NOAA Technical Report NOS CS 6

HIGH-RESOLUTION HOUSTON SHIP CHANNEL ADCP AND CTD SURVEY: MODEL-DATA INTERCOMPARISONS

Silver Spring, Maryland
March 2000

noaa National Oceanic and Atmospheric Administration

U.S. DEPARTMENT OF COMMERCE
National Ocean Service
Coast Survey Development Laboratory
Marine Modeling & Analysis Programs

Office of Coast Survey
National Ocean Service
National Oceanic and Atmospheric Administration
U.S. Department of Commerce

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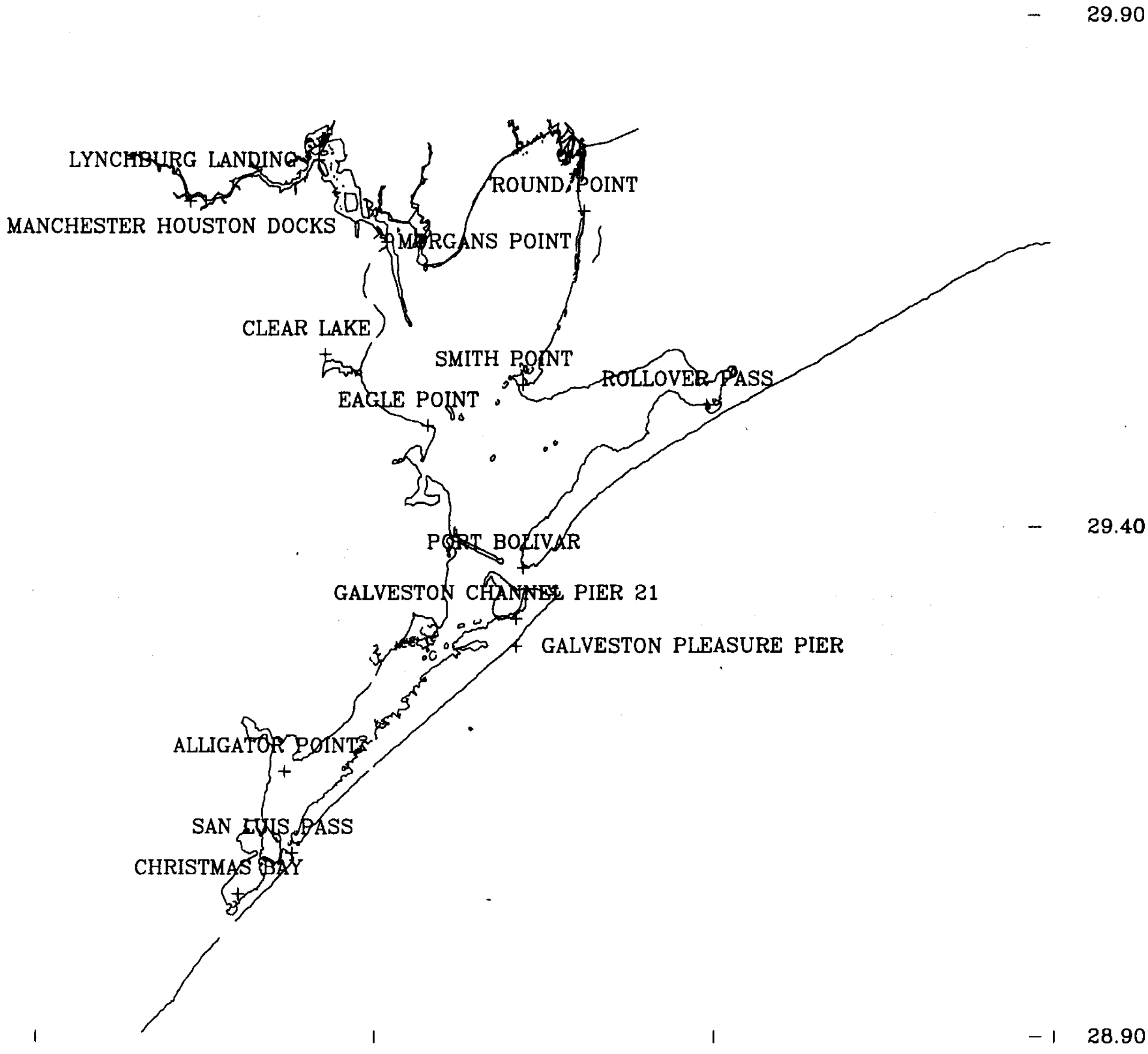
ABSTRACT

