NOAA Technical Report NOS OES 003

LONG ISLAND SOUND OCEANOGRAPHY PROJECT

SUMMARY REPORT, VOLUME 3:

SCIENTIFIC PUBLICATIONS

Silver Spring, Maryland
January 1994

noaa National Oceanic and Atmospheric Administration

U.S. DEPARTMENT OF COMMERCE
National Ocean Service
Office of Ocean and Earth Sciences
Marine Analysis and Interpretation Division
Coastal and Estuarine Oceanography Branch

Office of Ocean and Earth Science
National Ocean Service
National Oceanic and Atmospheric Administration
U.S. Department of Commerce

The Office of Ocean and Earth Sciences provides for the understanding of the coastal and ocean environment through the conduct of applied research and development in geophysics; the measurement, analyses, and product development of ocean and lake water levels; the collection, analyses, product development, and dissemination of coastal and global marine data; and the synthesis and interpretation with numerical and mechanistic modeling of global marine data sets. The Office cooperates with the U.S. Navy in conducting oceanographic activities for defense and mixed defense-civil sector purposes and applications.

It plans, develops and coordinates NOAA participation in Federally conducted oceanographic programs and activities, and facilitates cooperative programs, projects and activities with the oceanographic research community. It monitors and analyzes oceanographic activities between NOAA and other organizations and agencies; identifies potential conflicts, overlaps, and opportunities for joint or cooperative efforts; and develops and maintains cooperative agreements, Memoranda of Understanding and other arrangements as appropriate to resolve issues and to ensure maximum benefits from programs of mutual interest. It develops and maintains inventories of oceanographic programs, projects, systems and activities of other organizations and agencies to provide a basis for integrating current and future programs, systems and activities to ensure maximum efficiency and effectiveness in meeting national goals and requirements. The Office conducts research and development; carries out theoretical studies, data analyses, and engineering development; and formulates and executes programs encompassing technological development and application to oceanography, geophysics, geodesy, and related fields .

For the Great Lakes, coastal estuaries, sea coast and oceans, the Office plans, develops, and applies numerical and mechanistic models and produces predictions, forecasts, and analysis guidance materials of oceanographic and related marine meteorological phenomena; collects, analyzes and disseminates tide and water-level observations and associated information; and computes water-level datums for hydrographic, marine boundary and other special surveys. It evaluates and improves methods of data analysis; compares and integrates existing and new classes of data and products; provides and quality controls data sets and an array of output products; and assures science and technology transfer to and from the Office's programs and projects. The Office produces and disseminates operational marine environmental forecast and analysis guidance materials; manages and supports ocean climate studies; installs and operates real-time marine data collection systems; and formulates requirements for marine data sets and for data processing and communications systems; and designs and manages computer-based systems in support of these requirements.

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NOAA
U.S. DEPARTMENT OF COMMERCE

NOAA Technical Report NOS OES 003

LONG ISLAND SOUND OCEANOGRAPHY PROJECT

SUMMARY REPORT, VOLUME 3:

SCIENTIFIC PUBLICATIONS

Richard A. Schmalz, Jr.
L. Charles Sun
Eugene J. Wei

January 1994

U.S. DEPARTMENT OF COMMERCE
Ronald H. Brown, Secretary

National Oceanic and Atmospheric Administration
D. James Baker, Under Secretary

National Ocean Service
W. Stanley Wilson
Assistant Administrator

Office of Ocean and Earth Sciences
Melbourne G. Briscoe

Marine Analysis and Interpretation Division
Ledolph Baer

Coastal and Estuarine Oceanography Branch
Bruce Parker

NOTICE

This publication contains reproductions of papers submitted by members of the Coastal and Estuarine Oceanography Branch, Office of Ocean and Earth Sciences, NOS. The first three papers were refereed and published in *ESTUARINE AND COASTAL MODELING: Proceedings of the 2nd International Conference* held during November 13 - 15, 1991, in Tampa, Florida. The next two papers were published in *ADVANCES IN HYDROSCIENCE AND ENGINEERING: Proceeding of the 1993 International Conference on Hydroscience and Engineering* held during June 7 - 11, 1993, in Washington, DC. The next paper was refereed and published in *ESTUARINE AND COASTAL MODELING: Proceedings of the 3rd International Conference* held during September 8 - 10, 1993, in Chicago, Illinois. The final paper is to be presented at the *1994 National Conference on Hydraulic Engineering* held during August 1 - 5, 1994, in Buffalo, New York and is to be published in the conference proceedings.

CONTENTS

		Page
Simulation of Three-Dimensional Hydrodynamics in Long Island Sound: Annual Timescale	Richard A. Schmalz, Jr. . .	1
Simulation of Three-Dimensional Hydrodynamics in Long Island Sound: Seasonal Timescale	Eugene J. Wei . . .	15
A Numerical Model Simulation of Tidal Currents in Long Island and Block Island Sounds	L. Charles Sun . . .	27
Development of a Long Island Sound Tidal Circulation and Water Level Atlas	Eugene J. Wei . . .	39
Sensitivity of Residual Circulation in Long Island Sound to Tidal Datums	Richard A. Schmalz, Jr. . .	49
Numerical Decompostion of Eulerian Residual Circulation in Long Island Sound	Richard A. Schmalz, Jr. . .	59
Development of Long-term Three-Dimensional Hydrodyamics in Long Island Sound For Use in Water Quality Modeling	Richard A. Schmalz, Jr. . .	73

SIMULATION OF THREE-DIMENSIONAL HYDRODYNAMICS IN LONG ISLAND SOUND: ANNUAL TIMESCALES

Richard A. Schmalz, Jr.[1], M. ASCE

Abstract

The Mellor-Blumberg three-dimensional hydrodynamic model in application to Long Island Sound includes time varying water level residual, sea surface temperature, river inflow, and wind forcings. Prior to long term studies, simulated astronomic tides over the month of September 1988 are compared with reconstructed water levels at 15 locations. Root mean square (RMS) differences between model and reconstructed levels are order 10 cm. Simulated tidal currents are compared with reconstructed currents at 12 stations with RMS differences on the order of 20% of reconstructed range. The eighteen month period April 1988 - Sept 1989 is selected for long term simulation studies based upon available extensive CTD measurements. Simulated salinity and temperature vertical profiles agree in shape with measured CTD profiles over the entire Sound and demonstrate the ability of the model to develop, maintain, and erode observed thermocline and halocline structures. Simulated East River nontidal fluxes are in general agreement with preliminary analyses in magnitude and direction. Simulated Lagrangian residual circulation and salinity fields exhibit known phenomenological features. In conclusion, additional simulation plans and model enhancements are outlined.

Introduction

Long Island Sound is a unique major estuarine resource and is the subject of a comprehensive conservation management plan to be developed by EPA and NOAA. The plan will be developed based upon application of three-dimensional coupled hydrodynamic (NOAA/NOS) and water quality (EPA/HydroQual) models to define the role of circulation and transport processes in dissolved oxygen and nutrient distributions.

---

1 Oceanographer, National Oceanic and Atmospheric Administration, National Ocean Service, Office of Ocean and Earth Sciences, Marine Analysis and Interpretation Division, Coastal and Estuarine Oceanography Branch, 6010 Executive Blvd., Rockville, Maryland 20852.

The physical oceanographic field survey spatially extended from east of Governors Island near The Battery, through the East River and Long Island Sound to the outer boundaries of Block Island Sound and was conducted in two phases. During phase one from April 1988 to October 1989, water level and remote acoustic Doppler (RADS) current profiling measurements were performed by NOAA. Water level and current stations used for model comparison are shown in Figures 1 and 2, respectively. During the first six months, extensive CTD measurements were made by the State University of New York (SUNY) and the University of Connecticut (UCONN) at master stations along the thalweg and along north-south lateral transects. For the remaining twelve months, only thalweg master stations were sampled. CTD stations used for model comparison are shown in Figure 3. In phase two, NOAA conducted a 75-day survey during May - July 1990 to obtain additional acoustic Doppler current profiles, conductivity and temperature time series, and CTD measurements.

This paper focuses on the application of the Blumberg-Mellor (1980) three-dimensional hydrodynamic model to simulate circulation in Long Island Sound over long term annual time scales and presents simulation results encompassing the full eighteen month phase one measurement program. The application of the model to the phase two 75-day measurement program is the subject of a companion paper in this volume (Wei, 1991). Initially, this paper develops the hydrodynamic model formulation and application to Long Island Sound. Results of a one-month astronomic tide simulation over the period September 1988 are shown followed by simulation results for the entire eighteen month phase one measurement program. General model assessment and recommendations for future simulations and model enhancements conclude the paper.

Hydrodynamic Model Formulation and Application to Long Island Sound

The three-dimensional hydrodynamic model employs a general orthogonal curvilinear coordinate system (ϵ_1 , ϵ_2) in the horizontal (Blumberg and Herring, 1987) and a bottom and free-surface following (σ) coordinate in the vertical; e.g., the Cartesian coordinates, (x, y, z) $\rightarrow$ (ϵ_1, ϵ_2, σ). In this formulation, σ ranges from $\sigma = 0$, $z = \eta$ at the surface to $\sigma = -1$, $z = -H_o$ at the bottom, where $\sigma = (z - \eta)/(\eta + H_o)$ (Blumberg and Mellor, 1980; Blumberg and Mellor, 1987). The two horizontal velocity components are U_1 and U_2, such that $(U_1, U_2) = (h_1\, d\epsilon_1 dt^{-1}, h_2\, d\epsilon_2 dt^{-1})$, where the incremental squared arc length $ds^2 = h_1^2\, d\epsilon_1^2 + h_2^2\, d\epsilon_2^2$ with (h_1, h_2) the metrics of the orthogonal transformation. A new vertical velocity $\omega = D\, d\sigma dt^{-1}$ is related to $w = dz/dt$ by denoting the partial derivative with respect to arbitrary variable ϵ as $(\ )_\epsilon$ via the following relationship,

$$\omega = w - (h_1 h_2)^{-1} \left[h_2 U_1 \left(\sigma (D)_{\xi 1} + (\eta)_{\xi 1}\right) + h_1 U_2 \left(\sigma (D)_{\xi 2} + (\eta)_{\xi 2}\right)\right] - \left(\sigma (D)_t + (\eta)_t\right).$$

The vertical mixing (eddy) coefficients, K_M, K_H and K_q are evaluated using the level 2-1/2 turbulence closure model of Mellor and Yamada (1982) as modified by Galperin, et. al., (1988). The coefficients are given by: $K_M = q\ell S_M$, $K_H = q\ell S_H$

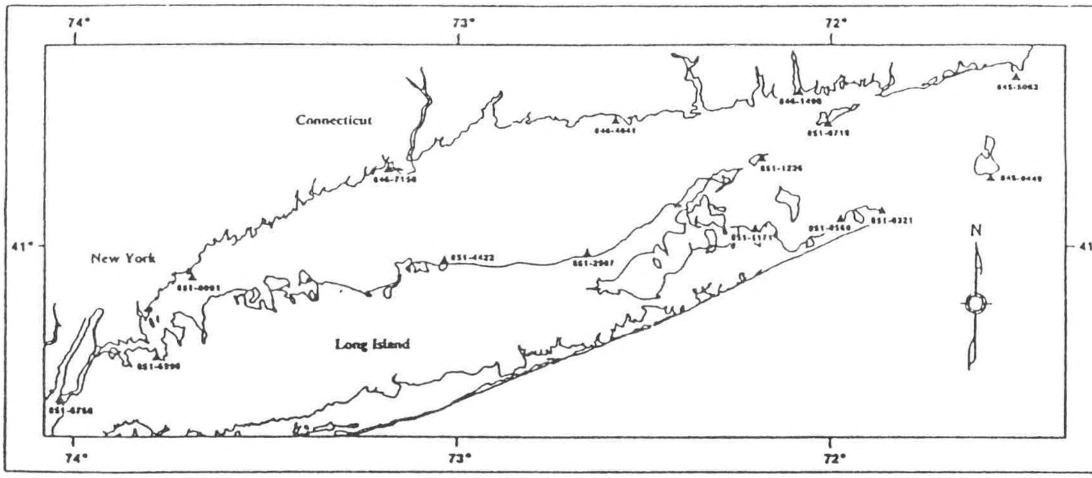

Figure 1: Water Level Model Comparison Stations

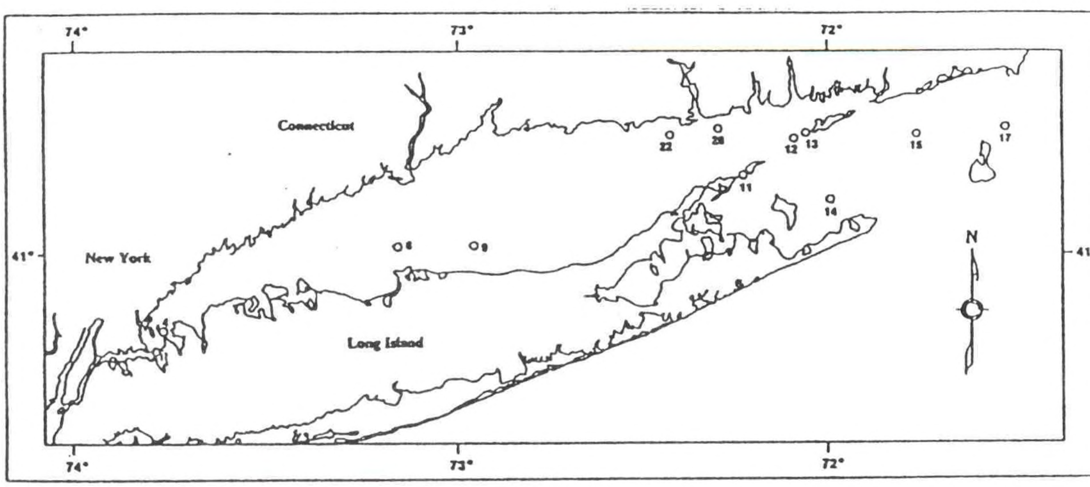

Figure 2: RADS Model Comparison Stations

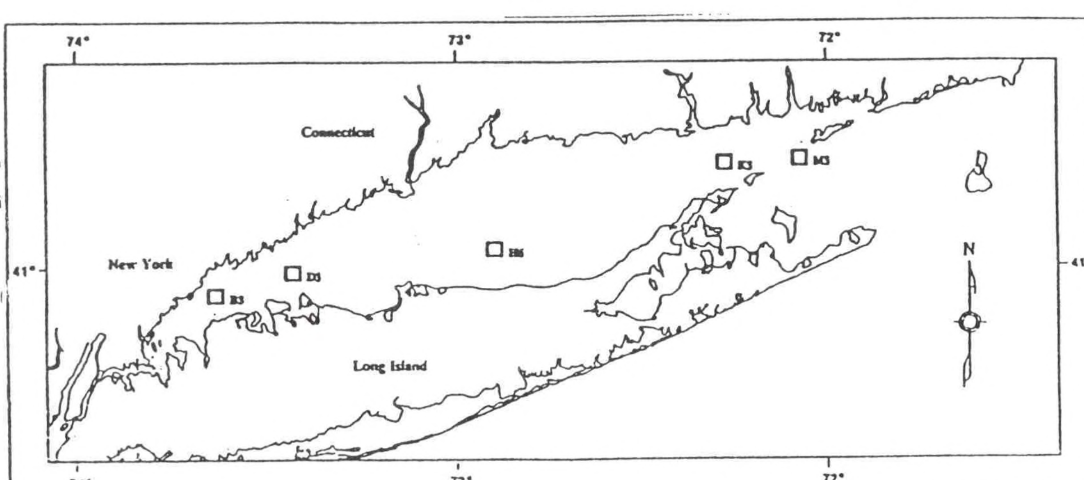

Figure 3: CTD Model Comparison Stations

and $K_q = 0.2\, q\ell$ where the stability functions, S_M and S_H, are analytically derived algebraic relations. Boundary conditions for nonturbulence quantities are given in Schmalz (1989). For q^2 and ℓ, $q^2 = (B_1)^{2/3}\, u_{\tau s}$, $\ell = 0$ at $\sigma = 0$, while at $\sigma = -1$, $q^2 = (B)^{2/3}\, u_{\tau b}$ and $\ell = 0$, where $u_{\tau s}$ and $u_{\tau b}$ are the friction velocities associated with the surface wind and bottom stresses, respectively.

The Lagrangian residual circulation is denoted as the sum of the Eulerian residual circulation and the Stokes drift by Longuet-Higgins (1969). Hamrick (1990) has represented the Stokes drift as the curl of a velocity vector potential in the following manner. Let (u,v,w) correspond to (dx / dt, dy / dt, D dσ / dt) and < > correspond to a suitable averaging operation over a period, which is selected as 2 M_2 or 24.84 hours, then the velocity vector potential $\mathbf{B}^T$ is given by the following form.

$$\begin{aligned} B_1^T &= \left< v \int_0^t \omega \, dt \right> - \left< vt \right>\left< \omega \right> \\ B_2^T &= \left< \omega \int_0^t u \, dt \right> - \left< \omega t \right>\left< u \right> \\ B_3^T &= \left< u \int_0^t v \, dt \right> - \left< ut \right>\left< v \right> \end{aligned} \qquad (1)$$

with $\mathbf{B}^T = (B_1^T, B_2^T, B_3^T)$.

In vector form, we have

$$\mathbf{u}_L = \mathbf{u}_E + \nabla \times \mathbf{B}^T \qquad (2)$$

where $\mathbf{u}_L \equiv$ Lagrangian residual circulation
$\mathbf{u}_E \equiv$ Eulerian residual circulation
$\nabla \times \mathbf{B}^T \equiv$ Stokes drift (curl of velocity vector potential)

We note immediately $\nabla \cdot \mathbf{u}_L = \nabla \cdot \mathbf{u}_E$ since $\nabla \cdot (\nabla \times \mathbf{B}^T) = 0$.

The governing partial differential equations are approximated via finite differences within an external/internal barotropic/baroclinic mode splitting context. All horizontal terms are explicitly differenced with the vertical diffusion terms implicitly treated to afford larger internal mode time steps (Blumberg and Herring, 1987).

In application to Long Island Sound, a rectilinear computational grid ($U_1 = u = dx/dt$, $U_2 = v = dy/dt$) employing 100 cells in the East-West and 37 cells in the North-South directions with a uniform length of 2.032 km was employed. Seven layers with cell centers at σ = - .050, - .141, - .283, - .5, - .717, - .859, and - .95 were employed in the vertical. River inflow boundaries were specified for the five major State of Connecticut rivers. Based upon average daily USGS streamflow and mean cross-sectional area, inflow velocities were specified for the external mode, while a parabolic vertical profile was assumed to hold for the internal mode. For salinity and temperature, a one-dimensional advection equation is used on outflow, while specified values for salinity and temperature are used on inflow. Total water surface elevations equal to the sum of the reconstructed astronomic tide and hourly water level residuals are specified at all open boundaries (The Battery, Spuyten water level residuals are specified at all open boundaries (The Battery, Spuyten Duyvil, and Block Island Sound). Inflow salinity S_s, and temperature T_s, surface values are computed from the following climatological forms:

$$T_s = T + T_a \cos(st + (V_o + u)_T - \phi_T) \tag{3}$$
$$S_s = S + S_a \cos(at + (V_o + u)_S - \phi_S)$$

where $T \equiv$ Daily average surface temperature at the first of each month
$S \equiv$ Daily average surface salinity at the first of each month
$(V_o + u)_T \equiv 0$
$(V_o + u)_S \equiv$ 81° corresponding to January 1, 1988 M_2
$\phi_T \equiv$ - 135° phase
$\phi_S \equiv$ kappa prime of the nearest water level station
$T_a \equiv$ 0.3 °C

$S_a \equiv$ 0.4 psu
$a \equiv$ 28.98 ° / hr , $s =$ 15 ° / hr

The vertical structure was obtained from monthly CTD casts. In order to specify the initial salinity and temperature fields based upon digitized CTD profiles a $1/r^2$ spatial interpolation is employed. The sea surface temperature is specified using a bi-linear interpolation scheme. Hourly wind data at LaGuardia Airport are assumed to hold over the entire model domain and are adjusted to overwater values using the Hsu (1986) formulation. The drag coefficient of Large and Pond (1981) is used to compute surface wind stress.

Astronomic Tide Simulation

Prior to long-term simulation, a simulation of the astronomic tide from 1 - 30 September 1988 was performed using a 300 second internal mode and 30 second external mode time step or 10:1 mode split. Water levels were reconstructed at The Battery, NY and along the open boundary in Block Island Sound from 24 tidal constituents. Average daily streamflows were input for the five major State of Connecticut rivers (Norwalk River, Mill and Quinnipiac Rivers, Housatonic River, Connecticut River, and Thames Rivers). Water level residuals and wind magnitudes were set to zero. A spatially uniform bottom roughness, z_o = 1 cm was employed except within the Connecticut rivers, wherein z_o = 4 cm was used. Simulated water level time series were compared with reconstructed levels in terms of rms difference over the one-month period as shown in Table 1.

Simulated water levels agree with reconstructed water levels to within order 10 cm. Simulated horizontal current component time series are compared with reconstructed currents corresponding to sigma level 5 in the model in order to avoid near surface and near bottom reflection interference in the observations. The ratio of the rms difference between simulated and reconstructed currents (cms) and the average reconstructed current range (cms) is presented by component in Table 2.

Reconstructed Tide Comparison Summary.

Station	Sta. ID	RMS Difference (cm)
The Battery, NY	851-8750	3
Willets Point, NY	851-6990	11
Rye Beach, NY	851-8091	11
Bridgeport, CT	846-7150	11
Cedar Beach, NY	851-4422	10
Madison Beach, CT	846-4041	12
Northville, NY	851-2987	10
New London, CT	846-1490	5
Montauk, NY	851-0560	6
Plum Island, NY	851-1236	11
Fisher Island, NY	851-0719	5
Three Mile Hbr, NY	851-1171	8
Montauk Pt, NY	851-0321	7
Vail Beach, RI	845-9449	6
Pt. Judith, RI	845-5083	1

Simulated horizontal currents at level 5 agree to with 20% of the reconstructed ranges in the (u,v) components. While additional grid resolution is warranted in regions of topographic variability, the overall tidal characteristics of Long Island Sound have been successfully simulated as further confirmed via harmonic analyses (Wei, 1991).

Long Term (Eighteen Month) Simulation

An eighteen month simulation including wind, water level residuals and river inflows was performed in three month intervals; i.e, six distinct three month duration simulations were performed with appropriate initial/restart conditions. In order to more realistically portray conditions in western Long Island Sound, the six major sewage treatment plants, combined sewer overflows, and five small New York State river inflows were used to dilute on a volumetric basis, the computed salinity in the corresponding inflow cells. In addition, the Harlem River was included as seven additional horizontal cells and minor grid modifications were made to more accurately represent the minor embayments in western Long Island Sound. The Harlem River boundary conditions for water surface elevation were developed as the sum of reconstructed levels and The Battery residuals. Salinity and temperature conditions were developed based upon correlation with Hudson River flows (HydroQual, 1990). Station H6 located in the central basin is used to illustrate the

Table 2. September 88 Astronomical Tide Simulation Horizontal Current Vs. Reconstructed Current Level 5 Comparison Summary. +/- means Model signal stronger/weaker than reconstructed current.

	U		V		
RADS Stations	RMS Diff.	Recstr. Range	RMS Diff.	Recstr. Range	Length of Analysis
1	13.3 +	10	21.0 +	80	29
4	6.2 +	30	13.7 +	40	29
8	10.0 +	90	5.2 +	5	29
9	9.5 +	40	2.6 +	5	29
11	42.6 -	150	21.5	100	29
12	33.3 +	100	46.0 +	60	29
13	21.6 -	206	19.2	100	29
14	41.3	100	5.2	15	29
15	10.4 +	80	7.6 +	12	29
17	17.6 +	75	8.4	10	15
20	9.7	110	10.7	60	29
22	10.9 +	100	9.2	20	29

ability of the simulation to develop, maintain, and erode the thermocline as shown in Figure 4.

The profile rms error and a stratification index (S.I.) defined as the absolute relative total (top to bottom) stratification difference between model and data stratification relative to data total (top to bottom) stratification are shown in the top legends. The simulation indicates a thermocline on 1 June 1988 (Julian Day 181) and by mid November (Julian Day 321) it has decayed. The thermocline is absent until it reappears by 23 May 1989 (Julian Day 509). The thermocline is maintained over the summer but appears to weaken by early September 1989 (Julian Day 615). Note the excellent agreement in the shape of the vertical temperature profiles between the simulation results and the data. Analogous comparisons between model versus observed salinity profiles for station H6 are shown in Figure 5. The simulated shapes of the profiles are in excellent agreement with the observations. The influence of the spring 1989 freshets are well simulated as shown by the profile comparison on 23 May 1989 (Julian Day 509).

In order to provide a Sound-wide assessment, average rms salinity and temperature errors are shown for stations B3, D3, H6, K3, and M3 in Table 3. Based upon 64 profiles, Sound-wide average rms temperature and salinity differences between simulation and digitized observation are approximately three-quarters of a degree centigrade and one half of a practical salinity unit, respectively.

