular applications that can take full advantage of that data for their needs. In the summer of 2009, such a service will become available through an OpenDAP/THREDDS server hosted at Stevens that will serve CF1.4 NetCDF NYHOPS model output files to the general public. These files can then be recognized and rendered by off-the-shelf software, including the Unidata Integrated Data Viewer (IDV), the NOAA GNOME oil spill tracking tool, the NASA Panoply software for global datasets, etc.

4 CONCLUSIONS

The inner workings, automation, and application of the new NYHOPS version III OFS for the NY/NJ Harbor and its surrounding coastal ocean have been described in some detail. With continuous support and commitment from academia, local government and industry, and US national funding agencies, the system will continue to evolve and serve the public well into the future. The presented system infrastructure is easily duplicable, and transferable, to other regions and ports throughout the world.

5 ACKNOWLEDGEMENTS

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