The National Ocean Service (NOS), as part of its Houston/Galveston Physical Oceanographic Real Time System (PORTS), has developed a prototype nowcast/forecast system to predict water level and currents within Galveston Bay and the Houston Ship Channel. NOS has continued the development and application of the Galveston Bay three-dimensional circulation model, originally sponsored by the NOS Partnership Project Program, to include a emergence/submergence scheme, and flux corrected salinity transport. In addition, a high resolution Houston Ship Channel model has been developed to more accurately predict currents within the channel. These two models form the hydrodynamic component of the prototype nowcast/forecast system. The National Weather Service (NWS) Aviation atmospheric model and NWS Techniques Development Laboratory Extratropical Storm Surge Model as well as the NWS Western Gulf River Forecast Center flow models are all integrated within the system to enable daily 24 hour nowcasts and 36 hour forecasts.

To further support NOS nowcast/forecast efforts in Galveston Bay, the NOAA Sea Grant Office funded a joint NOS and Texas A&M University (TAMU) high resolution Acoustic Doppler Current Profile (ADCP)/Conductivity Temperature Depth (CTD) survey of the Houston Ship Channel (HSC) under Contract No. 404-253 within the Sea Grant-NOAA Partnership Program for Strategic Research and Development.The focus of the project was to evaluate the performance of the nowcast/forecast system within the HSC. The survey conducted over a 4 nautical mile section of the HSC above Redfish Bar was performed during 8-9 September 1999. Five transects were occupied over a complete tidal cycle, and ADCP and CTD measurements made. This report describes the survey plan and measurements and the model versus data intercomparison results. An overall assessment of both the survey plan and modeling system is presented as well as recommendations for future surveys and nowcast/forecast system enhancements.

GALVESTON BAY BASE MAP



Base Map showing major locations referenced in this report.

1. INTRODUCTION

The National Oceanic and Atmospheric Administration installed a Physical Oceanographic Real Time System (PORTS) patterned after Bethem and Frey (1991) in June 1996 to monitor Galveston Bay based on previous measurements (Williams et al., 1990). Water surface elevation, currents at prediction depth (4.6m) as well as near-surface and near-bottom temperature and salinity, and meteorological information are available at six-minute intervals for five, three, and four stations, respectively, as shown in Figure 1.1. To complement the PORTS a nowcast/forecast system has been designed based on the National Ocean Service (NOS) Galveston Bay three-dimensional hydrodynamic model and the National Weather Service (NWS) Aviation atmospheric model. To simulate currents within the Houston Ship Channel (HSC), a finer resolution three-dimensional HSC model has been developed. The Galveston Bay model is used to provide bay wide water level and near entrance current forecasts as well as to directly provide water levels, density, and turbulence quantities to the HSC model for use in a one-way coupling. The combined model set forms the initial hydrodynamic component of the nowcast/forecast system and has been described in detail by Schmalz (1996, 1998, 1999).

To further support NOS nowcast/forecast efforts in Galveston Bay, the NOAA Sea Grant Office funded a joint NOS-TAMU ADCP/CTD survey of the HSC. The survey focused on the occupation of 5 transects at 1 nautical mile spatial increments along the HSC above Redfish Bar. Each transect was surveyed at 1-2 hour intervals over a complete tidal cycle. The location above Redfish Bar was selected in consultation with Mr. Dalton Krueger of the US Army Corps of Engineers (USACE), Galveston District, such that no interference with their on-going widening and deepening project would be encountered. In Chapter 2, we describe the high-resolution survey of the Houston Ship Channel and discuss the role of the nowcast/forecast system during the actual survey operations. In Chapter 3, comparisons of nowcast/forecast results versus PORTS measurements are first considered. Next, results of an initial model data intercomparison of salinity, temperature, vertical velocity, and transect normal velocity are presented. In Chapter 5, an overall assessment of both the survey and nowcast/forecast system is presented followed by a discussion of plans for additional channel surveys and nowcast/forecast system refinements.