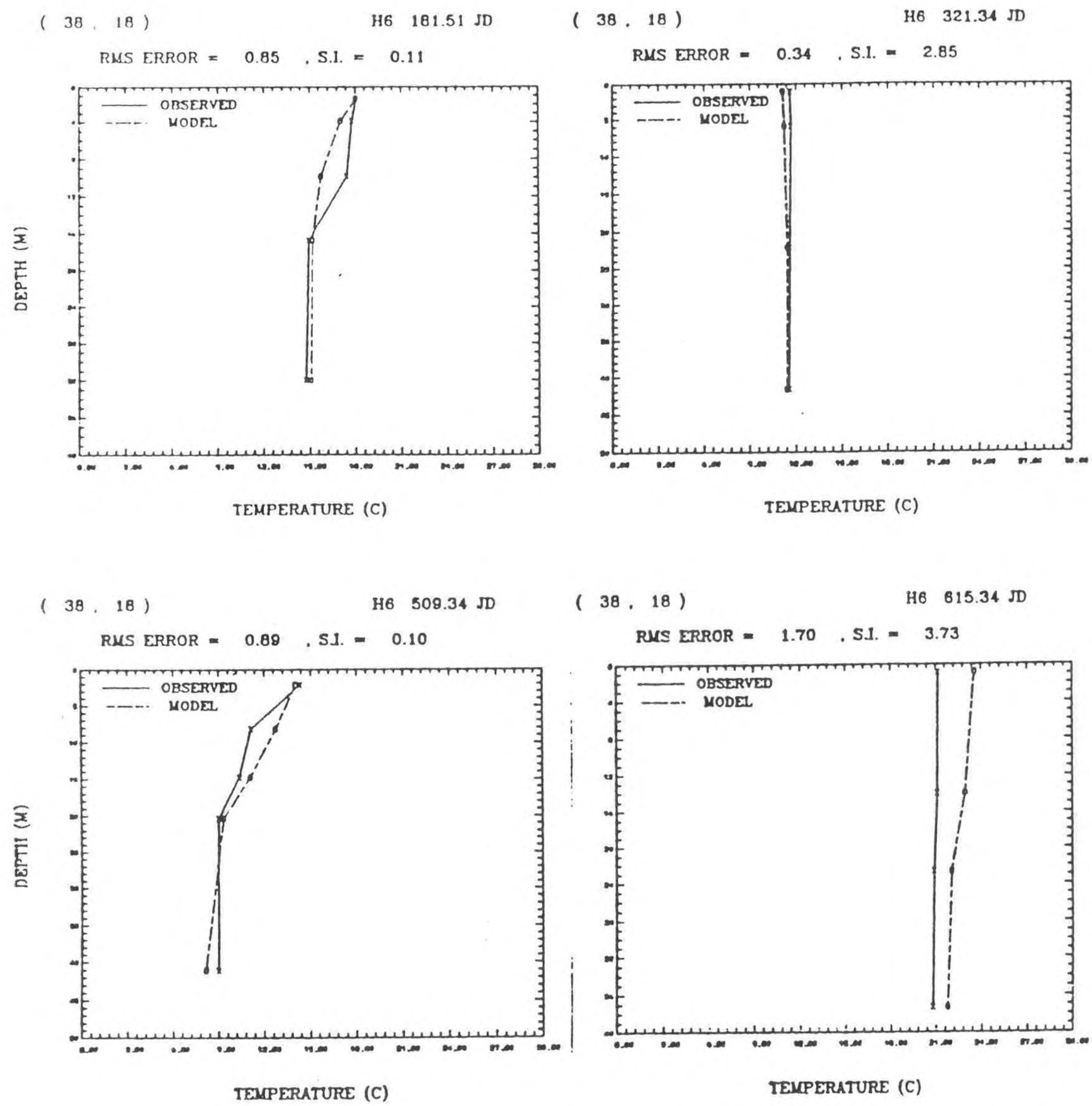

Figure 4: Comparison of Simulated and Observed Vertical Temperature Profiles (April 1988 - September 1989).

Simulated East River non-tidal fluxes for each month of the eighteen month period are presented in Table 4. Positive values indicate flow from western Long Island Sound into the East River in agreement with analysis of observations. Dr. Michael F. Devine (1991) has preliminarily computed non-tidal fluxes of 400 - 800 m^3/s. Simulated nontidal fluxes are in the upper ranges for most months.

Simulated Lagrangian residual currents at 2 meters depth and at 2 meters above the bottom as averaged over $2M_2$ tidal cycles for a duration of one month March 1989 ending on Julian Day 456.98 are shown in Figure 6 (a) and (b), respectively. The velocity magnitudes are plotted such that only velocities less than

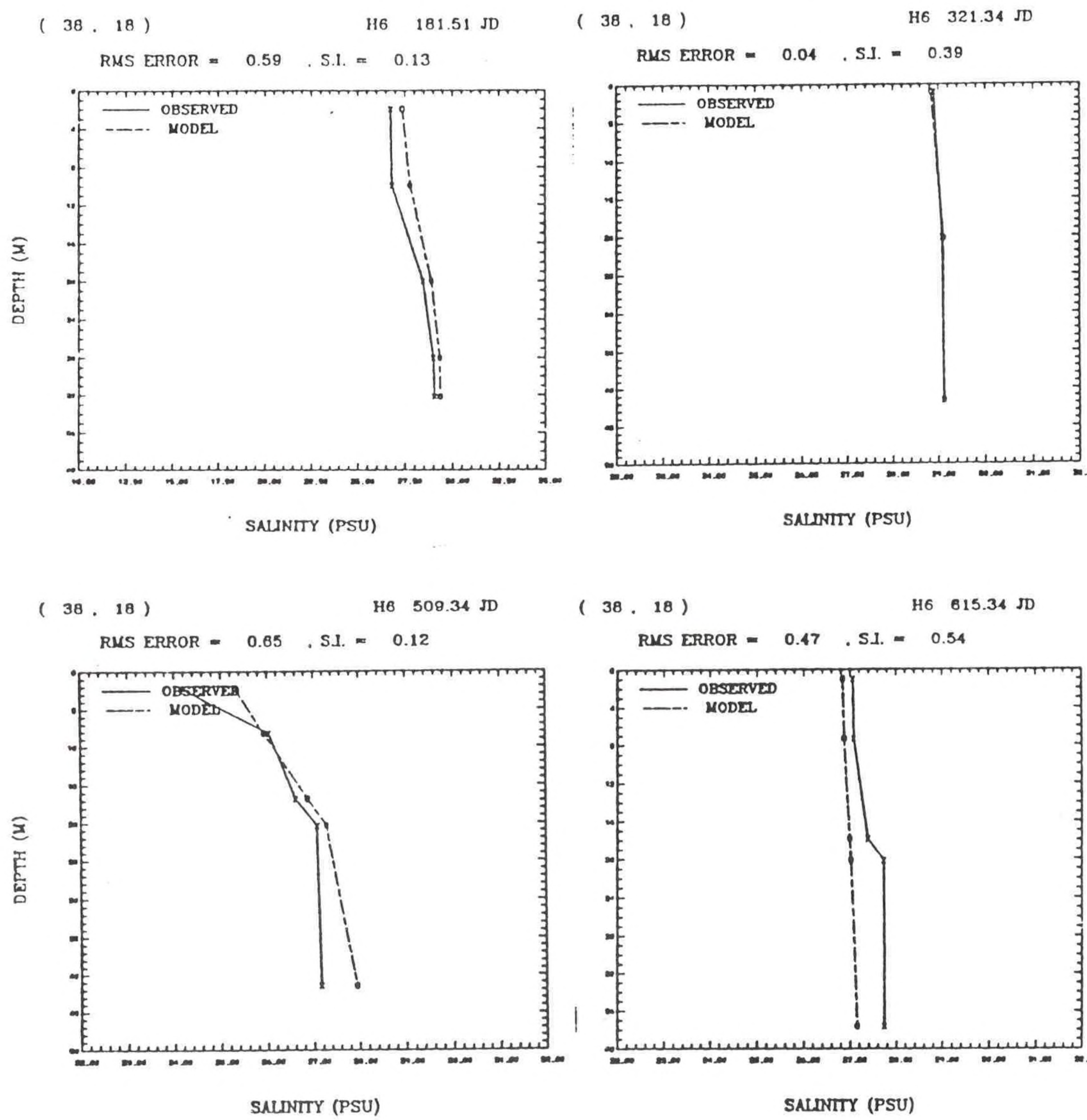

Figure 5: Comparison of Simulated and Observed Vertical Salinity Profiles (April 1988 - September 1989).

or equal to 5 cm/s are indicated. This strategy was adopted in order to portray the central basin circulation from 30 to 50 in horizontal index. Note the presence of a large counterclockwise gyre in the near-surface in agreement with general knowledge of Sound circulation described by Pritchard (1990). In the near bottom circulation shown in Figure 6 part (b), there exists a general east-west circulation in agreement with the known estuarine circulation as described by Pritchard (1990). In Figure 6 part (c), the simulated near surface (2m depth) salinity field is depicted. Note the "C" shape of the isohalines in the central basin from 30 to 50 in horizontal index, which is in agreement with observations and known surface salinity patterns (Pritchard, 1990).

Table 3 : Average RMS Salinity and Temperature Difference, Apr. 88 - Sept. 89.

Station	Number of Observations	RMS Salinity Difference (psu)	RMS Temperature Difference (°C)
B3	17	0.76	0.80
D3	15	0.44	0.83
H6	16	0.42	0.90
K3	6	0.35	0.58
M3	10	0.61	0.70
	total = 64	mean = 0.52	mean = 0.76

Table 4. Simulated East River Nontidal Fluxes (April 1988 - Sept. 1989).

Month	Year	Julian Day Range (1988)	Flux (m^3/s)
April	1988	92.64 - 122.65	1030.53
May		122.65 - 152.65	823.381
June		152.65 - 183.69	1051.00
July		183.69 - 214.74	967.00
August		214.74 - 244.74	840.46
Sept		244.74 - 275.78	1081.24
Oct		275.78 - 306.83	733.28
Nov		306.83 - 335.80	607.23
Dec		335.80 - 367.88	598.54
Jan	1989	367.88 - 398.92	399.58
Feb		398.92 - 425.82	529.18
March		425.82 - 457.90	694.25
April		457.90 - 487.90	777.18
May		487.90 - 517.91	369.04
June		517.91 - 548.95	714.15
July		548.95 - 579.99	795.25
August		579.99 - 610.00	936.65
Sept		610.00 - 638.97	718.50

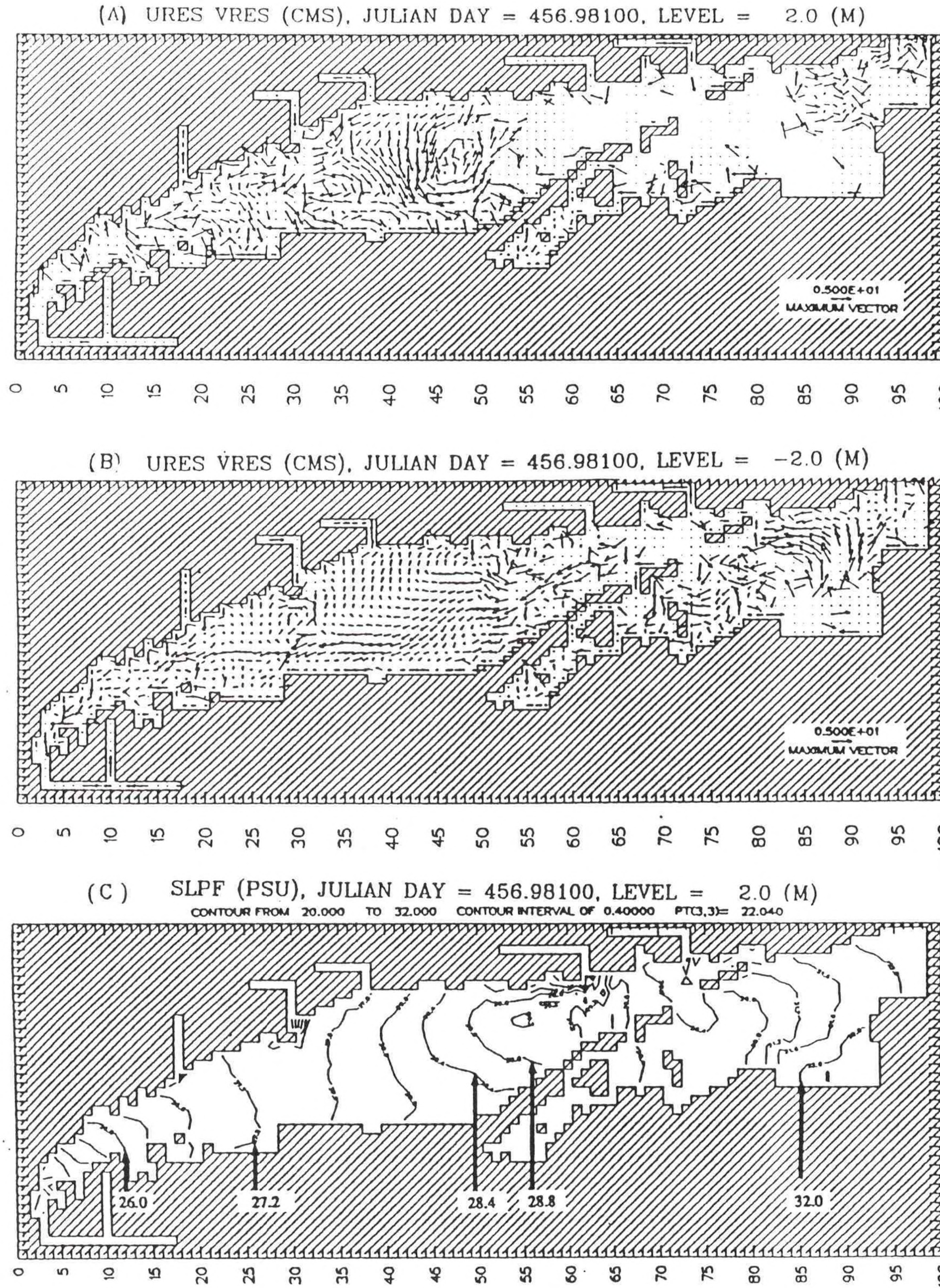

Figure 6. Simulated Residual Current Fields (Near Surface ≡ 2 m and Near Bottom ≡ -2m) and Salinity Field (Near Surface ≡ 2m).

Model Assessment and Additional Simulations and Enhancements

While the simulated vertical salinity and temperature structures agree in shape with observed digitized profiles to order .5 psu and .75 °C, respectively, it would be desirable to investigate the specification of surface heat fluxes and perhaps an increase in the number of vertical layers from 7 to 10, to see if further improvements in model performance can be obtained. The present computational grid is rectilinear and provides reasonable descriptions of the gross circulation patterns over Long Island Sound. Two areas of particular interest suggest nested refined curvilinear grids. Area one concerns the role of the Connecticut River plume in the overall salinity structure. While model results on the present grid show the influence of the plume to be confined to the immediate shoreline and propagation to the west in accord with general knowledge, additional finer resolution studies are warranted. In particular, an alternate passive constituent equation could be added to the model equation set to represent rhodamine dye. Dye releases within the Connecticut River could be simulated to further elucidate plume dynamics on both current and more refined curvilinear grid systems. The second area addresses the interaction between western Long Island Sound and the East-Harlem River tidal straits. It would be desirable to develop a much more refined curvilinear grid system extending through the East and Harlem Rivers and into western Long Island Sound as far east as station D3. The details of the circulation in western Long Island Sound could be further investigated within this grid structure resulting in more refined estimates of nontidal residual and salt fluxes.

Acknowledgements

This work was performed in conjunction with the joint NOAA - EPA Long Island Sound Study during the period March 1988 to the present within the Coastal and Estuarine Oceanography Branch under the supervision of Dr. Henry R. Frey. Both model developers, Professor George L. Mellor, Princeton University and Dr. Alan F. Blumberg, HydroQual, Inc., actively participated in several model evaluation and assessment meetings and provided overall advice and assistance. Dr. Eugene J. Wei greatly assisted with the computations by performing five three month simulations. Ms. Karen L. Earwaker and Mr. Richard W. Bourgerie performed the harmonic analysis used in the reconstruction of water levels and currents. Mr. Philip H. Richardson performed the CTD processing and analysis. Ms. Karen L. Earwaker further assisted in the development and preparation of the manuscript.

References

Blumberg, A.F. and G.L. Mellor. 1980. A Coastal Ocean Numerical Model. In: Mathematical Modeling of Estuarine Physics. Proceedings of an International Symposium, Hamburg, August 24 - 26, 1978. J. Sündermann and K.P. Holz, Eds., Springer-Verlag, Berlin.

Blumberg, A.F. and G.L. Mellor. 1987. A Description of a Three-Dimensional Coastal Ocean Circulation Model. In: Three-Dimensional Coastal Ocean Models, Coastal and Estuarine Sciences, 4, N. Heaps, Ed., American Geophysical Union, Washington, D.C., 1-16.

Blumberg, A.F. and H.J. Herring. 1987. Circulation Modeling Using Orthogonal Curvilinear Coordinates. In: Three-Dimensional Models of Marine and Estuarine Dynamics, J.C.J. Nihoul and B.M. Jamart, Eds., Elsevier, 55-88.

Devine, Michael J., NOAA/NOS/CEOB, Personal Communication.

Galperin, B. et.al. 1988. A Quasi-Equilibrium Turbulent Energy Model for Geophysical Flows. Journal of the Atmospheric Sciences, 45 (1) : 55-62.

Hamrick, J.M. 1990. The Dynamics of Long-Term Mass Transport in Estuaries, In: Coastal and Estuarine Studies, Vol. 38, R.T. Cheng (Ed.), Residual Currents and Long-term Transport, Springer-Verlag, New York.

Hsu, S.A. 1986. Correction of land-based wind data for offshore applications: a further evaluation. Journal of Physical Oceanography, 16, 390-394.

HydroQual, Inc. 1991. The Transport through the East River from Data and Three Dimensional Hydrodynamic Modeling, prepared for Management Committee Long Island Sound Estuary Study and New England Interstate Water Pollution Control Commission, Mahwah, New Jersey.

Large, W.G. and S. Pond 1981. Open ocean momentum flux measurements in moderate to strong winds. J. Physical Oceanography. 11, 324-326.

Longuet-Higgins, M.S. 1969. On the transport of mass by time-varying ocean currents, Deep-Sea Research, Vol. 16, 431-447.

Mellor, G.L. and T. Yamada, 1982. Development of a Turbulence Closure Model For Geophysical Fluid Problems, Rev. Geophys. Space Phys., 20, 851-875.

Pritchard, D.W. 1990. A Brief Description of the Circulation in Long Island Sound, unpublished note, prepared for Long Island Sound Study, EPA Region I and II, Washington, D.C.

Schmalz, R.A. 1990. A Review of Estuarine, Shelf and Ocean Hydrodynamics In: Proceeding of Estuarine and Coastal Modeling Conference, Nov. 15-17, 1989, Newport, Rhode Island, ASCE, New York, New York.

Wei, E.J. Simulation of Three-Dimensional Hydrodynamics in Long Island Sound: Seasonal Timescale. (This volume).

SIMULATION OF THREE-DIMENSIONAL HYDRODYNAMICS IN LONG ISLAND SOUND: SEASONAL TIMESCALE

Eugene J. Wei[1], Associate Member, ASCE

Abstract

The Mellor-Blumberg three-dimensional hydrodynamic model, as modified by National Ocean Service (NOS) of National Oceanic and Atmospheric Administration (NOAA) for application to Long Island Sound, New York, is employed to investigate astronomic tide and meteorologically induced circulation over the period May to July 1990. During this period, NOAA conducted an extensive measurement program to further observe vertical current structure (4 RADS-Remote Acoustic Doupler System-locations) and conductivity and temperature (CT) time series (5 locations) at The Battery, New York and throughout Long Island Sound. Conductivity, temperature, and depth (CTD) profiles were also taken in the longitudinal direction. As reported in this proceedings, climatological terms for salinity and temperature are prescribed on the open boundaries to effect simulations over long periods during which CT time series are not available. Of interest here, is to compare the results achieved using climatological boundary conditions versus these obtained from using observed CT forcings during a seasonal period when CT are available.

Introduction

Long Island Sound is an estuary located east of New York City with Long Island bordered to the south, and the states of New York and Connecticut to the north. The embayment is connected to the Atlantic Ocean through Block Island Sound to the east and East River/New York Harbor to the west (Figure 1). Semidiurnal tides (mainly M_2) dominate the tidal hydrodynamics throughout the

[1]Office of Ocean and Earth Sciences, National Ocean Service, NOAA
6010 Executive Blvd. Rockville, Maryland, 20852.

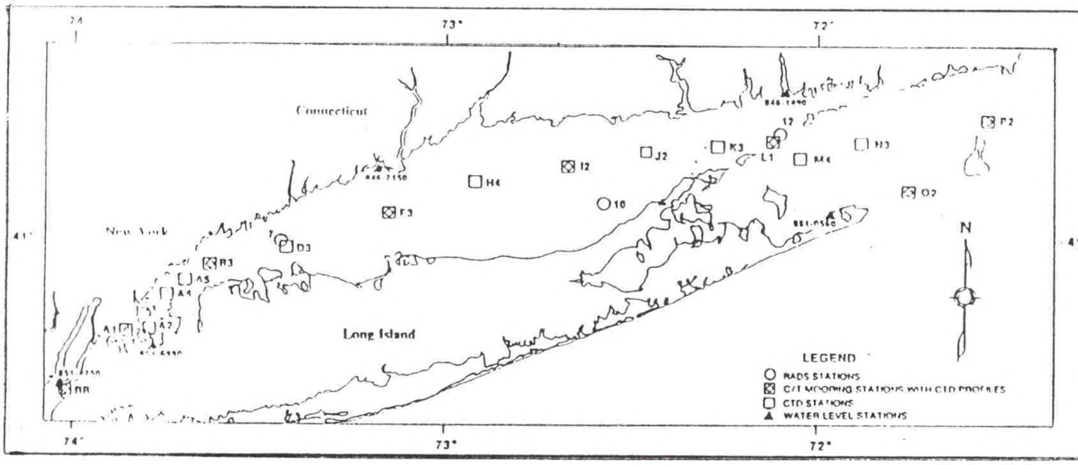

Figure 1. Long Island Sound and 1990 NOAA Stations

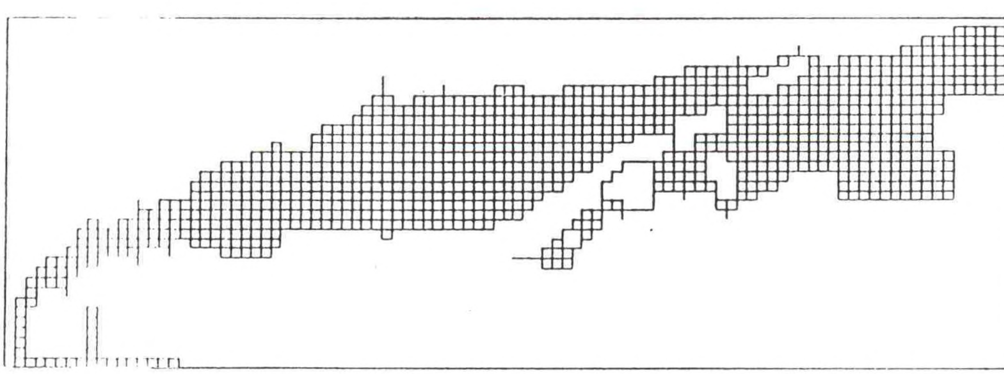

Figure 2. Long Island Sound Numerical Model Grid

sound from both entrances to the Atlantic Ocean and induce east-west tidal currents with residuals ranging from 5 to 15 cm/sec.

The development of such a populated area has created environmental stress to the sound. Severe hypoxia has been observed for the past few years, particularly in the western area. The water quality deterioration, therefore, became an important issue for the natural resources management of the sound. The principal objectives of the hydrodynamic modeling component of the Long Island Sound Oceanography Project (LISOP) are to provide the circulation information throughout the entire sound for the water quality modeling which, in turn, is used as the information basis for environmental management for the sound.

Since the setup of the Mellor-Blumberg three-dimensional hydrodynamic model (Blumberg and Mellor, 1987, Blumberg and Goodrich, 1990) for the project, the model has been revised extensively and calibrated thoroughly using field data. The annual-scale (18 months) model simulations (April 1988 to August 1989) have been performed to investigate the annual hydrodynamic variability (The results are presented in the accompanying article of this Proceedings). The information obtained from those simulations including water levels, flows, salinity and temperature fields, turbulent quantities will be used as the input to the water quality modeling. This article summarizes the seasonal timescale model simulation using data obtained from NOAA's 1990 LISOP field survey (May 9 to July 20), as a component of the model validation process.

1990 Field Data

NOAA conducted an extensive field survey in Long Island Sound from May to July, 1990, to acquire hydrographic data for the hydrodynamic model forcing and verification. The data covered included water level, current, CT, and CTD measurements. Detailed survey information regarding instrumentation, sampling periods, and data quality control procedures are described in a report (NOS, 1990). The schematic measurement locations are shown in Figure 1. The data from this survey are then utilized to provide either initial/boundary conditions or verifications for the seasonal simulation.

In addition to the in-situ hydrographic information collected by NOAA, the wind speed and direction records at LaGuardia Airport, New York, and flows of 5 major river systems in the area are also gathered as forcings for the simulation. The fresh-water discharges from sewage treatment plants and the combined sewer overflows (CSO), entering the western Long Island Sound in the mixing process, are obtained from the report (HydroQual, 1990).

Hydrodynamic Model

The hydrodynamic model used is a modified version of the Mellor-Blumberg three-dimensional shelf circulation model. The model has been modified by NOS for simulations of Long Island Sound including boundary forcings, code conversion for Cyber and Cray supercomputers, upwind difference for river advection to eliminate unreasonable salinity and temperature noise around the artificial river corner, and residual current interface with the water quality model. The model utilizes primitive equations for mass and momentum conservation, together with transport diffusion of salinity and temperature to 3D hydrodynamics generated by tides, wind, river inflows, and density currents. The model also applies a terrain- following vertical coordinate (sigma-coordinate) allowing the same number of vertical grid cells in the region. Either a rectangular coordinate or curvilinear coordinate can be used in horizontal plane. The internal-external mode split numerical technique improves the computation efficiency. A turbulence closure model (Mellor and Yamada, 1982) accounts for vertical mixing while the Smagorinsky formulation is used for horizontal diffusion.

Numerical Grid

The numerical model grid for Long Island Sound/Block Island Sound consists of 100 cells in the east-west direction and 37 cells in the north-south direction (Figure 2). The majority of water depths (taken from navigation charts and modified with available survey data) range from 20 m to 40 m with sloping bathymetry from both north and south shores. The deepest area, about 60 meters, is located at The Race, a narrow entrance from Block Island Sound to Long Island Sound. The relatively small bathymetric gradient throughout the sound prompts the use of 2 km square grid cell resolution for simplicity nevertheless with sufficient accuracy. Approximately 60% of the grids are water cells included in the dynamic computation. In the vertical, 7 layers grid resolution through the water column was used with exponentially decreased layer thickness toward the surface and bottom from the mid-depth. This efficient resolution technique best describes the vertical structure of salinity and temperature fields in the area with adequate accuracy. The East River, its west end as an open boundary (The Battery) to the model and a channel connecting New York Harbor and Long Island Sound, has been rotated approximately 135 degrees counter-clockwise for computational efficiency. The Harlem River, a distributary to the East River, provides salt-reduced water and acts as tidal flushing conduit to the sound. The other two open boundaries are located on the east side of Block Island Sound adjacent to the Atlantic Ocean separated by Block Island. Five river systems spreading along northern shore, namely the Norwalk, Housatonic, Quinnipiac, Connecticut, and Thames Rivers, provide significant quantities of fresh water to the sound.