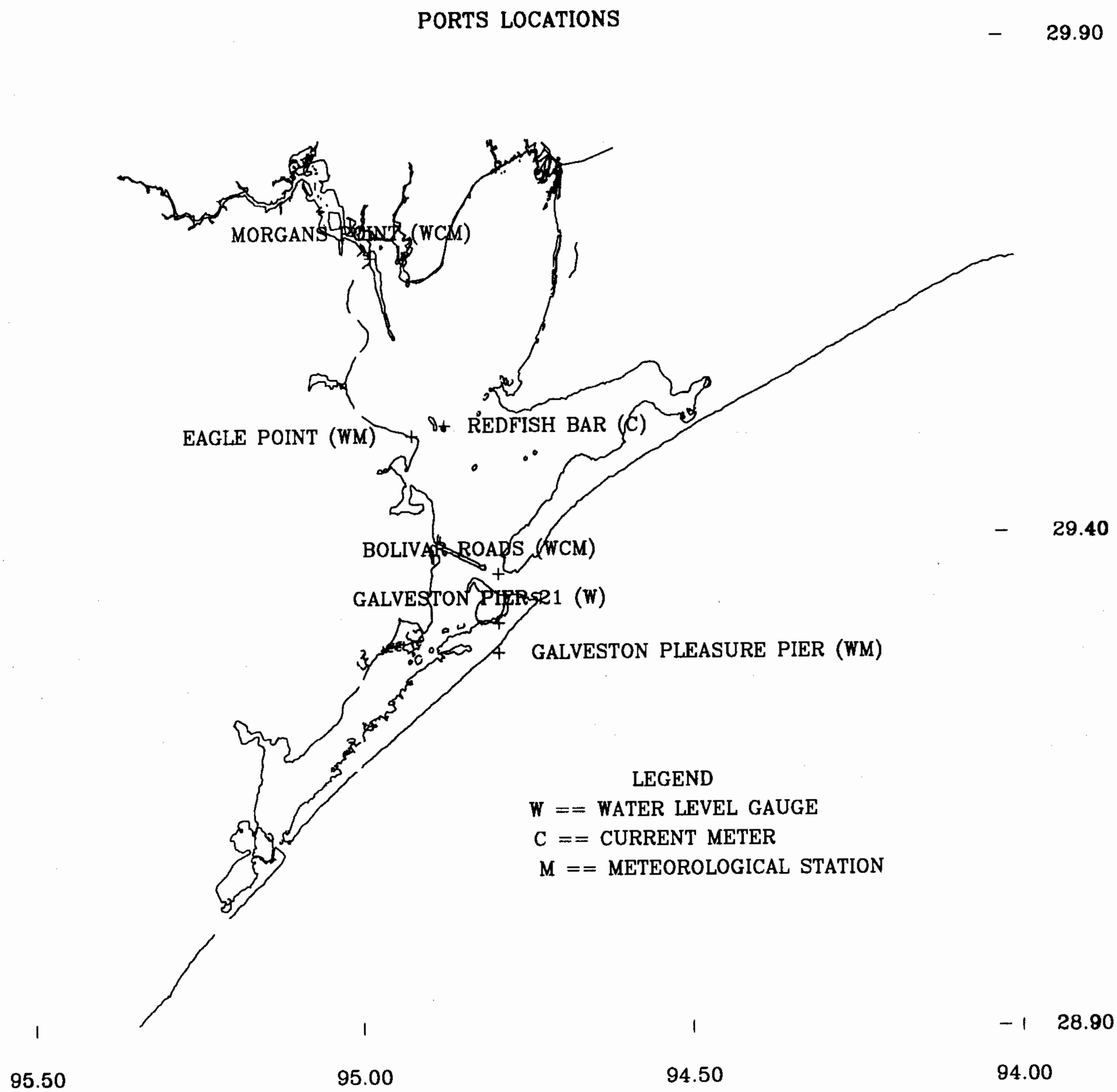


Figure 1.1 Galveston Bay PORTS Station Locations

2. HOUSTON SHIP CHANNEL SURVEY DESCRIPTION

The objective of the survey was to measure the current structure over the vertical across the entire width of several HSC cross sections. The HSC is dredged over a width of 400 ft to a project depth of 42 ft below USACE Project datum, which corresponds to Mean Low Tide (MLT). Channel side slopes are steep order 1:2.5 to 1:5 with several buried pipelines. The magnitude of across channel velocity variation was to be evaluated over channel depth. In addition, the vertical salinity and temperature structures were to be assessed at mid-channel locations. Of interest, was to observe the magnitude and spatial variation of the density stratification along a section of the HSC. A secondary focus was to attempt to measure the vertical velocity structure to assess the validity of the hydrostatic assumption used in the present modeling approach.

The survey was performed on 8-9 September 1999 over a 4 nautical mile segment of the Houston Ship Channel above Redfish Bar. These dates were selected to coincide with peak monthly predicted astronomical tidal currents in the vicinity of Redfish Bar. The five transects shown in Figure 2.1 were occupied over a complete tidal cycle. At each transect an ADCP pass was made from east to west followed by a CTD pass from west to east. Along the CTD pass a single mid-channel profile was obtained. Dr. Matthew Howard, TAMU, served as Principal Scientist and was assisted by Dr. Stephen DiMarco, TAMU. Mr. Edward Webb, TAMU, performed the CTD measurements with the assistance of Mr. Philip Richardson, NOS and Ms. Karen Earwaker, NOS. Mr. Paul Devine, RD Instruments, performed the towed ADCP measurements using the 1200 KHZ Broadband set for 13 one meter bins and 1 s ensembles. A high pecision GPS was used in conjunction with the bottom tracking feature of the ADCP system.