Numerical Simulation

Data collected from NOAA field survey and other sources were analyzed and processed to be either initial or boundary conditions as briefly described in the following. Hourly water elevation records from tide gauges at The Battery, Harlem River, Montauk Point, and Point Judith are used as forcings at open boundaries. Water level data are reduced to a common reference datum based on available sources. Linear interpretation of data was used along the east boundary. Daily averaged river flows, sewage treatment plant discharges and combined sewer overflows (in western Long Island Sound near East River and along East River) are the lateral fresh-water inputs to the system. Hourly wind speed and direction are used to compute wind stresses over the water surface. For baroclinic boundary forcings, two cases were tested; 1) "modified" climatological boundary conditions constructed based on CTD measurements through the water column at the beginning and the end of the simulation period then linearly interpreted in time, 2) observed hourly CT time series at the open boundaries. The salinity and temperature at open boundary is obtained by using a one-dimensional advection scheme based on: 1) interior cell values at previous time step during outflow, 2) the boundary value at previous time step and the present forcing value. Although the heat flux exchange technique between the water surface and the atmosphere may be used to determine the surface temperature temporal variation over the computation domain, it was decided that the temperature time series, as fluctuated from an interpreted mean value with S_2 tide frequency, was used to represent daily and seasonal surface temperature variations.

The simulation started at 0 hour, May 9, 1990 with initial condition at rest. CTD measurements at master stations together with 5 CT records were used to interpret initial 3D salinity and temperature fields. The simulation proceeded with 30 sec external and 150 sec internal time step respectively. The model simulated the dynamics of the sound for 72 days. In the following, only representative simulated results compared with observations will be discussed. In addition to water elevation and current results, the capability of the model to reproduce salinity and temperature vertical structures and the stratification temporal variability in the western Long Island Sound is also of concern due to the importance of those factors to water quality modeling and the hypoxia phenomenon.

Figure 3 shows the water elevation time history comparisons (only 7 days results presented for visualization) at 4 tide gauge locations, namely, Willets Point, Bridgeport, Port Jefferson, and New London. Further tide harmonic analysis revealed that the amplitude and phase discrepancies are less than 2 cm and 10 minutes between simulated results and observations for major constituents. Additional analyses regarding tide simulation are presented in the accompanying article of this Proceedings.

The current velocity, in general, is difficult to match between model results and observations in both magnitude and phase. Figure 4 shows current velocities in the x- and y- directions at sigma level 4 and 5 (at mid-depth and at one layer below) at RADS 10 location (see Figure 1). There is excellent agreement with respect to both u (x-direction) and v (y-direction) currents at level 5 while deviations appear in v current at level 4. The residual circulation patterns for the study area are presented in the other article (Schmalz, 1991).

Figure 5 shows salinity and temperature time series at CT location I2 (see Figure 1) for upper level (between layers 3 and 4) and lower level (between layers 5 and 6). It appeared that the model simulated the salinity and temperature time history with good accuracy at the upper level and satisfactory for the lower level with the same order of magnitude of salinity and temperature stratification temporal variability. It is noted that two type of baroclinic forcings (measured data and climatological data) essentially yield the same baroclinic time series in the interior.

Longitudinal salinity and temperature spatial distributions along the sound centerline (thalweg direction) are shown in Figure 6. The simulated results at near surface layer and near bottom layer at zero hour, day 176 (June 25) and day 199 (July 18, 1990) are compared with observations from CTD measurements obtained from field survey. It appears that the model reproduces salinity and temperature spatial variations in the east-west direction. Particularly, the model generates the same order of magnitude in salinity or temperature stratification, an important factor for water quality modeling.

Summary

The three-dimensional hydrodynamic model was applied to Long Island Sound for a 72-day seasonal timescale simulation. This simulation was part of the model validation process for annual timescale modeling effort in LISOP. In general, simulated results show good agreement with observations acquired during the 1990 NOAA field survey program. The baroclinic boundary forcings specified with either climatological data or CT records generate very similar salinity and temperature fields. This indicates that the climatological data can be used for boundary conditions when CT records are not available.

Acknowledgements

I would like to thank Dr. Richard Schmalz for his advice and suggestions to this work. The encouragement and support from Dr. Henry Frey, Chief of Coastal and Estuarine Oceanography Branch at NOS, is gratefully appreciated.

References

Blumberg, A.F. and Mellor, G.L. 1987. A Description of a Three-Dimensional Coastal Ocean Circulation Model. In: Three Dimensional Coastal Ocean Models, N. Heaps ed., American Geophysical Union, Washington, DC.

Blumberg, A.F. and Goodrich, D.M. 1990. Modeling of Wind-Induced Destratification in Chesapeake Bay. Estuaries Vol.13, No.3. 236-249, September 1990.

HydroQual, Inc. 1991. The Transport Through the East River from Data and Three Dimensional Hydrodynamic Modeling. Report NENG0013, HydroQual, Inc., Mahwah, New Jersey.

Mellor, G.L. and Yamada, T. 1982. Development of a Turbulence Closure Model for Geophysical Fluid Problems. Rev. Geophys. Space Phys., 20, No.4, 851-875.

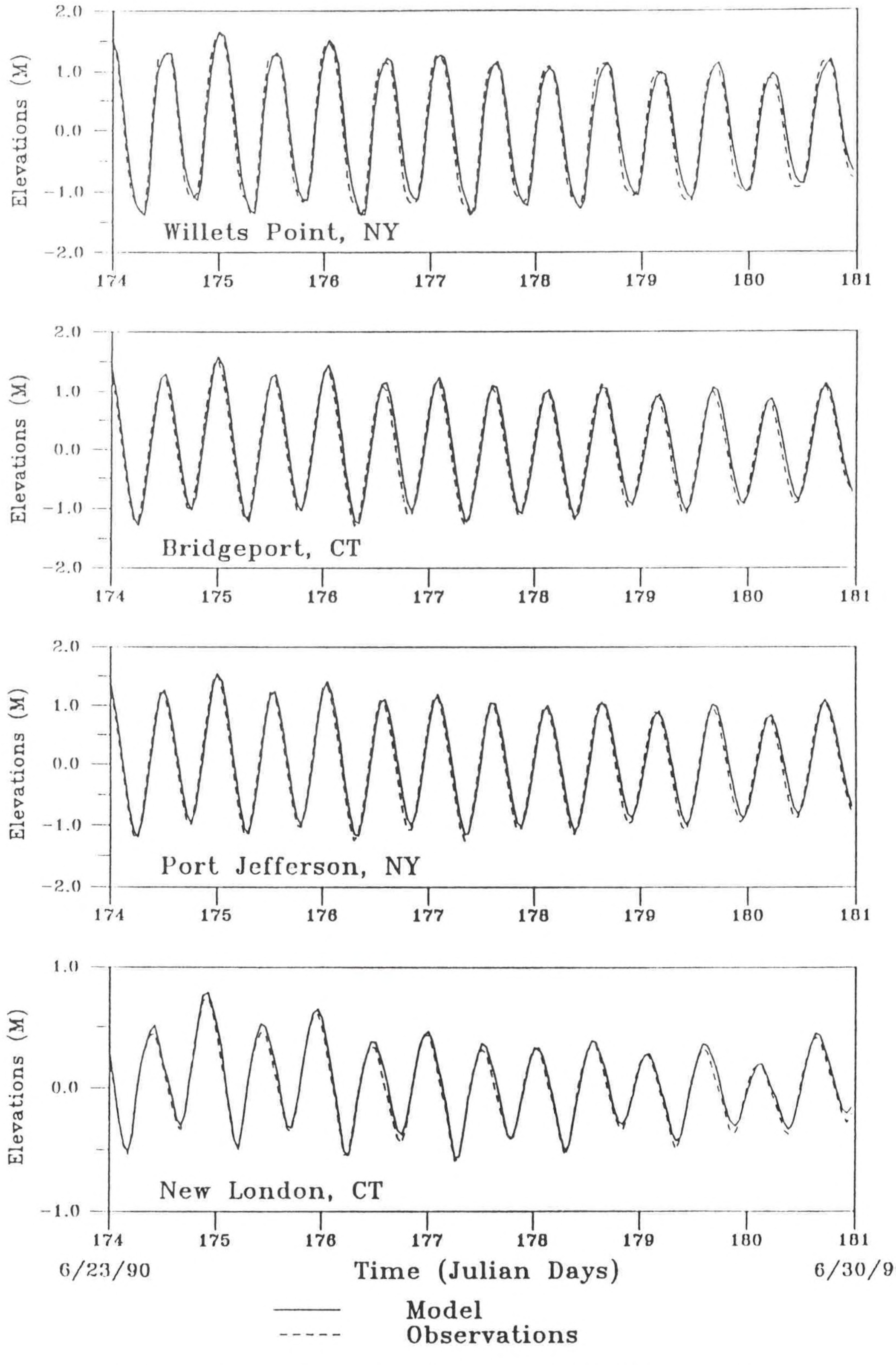

Figure 3. Water Levels at Long Island Sound

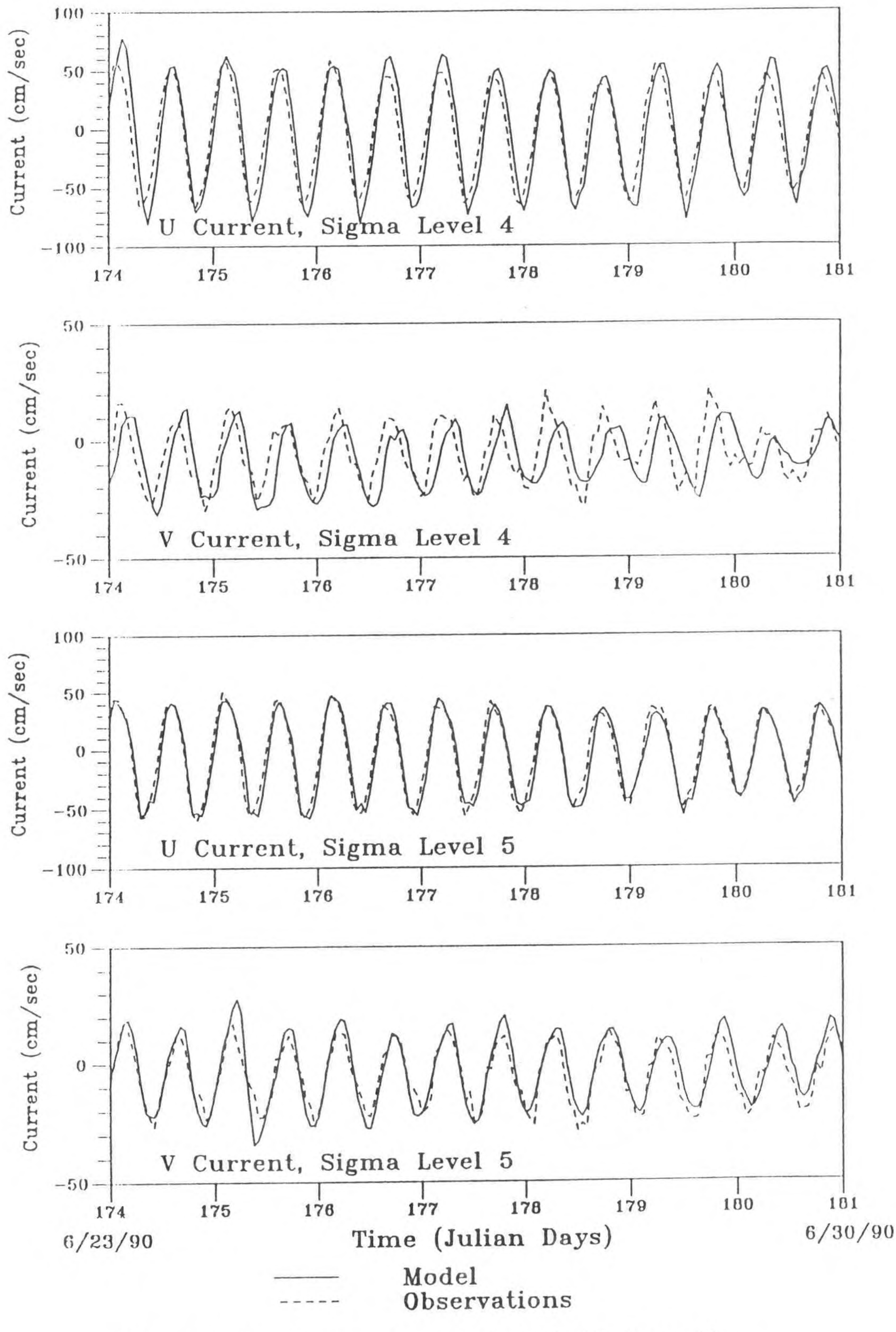

Figure 4. Currents at RADS 10 Location

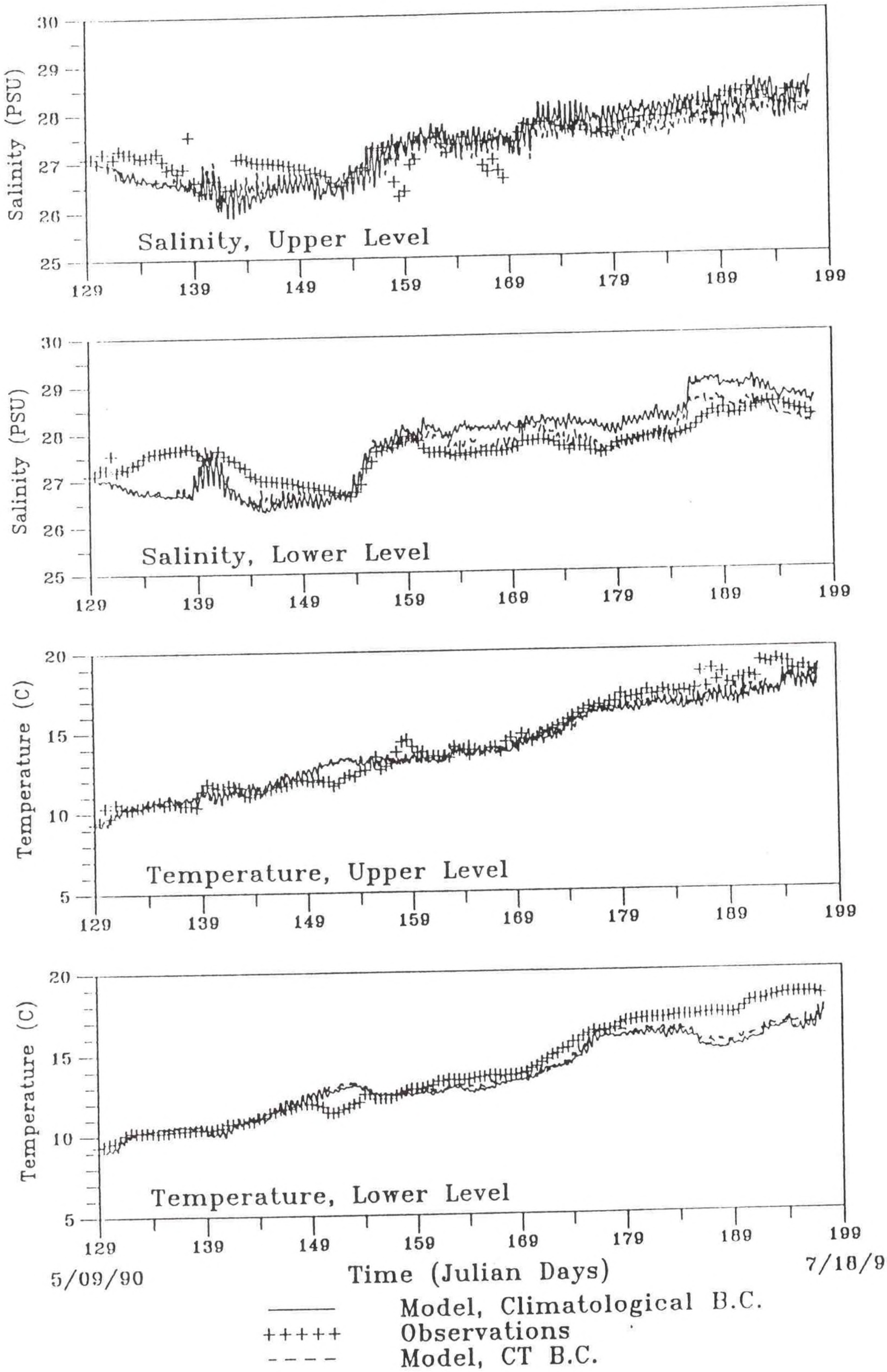

Figure 5. Salinity and Temperature at I2

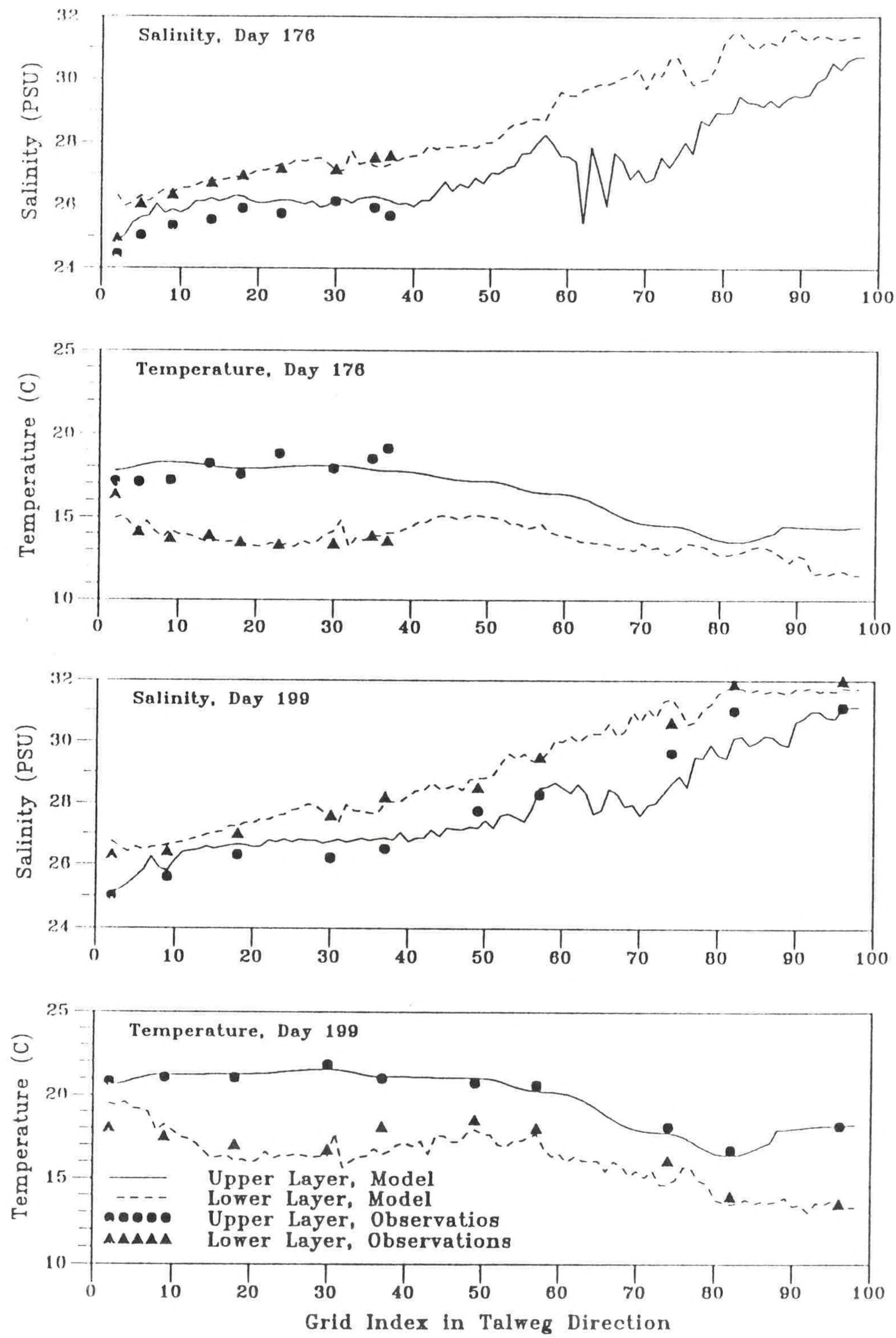

Figure 6. Longitudinal Salinity and Temperature Profiles

National Ocean Service, 1990. Long Island Sound Oceanography Project: 1988 - 1990. K. Earwaker ed., NOS Oceanographic Circulation Survey Report No.10, NOAA/NOS, Rockville, MD.

Schmalz, Richard A. Jr., 1992. Simulation of Three-dimensional Hydrodynamics in Long Sound : Annual Timescales. (This volume)

A NUMERICAL MODEL SIMULATION OF TIDAL CURRENTS IN LONG ISLAND AND BLOCK ISLAND SOUNDS

L. Charles Sun[1]

Abstract

A case study evaluating the predictive capability of a hydrodynamic model of Long Island Sound is presented. The model is a time dependent, three- dimensional, primitive equation, estuarine and coastal ocean circulation model incorporating realistic bottom boundary geometry and is driven by the astronomical tides. An assessment is made of the model's ability to simulate correctly the tidal circulation pattern in the Sound.

The model reproduces the tidal co-oscillation phenomenon observed at the eastern basin of Long Island Sound (assuming a node at The Race). Model predicted time series data of tidal elevations and currents agree remarkably well with the observational data.

Background

The Long Island Sound Study (LISS) is a comprehensive, interdisciplinary, cooperative research program, to identify the role of circulation and transport processes in dissolved oxygen and nutrient distribution, and to develop a management plan to improve water quality in Long Island Sound. NOAA's National Ocean Service(NOS), as a participant of the LISS, was given the responsibility to develop and validate a hydrodynamic model as it is applied to the Sound.

In this paper we have adapted a time-dependent, three dimensional, primitive equation, estuarine and coastal ocean circulation model to the Sound. The primary purpose of this paper is to test the general capability of the model to simulate correctly tidal currents. With a numerical hydrodynamic model, we want to reproduce all major constituents over the simulated domain. Over that area, the astronomical tides can be considered as long, shallow-water waves forced by the

[1]Oceanographer, NOAA, National Ocean Service, 6010 Executive Blvd., Rockville, MD 20852

oscillations of the open boundaries, propagating across the basin, partly reflected by the bottom, and distorted by friction and nonlinear shallow water processes.

This paper is organized in the following manner. The numerical model is briefly described in section 2. The results obtained from a 30-day simulation of the model run are discussed in section 3 followed by the comparisons of model results and observations. Conclusions and discussions on future works are given in Section 5.

Description of the Numerical Model

The numerical model used in this study is a time-dependent, three-dimensional, primitive equation, estuarine and coastal ocean circulation model described in the papers published by Blumberg and Mellor (1983,1987). The model includes a turbulence closure scheme (Mellor and Yamada, 1982) to provide vertical mixing coefficients. Together with the sigma coordinate, the model can provides realistic bottom boundary layers which are important in tidally driven, shallow water estuaries.

In this study, boundary conditions are: The fluxes of momentum (wind stress), heat (T), and salt (S) are set to zero at the sea surface (assuming free surface approximation); the fluxes of heat and salt should vanish at the bottom, and for the east-west (u) and north-south (v) current component, the computed solutions are matched with the turbulence law of the wall which extends the computed u and v into the viscous sub-layer where the non-slip bottom boundary condition is satisfied; at the lateral boundaries, the values of T and S are specified along inflowing boundary points and a radiation condition is used along outflowing boundary points; the sea surface elevation is prescribed as a function of time and space specified at non-material (open) boundaries while the values of u and v as well as the fluxes of T and S should vanish at material (closed) boundaries. The initial condition is variables u, v, T and S given for all computational grid points at time $t = 0$.

The numerical model use the "external-internal" mode-splitting technique to separate the 2-dimensional calculation of the vertically integrated equations (external mode) from the 3-dimensional calculation of the vertical structure equations (internal mode). The external mode calculation results in updates for surface elevation and the vertically averaged velocities. The internal mode calculation results in updates for u, v, T, S and the turbulence quantities. A staggered, centered, second-order spatial differences were used for all spatial derivatives. The Courant-Friedrichs-Levy (CFL) computational stability condition requires the time step should not be longer than the length of time necessary for a gravity wave to move one grid interval.

Model geometry, shown in Figure 1, simulates the geography of Long Island and Block Island Sounds from 71°28' W to 73°46' W and from 40°35' N to 41°23' N. In the area under investigation, the orientation of the East River is artificially rotated counter-clockwise into the model domain, and is aligned with the direction of model x-axis. The computational domain has a 100 x 37 lateral grid with horizontal square cells of 2032 m on a side and eight levels with irregular vertical spacing in sigma (σ) space (σ = 0.0, -0.1, -0.2, -0.4, -0.6, -0.8, -0.9, and -1.0).

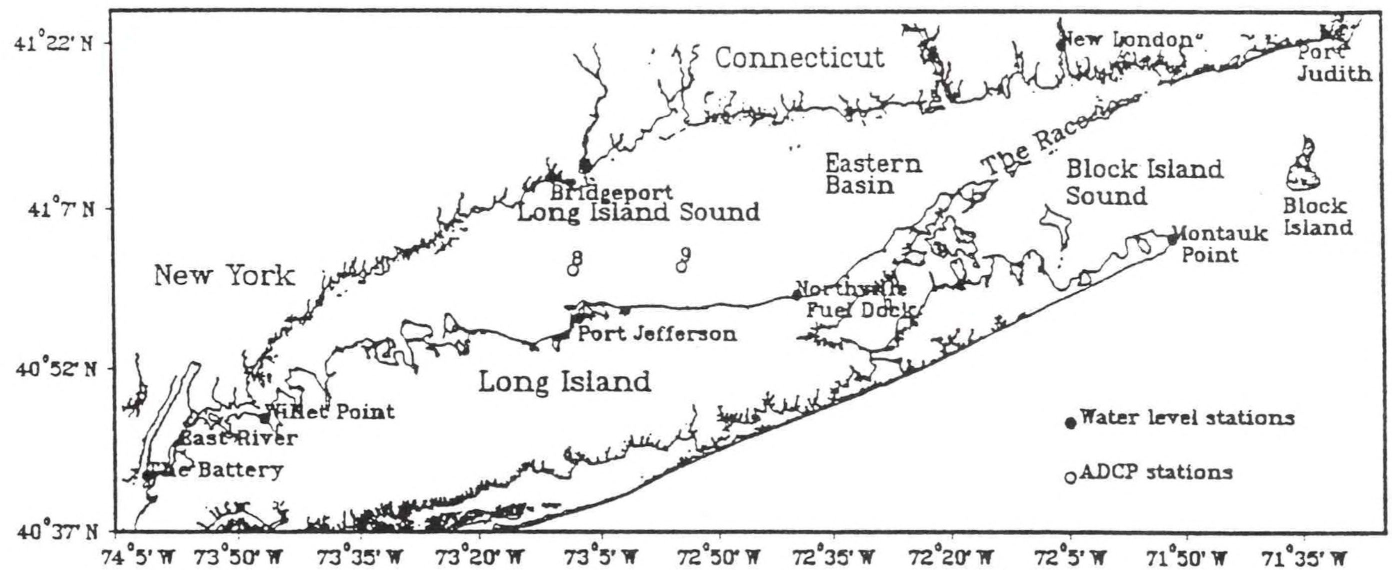

Figure 1. Model simulation area and NOAA/NOS Long Island Sound Project water level and acoustic Doppler current profiler (ADCP) station locations.