2.1. CTD Data Processing and Analysis

A SeaBird SBE 19 Seacat Profiler (V2.1E, SN 371) was used to perform the salinity/conductivity/ temperature measurements at each transect. CTD datasets were post-calibrated and corrected by Mr. Edward Webb, TAMU. It was necessary to edit some of the bottom points in the files to remove instabilities in density. Edited files were also provided to Mr. Douglas Webb, Webb Research Inc., in support of a Small Business Independent Research Project addressing the measurement of average harbor water density. Representative profiles are shown at Transect 2 in Figure 2.2 and Figure 2.3 corresponding to peak weak flood and strong ebb conditions, respectively. Note the increase in the bottom salinity bottom of order 3 PSU and the deepening of the halocline on the strong ebb relative to the weak flood. Relatively strong vertical mixing processes seem to be involved within the channel to cause this behavior. The strong ebb profiles exhibit order 8 PSU salinity stratification despite the very low inflows to the Bay over the summer months prior to the survey. With respect to temperature, the diurnal heating cycle was prevalent in the surface, which heated and cooled ± 0.5 deg C with respect to the bottom waters of the channel.

2.2. ADCP Data Processing Steps and Analysis

Program TRANSECT (Version 4.041) developed by RD Instruments was used to playback the raw ADCP data (RFILES) obtained from TAMU in ASCII out mode to place navigation positions on the associated output files. These files were then scanned and edited such that at the times near each CTD cast a separate ADCP datafile was created. Within this ADCP datafile, all points are near the navigation channel markers and within +/- 6 minutes of the CTD cast time. In addition, certain bearing limits were imposed to insure a reasonable representation of the transect between the appropriate channel markers. Program ADCP_SCAN written by Dr. Richard Schmalz, NOS/CSDL was used to create these ADCP files; one for each CTD cast. The CTD passes shown in Table 2.1 were selected by NOS to reduce ship wake interferences. Note order 5 ADCP datafiles and associated CTD casts were available at the two end transects, with approximately 10 ADCP datafiles and CTD casts available for the three interior transects (See Table 2.1 and Table 2.2).

These data were used to compute the transports normal to the navigation channel markers (plus coinciding with the flood direction) using Program ADCP_TRANSPORT written by Mr. Philip Richardson and Dr. Richard Schmalz, NOS as shown in Table 2.2. At Transect 2, maximum flood and ebb transports were 690 m^3/s and 458 m^3/s, respectively. These transports represented peak flood and ebb conditions and are further investigated by use of an IDL contour plot program developed by Mr. Philip Richardson, NOS. At Transect 2, normal velocity contours are shown for these peak flood and ebb directed transports in Figures 2.4 and 2.5, respectively. Note the associated salinity, temperature, and density profiles previously shown in Figures 2.2 and 2.3, respectively. On flood a central core region of high flow velocity is noted in Figure 2.4, while on ebb (Figure 2.5), no strong core region is evident. This phenomenon was observed in many of the flood /ebb plots at each transect. In Table 2.3, the astronomical tidal current predictions are given for Redfish Bar. Note the stronger ebb versus flood for the stronger peak currents and the stronger flood versus ebb for the weaker peak currents. Note the measured peak flood transport occurred within order 1 hour of the weak flood, while the measured peak ebb transport occurred over 7.5 hours after the strong ebb. Note the nowcast/forecast times of peak and minimum currents at Redfish Bar show order 0.5 hr delay from Bolivar Roads in contrast to delays of order 1.5-2.0 hrs suggested in Table 2 of the NOAA/NOS Tidal Current Tables and based on comparison with PORTS measurements are more accurate. Based on the nowcast results, the measured peak flood transport occurred at weak flood, while the measured peak ebb transport occurred approximately 3 hours after the strong ebb. One would expect the peak ebb transport on strong ebb (458 m^3/s) to be order 2-3 times larger than the peak flood transport on weak flood (690 m^3/s) under normal astronomical tide conditions if both vertical profiles were similar. However, on the flood we note a strong core region or backward "C" type vertical profile while on ebb a backslash or "/" vertical profile is observed. While near surface peak ebb current strengths are order 2-3 times near surface weak flood currents, when the above profiles are integrated over the vertical, the net transports would be nearly equal as at Transect 2.