This leads to a external mode time step of 30 seconds and a internal mode time step of 300 seconds. The temperature and salinity data collected in the Sound from June to August, 1988 were linearly interpolated into model grids to provide the initial condition for the model run. The computation starts from rest, and the tidal oscillation is progressively spun up inside the computational domain through the open boundary forcing, where sea surface elevations are prescribed as a single harmonic series:

$$\eta(t) = \eta_0 + \sum_{i=1}^{m} f_i \eta_i \cos(\omega_i + \psi_i - \kappa_i) \tag{1}$$

where

m: the number of selected tidal constituents,
i: subscript representing individual tidal constituent,
f_i: the reduction factor of constituent i,
Ψ_i: equilibrium argument of constituent i when t = 0,
η_0: mean height of surface elevations,
η_i: amplitude of constituent i.
κ_i: lag of phase (epoch) of constituent i.

In this paper a total of 24 tidal constituents were prescribed at the open boundaries. They were: J_1, K_1, K_2, L_2, M_1, M_2, M_4, M_6, M_8, N_2, $2N_2$, O_1, OO_1, P_1, Q_1, $2Q_1$, R_2, S_2, S_4, S_6, T_2, λ_2, ν_2, and ρ_1. For each constituent i, the values of f_i and Ψ_i remain the same for all places, but the values of η_i and κ_i are determined from the Fourier harmonic analysis. For the area under consideration the tidal amplitudes and phases for selected tidal constituents were specified at The Battery, Mountauk Point, NY, and Port Judith, RI, and were linearly interpolated along model open boundary between Montauk Point, NY, and Block Island, as well as model open boundary between Block Island and Port Judith, RI. The mean heights of surface elevations at the model open boundaries were removed in our present study. Temperature and salinity were fixed at The Battery and the open boundaries described above during the model run. The model computation was started on the model time of September 1, 1988 and was run for 30 days.

In this study we used a quadratic from to represent bottom friction, i.e.,

$$\frac{\kappa^2}{(\ln(z/z_0))^2}(u^2 + v^2)^{1/2}[u,v], \tag{2}$$

and the Samgorinsky diffusivity formula for horizontal diffusion,

$$A_M = \frac{1}{2} C \Delta x \Delta y \sqrt{\left(\frac{\partial u}{\partial x}\right)^2 + \frac{1}{2}\left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2}\,, \tag{3}$$

where κ = 0.4 is the von Karman constant, z_0 is the bottom roughness parameter, and Δx and Δy are the x- and y-axis model grid spacings. Numerical experiments were run to select the values of z_0, and constant, C, such that the model predicted harmonic constants of water surface elevation agree with the observed ones. Sensitivity study show that the optimal values of z_0 and C are 1 centimeter and 0.05, respectively.

Model Results

A 29-day Fourier harmonic analysis (an updated version of Dennis and Long [1971] based on Schureman [1958]) was used to analyze the model predicted hourly tidal height data. Figure 2 show the model predicted tidal amplitude in centimeters (solid lines) and phase in hours with respect to Greenwich (dashed lines) for M_2 tide. It is clearly shown in Figure 2 that M_2 tide produce a virtual amphidromic point off Montauk Point around which the crest of tidal waves rotate in a counter-clockwise direction and the tidal heights increase on the right hand side of Block Island Sound as waves move into the sound. We define R to be the values of the ratio of the tidal amplitudes of the two major diurnal, K_1, and O_1, to the two major semi-diurnal constituents, M_2, and S_2. We discovered that the values of R remain fairly constant between 0.15 and 0.25, with slightly over 0.30 near Montauk Point, NY. This finding indicates that the semidiurnal tides are predominate in the area (Defant, 1961). This type of tides is characterized by the occurrence of two high waters and two low waters in the lunar day of 24 hr 50 min, and the height of successive high waters and successive low waters is approximately the same.

Since the tides are dominated by the semidiurnal tide, we will select the M_2 tide as an example to illustrate the tidal characteristics in the region. As shown in Figure 2, the tidal amplitude of M_2 tide is approximately 45 cm at the entrances of Block Island Sound, and is decreased slightly to 30 cm inside the Sound. As the M_2 tide propagates into Long Island Sound, its amplitude increases from east to west remarkably at first by about 40 cm in the short distance of 40 km between The Race and Northville Fuel Dock, NY. This large tidal amplitude gradient is related to the co-oscillation phenomenon, assuming a node at The Race (Swanson, 1976). After the tide leaves the eastern basin of Long Island Sound, its amplitude then gradually increases to a maximum value of about 115 cm near Willets Point, NY, within a distance of 90 km. To the west of Willets Points, the tidal amplitude decreases by 50 cm between Willets Point and The Battery, a distance of about 20 km.

As shown in Figure 2, high water occurs about 12.70 hours after the moon crosses the Greenwich meridian at the entrances of Block Island Sound, as the tide moves into the Sound, shoaling and coastal restriction slow it down. High water takes more than an hour to progress from Montauk Point to The Race. In Long Island Sound the time of high water occurs later progressively to the west, arriving at Willets Point some two hours after it did at The Race. One notable feature is that high water takes only a half hour to traverse the last 90 km. In the East River, the tide wave slows markedly. The wave requires over three hours to traverse the

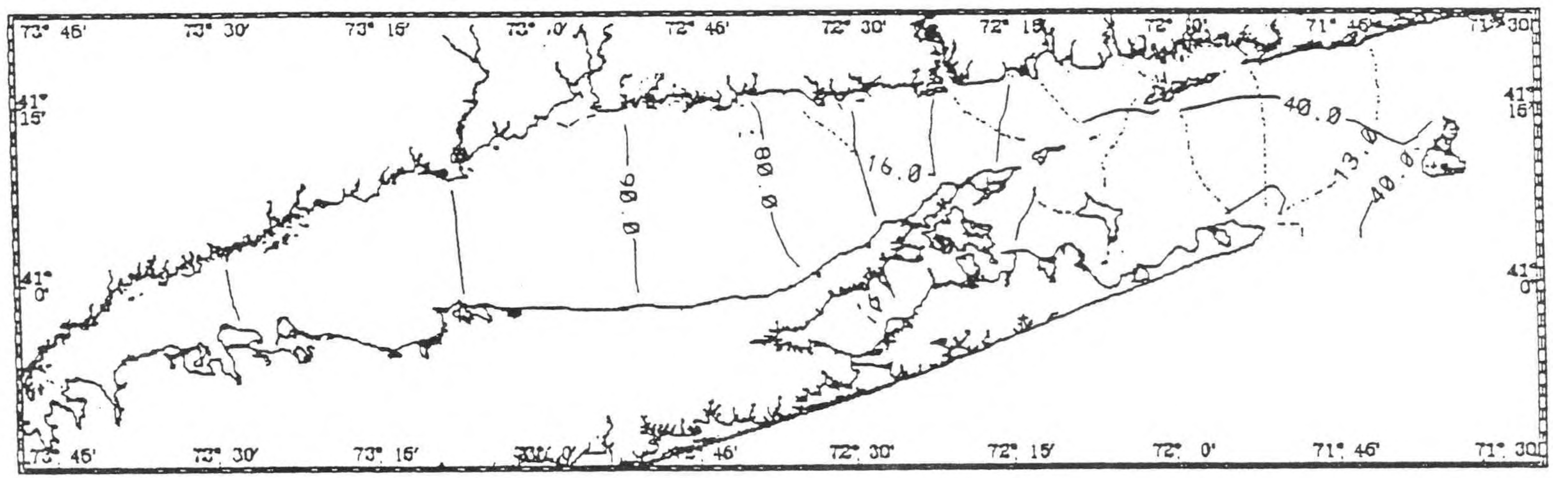

Figure 2. M_2 co-amplitude in centimeters (solid curves) and co-phase in hours with respective to Greenwich (dashed curves) calculated from the model predicted elevations. The contour intervals of co-amplitude and co-phase curves are 10 centimeters and 0.5 hours, respectively.

relatively short distance of 23 km form The Battery to Willets Point. Those findings agree well with tidal characteristics observed in the area (Swanson, 1976).

Comparison with Data

In this study water level and acoustic Doppler current profiler (ADCP) observations were obtained from a field survey conducted by NOS from June to October 1988. This survey was the first phase of the physical oceanographic field effort of NOS's Long Island Sound Oceanography Project (Earwaker, 1990). For model validation we decided to use water level observations at The Battery (BA), Bridgeport (BR), Cedar Beach (CB), Madison Beach (MB), New London (NL), Port Judith (PJ), and Willets Point (WP) stations and ADCP data from the ADCP Station No. 8 and 9. See Figure 2 for the water level and ADCP station locations. The ADCP recorded data for 1-meter increments throughout the water column beginning about 0.5 meters above the transducer head, but only the ADCP data recorded at the water depth close to the model level depth were used for model validation. For further information about these observations, consult Table 1.

An harmonic analysis of water level data at selected water level stations was performed. Table 2 summaries the harmonic constants, tidal amplitudes in centimeters and phases in hours with respective to Greenwich, of five major constituents, M_2, S_2, N_2, K_1, and O_1 at selected water level stations. Model predicted values of harmonic constants are also displayed for comparisons. The values of variable S shown in the last column of Table 2 is an index of prediction skill defined

Table 1. NOS Long Island Sound Oceanography Project water level stations and acoustic Doppler current profiler (ADCP) stations summary.

Station Name	Station Number	Latitude (N)	Longitude (W)	Data Availability
The Battery (BA), NY	851-8750	40°42.1'	74°01.0'	04/01/88 - 07/31/90
Bridgeport (BR), CT	846-7150	41°09.9'	73°10.9'	04/01/88 - 05/02/88
Cedar Beach (CB), NY	851-4422	40°57.9'	73°02.6'	03/22/88 - 05/22/88
Madison Beach (MB), CT	846-4041	41°16.2'	72°35.4'	03/16/88 - 05/07/88
New London (NL), CT	846-1409	41°21.9'	72°05.7'	04/01/88 - 07/31/90
Pt. Judith (PJ), RI	846-7150	41°09.9'	71°29.3'	03/01/88 - 07/24/90
Willets Point (WP), NY	851-6990	40°47.7'	73°46.9'	04/01/88 - 07/31/90
ADCP stations	8	41°01.3'	73°08.4'	07/14/88 - 09/13/88
	9	41°01.6'	72°54.7'	08/02/88 - 09/13/88

as

$$S = (1 - \frac{\sum (Q_p - Q_0)^2}{\sum Q_0^2})^{1/2} \qquad (4)$$

A value of S = 1 means prediction accuracy of 100%. Here Q_o and Q_p are the "observed" and "predicted" time series. Both are re-constructed from the analyzed harmonic constants of the observed and model predicted time series. The non-tidal fluctuations are, therefore, entirely smoothed out in the re-constructed time series.

Examination of Table 2 shows that the composite rms difference in tidal amplitudes (phases) between model and is approximate 10 cm (15 min.), and the prediction skill is nearly 100% at all selected water level stations, excluding the water level station at New London (97% prediction accuracy). The error of predicted water level at New London is due to the fact that New London water level station is located approximately 5 km up a river from the model basin, which is not properly resolved in the model grid.

Figure 3 shows time series comparison between the model predicted (solid curves) and observed (dashed curves) u-axis component current velocities in periods from Day 246 to Day 255 at ADCP station 9. The positive values of u indicate that the tidal currents move eastward. The model predicated current velocities agree remarkably well with the observations.

By assuming that the tidal current velocities can be expressed by the sum of a series of harmonic terms involving the same periodic constituents that are found in the tides, we have calculated the harmonic constants of tidal current amplitude and phase for model predicted and observed currents. As an example Table 3 shows comparison of model predicted and observed harmonic constants for tidal current constituents at 20 m abotve bottom at the ADCP station nos. 8 and 9. Agreements between predicted and observed current amplitudes are best for M_2. Both predicted and observed tidal currents are more energetic in the u-component of current velocities. The prediction skill for the u-component velocities are 0.95 and 0.98 at the ADCP Station Nos. 8 and 9, respectively.

Conclusions and Discussions

A case study evaluating the predictive capability of a hydrodynamic model of Long Island Sound is presented in this paper. The model driven by the astronomical tides has successfully simulated the tidal circulation pattern in the Sound. The model reproduces the tidal co-oscillation phenomenon observed at the eastern basin of Long Island Sound (assuming a node at The Race). Model predicted time series data of tidal elevations and currents agree remarkably well with the observational data.

However, there are still important unaddressed observational and model problems concerning the realistic current circulation pattern in Long Island Sound. In a parallel modeling effort, the Coastal and Estuarine Oceanography Branch of NOS is currently running a 18-month simulation (starting from June 1988) by

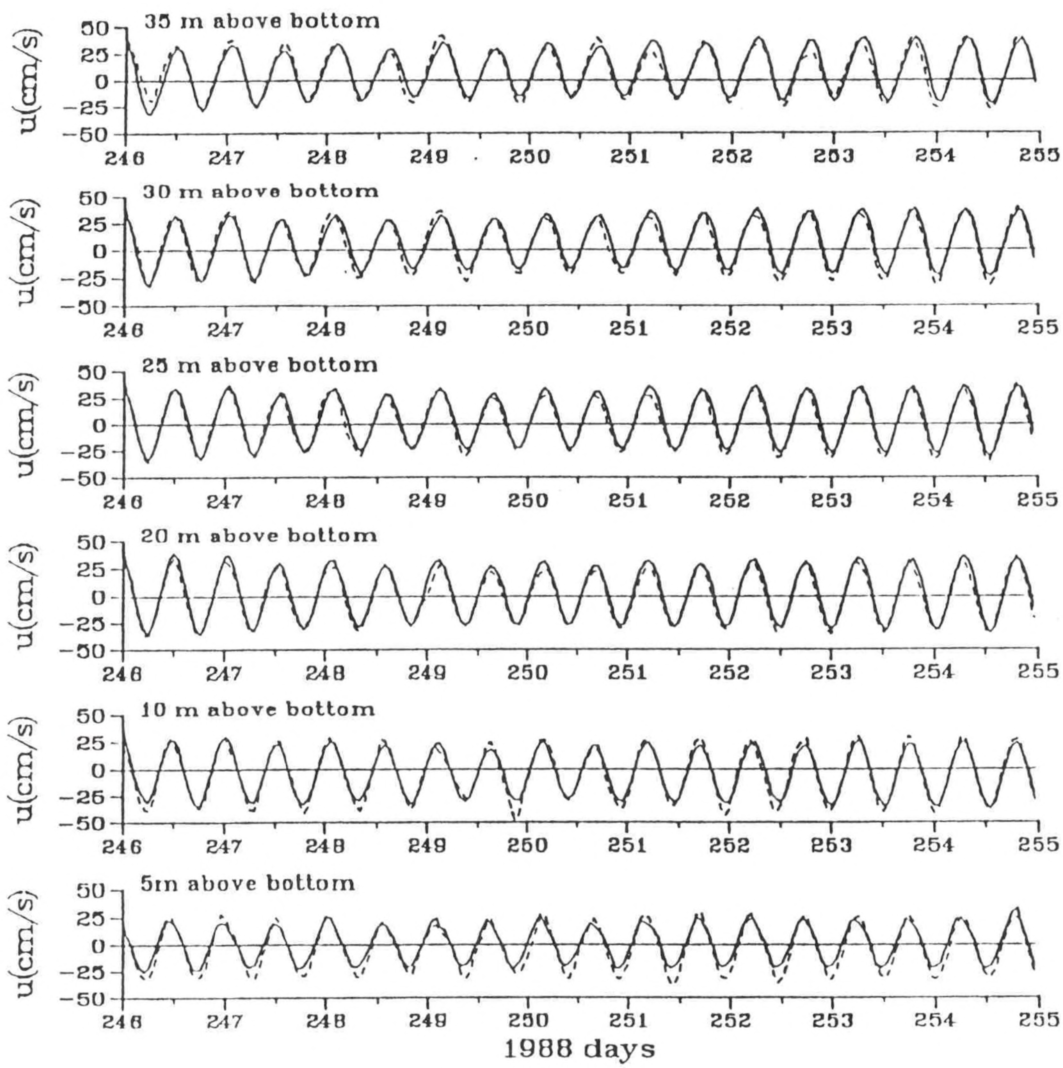

Figure 3. Time series comparison of east-west (u) component velocities at the ADCP station no. 9. Solid curves are model results and dashed curves are observations.

Table 2. Comparison of model (M) predicted and observed (O) tidal elevation harmonic constants, amplitude (A) and phase (G) of the five major tidal constituents, M_2, S_2, N_2, K_1, and O_1 in Long Island and Block Island sounds. The phases given here are in units of Greenwich high water intervals. Symbols, BA, BR, CB, MB, MP, NL, NV, PI, PJ, and WP represent the LISOP water level stations displayed in Table 1. The values of S represent the model prediction skill.

	M_2		S_2		N_2		K_1		O_1	
	A (cm)	G (hr)	A (cm)	G (hr)	A (cm)	G (hr)	A (cm)	G (hr)	A (cm)	G (hr)
BA: S = 0.99										
M:	14.20	13.23	13.30	13.69	13.60	12.88	11.30	12.45	5.10	12.79
O:	64.13	13.20	13.32	13.61	14.30	12.79	9.78	12.08	5.18	12.95
BR: S = 0.99										
M:	103.1	16.35	16.20	16.73	21.50	16.11	10.70	12.73	5.40	15.12
O:	98.5	16.14	16.64	16.46	21.52	15.68	9.11	12.68	6.55	15.68
CB: S = 1.00										
M:	98.30	16.41	15.40	16.79	20.50	16.17	10.50	12.79	5.30	15.19
O:	93.51	16.32	15.03	16.64	17.92	15.97	11.49	12.89	5.88	15.61
MB: S = 0.99										
M:	78.00	16.03	11.90	16.36	16.60	15.76	9.90	12.43	5.10	14.89
O:	72.79	15.80	11.58	16.07	12.80	15.14	10.03	12.33	6.34	15.54
NL: S = 0.97										
M:	42.50	14.56	7.30	14.59	9.80	14.25	8.40	11.60	4.50	14.24
O:	36.61	14.42	7.16	14.29	8.93	13.86	7.47	11.89	5.21	14.57
PJ: S = 1.00										
M:	45.60	12.62	9.00	12.97	9.70	12.52	7.00	10.82	4.00	13.48
O:	45.72	12.60	9.72	12.85	9.97	12.35	8.05	11.37	4.21	14.78
WP: S = 0.99										
M:	115.0	16.54	18.10	16.92	23.70	16.30	11.20	12.84	5.50	15.21
O:	109.1	16.50	18.90	16.81	24.02	16.10	9.36	12.94	6.49	15.89

Table 3: Comparison of model predicted (M) and observed (O) harmonic constants of the tidal current constituents at the ADCP Stations 8 and 9 in Long Island Sound.

		Station 8				Station 9			
	model or	v-axis		u-axis		v-axis		u-axis	
constituent	obs.	ampl. (cm/s)	phase (deg.)	ampl. (cm/s)	phase (deg.)	ampl. (cm/s)	phase (deg.)	ampl. (cm/s)	phase (deg.)
K_1	M:	0.344	109.6	1.843	213.6	0.034	160.7	2.057	195.5
K_1	O:	0.565	224.3	0.672	134.6	0.487	198.9	0.578	222.1
K_2	M:	0.288	77.1	1.432	110.8	0.130	330.6	1.453	99.3
K_2	O:	0.428	127.4	1.599	90.4	0.356	352.3	1.429	90.8
M_2	M:	5.585	53.4	31.82	78.7	4.025	343.6	32.64	67.5
M_2	O:	6.633	63.9	33.53	59.2	2.979	327.0	33.04	58.9
M_4	M:	0.371	289.0	2.192	269.6	0.413	36.7	1.189	261.4
M_4	O:	1.620	170.7	2.368	273.8	0.481	123.8	0.869	305.9
M_6	M:	0.324	149.9	1.351	184.0	0.256	53.1	0.511	171.0
M_6	O:	0.850	118.3	1.556	156.4	0.471	28.9	0.674	132.4
N_2	M:	1.266	21.2	5.949	59.8	1.453	200.9	6.608	49.9
N_2	O:	1.487	21.3	7.232	39.9	0.934	356.2	6.514	40.4
O_1	M:	0.204	235.6	0.794	250.3	0.522	8.7	0.967	214.5
O_1	O:	0.805	84.3	2.506	239.2	0.221	35.3	0.957	234.2
S_2	M:	1.058	75.3	5.265	108.3	0.477	331.6	5.343	96.9
S_2	O:	1.574	122.6	5.879	88.1	1.309	350.4	5.254	88.4

including fresh water inflows from the Harlem and the Connecticut Rivers as well as wind forcing in the model. The success of this model run will help us to understand the dynamic processes which cause the hypoxia occurred in the western end of Long Island Sound.

Further model efforts are planed to study the magnitudes and directions of tidally-induced residual currents in the area, since they are important for long-term mass transport and for water mass exchange between different basins.

Acknowledgements

Thanks are due to Dr. Kurt Hess for his careful reading and commenting on the manuscript; special thanks to Dr. Richard Schmalz for his many helpful explanations of the NOS Long Island Sound model.

References

Blumberg, A.F. and G.L. Mellor, 1983: Diagnostic and prognostic numerical circulation studies of the South Atlantic Bight. J. Geophys. Res., **88**, 4579-4592.

Blumberg, A.F. and G.L. Mellor, 1987: A description of a three-dimensional coastal ocean circulation model, in Three-Dimensional Coastal Ocean Models, vol. 4, edited by N. Heaps, pp. 208, American Geophysical Union, Washington, D.C.

Defant, A. 1961: Physical Oceanography, Vol. 2, MacMillan, New York.

Dennis, R.E. and E. E. Long, 1971: A user's guide to a computer program for harmonic analysis of data at tidal frequencies , Tech. Rep. NOS41, NOAA, Rockville, MD, 31pp.

Earwaker, K. L., 1990: Long Island Sound Oceanography Project: 1988-1900. NOS Oceanographic Survey Report No. 10, NOAA, Rovkville, MD, 57 pp.

Mellor, G.L. and T. Yamada, 1982: Development of a turbulence closure model for geophysical fluid problems. Rev. Geophys. Space Phys., **20**, 851-875.

Schureman, P., 1958: Manual of harmonic analysis and prediction of tides. Spec. Pub. 98, U.S. Coast and Geodetic Survey, Washington, D.C., 317pp.

Swanson, R.L., 1976: Tides. MESA New York Bight Atlas Monograph 4, New York Sea Grant Institute, Albany, New York.

DEVELOPMENT OF A LONG ISLAND SOUND TIDAL CIRCULATION AND WATER LEVEL ATLAS

Eugene J. Wei[1]

Abstract

The National Ocean Service (NOS) of the National Oceanic and Atmospheric Administration (NOAA) has the mission to predict currents and water levels in the nation's estuaries and coastal waterways. Prediction relies on traditional field data acquisition and analysis methods, state-of-the-art measurement technologies, and both numerical and analytical models. The *Long Island Sound Tidal Circulation and Water Level Forecast Atlas* is the product of such predictions.

A calibrated three-dimensional hydrodynamic model has been employed to simulate tides and currents in Long Island and Block Island Sounds east of Throgs Neck, NY to the open Atlantic Ocean boundary near Block Island, RI. The tidal dynamics of Long Island Sound are determined by the characteristics of the tide wave entering the Sound at two locations: New York Harbor (through the East River) and Block Island Sound. The mean tides at these boundaries, determined from long term predictions based on harmonic analysis, are used as the model forcing to predict the average tides and currents in the Sound. The simulated tides and currents are then displayed in the atlas as hourly charts covering one complete tidal cycle. Adjustment factors which account for the time-variation of tide range at open ocean boundaries are computed based on various tidal simulations. The accuracy of the atlas-predicted tides and currents at several locations are statistically analyzed and compared with observations.

Introduction

The *Long Island Sound Tidal Circulation and Water Level Forecast Atlas,* a product of the Long Island Sound Oceanography Project (LISOP), was developed by the Coastal and Estuarine Oceanography Branch (CEOB) within the NOS. The tidal circulation and water level forecast atlas provides graphical techniques for predicting the tide and tidal current in Long Island Sound from east of Throgs Neck, NY, to

---

1. Oceanographer, NOAA/NOS, Rockville, Maryland 20852.

the entrance to the Atlantic Ocean near Block Island, RI.

A graphical display of the changing circulation and tidal height for the entire estuary, including nearshore areas, is presented in the atlas as a series of tidal charts. Each hour of the tidal cycle is represented by a panel produced by a three-dimensional numerical hydrodynamic model of Long Island Sound. Current direction and speed are shown for each hour of the tidal cycle at 180 locations, including locations of special navigational or environmental interest where current measurements were not made owing to traditional instrumentation, budget constraints, or inaccessibility. The tidal height charts graphically display spacially-varying water levels over the entire waterway for each hour of the tidal cycle. Because the charts are model-generated, tidal water level predictions are no longer limited to a few coastal locations. Instead, coheight contours traverse the entire estuary and represent the effects of changing bathymetry on the tide.

The charts of tidal currents at 4.6 meters (15 feet) below the surface and tidal heights in this atlas are based on a mean tidal cycle obtained from averaging values of reconstructed astronomic tides for a 5-year period for four boundary stations that are referenced to Montauk Point, NY. The charts can be used to predict the tide or tidal current for specific dates and times when used in conjunction with the daily tide predictions for Montauk Point, NY, the reference station, provided in the *NOS Tide Tables*.

Hydrodynamic Model

The hydrodynamic model used is a modified version of the Mellor-Blumberg (Blumberg and Mellor, 1987) three-dimensional shelf circulation model. The model has been modified by NOS for simulations of Long Island Sound. The model utilizes primitive equations for mass and momentum conservation, together with transport diffusion of salinity and temperature to represent three-dimensional hydrodynamics generated by tides, wind, river inflows, and density currents. The model also applies a terrain-following vertical coordinate (sigma-coordinate) allowing the same number of vertical grid cells in the region. Either a rectangular coordinate or curvilinear coordinate can be used in the horizontal plane. The internal-external mode split numerical technique improves the computation efficiency. A turbulence closure model (Mellor and Yamada, 1982) accounts for vertical mixing while the Smagorinsky formulation is used for horizontal diffusion. Model formulations are described in detail by Schmalz (in preparation).