2.3. Role of the Nowcast/Forecast System During Survey Operations

The prototype nowcast/forecast system was in an extended demonstration mode during the survey period and was used to provide forecasts of the hydrodynamic conditions in Galveston Bay as a whole and near Redfish Bar in the vicinity of the survey operations. The nowcasts and forecasts were performed by Dr. Richard Schmalz, NOS and provided via Internet on website http://chartmaker.ncd.noaa.gov/cs/lab/op/gbfore. In addition, forecast bulletins were prepared and conveyed over cell phone to Ms. Karen Earwaker, NOS, onboard the survey vessel.

Table 2.1. Houston Ship Channel Survey CTD Profile Inventory
Note Cast Sequence # denotes CTD cast number and associated ADCP transect number.

STATION NAME	: 65-66a Channel Marker ID Numbers
CAST SEQUENCE #:	003 4
CAST DATE-TIME	: 09/08/1999 21:04:00 MM/DD/YYYY UTC
LATITUDE	: 29.559175 N
LONGITUDE	: 94.916381 W
STATION NAME	: 67-68a Channel Marker ID Numbers
CAST SEQUENCE #:	005 5
CAST DATE-TIME	: 09/08/1999 21:38:00 MM/DD/YYYY UTC
LATITUDE	: 29.567787 N
LONGITUDE	: 94.923324 W
STATION NAME	: 67-68b Channel Marker ID Numbers
CAST SEQUENCE #:	006 5
CAST DATE-TIME	: 09/08/1999 21:44:00 MM/DD/YYYY UTC
LATITUDE	: 29.568121 N
LONGITUDE	: 94.922452 W
STATION NAME	: 65-66a Channel Marker ID Numbers
CAST SEQUENCE #:	007 4
CAST DATE-TIME	: 09/08/1999 22:10:00 MM/DD/YYYY UTC
LATITUDE	: 29.558975 N
LONGITUDE	: 94.916129 W
STATION NAME	: 63-64a Channel Marker ID Numbers
CAST SEQUENCE #:	008 3
CAST DATE-TIME	: 09/08/1999 22:33:00 MM/DD/YYYY UTC
LATITUDE	: 29.549919 N
LONGITUDE	: 94.909580 W
STATION NAME	: 61-62a Channel Marker ID Numbers
CAST SEQUENCE #:	010 2
CAST DATE-TIME	: 09/08/1999 23:09:00 MM/DD/YYYY UTC
LATITUDE	: 29.540716 N
LONGITUDE	: 94.902341 W
STATION NAME	: 61-62b Channel Marker ID Numbers
CAST SEQUENCE #:	011 2
CAST DATE-TIME	: 09/08/1999 23:14:00 MM/DD/YYYY UTC
LATITUDE	: 29.541108 N
LONGITUDE	: 94.901777 W
STATION NAME	: 59-60b Channel Marker ID Numbers
CAST SEQUENCE #:	012 1
CAST DATE-TIME	: 09/08/1999 23:50:01 MM/DD/YYYY UTC
LATITUDE	: 29.531837 N
LONGITUDE	: 94.894874 W
STATION NAME	: 61-62b Channel Marker ID Numbers
CAST SEQUENCE #:	013 2
CAST DATE-TIME	: 09/09/1999 00:23:00 MM/DD/YYYY UTC
LATITUDE	: 29.540790 N
LONGITUDE	: 94.901881 W
STATION NAME	: 66-65b Channel Marker ID Numbers
CAST SEQUENCE #:	014 4
CAST DATE-TIME	: 09/09/1999 02:15:00 MM/DD/YYYY UTC
LATITUDE	: 29.559393 N
LONGITUDE	: 94.915830 W
STATION NAME	: 67-68b Channel Marker ID Numbers
CAST SEQUENCE #:	015 5
CAST DATE-TIME	: 09/09/1999 02:42:00 MM/DD/YYYY UTC
LATITUDE	: 29.568264 N
LONGITUDE	: 94.922776 W
STATION NAME	: 65-66b Channel Marker ID Numbers
CAST SEQUENCE #:	016 4
CAST DATE-TIME	: 09/09/1999 03:20:54 MM/DD/YYYY UTC
LATITUDE	: 29.559262 N
LONGITUDE	: 94.915403 W
STATION NAME	: 63-64b Channel Marker ID Numbers
CAST SEQUENCE #:	017 3
CAST DATE-TIME	: 09/09/1999 03:42:00 MM/DD/YYYY UTC
LATITUDE	: 29.549926 N
LONGITUDE	: 94.909102 W
STATION NAME	: 61-62b Channel Marker ID Numbers
CAST SEQUENCE #:	018 2
CAST DATE-TIME	: 09/09/1999 04:05:00 MM/DD/YYYY UTC
LATITUDE	: 29.540802 N
LONGITUDE	: 94.902175 W
STATION NAME	: 59-60b Channel Marker ID Numbers
CAST SEQUENCE #:	019 1