Long Island Sound is an estuary located east of New York City with Long Island bordered to the south, and the states of New York and Connecticut to the north. The embayment is connected to the Atlantic Ocean through Block Island Sound to the east and East River/New York Harbor to the west (Figure 1). The numerical model grid consists of 100 cells in the east-west direction with 37 cells in the north-south direction (Figure 2). The majority of water depths range from 20 to 40 meters with sloping bathymetry from both north and south shores. The relatively small bathymetric gradient throughout the Sound prompts the use of 2-km square grid cell resolution for simplicity and with sufficient accuracy. Approximately 60% of the grid cells are water cells included in the dynamic computation. In the vertical, seven layers with exponentially decreased layer thickness toward the surface and bottom from the mid-depth are used through the water column. This efficient resolution technique best describes the vertical structure of salinity and temperature fields in the area with adequate accuracy. The East River, its west end as an open boundary (The Battery) to the model and a channel connecting New York Harbor and Long Island Sound, has been rotated approximately 135 degrees counter-clockwise for computational efficiency. The other two open boundaries, one from Point Judith to Vail Beach and the other from Vail Beach to Montauk Point, are located on the east side of Block Island Sound adjacent to the Atlantic Ocean separated by Block Island. Five river systems, namely the Norwalk, Housatonic, Quinnipiac, Connecticut, and Thames Rivers, located along the north shore of the Sound are included in the grid.

The model has been extensively calibrated and validated with available field data (Schmalz, 1992 and 1993, and Wei, 1992) from LISOP. The objective of the atlas is to predict tidal characteristics throughout the Sound, particularly the tidal currents, the model validation procedure was based on the model-generated currents and tide heights with observations.

Water level observations at the model open boundaries at The Battery, Montauk Point, Vail Beach, and Pt. Judith were analyzed by traditional NOS harmonic analysis (Shureman, 1958) to obtain tide harmonic constants. These harmonic constants were then used to re-construct astronomical tide boundary conditions (referenced to mean sea level) for the model. A 32 days tidal simulation, without wind and river flow, started for the date August 30, 1988. Simulated tide and current reach a stationary state in two days, although the buoyancy force inherent to the density field may require a longer time to stabilize, its effect on the tidal characteristics are expected to be negligible. Thirty days of simulated currents and water levels were then analyzed and compared with observed data. The root-mean-square (RMS) differences of the M_2 constituent amplitude and phase at 11 Acoustic Doppler Current Profiler (ADCP) stations and eight tide stations (Figure 1) are 16.0 cm/sec and 11.6 degrees for current speeds and 5.9 cm and 8.0 degrees for water levels, respectively. These numbers show that the model is capable of accurately reproducing major tidal current characteristics in the Sound.

Mean Tide Simulation

The assumption underlying the atlas production is that the tidal dynamics of Long Island Sound are determined by the characteristics of the tide wave entering the Sound at two boundaries from the Atlantic Ocean; New York Harbor through the East River and Block Island Sound. Tidal heights and currents presented in the atlas are for an average tidal cycle throughout the Sound. An approach to achieve this objective is to develop the "average" tide boundary conditions for the hydrodynamic model in order to obtain the "average" tidal height and currents throughout the Sound. This procedure is described briefly as follows (Wei, in preparation).

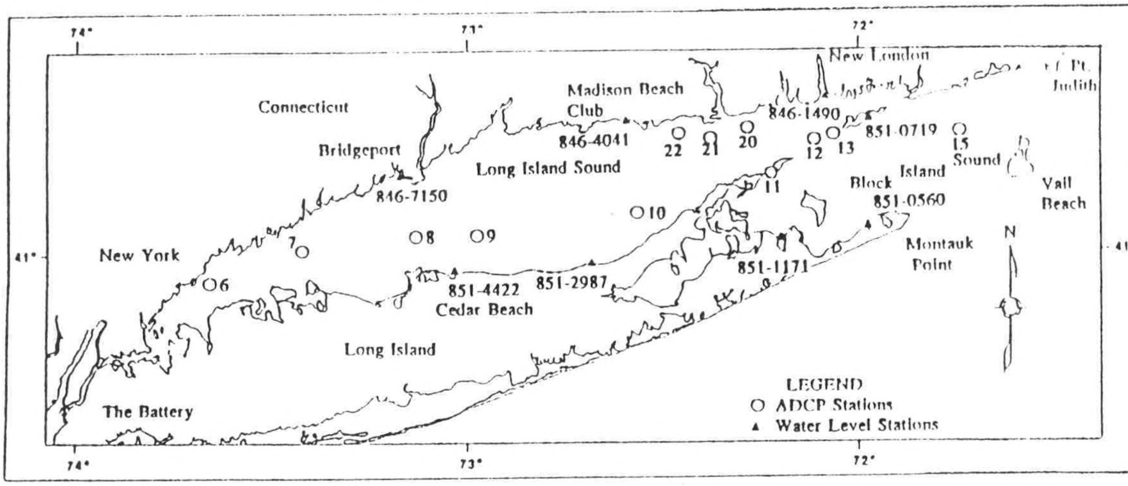

Figure 1 Long Island Sound and NOAA Stations

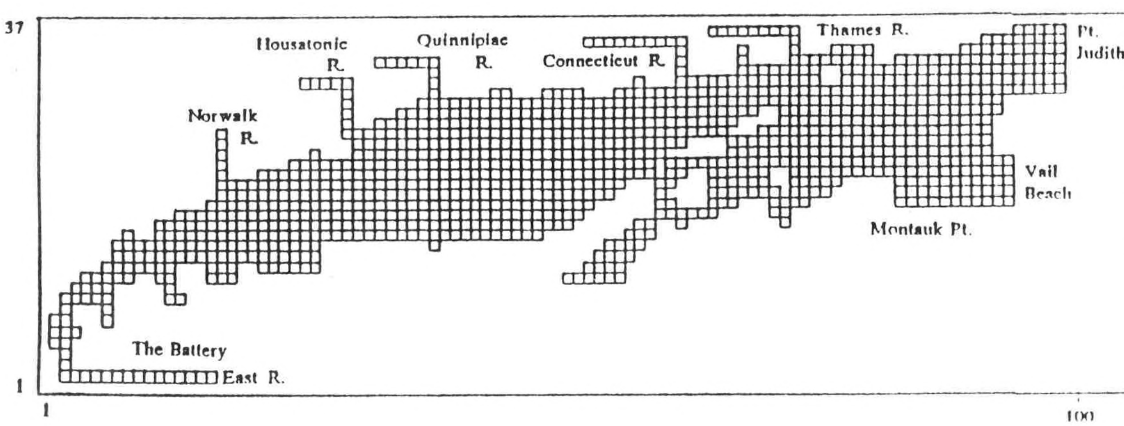

Figure 2 Long Island Sound Model Grid

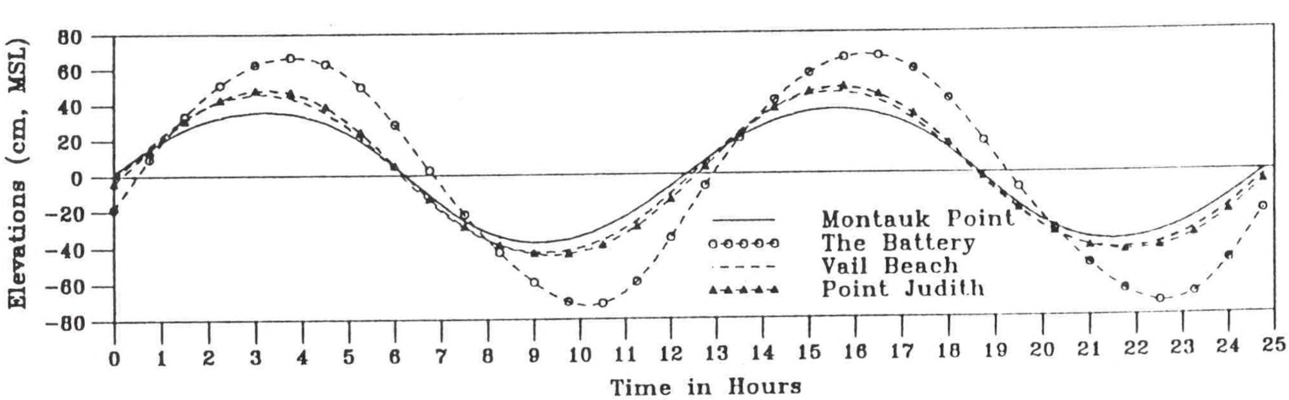

Figure 3 Averaged Tides at Open Boundaries

Five years (1992 to 1996) tide predictions were made with harmonic constants at open boundaries. The predicted tides were then averaged over a M_2 tidal cycle (12.42 hours) to obtain the averaged tide (Figure 3). The average phase lags of high tides at The Battery, Vail Beach, and Point Judith to Montauk Point were computed (1.13, 0.14, and 0.33 hours, respectively) based on each tidal cycle over the five years.

Sensitivity simulations with different seasonal density fields indicated that RMS differences of simulated tide characteristics, such as tide ranges and mean maximum flood and ebb currents, with *NOS Tide Tables* and *NOS Tidal Current Tables* were insignificant. It is also found that the accuracy were improved if yearly averaged flows of five rivers in Connecticut were included in the model. In addition, the yearly average wind effect on the tide and tidal current was insignificant based on sensitivity tests. The simulated water levels at Bridgeport, New London, and Madison Beach, CT, are presented in Figure 4.

Hourly water levels and current speeds from this simulation were then used to plot the 13 tidal charts for a tidal cycle in the atlas, assigning the time that high tide occurs at Montauk Point as hour 0. Figure 5 gives example of the atlas chart during the flood phase. A mean tidal level chart is also required for the time prediction using the atlas since the mean sea level (MSL) has been used as the model datum and the water level charts in the atlas are referred to nautical chart datum, the mean lower low water (MLLW). Water levels must be converted to MSL to find the adjustment factor for different tidal height.

Development of Adjustment Factors

The simulation described above represents the average tide condition in Long Island Sound. However, tidal heights and currents vary from day to day, principally in accordance with the phase, parallax, and declination of the moon. The magnitude of the tide and current speed in the Sound dynamically depend on the high tide amplitude of that tidal cycle at the open boundaries. Therefore, the values obtained from the charts must be adjusted using a table along with daily high tide predictions at Montauk Point.

The procedure starts with the construction of the statistical distribution of high and low tides predicted from harmonic analysis for 5 years (1992-1996) at four open boundaries. The distributions of high tides for Montauk Point (solid-line) and The Battery (dashed-line) are shown in Figure 6 as an example.

The amplitude of the average tide boundary condition during high tide is the water level at 50% of the cumulative distribution (38.6 cm for Montauk Point; Figure 6). This average high tide amplitude was then increased and decreased by 50% to obtain the amplitudes for two additional scenarios at Montauk Point (57.9 cm and 19.3 cm respectively). The corresponding cumulative distribution of these amplitudes are 89.6% and 17.8%, respectively. Based on the assumption that the same probability distribution exists at all open boundaries, the high tide amplitudes at The Battery for these two scenarios are found to be 91.4 cm and 51.5 cm, respectively. The high tide amplitudes at Vail Beach and Point Judith can be

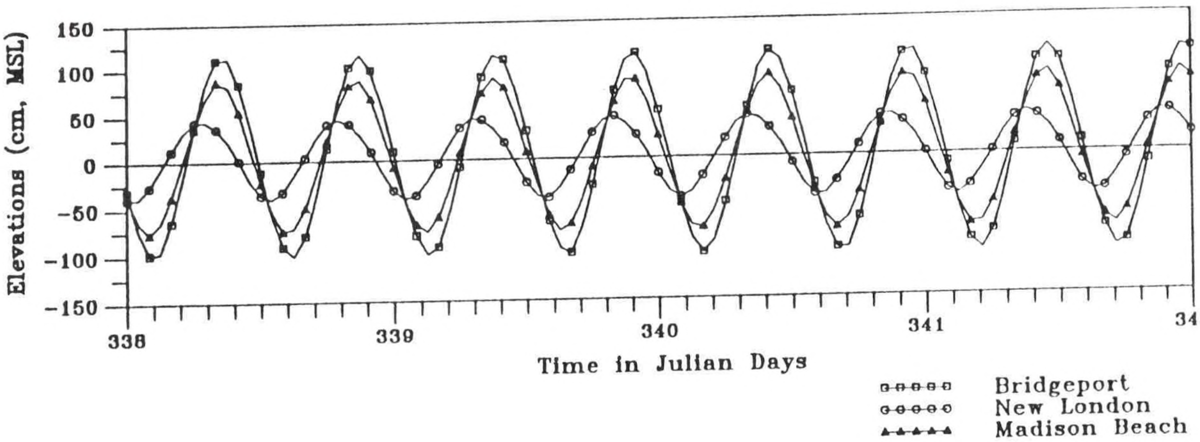

Figure 4 Simulated Water Level Time History for Average Tide

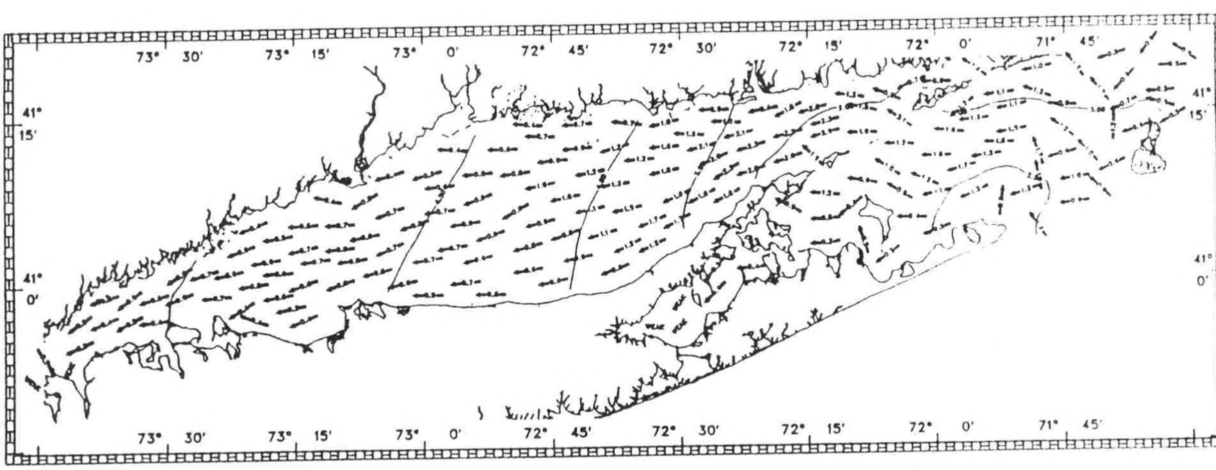

Figure 5 Tidal Chart During Flood

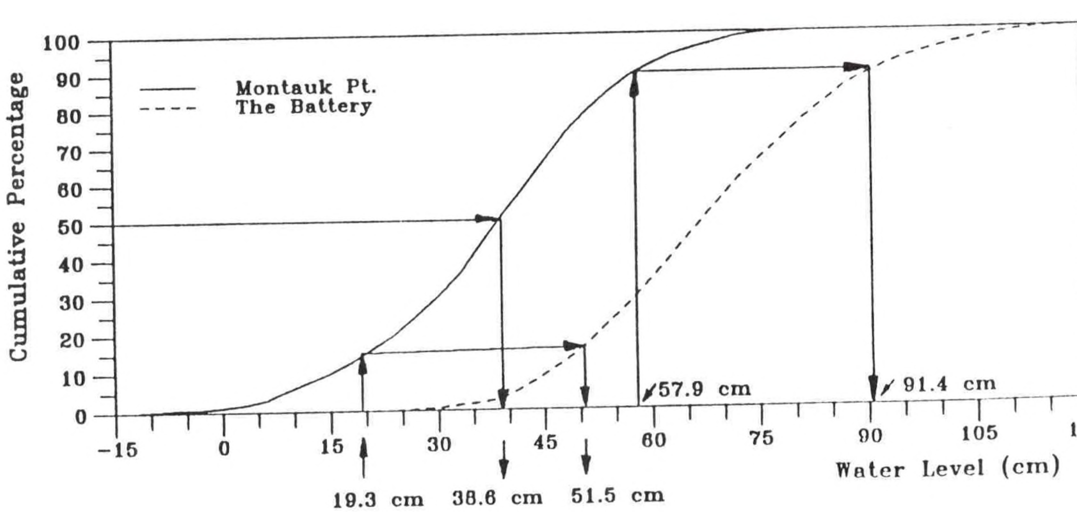

Figure 6 Cumulative Distribution of Harmonically Predicted High Tide

obtained using their cumulative distributions. Thus, boundary conditions for two scenarios representing 50% greater/smaller tidal amplitudes from the average tide condition were established. The same procedure was repeated using 75% and 25% increases and decreases from the averaged tide condition. Overall, there are seven different scenarios encompassing more than 95% of the tide height occurrences at open boundaries.

For each scenario, the ratio of the sum of simulated water levels (or currents) at each water grid location from a given scenario to that from the average tide simulation are computed at every hour after high water at Montauk Point for a tidal cycle. Repeating the procedure for each scenario and each hour (up to and including hour 12) after high tide at Montauk Point, and using the chart datum as reference datum, the adjustment factors for current speed and water level can be obtained and are shown in Table 1.

Table 1: Factors for adjusting current speeds and water levels

Tide Height (feet)	Hour After High Water at Montauk Point, NY												
at Montauk Pt, NY	0	1	2	3	4	5	6	7	8	9	10	11	12
(a) for current speeds													
1.2 to 1.4	0.54	0.67	0.83	0.98	0.69	0.44	0.57	0.67	0.83	0.97	0.98	0.44	0.50
1.5 to 1.7	0.66	0.75	0.87	0.99	0.74	0.59	0.68	0.77	0.87	0.98	0.98	0.58	0.63
1.8 to 2.0	0.78	0.84	0.92	0.99	0.80	0.72	0.79	0.86	0.92	0.98	0.99	0.72	0.76
2.1 to 2.3	0.89	0.91	0.95	0.99	0.87	0.86	0.90	0.93	0.96	0.99	0.99	0.87	0.89
2.4 to 2.6	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2.7 to 2.9	1.08	1.06	1.05	1.03	1.13	1.12	1.09	1.07	1.04	1.01	1.04	1.12	1.10
3.0 to 3.2	1.18	1.14	1.10	1.06	1.23	1.22	1.18	1.14	1.09	1.05	1.11	1.24	1.21
3.3 to 3.5	1.26	1.20	1.15	1.10	1.34	1.32	1.26	1.21	1.16	1.09	1.17	1.34	1.29
3.6 to 3.9	1.35	1.26	1.20	1.14	1.45	1.42	1.34	1.28	1.24	1.13	1.24	1.44	1.36
(b) for water levels													
1.2 to 1.4	0.80	0.33	0.52	0.64	0.70	0.78	0.85	0.39	0.26	0.42	0.60	0.60	0.74
1.5 to 1.7	0.84	0.49	0.64	0.72	0.77	0.83	0.88	0.54	0.49	0.62	0.70	0.75	0.80
1.8 to 2.0	0.88	0.65	0.76	0.81	0.84	0.88	0.91	0.61	0.70	0.78	0.82	0.84	0.86
2.1 to 2.3	0.92	0.81	0.87	0.90	0.91	0.93	0.94	0.80	0.87	0.90	0.92	0.92	0.92
2.4 to 2.6	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2.7 to 2.9	1.08	1.15	1.11	1.08	1.07	1.06	1.06	1.21	1.12	1.09	1.08	1.07	1.07
3.0 to 3.2	1.19	1.30	1.22	1.17	1.15	1.14	1.14	1.41	1.25	1.19	1.16	1.16	1.17
3.3 to 3.5	1.29	1.45	1.32	1.26	1.23	1.21	1.22	1.58	1.35	1.27	1.24	1.24	1.26
3.6 to 3.9	1.38	1.59	1.41	1.34	1.30	1.28	1.29	1.73	1.43	1.34	1.31	1.31	1.33

To obtain a predicted tidal current speed and direction for a particular time at a specific location, the following steps should be carried out (procedure for the tide will be similar):

(1) Look in the *NOS Tide Tables* for Montauk Point, NY, to find the time of the high water just before the time of interest. Determine the number of hours after high water that the time of interest represents and select the corresponding tidal chart. (If this time falls between two tidal circulation chart times, the following calculations can be carried out for each chart and the results prorated.)

(2) On the hourly tidal chart, find the current arrow nearest the location of interest. This arrow, with speed in knots at the center, shows the predicted direction of flow for the time of interest.

(3) From the daily prediction table, find the height of high water corresponding to the time of high water found in step (1) above. Since the atlas charts represent the tidal characteristics obtained by forcing the model with open boundary average tides which do not include seasonal changes in sea level from the solar long-period constituents (Ssa and Sa), the height of high water found from the *NOS Tide Tables* needs to be corrected by this seasonal adjustment.

(4) Locate this adjusted height value in Table 1 and find the adjustment factor corresponding to the hours after high water chart chosen from step (1) above.

(5) Apply this factor to the speed value found in step (2) to obtain the predicted speed in knots.

(6) If proration is needed, repeat steps 1-6 for the second hour; then prorate the results to find the final predicted speed for the time of interest.

Accuracy of the Tidal Atlas

The current and water level charts presented in this atlas are the tidal predictions based on model simulations and do not include the nontidal effects of wind and atmospheric pressure which can also affect water level and circulation. A statistical analysis was carried out in which 18 months of observed water level and current data obtained by NOS in Long Island Sound from 1988 to 1990 were compared with tide and tidal current predictions using this atlas. The objective of this analysis was to determine the accuracy of the atlas predictions that the user could expect in different areas of the estuary. These analysis results cover a limited time period, generally 2 months to 2 years, for any particular location. For extreme meteorological conditions, actual differences in water level or currents can be larger than the differences presented below.

Hourly tidal current predictions from the atlas charts were compared with observed currents, which include the climatological, meteorological, and non-tidal effects, at 10 current meter stations during the 1988-1990 field survey (Earwaker, 1990). The average RMS difference between atlas-predicted and observed currents is about 0.36 knot. The mean ratio of atlas-predicted to the observed current is 1.07 indicating that, overall, the atlas-predicted current could be 7% more than observed currents.

The magnitude and the time of maximum flood and ebb tidal currents predicted by atlas charts at The Race were compared with tidal current predictions in the *NOS Tidal Current Tables* for two years; 1992 and 1993. The analysis indicates that atlas-predicted currents at The Race are within 0.8 knot of *NOS Tidal Current Tables* predictions 91.6 percent of the time and within 1.0 knot 97 percent of the time. The mean ratio of atlas-predicted to *NOS Tidal Current Tables* is 0.99, implying that maximum currents predicted by atlas charts are very close to that predicted in *NOS Tidal Current Tables*. The time of maximum flood and ebb occurs within 30 minutes of those predicted for The Race in the *NOS Tidal Current Tables* 83 percent of the time.

The average percentage of time that the hourly tide prediction was within 0.3 m of observed water level was 92.5 percent for eight locations where long term observations were made. The average RMS difference was 0.2 m. Tidal extremes (high and low tides) were also compared. The atlas-predicted high and low tides were 96.4 percent of time within 0.26 m of *NOS Tide Tables* predictions at Bridgeport CT and 96.8 percent within 0.23 m feet at New London, CT.

Conclusions

The *Long Island Sound Tidal Circulation and Water Level Forecast Atlas* provides graphical techniques for predicting the tide and tidal current from east of Throgs Neck, NY, to the entrance of the Atlantic Ocean near Block Island, RI. This paper documents the procedure of producing the atlas. The use of a three-dimensional hydrodynamic model advances the current prediction at the depth of most interest to the mariners that a two-dimensional model could not accurately achieve. The time-variant adjustment factors for tide and current predictions from the mean tide condition improves the atlas prediction accuracy.

The basic assumption in the Long Island Sound tidal atlas is that tide characteristics in the Sound simply depends on the high tide at open boundaries. Although the local geographical effect (among others) on the tide and tidal current is implicitly resolved by the model, the accuracy of the atlas prediction still depends strongly on the numerical model representation such as grid resolution and integration scheme. The adjustment factor represented by the average value through the entire Sound is a first approximation and the prediction may lose accuracy at any particular location. Due to the constraint of the existing procedures, the effects of extreme meteorological events, which may cause abnormal tide and currents, were not included in this study. The prediction accuracy can be improved further to include meteorological, climatological, and other potential effects. Therefore, computerized digital data coupled with user friendly PC-based graphical representations can produce a highly accurate tide forecast system.

Acknowledgements

Dr. Henry Frey, former Chief of CEOB at NOS, initiated the production of the Long Island Sound Tide and Tidal Forecast Atlas. Ms. Karen L. Earwaker assisted in the data analysis for developing tidal charts in the atlas. Dr. Richard A. Schmalz provided the Long Island Sound model for the atlas. He and Dr. Kurt W. Hess also provided technical guidance through many discussions in the development of the atlas. All of their contributions are gratefully appreciated.

References

Blumberg, A. F., and Mellor, G. L. (1987). "A description of a three-dimensional coastal ocean circulation model". In Three-Dimensional Coastal Ocean Models, Vol. 4, edited by N. Heaps, pp. 208, American Geophysical Union, Washington, D.C.

Earwaker, K.L., (1990) NOS Oceanographic Circulation Survey Report No. 10, Long Island Sound Oceanography Project: 1988 - 1990, NOAA/NOS, Rockville, Maryland.

Mellor, G.L., and Yamada, T (1982) "Development of a Turbulence Closure Model for Geophysical Fluid Problems", Rev. Geophys. Space Phys., 20, No. 4, 851-875.

Schmalz, R. A., (1992) "Simulation of Three-Dimensional Hydrodynamics in Long Island Sound: Annual Timescales", Proceedings of the 2nd International Conference on Estuarine and Coastal Modeling, ASCE, Nov. 13-15, 1991, Tampa, FL.

Schmalz, R. A., (in preparation) Application and Documentation of a Three-Dimensional Circulation Model, Volume 1 of Final Report - NOS Long Island Sound Oceanography Project, NOS, NOAA, Rockville, MD.

Shureman, P., (1958) Manual of Harmonic Analysis and Prediction of Tides, U.S. Government Printing Office, Washington, D.C..

Wei, E. J., (1992) "Simulation of Three-Dimensional Hydrodynamics in Long Island Sound: Seasonal Timescales", Proceedings of the 2nd International Conference on Estuarine and Coastal Modeling, ASCE, Nov. 13-15, 1991, Tampa, FL.

Wei, E.J., (in preparation) Development and Validation of a Tidal Circulation and Water Level Atlas, Volume 3 of Final Report - NOS Long Island Sound Oceanography Project, NOS, NOAA, Rockville, MD.