CAST DATE-TIME	: 09/09/1999 04:25:00 MM/DD/YYYY UTC
LATITUDE	: 29.531660 N
LONGITUDE	: 94.894608 W
STATION NAME	: 61-62b Channel Marker ID Numbers
CAST SEQUENCE #:	020 2
CAST DATE-TIME	: 09/09/1999 05:03:00 MM/DD/YYYY UTC
LATITUDE	: 29.540613 N
LONGITUDE	: 94.901081 W
STATION NAME	: 63-64b Channel Marker ID Numbers
CAST SEQUENCE #:	021 3
CAST DATE-TIME	: 09/09/1999 05:26:00 MM/DD/YYYY UTC
LATITUDE	: 29.549865 N
LONGITUDE	: 94.908622 W
STATION NAME	: 65-66b Channel Marker ID Numbers
CAST SEQUENCE #:	022 4
CAST DATE-TIME	: 09/09/1999 05:51:00 MM/DD/YYYY UTC
LATITUDE	: 29.558807 N
LONGITUDE	: 94.915670 W
STATION NAME	: 67-68b Channel Marker ID Numbers
CAST SEQUENCE #:	023 5
CAST DATE-TIME	: 09/09/1999 06:20:00 MM/DD/YYYY UTC
LATITUDE	: 29.568044 N
LONGITUDE	: 94.922998 W
STATION NAME	: 65-66b Channel Marker ID Numbers
CAST SEQUENCE #:	024 4
CAST DATE-TIME	: 09/09/1999 06:50:00 MM/DD/YYYY UTC
LATITUDE	: 29.559410 N
LONGITUDE	: 94.915700 W
STATION NAME	: 63-64b Channel Marker ID Numbers
CAST SEQUENCE #:	025 3
CAST DATE-TIME	: 09/09/1999 07:11:00 MM/DD/YYYY UTC
LATITUDE	: 29.547741 N
LONGITUDE	: 94.908393 W
STATION NAME	: 61-62b Channel Marker ID Numbers
CAST SEQUENCE #:	026 2
CAST DATE-TIME	: 09/09/1999 07:31:00 MM/DD/YYYY UTC
LATITUDE	: 29.540969 N
LONGITUDE	: 94.901752 W
STATION NAME	: 59-60b Channel Marker ID Numbers
CAST SEQUENCE #:	027 1
CAST DATE-TIME	: 09/09/1999 08:05:00 MM/DD/YYYY UTC
LATITUDE	: 29.532054 N
LONGITUDE	: 94.894805 W
STATION NAME	: 61-62b Channel Marker ID Numbers
CAST SEQUENCE #:	028 2
CAST DATE-TIME	: 09/09/1999 08:32:00 MM/DD/YYYY UTC
LATITUDE	: 29.541329 N
LONGITUDE	: 94.901862 W
STATION NAME	: 63-64b Channel Marker ID Numbers
CAST SEQUENCE #:	029 3
CAST DATE-TIME	: 09/09/1999 09:01:00 MM/DD/YYYY UTC
LATITUDE	: 29.550404 N
LONGITUDE	: 94.909109 W
STATION NAME	: 65-66b Channel Marker ID Numbers
CAST SEQUENCE #:	030 4
CAST DATE-TIME	: 09/09/1999 09:35:00 MM/DD/YYYY UTC
LATITUDE	: 29.559575 N
LONGITUDE	: 94.916246 W
STATION NAME	: 67-68b Channel Marker ID Numbers
CAST SEQUENCE #:	031 5
CAST DATE-TIME	: 09/09/1999 09:58:00 MM/DD/YYYY UTC
LATITUDE	: 29.568894 N
LONGITUDE	: 94.922927 W
STATION NAME	: 65-66b Channel Marker ID Numbers
CAST SEQUENCE #:	032 4
CAST DATE-TIME	: 09/09/1999 10:30:00 MM/DD/YYYY UTC
LATITUDE	: 29.559830 N
LONGITUDE	: 94.916220 W
STATION NAME	: 63-64b Channel Marker ID Numbers
CAST SEQUENCE #:	033 3
CAST DATE-TIME	: 09/09/1999 10:53:00 MM/DD/YYYY UTC
LATITUDE	: 29.550444 N
LONGITUDE	: 94.909470 W
STATION NAME	: 61-62b Channel Marker ID Numbers
CAST SEQUENCE #:	034 2
CAST DATE-TIME	: 09/09/1999 11:19:00 MM/DD/YYYY UTC
LATITUDE	: 29.541909 N
LONGITUDE	: 94.902249 W
STATION NAME	: 59-60b Channel Marker ID Numbers
CAST SEQUENCE #:	035 1
CAST DATE-TIME	: 09/09/1999 11:45:00 MM/DD/YYYY UTC
LATITUDE	: 29.532681 N
LONGITUDE	: 94.895644 W
STATION NAME	: 61-62b Channel Marker ID Numbers
CAST SEQUENCE #:	036 2
CAST DATE-TIME	: 09/09/1999 12:04:00 MM/DD/YYYY UTC
LATITUDE	: 29.541838 N
LONGITUDE	: 94.902807 W
STATION NAME	: 63-64b Channel Marker ID Numbers
CAST SEQUENCE #:	037 3
CAST DATE-TIME	: 09/09/1999 12:27:07 MM/DD/YYYY UTC
LATITUDE	: 29.550341 N
LONGITUDE	: 94.909346 W
STATION NAME	: 65-66b Channel Marker ID Numbers