SENSITIVITY OF RESIDUAL CIRCULATION IN LONG ISLAND SOUND TO TIDAL DATUMS

Richard A. Schmalz, Jr.[1]

Abstract

The Blumberg-Mellor (1980, 1987) three-dimensional hydrodynamic model modified to include time varying river inflows, residual water levels, wind forcing, sewage treatment plant inflows, and combined sewer overflows is employed to simulate the residual circulation in Long Island and Block Island Sounds in support of water quality management. In order to simulate realistic residual circulation patterns and representative water mass fluxes throughout Long Island Sound and the East River, New York, it is necessary to specify absolute mean sea level with respect to a vertical tidal (model) datum on all model water surface elevation boundaries. These mean elevations are often expressed with respect to several vertical tidal (model) datums. This motivates study of the sensitivity of the residual circulation to these datums.

A numerical investigation of the sensitivity of near surface and near bottom hourly residual circulation averaged over the month of April 1988 (representative of average annual stratification) to the following three tidal datums: 1) uniform mean sea level (MSL), 2) National Geodetic Vertical Datum (NGVD) (1929), and 3) North American Vertical Datum (NAVD) (1988) is presented. For each datum, an astronomical tide with density effect simulation is performed comprising the astronomic tide simulation series. A second complete meteorological forcing simulation series is performed in which for each datum in addition to the astronomic tide with density effect, residual water levels and winds are included. Sound-wide residual circulation patterns and salinity and temperature at several tide gage locations are compared for both simulation series. The sensitivity of the nontidal fluxes at Throgs Neck, New York, located at the confluence of the East River, New York, and western Long Island Sound to these vertical tidal datums is also shown. Conclusions are drawn and recommendations are advanced for additional measurements and simulations.

---

1 Oceanographer, National Oceanic and Atmospheric Administration, National Ocean Service, Office of Ocean and Earth Sciences, Marine Analysis and Interpretation Division, Coastal and Estuarine Oceanography Branch, 6010 Executive Blvd., Rockville, Maryland 20852.

Introduction

Long Island Sound is a unique major estuarine resource and is the subject of a comprehensive conservation management plan to be developed by the Environmental Protection Agency (EPA) and the National Oceanic and Atmospheric Administration's National Ocean Service (NOAA/NOS). The plan will be developed based upon application of three-dimensional coupled hydrodynamic (NOAA/NOS) and water quality (EPA) models to define the role of residual circulation and transport processes in dissolved oxygen and nutrient distributions.

In an effort to investigate recent (1987 -1992) hypoxic/anoxic events in western Long Island Sound, two major contributions are of particular interest. One major contribution is due to the residual circulation gyral structure in the western and central basins as discussed by Pritchard (1990). A second major contribution is the East River system influence on western Long Island Sound. In an effort to study these contributions, this paper investigates the sensitivity of the western Sound residual circulation gyral structure and the magnitude of the nontidal fluxes near Throgs Neck, NY, at the entrance of the East River to western Long Island Sound to vertical tidal datums. A brief history of vertical tidal datums and their methods of construction is given by Zilkoski et al. (1992). Initially, the hydrodynamic model formulation and application to Long Island Sound is outlined. The sensitivity of simulated residual gyral structures averaged over April 1988 under astronomic tide with density with respect to each vertical tidal datum is next presented. Sensitivities of simulated residual gyre structures under complete meteorological forcing (water level and wind effects additionally included) over the same period are then presented. The sensitivity of temperature and salinity at internal tide stations is then discussed. Non-tidal fluxes at Throgs Neck, NY are presented for both simulation series. Conclusions are drawn and recommendations made for additional measurements and simulations.

Model Formulation and Application to Long Island Sound

The three-dimensional hydrodynamic model employs a general orthogonal curvilinear coordinate system (ϵ_1 , ϵ_2) in the horizontal (Blumberg and Herring, 1987) and a bottom and free-surface following (σ) coordinate in the vertical ; e.g., the Cartesian coordinates, (x, y, z) $\rightarrow$ (ϵ_1, ϵ_2, σ). In this formulation, σ ranges from $\sigma = 0$, $z = \eta$ at the surface to $\sigma = -1$, $z = -H_o$ at the bottom, where $\sigma = (z - \eta)/(\eta + H_o)$ (Blumberg and Mellor, 1980; Blumberg and Mellor, 1987). The vertical mixing (eddy) coefficients, K_M, K_H and K_q are evaluated using the level 2-1/2 turbulence closure model of Mellor and Yamada (1982) as modified by Galperin, et al., (1988).

The governing partial differential equations are approximated via finite differences within an external/internal barotropic/baroclinic mode splitting context. All horizontal terms are explicitly differenced with the vertical diffusion terms implicitly treated to afford large internal mode time steps. Boundary conditions are discussed in Blumberg and Herring (1987) and in Schmalz (1990).

In application to Long Island Sound, a rectilinear computational grid employing 100 cells in the east-west and 37 cells in the north-south directions with a uniform length of 2.032 km was employed. Seven layers with cell centers at σ = - 0.050, - 0.141, - 0.283, - 0.5, - 0.717, - 0.859, and - 0.95 were employed in the vertical. A 150 second internal mode and 30 second external mode time step or 5:1 mode split was used. Water levels were reconstructed at The Battery, NY and Spuyten Duyvil, NY and along the open boundary in Block Island Sound from 24 tidal constituents. The total water level is specified as the sum of the 24 tidal constituent contributions and an offset from mean sea level to the appropriate vertical datum (shown in the first four lines of Table 1 for the boundary stations). Average daily streamflows were input for the five major State of Connecticut rivers (Norwalk River, Mill and Quinnipiac Rivers, Housatonic River, Connecticut River, and Thames River) and five New York State streams. Sewage treatment plant and combined sewer overflows were also included. A spatially uniform bottom roughness, z_0 = 1 cm was employed except within the Connecticut rivers, wherein z_0 = 4 cm was used. For salinity and temperature, a one-dimensional advection equation is used on outflow, while climatological forms (Schmalz, 1992) for salinity and temperature are used on inflow.

Astronomic Tide Simulation Series

A simulation of the astronomic tide from 1 - 30 April 1988 including density effects was performed for each vertical tidal datum. While the simulation period encompasses only a one month period, the stratification for April 1988 is representative of the annual mean and the major tidal variations are captured over a 29 day period. Simulated Eulerian residual currents using the NAVD (1988) tidal datum at 2 meters depth and at 2 meters above the bottom as averaged hourly for the duration of April 1988 are shown in Figure 1 (a) and (b), respectively. The velocity magnitudes are plotted such that only velocities less than or equal to scale arrow length are indicated. This strategy was adopted in order to portray the central basin circulation from 30 to 50 in horizontal index. Note the presence of a large counterclockwise pair of near-surface gyres in agreement with general knowledge of Sound circulation described by Pritchard (1990). In the western Sound near bottom circulation shown in Figure 1 (b), there exists a general east-west circulation in agreement with the known estuarine circulation as described by Pritchard (1990). In Figure 1 (c), the simulated near surface (2m depth) salinity field is depicted. Note the "C" shape of the isohalines in the central basin from 30 to 50 in horizontal index, which is in agreement with observations and known surface salinity patterns (Pritchard, 1990). Simulated correspondingly averaged Eulerian residual circulation patterns for both MSL and NGVD (1929) tidal datums are nearly identical to those shown in Figure 1 for NAVD (1988).

In order to check the consistency of the three vertical datums, simulated 29-day mean water levels were compared with observed mean water levels over the 1960 - 1978 tidal epoch with respect to each of the three vertical datum as shown in Table 1. Note the first four stations are on the model water level boundary and the 29-day

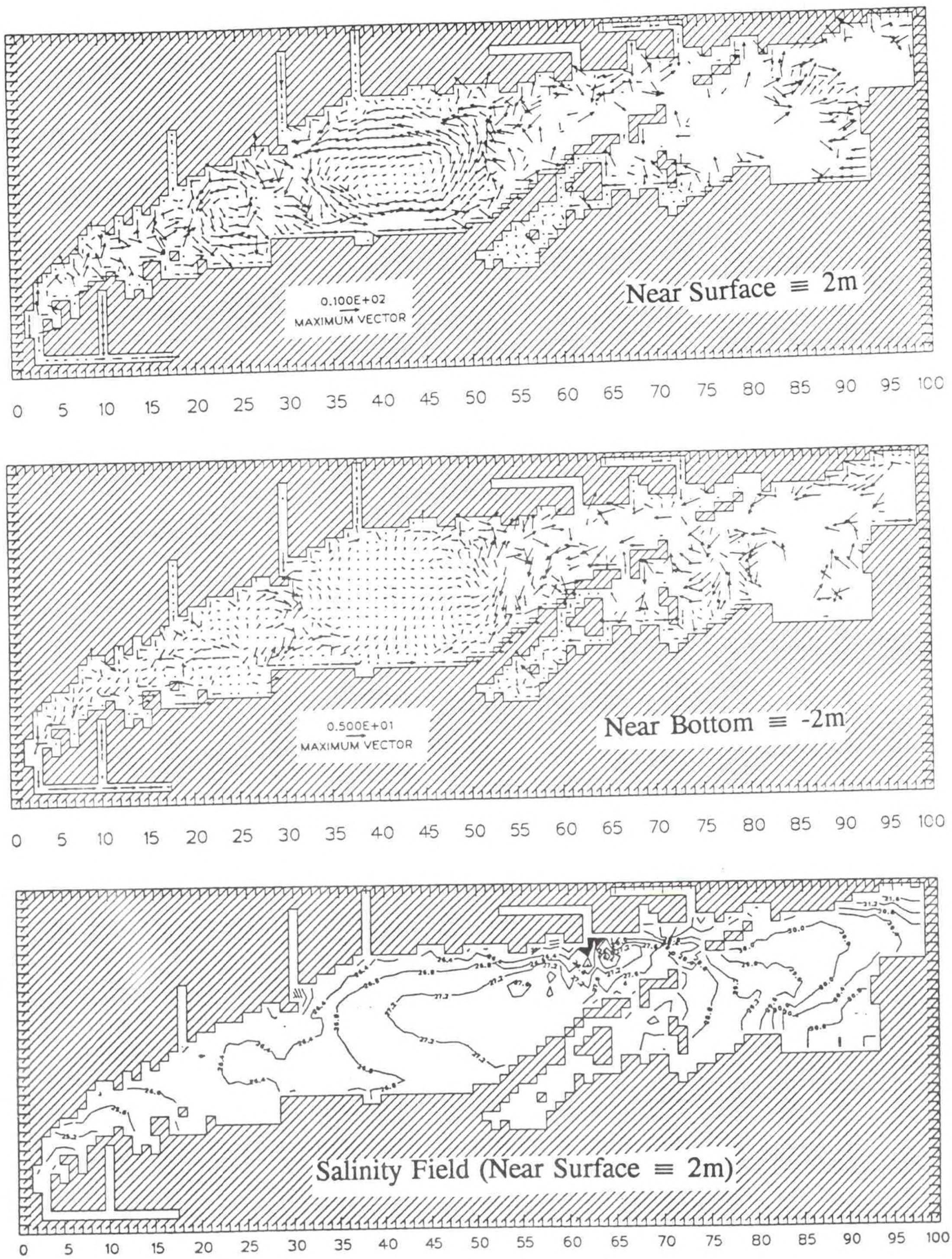

Figure 1: Simulated Astronomic NAVD (1988) Tidal Datum
Residual Current (cm/s) Fields (Near Surface ≡ 2m and Near Bottom ≡ -2m)
and Salinity (psu) Field (Near Surface ≡ 2m)

simulated mean water levels correspond within print format precision to the observed tidal epoch mean levels. Average differences in mm are given for the remaining four internal stations, which proceed from east to west and alternate between the

Table 1: April 1988 Simulated (S) vs Observed (O) Mean Water (mm) Level Summary

Station	NOS No.	NGVD (1929)		MSL		NAVD (1988)	
		S	O	S	O	S	O
The Battery, NY	851-8750	213	213	0	0	-122	-123
Spuyten Duyvil, NY	851-8760	262	262	0	0	-58	-59
Montauk Pt., NY	851-0321	139	139	0	0	-147	-148
Pt. Judith, RI	845-5083	110	111	0	0	-169	-169
Willets Point, NY	851-6990	171	216	57	0	-109	-113
Bridgeport, CT	846-7150	167	210	53	0	-112	-130
Port Jefferson, NY	851-8091	163	162	48	0	-118	-145
New London, CT	846-1490	131	146	16	0	-150	-145
Average Difference		25.5		43.5		13.5	

Connecticut and Long Island shorelines. Simulated mean water levels are in closest agreement with observed mean water levels with respect to the most recent vertical datum NAVD (1988) to order 15 mm. Mean discrepancies, for these four stations, between simulated and observed mean levels are order 25 mm and 45 mm for the NGVD (1929) and MSL vertical tidal datums, respectively.

Complete Meteorological Forcing Simulation Series

In order to investigate the difference in the total residual circulation structure induced by using the three tidal datums, the three simulation series was repeated but with the inclusion of wind effects and water level residual forcings. Hourly wind data at LaGuardia Airport are assumed to hold over the entire model domain and are adjusted to overwater values using the Hsu (1986) formulation. The drag coefficient of Large and Pond (1981) is used to compute surface wind stress. Water level residuals at The Battery, NY were transferred to Spuyten Duyvil, NY, while the residuals at Montauk Point, NY were transferred to the entire Block Island Sound open boundary. The mean water level residuals at The Battery, NY and Montauk Point, NY were 125 mm and 144 mm, respectively for April 1988. Mean hourly winds were 11.2 kts. Winds exceeded 20 kts for only 22 hours and the maximum wind was 24 kts. Hourly wind directions were subtracted from 90° to produce a strong up-estuary monthly average (unit vector) wind direction of 111° meteorological convention. Mean average daily flows for the Norwalk, Housatonic, Mill and

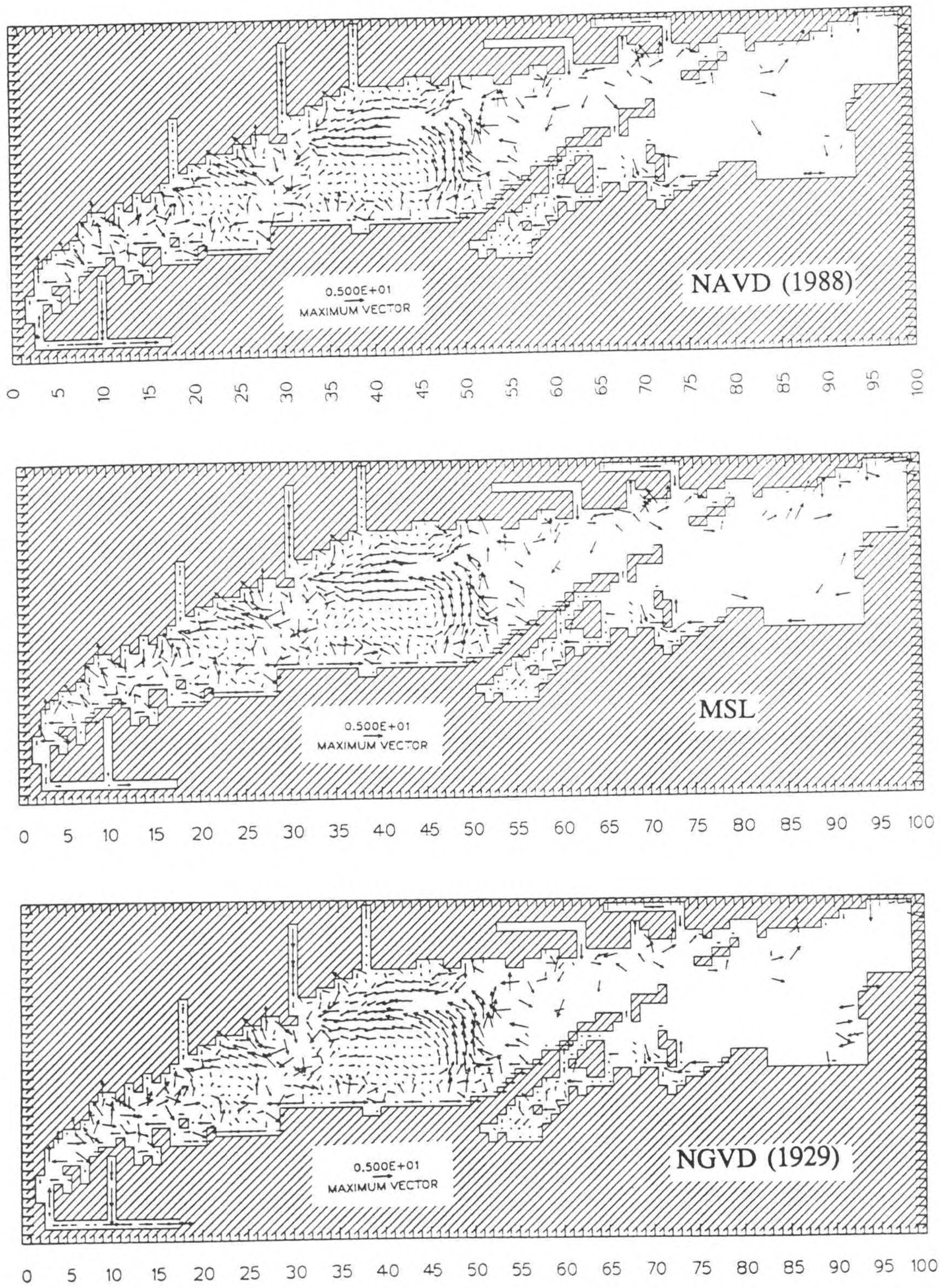

Figure 2: Simulated (Near Surface ≡ 2m) Meteorologic Forcing Residual Current (cm/s) Fields NAVD (1988), MSL, and NGVD (1929)

Quinnipiac, Connecticut, and Thames River systems were 69 cfs, 3296 cfs, 275 cfs, 34307 cfs, and 2920 cfs, respectively. Simulated Eulerian residual circulation at 2 meter depth is shown in Figure 2 for each simulation. While the general circulation pattern is not disturbed by employing different tidal datums as was previously noted for the astronomic tide series, the residual gyre structure in the surface under astronomic tide and density (Figure 1 (a)) has been significantly altered in the complete meteorologically forced case with currents strengthened in the north and reduced in the south.

Temperature and Salinity Sensitivity

Simulated near surface and near bottom values for temperature and salinity are compared at the end of the one-month simulation for both simulation series in Tables 2 and 3, respectively. Since the surface temperature is specified, all series ______

Table 2. Simulated Surface (S) and Bottom (B) Temperature 30 April 1988

Simulation	Willets Point NY		Bridgeport CT		Port Jefferson NY		New London CT	
	S	B	S	B	S	B	S	B
NGVD (1929)	9.7	6.0	8.8	7.0	8.7	5.4	7.3	6.9
NGVD (1929) with residuals	9.7	8.8	8.8	8.5	8.7	7.4	7.3	7.1
Mean Sea Level	9.7	6.4	8.8	7.0	8.7	5.1	7.3	6.6
Mean Sea Level with residuals	9.7	8.8	8.8	8.4	8.7	7.4	7.3	7.0
NAVD (1988)	9.7	6.2	8.8	7.0	8.7	5.3	7.3	6.8
NAVD (1988) with residuals	9.7	8.8	8.8	8.4	8.7	7.5	7.3	7.1

Table 3: Simulated Surface (S) and Bottom (B) Salinity 30 April 1988

Simulation	Willets Point NY		Bridgeport CT		Port Jefferson NY		New London CT	
	S	B	S	B	S	B	S	B
NGVD (1929)	24.8	26.3	26.2	26.5	26.2	27.3	23.7	30.4
NGVD (1929) with residuals	23.6	25.6	26.5	26.6	26.9	27.1	27.5	28.4
Mean Sea Level	25.4	26.3	26.2	26.6	26.5	27.5	24.1	30.7
Mean Sea Level with residuals	25.3	26.1	26.6	26.6	27.0	27.1	27.0	28.8
NAVD (1988)	25.0	26.2	26.2	26.5	26.4	27.4	24.1	30.3
NAVD (1988) with residuals	24.5	25.9	26.6	26.7	27.0	27.1	26.8	28.9

In the case of salinity, series maximum surface and
bottom salinity differences of order 1.0 psu and 0.5 psu, respectively, occur at Willets Point, NY.
At all other stations, series differences are generally less than 0.3 psu. Since the salinity and temperature are specified at the boundaries, this would imply that over a long-term 18-month simulation, salinity and temperature distributions would be very similar for each of the three tidal datums throughout the majority of Long Island Sound except in the near surface in the extreme western Sound.

Non-tidal Fluxes at Throgs Neck, NY

The non-tidal flux in the East River at Throgs Neck, NY changes by approximately 450 m^3/s as shown in Table 4 based upon the vertical tidal datum employed. For non-tidal fluxes of this order, this raises the question as to which tidal datum should be used. Based upon the results of the astronomic tide simulation series, NOAA/NOS has used the most consistent with internal tide station NAVD (1988) datum. In initial simulations over the eighteen month period April 1988 - September 1989, the average nontidal fluxes at Throgs Neck, NY (using the sign convention of Table 4) are order -125 m^3/s over the full depth with corresponding average upper layer and lower layer fluxes of order 400 m^3/s and -525 m^3/s respectively.

Table 4: Simulated Nontidal Fluxes At Throgs Neck, NY

Simulation	Total East River[1] at Throgs Neck (m^3/s)	Upper[1] Layer (m^3/s)	Lower[1] Layer (m^3/s)
NGVD (1929)	121	678	-557
NGVD (1929) with residuals	-65	451	-516
Mean Sea Level	-333	162	-495
Mean Sea Level with residuals	-521	102	-623
NAVD (1988)	-111	381	-492
NAVD (1988) with residuals	-302	232	-534

Note: 1 ≡ Plus direction from East River into Western Long Island Sound

---

Minimum and maximum values of these fluxes over the 18-month period were order (-300 m^3/s, 100 m^3/s), (250 m^3/s, 750 m^3/s), and (-750 m^3/s,-300 m^3/s), respectively.

Conclusions and Recommendations

The structure of the western Sound residual circulation gyral pair is not influenced by the choice of vertical tidal datum in either the astronomic tide with density case or in the case of complete meteorological forcing. The residual circulation fields are quite different in structure under these two cases, indicating the significance of the water level residual and wind forcings. It is recommended that additional simulations be undertaken in order to separate these effects and further examine the density and tidal components. Salinity and temperature fields are sensitive to choice of vertical datum only at the confluence of the East River. Nontidal fluxes at Throgs Neck, NY differ by 450 m^3/s based on vertical tide datum employed. In order to estimate nontidal fluxes near Throgs Neck, NY and further quantify the gyre structure in the western Sound, additional ADCP measurements both fixed and towed should be made. In conjunction with this effort, it would be desirable to investigate the development of a refined curvilinear grid system in western Long Island Sound. The present NOAA/NOS hydrodynamic model could be used to provide boundary conditions. The details of the circulation in western Long Island Sound could be further investigated within the refined grid structure resulting in improved nontidal mass flux estimates, which would increase our ability to effectively manage the fragile resources of the western Sound.

Acknowledgements

This work was performed in conjunction with the joint NOAA - EPA Long Island Sound Study within the Coastal and Estuarine Oceanography Branch under the supervision of Dr. Henry R. Frey. Professor Donald W. Pritchard, State University of New York, and Drs. Kurt W. Hess and Wayne L. Wilmot NOAA/NOS have provided many valuable insights. Both model developers, Professor George L. Mellor, Princeton University and Dr. Alan F. Blumberg, HydroQual, Inc., actively participated in several model evaluation and assessment meetings and provided overall advice and assistance.

References

Blumberg, A.F. and Mellor, G.L. (1980) "A Coastal Ocean Numerical Model" In: Mathematical Modeling of Estuarine Physics. Proceedings of an International Symposium, Hamburg, August 24 - 26, 1978. J. Sündermann and K.P. Holz, Eds., Springer-Verlag, Berlin.

Blumberg, A.F. and Mellor, G.L. (1987) "A Description of a Three-Dimensional Coastal Ocean Circulation Model", In: Three-Dimensional Coastal Ocean Models, Coastal and Estuarine Sciences, 4, N. Heaps, Ed., American Geophysical Union, Washington, D.C., 1-16.

Blumberg, A.F. and Herring, H.J. (1987) "Circulation Modeling Using Orthogonal Curvilinear Coordinates", In: Three-Dimensional Models of Marine and Estuarine Dynamics, J.C.J. Nihoul and B.M. Jamart, Eds., Elsevier Publishing Company, 55-88.

Galperin, B. et al. (1988) "A Quasi-Equilibrium Turbulent Energy Model for Geophysical Flows", Journal of the Atmospheric Sciences, 45 (1) : 55-62.

Hsu, S.A. (1986) "Correction of Land-based Wind Data for Offshore Applications: A Further Evaluation", Journal of Physical Oceanography, 16, 390-394.

Large, W.G. and Pond, S. (1981) "Open Ocean Momentum Flux Measurements in Moderate to Strong Winds", Journal of Physical Oceanography, 11, 324-326.

Mellor, G.L. and Yamada, T. (1982) "Development of a Turbulence Closure Model For Geophysical Fluid Problems", Rev. Geophys. Space Phys., 20, 851-875.

Pritchard, D.W. (1990) A Brief Description of the Circulation in Long Island Sound, unpublished note, prepared for Long Island Sound Study, EPA Region I and II, Washington, D.C.

Schmalz, R.A. (1990) "A Review of Estuarine, Shelf and Ocean Hydrodynamics", In: Proceeding of Estuarine and Coastal Modeling Conference, Nov. 15-17, 1989, Newport, Rhode Island, ASCE, New York, New York.

Schmalz, R.A. (1992) "Simulation of Three-Dimensional Hydrodynamics in Long Island Sound: Annual Timescales", In: Proceedings of 2nd International Conference on Estuarine and Coastal Modeling, Nov. 13-15, 1991, Tampa, Florida, ASCE, New York, New York.

Zilkoski, D.B. et al. (1992) "Results of the General Adjustment of the North American Vertical Datum of 1988", Surveying and Land Information Systems, Vol. 52, 3, 133-149.