Table 2.1. Houston Ship Channel Survey CTD Profile Inventory (Cont.)
Note Cast Sequence # denotes CTD cast number and associated ADCP transect number.

```
CAST SEQUENCE #: 038  4
CAST DATE-TIME : 09/09/1999 12:49:05 MM/DD/YYYY UTC
LATITUDE       : 29.559460 N
LONGITUDE      : 94.916650 W
STATION NAME   : 67-68b Channel Marker ID Numbers
CAST SEQUENCE #: 039  5
CAST DATE-TIME : 09/09/1999 13:41:31 MM/DD/YYYY UTC
LATITUDE       : 29.568878 N
LONGITUDE      : 94.924229 W
STATION NAME   : 65-66b Channel Marker ID Numbers
CAST SEQUENCE #: 040  4
CAST DATE-TIME : 09/09/1999 14:03:09 MM/DD/YYYY UTC
LATITUDE       : 29.560186 N
LONGITUDE      : 94.916146 W
STATION NAME   : 63-64b Channel Marker ID Numbers
CAST SEQUENCE #: 041  3
CAST DATE-TIME : 09/09/1999 14:29:27 MM/DD/YYYY UTC
LATITUDE       : 29.550832 N
LONGITUDE      : 94.909234 W
STATION NAME   : 61-62b Channel Marker ID Numbers
CAST SEQUENCE #: 042  2
CAST DATE-TIME : 09/09/1999 15:11:11 MM/DD/YYYY UTC
LATITUDE       : 29.537722 N
LONGITUDE      : 94.900636 W
STATION NAME   : 59-60b Channel Marker ID Numbers
CAST SEQUENCE #: 043  1
CAST DATE-TIME : 09/09/1999 16:00:18 MM/DD/YYYY UTC
LATITUDE       : 29.531941 N
LONGITUDE      : 94.895493 W
STATION NAME   : 61-62b Channel Marker ID Numbers
CAST SEQUENCE #: 044  2
CAST DATE-TIME : 09/09/1999 16:20:56 MM/DD/YYYY UTC
LATITUDE       : 29.541011 N
LONGITUDE      : 94.902677 W
STATION NAME   : 63-64b Channel Marker ID Numbers
CAST SEQUENCE #: 045  3
CAST DATE-TIME : 09/09/1999 16:42:00 MM/DD/YYYY UTC
LATITUDE       : 29.550387 N
LONGITUDE      : 94.909216 W
STATION NAME   : 65-66b Channel Marker ID Numbers
CAST SEQUENCE #: 046  4
CAST DATE-TIME : 09/09/1999 17:09:08 MM/DD/YYYY UTC
LATITUDE       : 29.559297 N
LONGITUDE      : 94.915847 W
STATION NAME   : 67-68b Channel Marker ID Numbers
CAST SEQUENCE #: 047  5
CAST DATE-TIME : 09/09/1999 17:36:00 MM/DD/YYYY UTC
LATITUDE       : 29.568392 N
LONGITUDE      : 94.923241 W
STATION NAME   : 65-66b Channel Marker ID Numbers
CAST SEQUENCE #: 048  4
CAST DATE-TIME : 09/09/1999 17:58:00 MM/DD/YYYY UTC
LATITUDE       : 29.559623 N
LONGITUDE      : 94.916034 W
STATION NAME   : 63-64b Channel Marker ID Numbers
CAST SEQUENCE #: 049  3
CAST DATE-TIME : 09/09/1999 18:26:00 MM/DD/YYYY UTC
LATITUDE       : 29.549881 N
LONGITUDE      : 94.909292 W
STATION NAME   : 61-62b Channel Marker ID Numbers
CAST SEQUENCE #: 050  2
CAST DATE-TIME : 09/09/1999 18:48:00 MM/DD/YYYY UTC
LATITUDE       : 29.541022 N
LONGITUDE      : 94.902306 W
STATION NAME   : 59-60b Channel Marker ID Numbers
CAST SEQUENCE #: 051  1
CAST DATE-TIME : 09/09/1999 19:11:00 MM/DD/YYYY UTC
LATITUDE       : 29.535089 N
LONGITUDE      : 94.896071 W
STATION NAME   : 61-62b Channel Marker ID Numbers
CAST SEQUENCE #: 052  2
CAST DATE-TIME : 09/09/1999 19:51:00 MM/DD/YYYY UTC
LATITUDE       : 29.540552 N
LONGITUDE      : 94.902041 W
STATION NAME   : 63-64b Channel Marker ID Numbers
CAST SEQUENCE #: 053  3
CAST DATE-TIME : 09/09/1999 20:15:00 MM/DD/YYYY UTC
LATITUDE       : 29.550541 N
LONGITUDE      : 94.909369 W
STATION NAME   : 65-66b Channel Marker ID Numbers
CAST SEQUENCE #: 054  4
CAST DATE-TIME : 09/09/1999 20:38:16 MM/DD/YYYY UTC
LATITUDE       : 29.558795 N
LONGITUDE      : 94.915920 W
STATION NAME   : 67-68b Channel Marker ID Numbers
CAST SEQUENCE #: 055  5
CAST DATE-TIME : 09/09/1999 21:05:00 MM/DD/YYYY UTC
LATITUDE       : 29.567593 N
LONGITUDE      : 94.923475 W
STATION NAME   : 65-66b Channel Marker ID Numbers
CAST SEQUENCE #: 056  4
CAST DATE-TIME : 09/09/1999 21:41:00 MM/DD/YYYY UTC
LATITUDE       : 29.558882 N
LONGITUDE      : 94.915903 W
STATION NAME   : 63-64b Channel Marker ID Numbers
CAST SEQUENCE #: 057  3
CAST DATE-TIME : 09/09/1999 22:03:00 MM/DD/YYYY UTC
LATITUDE       : 29.549943 N
LONGITUDE      : 94.908779 W
STATION NAME   : 61-62b Channel Marker ID Numbers
CAST SEQUENCE #: 058  2
CAST DATE-TIME : 09/09/1999 22:44:00 MM/DD/YYYY UTC
LATITUDE       : 29.541111 N
LONGITUDE      : 94.902286 W
STATION NAME   : 59-60b Channel Marker ID Numbers
CAST SEQUENCE #: 059  1
CAST DATE-TIME : 09/09/1999 23:22:00 MM/DD/YYYY UTC
LATITUDE       : 29.532112 N
LONGITUDE      : 94.895166 W
```