NUMERICAL DECOMPOSITION OF EULERIAN RESIDUAL CIRCULATION IN LONG ISLAND SOUND

Richard A. Schmalz, Jr.[1]

Abstract

The Blumberg-Mellor (1980, 1987) three-dimensional hydrodynamic model modified to include time varying river inflows, residual water levels, wind forcing, sewage treatment plant inflows, and combined sewer overflows is employed to simulate the Eulerian residual circulation in Long Island and Block Island Sounds in support of water quality management. Two simulation series are performed in order to decompose this circulation into the following components: 1) astronomic tide generated, 2) density driven, 3) local wind-driven, and 4) non-local shelf wind-driven. Near surface and near bottom circulation component fields are compared illustrating the importance of the local wind on both the near surface and near bottom structures. Sensitivity of the Eulerian residual circulation on local wind direction is briefly considered. Individual component contributions to the nontidal fluxes at Throgs Neck, New York, located at the confluence of the East River, New York, and western Long Island Sound are evaluated. Conclusions are drawn on component characteristics and recommendations made for additional process studies to further investigate the density and local wind components.

Introduction

Long Island Sound is a unique major estuarine resource and is the subject of an ongoing comprehensive conservation management plan being developed by the Environmental Protection Agency (EPA) and the National Oceanic and Atmospheric Administration's National Ocean Service (NOAA/NOS). The plan will be developed based upon application of three-dimensional coupled hydrodynamic (NOAA/NOS) and water quality (EPA) models to define the role of residual circulation and transport processes in dissolved oxygen and nutrient distributions.

---

1 Oceanographer, National Oceanic and Atmospheric Administration, National Ocean Service, Office of Ocean and Earth Sciences, Marine Analysis and Interpretation Division, Coastal and Estuarine Oceanography Branch, SSMC4 Rm. 6540 1305 East-West Highway, Silver Spring, Maryland 20910.

In an effort to investigate recent (1987 -1992) hypoxic/anoxic events in western Long Island Sound, two major aspects of the residual circulation are of particular interest: 1) the gyral structure in the western and central basins as discussed by Pritchard (1990) and 2) the East River system influence on western Long Island Sound. In an effort, to quantify these aspects, this paper considers the numerical investigation of the composition of the western Sound Eulerian residual circulation gyral structure and the magnitude of the nontidal fluxes near Throgs Neck, NY, at the entrance of the East River to western Long Island Sound. Initially, the hydrodynamic numerical model formulation and application to Long Island Sound is outlined. Simulation series one is conducted to estimate astronomic tide and density components of the Eulerian residual circulation, while simulation series two is performed to evaluate local and non-local shelf wind components. Simulation series results are used to decompose the Eulerian residual circulation and sensitivity to local wind effects is also considered. Non-tidal fluxes at Throgs Neck, NY are then presented for each simulation. Conclusions and recommendations for additional process studies conclude the paper.

Model Formulation and Application to Long Island Sound

The three-dimensional hydrodynamic model employs a general orthogonal curvilinear coordinate system (ϵ_1 , ϵ_2) in the horizontal (Blumberg and Herring, 1987) and a bottom and free-surface following (σ) coordinate in the vertical; e.g., the Cartesian coordinates, $(x, y, z) \rightarrow (\epsilon_1, \epsilon_2, \sigma)$. In this formulation, $\sigma = 0$, $z = \eta$ at the surface and $\sigma = -1$, $z = -H_o$ at the bottom, where $\sigma = (z - \eta) / (\eta + H_o)$ (Blumberg and Mellor, 1980; Blumberg and Mellor, 1987). The vertical mixing (eddy) coefficients, K_M, K_H and K_q are evaluated using the level 2-1/2 turbulence closure model of Mellor and Yamada (1982) as modified by Galperin et al. (1988).

The governing partial differential equations are approximated via finite differences within an external/internal (barotropic/baroclinic) mode splitting context. All horizontal terms are explicitly differenced with the vertical diffusion terms treated implicitly to afford large internal mode time steps. Boundary conditions are discussed in Blumberg and Herring (1987) and in Schmalz (1990).

In application to Long Island Sound, a rectilinear computational grid employing 100 cells in the east-west and 37 cells in the north-south directions with a uniform length of 2.032 km was employed. Seven layers with cell centers at σ = -0.050, - 0.141, - 0.283, - 0.5, - 0.717, - 0.859, and - 0.95 were employed in the vertical. A 150 second internal mode and 30 second external mode time step or 5:1 mode split was used to simulate the period 1 - 30 April 1988. The Eulerian residual circulation is computed by dividing the internal mode transport per unit width at each sigma level averaged over one hour by the averaged internal mode depth over a one hour period and subsequently averaging these hourly sigma level quotients over the complete month. Water levels were reconstructed at The Battery, NY and Spuyten Duyvil, NY and along the open boundary in Block Island Sound from 24 tidal constituents and were specified relative to the 1988 North American Vertical Datum. Average daily streamflows were input for the five major State of Connecticut rivers

(Norwalk River, Mill and Quinnipiac Rivers, Housatonic River, Connecticut River, and Thames Rivers) and five New York State streams (~ 65 cfs). Mean April 1988 average daily flows for the Norwalk, Housatonic, Mill and Quinnipiac, Connecticut, and Thames River systems were 69 cfs, 3296 cfs, 275 cfs, 34307 cfs, and 2920 cfs, respectively. Sewage treatment plant (~1500 cfs) and combined sewer overflows (~220 cfs) were also included. For salinity and temperature, a one-dimensional advection equation is used on outflow, while climatological forms (Schmalz, 1992) for salinity and temperature are used on inflow. A spatially uniform bottom roughness of z_o = 1 cm was employed except within the Connecticut rivers, wherein z_o = 4 cm was used. Atmospheric pressure anomalies are not considered.

Astronomic Tide and Density: Simulation Series 1

In order to study the contribution of the astronomic tide and density on the Eulerian residual circulation a series of two simulations was performed. While the simulation period encompasses only a one month period (April 1988), the stratification is representative of the annual mean and the major tidal variations are captured over a 30 day period. In Simulation 1 Series 1, the astronomic tide including density effects was considered. In the Simulation 2 Series 1, the density gradients are set to zero. Simulated monthly averaged near surface Eulerian residual currents at 2 meters depth are shown in Figure 1 part (a) for astronomic tide with density effects, in part (b) for astronomic tide alone excluding density effects, and in part (c) for the density effects (assumed equal to the difference between part (a) and part (b) circulations). In Figure 2, simulated monthly averaged near bottom Eulerian residual circulations are presented in analogous fashion. The velocity magnitudes are plotted such that only velocities less than or equal to scale arrow length are indicated. This strategy adopted in order to portray the western and central basin circulations from 20 - 30 and 30 - 50 in horizontal indicies, respectively, has been used in all subsequent figures (2-6). Note in Figure 1 part (a) for the astronomic tide with density effects, the presence of a large counterclockwise pair of gyres (one in the western and one in the central basin) in agreement with general knowledge of Sound circulation described by Pritchard (1990). In the near surface circulation for the astronomic tide alone shown in Figure 1 part (b), the pair of gyres is still evident, but is much weaker. The strong westerly-directed surface density currents near the Connecticut shoreline and easterly-directed surface density currents near the Long Island shoreline as shown in Figure 1 part (c) serve to strengthen these surface gyral structures. For the near bottom astronomic tide plus density circulation in Figure 2 part (a), it is noted that the surface gyre in the central basin has penetrated to the bottom with reduced spatial expanse (north of horizontal index 50). In Figure 2 part (b), for the astronomic tide alone, this gyre is no longer present. It is the contribution of the density currents in this region, which acts to produce the gyre as shown in Figure 2 part (c). In general, the near bottom density currents are directed up-estuary and are significantly stronger than those induced by the astronomic tide alone.

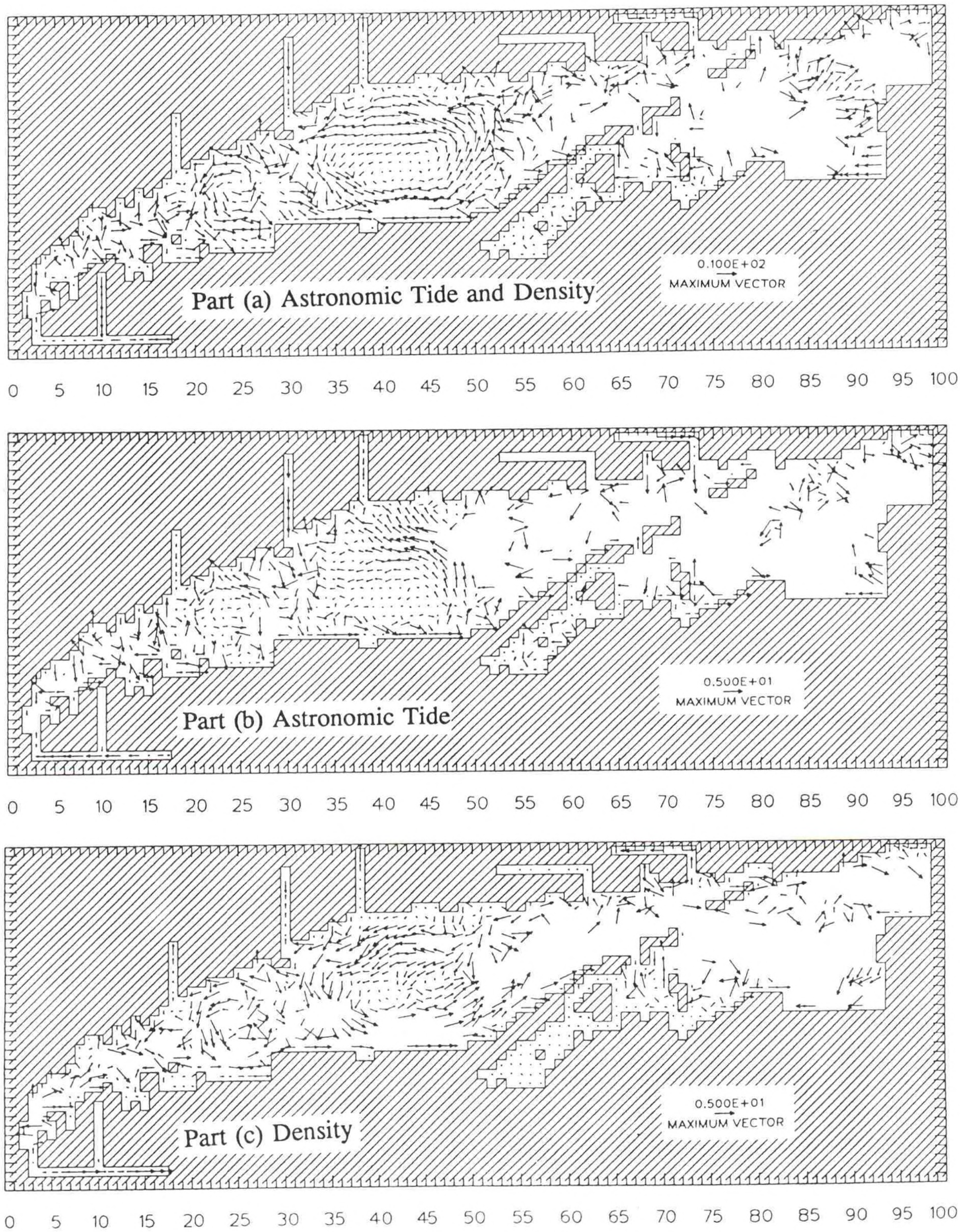

Figure 1: Simulated (Near Surface ≡ 2m) Eulerian residual Current (cm/s) Fields: Part (a) Astronomic Tide and Density, Part (b) Astronomic Tide, Part (c) Density

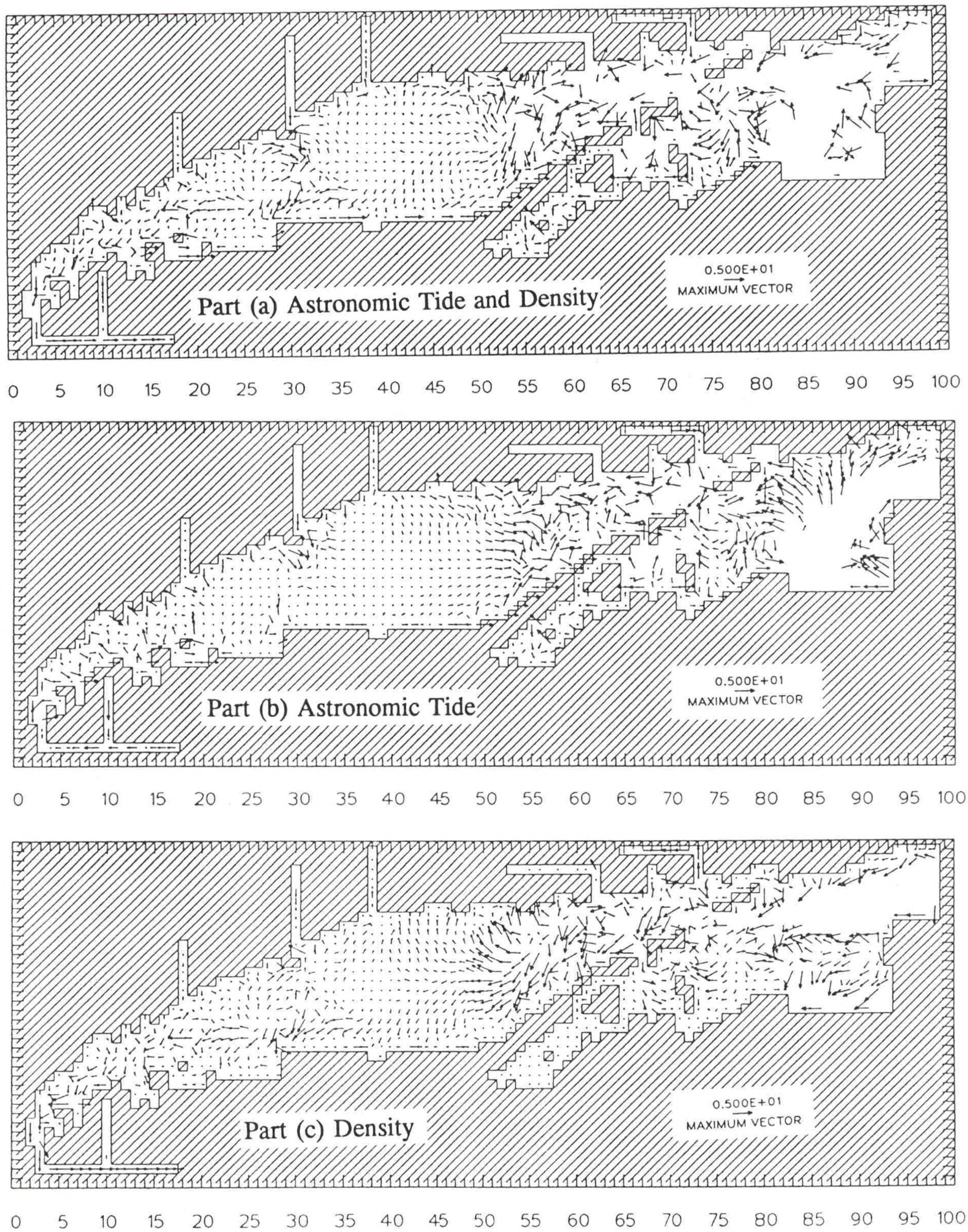

Figure 2: Simulated (Near Bottom ≡ -2m) Eulerian residual Current (cm/s) Fields: Part (a) Astronomic Tide and Density, Part (b) Astronomic Tide, Part (c) Density

Wind Forcing: Simulation Series 2

In order to investigate the difference in the Eulerian residual circulation structure induced by local and non-local wind effects, three additional simulations were performed in which astronomic tide and density effects were included. Hourly wind data at LaGuardia Airport are used to represent local wind effects and assumed to hold over the entire model domain after adjustment to overwater values using the Hsu (1986) formulation. The drag coefficient of Large and Pond (1981) is used to compute surface wind stress. Mean monthly hourly wind speed and direction at LaGuardia, NY were 11.2 kts and from 340 degrees true, respectively, with a maximum wind speed of 24 kts and speeds greater than 20 kts occurring for only 22 hours during the entire month. Water level residuals at The Battery, NY (also transferred to Spuyten Duyvil, NY) and at Montauk Point, NY (transferred to the entire Block Island Sound open boundary) were assumed to represent non-local shelf wind effect. The mean monthly water level residuals at The Battery, NY and Montauk Point, NY were 125 mm and 144 mm, respectively. In Simulation 1 Series 2, both wind effects were included. In Simulation 2 Series 2, water level residuals were set to zero in order to consider local Sound-wide wind forcings only. In Simulation 3 Series 2, local Sound-wide winds were set to zero, while water level residuals were retained in order to represent non-local shelf wind forcings. Total wind induced Eulerian residual circulation is assumed equal to the difference between the complete wind forced (Simulation 1 Series 2) and the astronomic tide with density simulation (Simulation 1 Series 1). Local wind forcing induced Eulerian residual circulation was assumed to be equal to the difference between the complete wind forced (Simulation 1 Series 2) and the water level residual forced (Simulation 3 Series 2) simulated fields. Non-local shelf forcing induced Eulerian residual circulation was assumed equal to the difference between the complete meteorologically forced (Simulation 1 Series 2) and the local wind forced (Simulation 2 Series 2) simulated fields. Simulated near surface Eulerian residual circulation at 2 meter depth is shown in Figure 3 part (a) for total wind forcing, in part (b) for local wind forcing, and in part (c) for non-local shelf wind forcing, respectively. Simulated near bottom Eulerian residual circulations are presented in Figure 4 in an analogous manner. In Figure 3, parts (a) and (b) are nearly identical, indicating the dominance of local wind forcing over shelf wind forcings on near surface current structures. The majority of the surface currents exceed 5 cm/s. In Figure 3 part (c), the effects of the shelf wind forcings appear to be order 1 -2 cm/s or less. In Figure 4, parts (a) and (b) are almost identical, again indicating the dominance of local wind forcings over extremely small (< 1 cm/s) shelf wind forcing induced near bottom currents shown in part (c).

Eulerian Residual Circulation Decomposition and Sensitivity to Local Wind Forcing

In order to decompose the simulated Eulerian residual near surface and bottom currents shown in Figure 5, western and central mid-basin residual component current strengths were estimated from Figures 1 and 3 and from Figures 2 and 4,

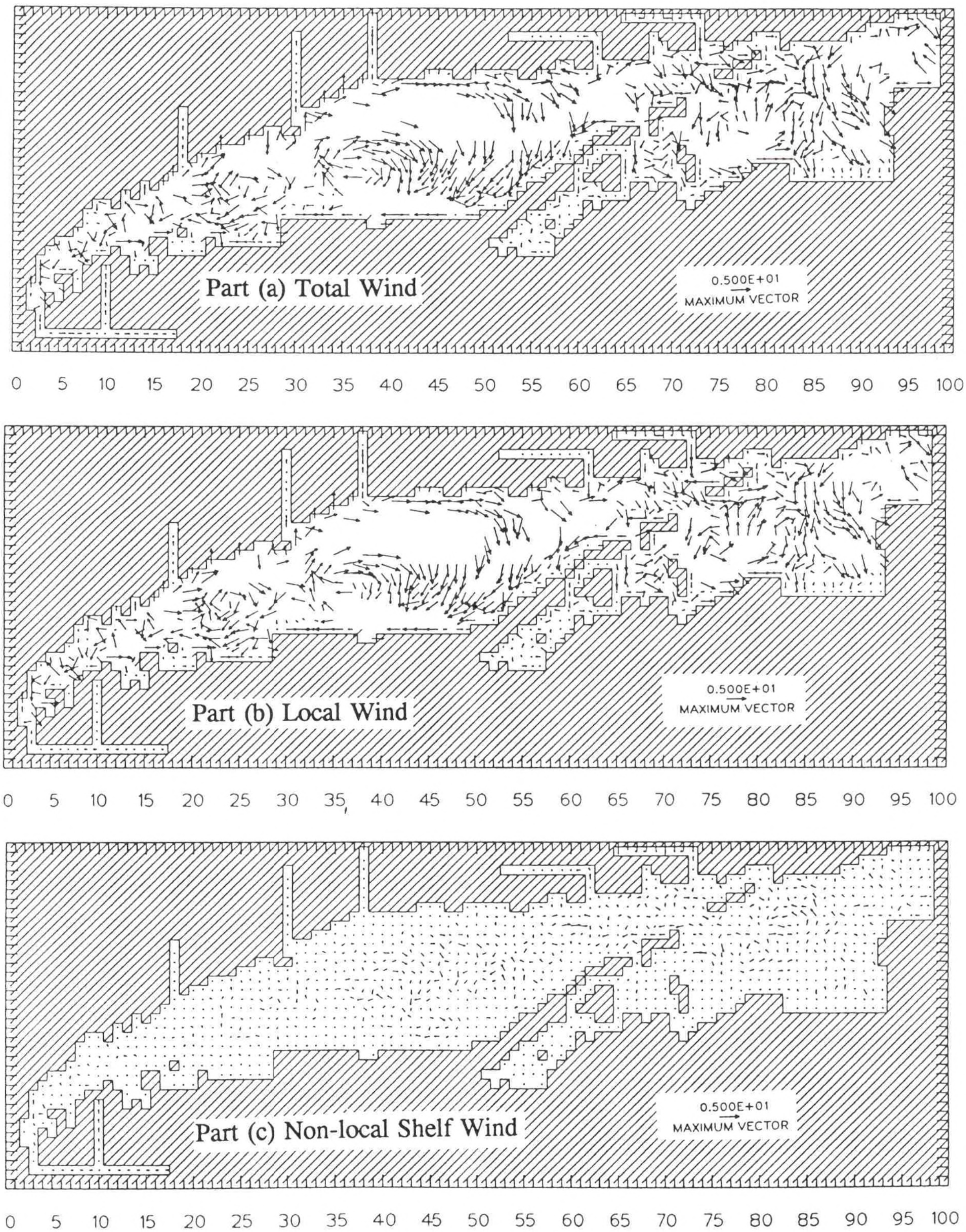

Figure 3. Simulated (Near Surface ≡ 2m) Eulerian residual Current (cm/s) Fields: Part (a) Total Wind , Part (b) Local Wind , and Part (c) Non-local Shelf Wind

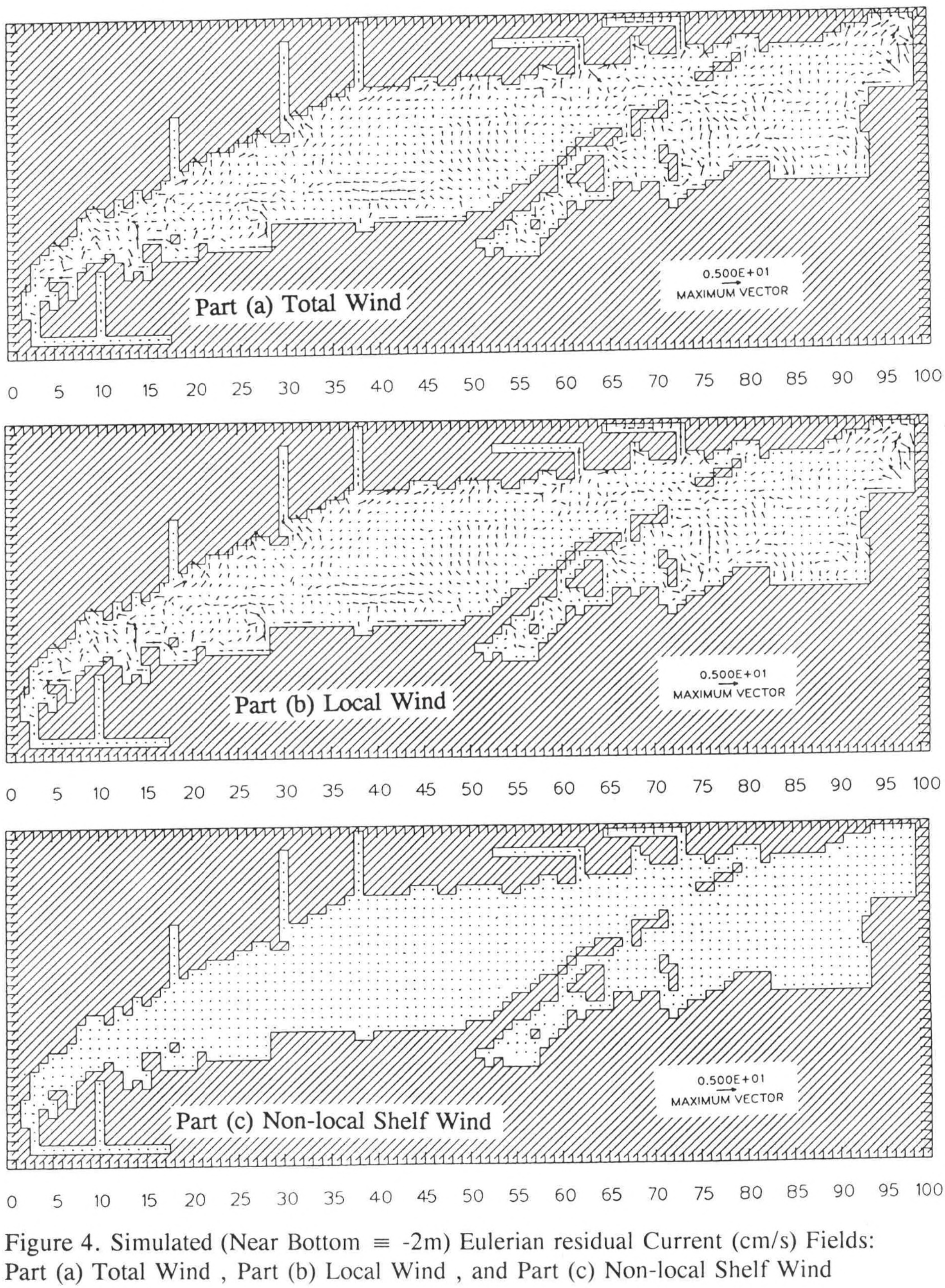

Figure 4. Simulated (Near Bottom ≡ -2m) Eulerian residual Current (cm/s) Fields: Part (a) Total Wind , Part (b) Local Wind , and Part (c) Non-local Shelf Wind

respectively and are given in Table 1. For near surface currents, the astronomic tide, density and local wind forcing induced currents are of same order of magnitude with the non-local shelf wind effects an order of magnitude less. For near bottom currents, density and local wind effects appear slightly larger than astronomic tide effects and shelf wind effects are nearly zero. Of particular interest, is to compare Figure 5 part (a) with Figure 1 part (a) and note the collapse of the near surface central basin gyre into two smaller gyres separated by a large north-south flow region due to the combined local and non-local shelf wind effects.

In order to further investigate the effect of local wind forcings on the total Eulerian residual circulation, an additional simulation was performed in which wind directions were subtracted from 90 °, resulting in a strong up-estuary average wind direction from 110 ° true in contrast to 340 ° true. The near surface and near bottom Eulerian residual circulations are as shown in Figure 6. In Figure 6 part (a), the near surface currents are similar in structure to those shown for the astronomic tide with

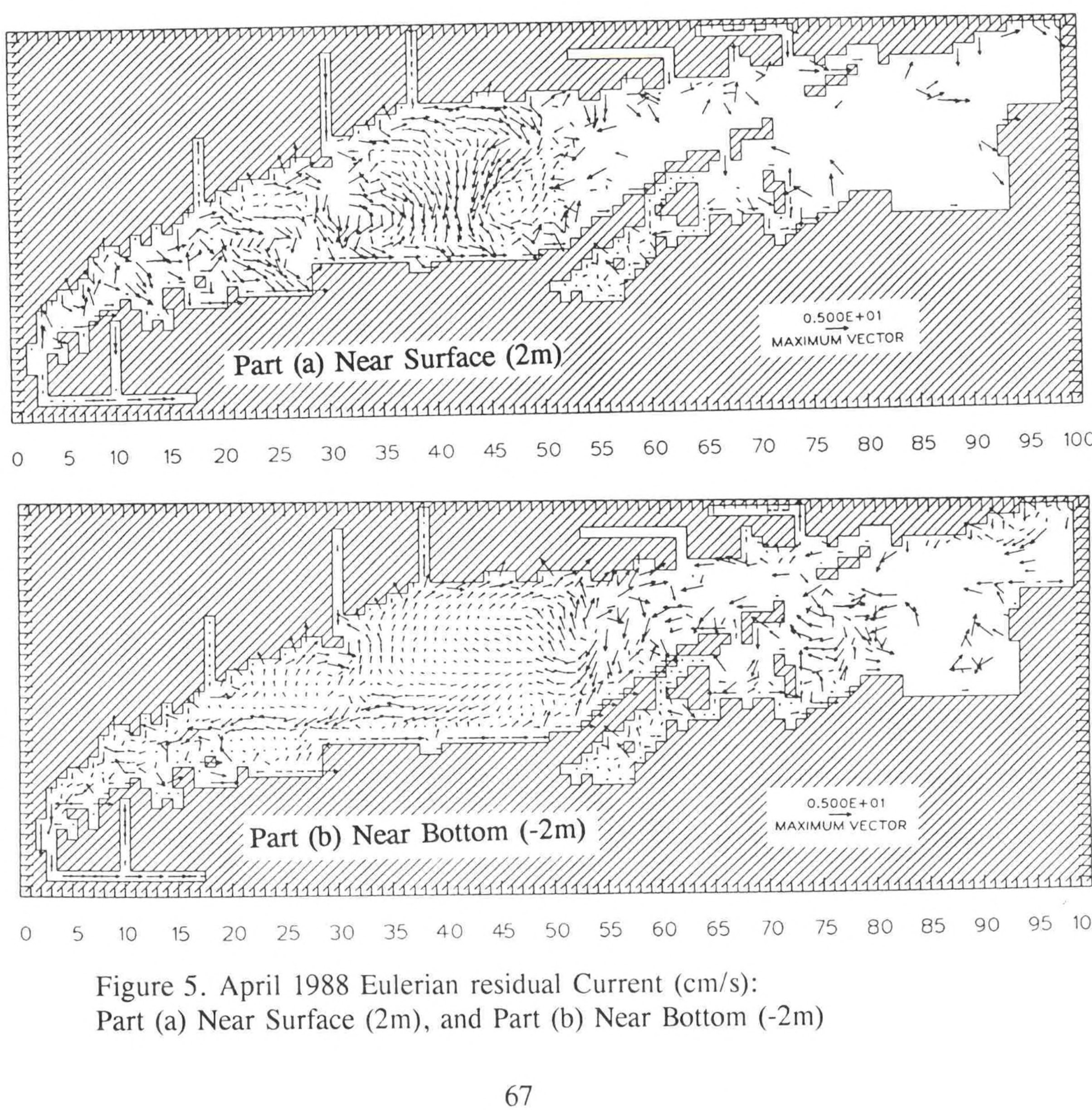

Figure 5. April 1988 Eulerian residual Current (cm/s):
Part (a) Near Surface (2m), and Part (b) Near Bottom (-2m)

Table 1: Mid-basin Near Surface/Near Bottom Eulerian Residual Current Strengths

Circulation Component	Western Basin (cm/s)	Central Basin (cm/s)
Astronomic Tide	5 / 1	5 / 1
Density	5 / 2	5 / 2
Total Wind Forcing	5 / 1.5	5 / 1.5
Local Wind Forcing	5 / 1.5	5 / 1.5
Non-local Shelf Winds	.5 / 0	.5 / 0

density case shown in Figure 1 part (a);e.g., there is no collapse of the near surface central basin gyre as in Figure 5 part (a). Changes in the near bottom structure of the gyre at horizontal index 50 also occur as may be seen by comparing part (b) of Figures 5 and 6. Thus local wind forcings play a major role in the structure of the western and central basin gyral pair.

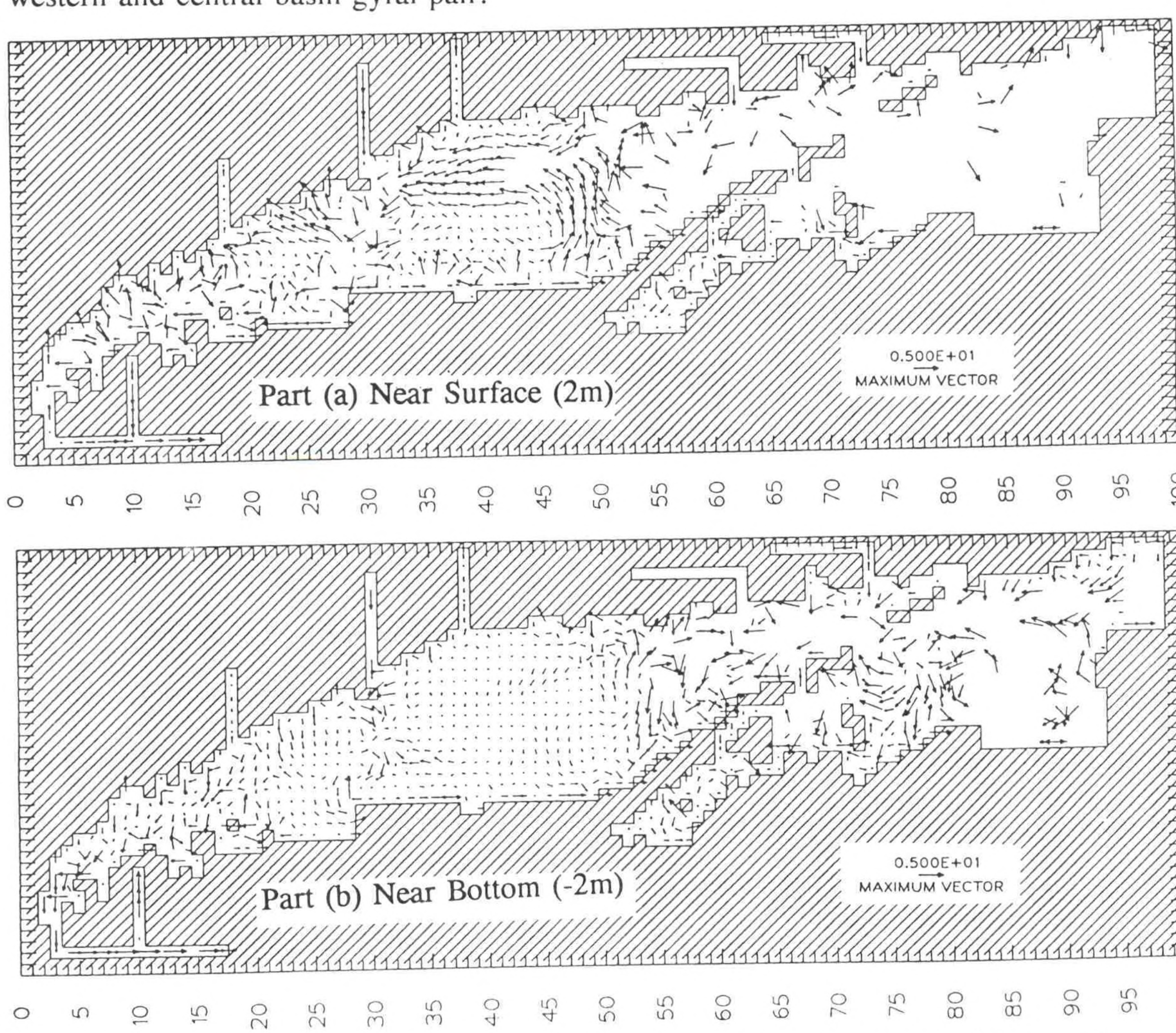

Figure 6. April 1988 (90° - Wind Direction) Eulerian residual Current (cm/s): Part(a) Near Surface (2m), and Part (b) Near Bottom (-2m)

Non-tidal Fluxes at Throgs Neck, NY

Simulated non-tidal fluxes in the East River at Throgs Neck, NY are given in Table 2 for each simulation in both series. For the astronomic tide without density effects, a very weak lower layer flow is produced and the direction of the total nontidal flux is from the East River into Long Island Sound. With the inclusion of density effects, a strong lower layer flow is developed and the upper layer flow is also enhanced resulting in a total nontidal flux of order 100 m^3/s into the East River from Long Island Sound. If one considers the astronomic tide with density to represent a baseline condition and the wind effects to represent perturbations thereabout, then from Table 2, the local wind contribution to the upper and lower fluxes is -119 m^3/s and + 112 m^3/s, respectively. Thus local wind effects are in opposite directions in upper and lower layers and of nearly equal strength of order 100 m^3/s, the size of the net transport for astronomic tide and density. From Table 2, the non-local wind contribution to the upper and lower fluxes is -72 m^3/s and -12 m^3/s, respectively. Layer non-local shelf wind effects are in the same direction and result in a net transport of 84 m^3/s, order of the total transport for astronomic tide and density, from the East River into western Long Island Sound. By linear analysis one would estimate the upper and lower layer fluxes for the total wind forcing case as the sum of these contributions; e.g., 381 m^3/s + -119 m^3/s + -72 m^3/s = 190 m^3/s and -492 m^3/s + 112 m^3/s + -12 m^3/s = -392 m^3/s, respectively. These values are extremely close to the values obtained of 180 m^3/s and -353 m^3/s, respectively, indicating weak nonlinearity in wind effects.

Table 2: Simulated Nontidal Fluxes At Throgs Neck, NY

Simulation	Total East River[1] at Throgs Neck (m^3/s)	Upper[1] Layer (m^3/s)	Lower[1] Layer (m^3/s)
Astronomic tide with density	-111	381	-492
Astronomic tide without density	240	260	-20
Total Wind Forcing	-173	180	-353
Local Winds	-118	262	-380
Non-local Winds	-195	309	-504

Note: 1 ≡ Positive direction is from the East River into Western Long Island Sound

Conclusions and Recommendations

Individual components of the Eulerian residual circulation for the one month period (April 1988) have been estimated via numerical simulation. The counterclockwise gyre pair in the western and central basins is present in the astronomic tide alone simulation. The density contribution enhances the gyral structure substantially. It is recommended that alternate freshwater inflow patterns be considered to further investigate their effects on the density contribution. Also it was determined that local wind effects, which for April 1988 indicate a 2-4 day variability, substantially alter the monthly averaged near surface and near bottom gyral structures. Finally, it is recommended to further investigate gyral structure sensitivity on meteorology by considering additional uniform and non-uniform spatial wind and atmospheric pressure fields.

Acknowledgements

This work was performed in conjunction with the joint NOAA - EPA Long Island Sound Study within the Coastal and Estuarine Oceanography Branch under the supervision of former Chief, Dr. Henry R. Frey, and present Chief, Dr. Bruce B. Parker. Professor D.W. Pritchard, State University of New York, Dr. Kurt W. Hess, NOAA/NOS, Professor George L. Mellor, Princeton University and Dr. Alan F. Blumberg, HydroQual, Inc., have provided many valuable modeling insights.

References

Blumberg, A.F. and G.L. Mellor. 1980. A Coastal Ocean Numerical Model. In: Mathematical Modeling of Estuarine Physics. Proceedings of an International Symposium, Hamburg, August 24 - 26, 1978. J. Sündermann and K.P. Holz, Eds., Springer-Verlag, Berlin.

Blumberg, A.F. and G.L. Mellor. 1987. A Description of a Three-Dimensional Coastal Ocean Circulation Model., In: Three-Dimensional Coastal Ocean Models, Coastal and Estuarine Sciences, 4, N. Heaps, Ed., American Geophysical Union, Washington, D.C., 1-16.

Blumberg, A.F. and H.J. Herring. 1987. Circulation Modeling Using Orthogonal Curvilinear Coordinates, In: Three-Dimensional Models of Marine and Estuarine Dynamics, J.C.J. Nihoul and B.M. Jamart, Eds., Elsevier Publishing Company, 55-88.

Galperin, B. et al. 1988. A Quasi-Equilibrium Turbulent Energy Model for Geophysical Flows, Journal of the Atmospheric Sciences, 45 (1) : 55-62.

Hsu, S.A. 1986. Correction of Land-based Wind Data for Offshore Applications: A Further Evaluation, Journal of Physical Oceanography, 16, 390-394.

Large, W.G. and S. Pond. 1981. Open Ocean Momentum Flux Measurements in Moderate to Strong Winds, Journal of Physical Oceanography, 11, 324-326.

Mellor, G.L. and T. Yamada. 1982. Development of a Turbulence Closure Model For Geophysical Fluid Problems, Rev. Geophys. Space Phys., 20, 851-875.

Pritchard, D.W. 1990. A Brief Description of the Circulation in Long Island Sound, unpublished note, prepared for Long Island Sound Study, EPA Region I and II, Washington, D.C.

Schmalz, R.A. 1990. A Review of Estuarine, Shelf and Ocean Hydrodynamics, In: Proceeding of Estuarine and Coastal Modeling Conference, Nov. 15-17, 1989, Newport, Rhode Island, ASCE, New York, New York.

Development of Long-Term Three-Dimensional Hydrodynamics in Long Island Sound For Use in Water Quality Modeling

Richard A. Schmalz, Jr.[1], M. ASCE

Abstract

The Blumberg-Mellor (1987) three-dimensional hydrodynamic model has been adapted by the National Oceanic and Atmospheric Administration's National Ocean Service (NOS) to provide hydrodynamic fields for use in United States Environmental Protection Agency (EPA) water-quality modeling studies in support of water quality management of the Sound. The NOS model has been calibrated to astronomical tide over September 1989 and residual circulation and thermohaline structures during the eighteen month period, April 1988 -September 1989 (Schmalz, 1994).

Since NOS acoustic Doppler current profiler (ADCP) measurements were not intended to provide detailed flow characterization in the East River, NOS recommended EPA development of a fine grid East and Harlem River System three-dimensional hydrodynamic model to directly provide nontidal transport targets for the coarser grid NOS model. The development of the appropriate NOS model datum offsets required to meet these targets is initially considered. Next, results of three eighteen month simulations using the appropriate offsets are presented. An objective simulation selection procedure is outlined for comparison and evaluation of the three simulation set. Finally, results are summarized and conclusions drawn with respect to the development of coordinated measurement and modeling techniques in support of water quality modeling.

Introduction

The Blumberg-Mellor (1987) three-dimensional hydrodynamic model has been adapted by NOS to include time varying water level residual, sea surface temperature, river inflow, and wind forcings to provide hydrodynamic fields for use in EPA water quality modeling studies (Schmalz, 1994). The NOS model has been calibrated to astronomical tide over September 1989 with rms differences between

1 Oceanographer, National Oceanic and Atmospheric Administration, National Ocean Service, Office of Ocean and Earth Sciences, Marine Analysis and Interpretation Division, Coastal and Estuarine Oceanography Branch, 1305 East-West Highway, Rm 6540, Silver Spring, Maryland 20910. (301) 713-2809.

model and reconstructed water levels on the order of 10 cm at 15 stations and between model and reconstructed currents on the order of 20% of reconstructed range at 12 stations (Schmalz, 1994). The nine month period, April - December 1988, was used to calibrate while the nine month period, January - September 1989, was used to verify the thermohaline structure based upon extensive conductivity-temperature depth (CTD) measurements. Sound-wide simulated salinity and temperature vertical profiles demonstrate the ability of the NOS model to develop, maintain, and erode observed thermocline and halocline structures. To supplement NOS ADCP measurements, the EPA fine grid East and Harlem River System three-dimensional hydrodynamic model has been calibrated to nontidal velocity derived from these measurements and used to provide nontidal transport targets. The development of the appropriate NOS model datum offsets to meet these targets and the results of three eighteen month simulations using the appropriate offsets are considered. An objective simulation assessment is developed and finally, results to date are summarized.

Nontidal Flux Targets

Since ADCP measurements were made at only one point in the cross-section at Throgs Neck, NY, and also in the North College Point/South Clason, NY, section, it was felt that considerable uncertainties would exist in estimates of the nontidal volume fluxes through the East River based on these measurements. Uncertainties exist in assigning areas of flow uniformity, in assigning ADCP bin numbers to distance above bottom, and in determining cross-sectional areas. Since the NOS hydrodynamic model grid is only one cell wide and the grid is folded in the East River, EPA developed a ten vertical level, fine horizontal resolution hydrodynamic model in the East River. This fine resolution model was calibrated, within approximately 1 cm/s rms difference, to the vertical mean profile of the North College Point and South Clason ADCP velocity measurements during the period May - August 1989 and provided target fluxes for the NOS hydrodynamic model. Hourly nontidal target flux variances at the Throgs Neck section in the inverse frequency band 34 to 120 hours were determined by using the recursive Martin filter with 30 weights as discussed by McClain and Walden (1979).

The first objective was for the NOS model to match these EPA fine resolution East River model nontidal fluxes to within ± 100 m^3/s for each month, May - August 1989. The second objective was that at the Throgs Neck section, the square root of the variance of hourly volume fluxes per unit depth in the inverse frequency band from 34 to 120 hours, in NOS model level 2 near the middle of the eastward flowing upper layer and in NOS model level 6 near the middle of the westward flowing lower layer should agree with the EPA fine resolution East River model values to within 50%.

Several simulations using a one month spin-up were run over the five month period April - August 1989. The EPA fine resolution East River model salinity and temperature time series were used at The Battery, NY and Spuyten Duyvil, NY. The EPA fine resolution East River model used mean sea level minus the average of the hourly water levels at The Battery over the period April 10 - August 31, 1989 relative to local mean sea level as model datum. The following offsets to local mean sea level (0.0 cm, 6.0 cm, and 3.6 cm) were applied to The Battery, Spuyten Duyvil, and Willets Point, respectively. In the NOS hydrodynamic model, the North American Vertical Datum, NAVD (1988), as described by Zilkoski (1992) was used as the model datum. Offsets to local mean sea level of 0.0 cm and -0.4 cm were applied at The Battery and Spuyten Duyvil, respectively, in order to obtain equivalent absolute water surface elevations differences between these locations in both models. The local mean sea level offset relative to NAVD (1988) was adjusted from 2.5 to 7.2 cm over the entire period at the Block Island Sound open boundary while salinities of 30 and 31 psu from July 1 - October 1, 1989 were considered along this boundary. Two different geometries for the East and Harlem River System were also considered.

The final NOS target run employed the original East River geometry with a 6.7 cm offset and a value of 30 psu applied at the Block Island Sound open boundary. In Table 1, the comparison between the final NOS target run and the EPA flux targets is shown. In general, the variances are similar in both models, with the NOS model showing greater variability, especially in the surface level.

Table 1. Comparison of NOS Final Target Simulation with EPA Flux Targets

I. Monthly-averaged volumetric flowrates (m^3/s) with targets. Note: "-" means toward New York Harbor. Difference is NOS minus EPA.

	Source	May	June	July	August
			Throgs Neck Cross Section		
Total	NOS	-279	-386	-351	-344
	Diff.	3	-6	-89	-20
Upper	NOS	332	228	191	63
	Diff.	91	0	-18	-58
Lower	NOS	-611	-614	-542	-407
	Diff.	-89	-5	-71	37
			North College Point to South Clason Cross Section		
Total	NOS	-287	-393	-353	-352
	Diff.	-14	-20	-98	-34
			The Battery Cross Section		
Total	NOS	-341	-441	-396	-401
	Diff.	12	-1	-60	-16

II. Square root of filtered flux variance (m^3/s) at Throgs Neck, NY for May-August 1989.

NOS Layer	1	2	3	4	5	6	7
NOS	165	86	78	69	49	22	18
% Diff.	---	46	--	--	--	27	-

After meeting the above targets, three eighteen month simulations, NOS 5/93, NOS 6/93 and NOS 6/93R, were performed in 9 two-month segments on a CRAY YMP2/216. EPA also performed a corresponding eighteen month simulation with their fine scale East River model.

Eighteen Month Simulations

For the NOS 5/93 simulation, Montauk Point, NY, water level residuals were used along the Block Island Sound open boundary during the period April - September 1988, while Montauk, NY, water level residuals were used for the following 12 months. Salinity, temperature, and water surface elevation time series at The Battery, and Spuyten Duyvil, equivalent to those in the EPA fine scale East River model were used.

For the NOS 6/93 simulation, the Montauk water level residuals were used in place of Montauk Point water level residuals during the April - September 1988 period in order to improve the correspondence in nontidal fluxes at Throgs Neck between the two models. Surface salinities at the Block Island Sound open boundary were lowered from 32 psu to 31 psu from September 1, 1988 - May 1, 1989 in order to improve model and data salinity agreement throughout the Sound. The August 1, 1988 temperature boundary condition along the Block Island Sound open boundary was adjusted in order to improve the model and data temperature agreement in Block Island Sound. These salinity and temperature adjustments were within the uncertainty of the boundary specification due to the spatial and temporal availability of the data.

The NOS 6/93R simulation was restarted from the NOS 6/93 simulation after 10 months on February 1, 1989. Surface salinities at the Block Island Sound open boundary were lowered from 32 psu to 31 psu on March 1, 1989 only. Surface salinities on April 1 and May 1, 1989 were kept at 32 psu. These modifications insured that the Block Island Sound open boundary salinity conditions corresponded exactly to the April 1 - September 1, 1989 period used in the final NOS target simulation.

Results of each simulation are summarized in Table 2 in terms of salinity and temperature response, stratification, and nontidal flux at Throgs Neck. In order to assess the salinity and temperature response, the rms differences between the observed CTD and model profiles based on downcast data for 227 CTD casts were computed. With respect to salinity, the rms difference between model and observation are approximately 0.5 to 0.7 psu for NOS 6/93. For temperature, the corresponding values are order 0.8 °C. In order to compare the stratification an index, S.I., is computed as the absolute value of the difference between the absolute value of surface minus bottom data values and the absolute value of surface minus bottom model values. In the case of salinity, the stratification index remains nearly constant at 0.4 to 0.5 psu during the first nine months, and at 0.6 psu during the second nine months for all simulations. For temperature, the stratification index is 0.7 to 0.8 °C in NOS 5/93, NOS 6/93, and NOS 6/93R.

As shown in Table 2, nontidal fluxes as averaged over the complete eighteen month period for the EPA fine resolution East River model and for each of the three NOS eighteen month simulations agree in total at Throgs Neck, to within 20 to 40 m^3/s. Agreement at The Battery and Spuyten Duyvil is order 40 m^3/s. At Throgs

Table 2. Comparison of NOS Eighteen Month Simulation Characteristics
Cal. = Calibration Period , Ver. = Verification Period

Factor	NOS 5/93	NOS 6/93	NOS 6/93R
(Cal.,Ver.) RMS Salinity (psu)	(0.58,1.08)	(0.53,0.67)	(0.53,0.80)
(Cal.,Ver.) S.I. Salinity (psu)	(0.46,0.59)	(0.39,0.58)	(0.39,0.59)
(Cal.,Ver.) RMS Temp. (°C)	(0.82,0.78)	(0.78,0.77)	(0.78,0.74)
(Cal.,Ver.) S.I. Temp. (°C)	(0.82,0.75)	(0.72,0.74)	(0.72,0.72)
Flux differences (m^3/s)*			
Total	-41	15	13
Upper, Lower)	(-53,11)	(-22,36)	(-21,33)

* Differences equal to NOS minus EPA eighteen month averages at Throgs Neck, NY.

Neck both the upper and lower layer nontidal fluxes for each of the three NOS simulations correspond to the EPA fine resolution East River model to order 30 m^3/s, which is in the range of the agreement in the total nontidal fluxes.

Eighteen Month Simulation Skill Assessment

In order to determine the skill of each of the three NOS simulations, the six factors in Table 2 were equally weighted and assigned a rank of from 1 to 3. A rank of 1 corresponded to the superior measure. For a given factor, if the simulations were judged to tie, then the total of the two ranks was divided equally between the simulations. The total scores were 17, 9, and 10 for NOS 5/93, NOS 6/93, and NOS 6/93R, respectively, in which the lowest score represents the best simulation.

Summary and Conclusions

The measurement program was structured so as to provide salinity, temperature, and residual circulation information for calibration of the NOS large scale model as well as to provide limited measurements of current profiles within the East River. The modeling program consisted of two distinct phases. In phase one, the EPA fine resolution curvilinear hydrodynamic model was calibrated to NOS ADCP measurements within the East River. In the second phase, the large scale NOS Long Island Sound hydrodynamic model was calibrated to CTD data and the East River nontidal flux targets developed in phase one. Agreement in total nontidal fluxes and in upper and lower fluxes between the two models is within the uncertainty of the estimates of the EPA fine scale East River model.

While NOS 6/93 was judged to be the best eighteen month simulation, residual circulation for all three simulations has been provided to EPA for calibration of their companion water quality model. Completion of the EPA water quality model calibration over the same eighteen month period will allow further assessment of additional measurement and modeling requirements from an integrated hydrodynamic and water quality modeling perspective.

References

Blumberg, A.F. and G.L. Mellor. 1987. A Description of a Three-Dimensional Coastal Ocean Circulation Model., In: Three-Dimensional Coastal Ocean Models, Coastal and Estuarine Sciences, 4, N. Heaps, Ed., American Geophysical Union, Washington, DC, 1-16.

McClain, C.R. and H. Walden. 1979. On the performance of the Martin digital filter for high- and low-pass applications, NASA Technical Memorandum 80593, GSFC, Greenbelt, Maryland, pp24.

Schmalz, R.A. 1994. Numerical Decompostion of Eulerian Residual Circulation in Long Island Sound, In: Proceeding of 3rd International Estuarine and Coastal Modeling Conference, Sep. 8-10, 1993, Chicago, Illinois, ASCE, New York, NY, (In Press).

Zilkoski, D.B., J.H.Richards, and G.M. Young 1992. Results of the General Adjustment of the North American Vertical Datum of 1988, Surveying and Land Information Systems, Vol. 52, 3, 1992, 133-149.