Table 2.2. Houston Ship Channel Survey Transect Transports

Transect / # Passes	Max Flood (m3/s)	Max Flood CTD Cast	Max Ebb (m3/s)	Max Ebb CTD Cast
T1 / 5	292 +	X1.07 - 059	-295	X1.02 - 019*
T2 / 8	690	X2.14 - 058	-458	X2.05 - 020
T3 / 9	464	X3.06 - 033	-402	X3.03 - 021
T4 / 10	410	X4.02 - 007	-249	X4.05 - 022
T5 / 4	271	X5.05 - 031	-113	X5.04 - 023

Note + indicates a transport based on less than a full channel width. Note *, X1.02 - 019 denotes CTD cast sequence number 19 associated with transect 1, pass 2 and as referenced in Table 2.1.

Table 2.3. Redfish Bar Predicted Astronomical Tidal Currents 8-9 September 1999 (from Tidal Current Tables 1999). Note times are in UTC for reference to ADCP contour and S/T profiles.

Date	Week Day	Slack h m	Maximum h m	Current Strength kts
8	Wednesday	21 59	04 06	2.2 Ebb
9	Thursday	09 58	11 22	1.5 Flood
9	Thursday	14 01	17 18	0.5 Ebb
9	Thursday	21 37	22 42	0.7 Flood
9	Thursday	23 04	04 51	2.0 Ebb

Note principal flood/ebb directions are 322/142 Degrees True. Note all five transect flood directed normals are considered to be 326 Degrees True.

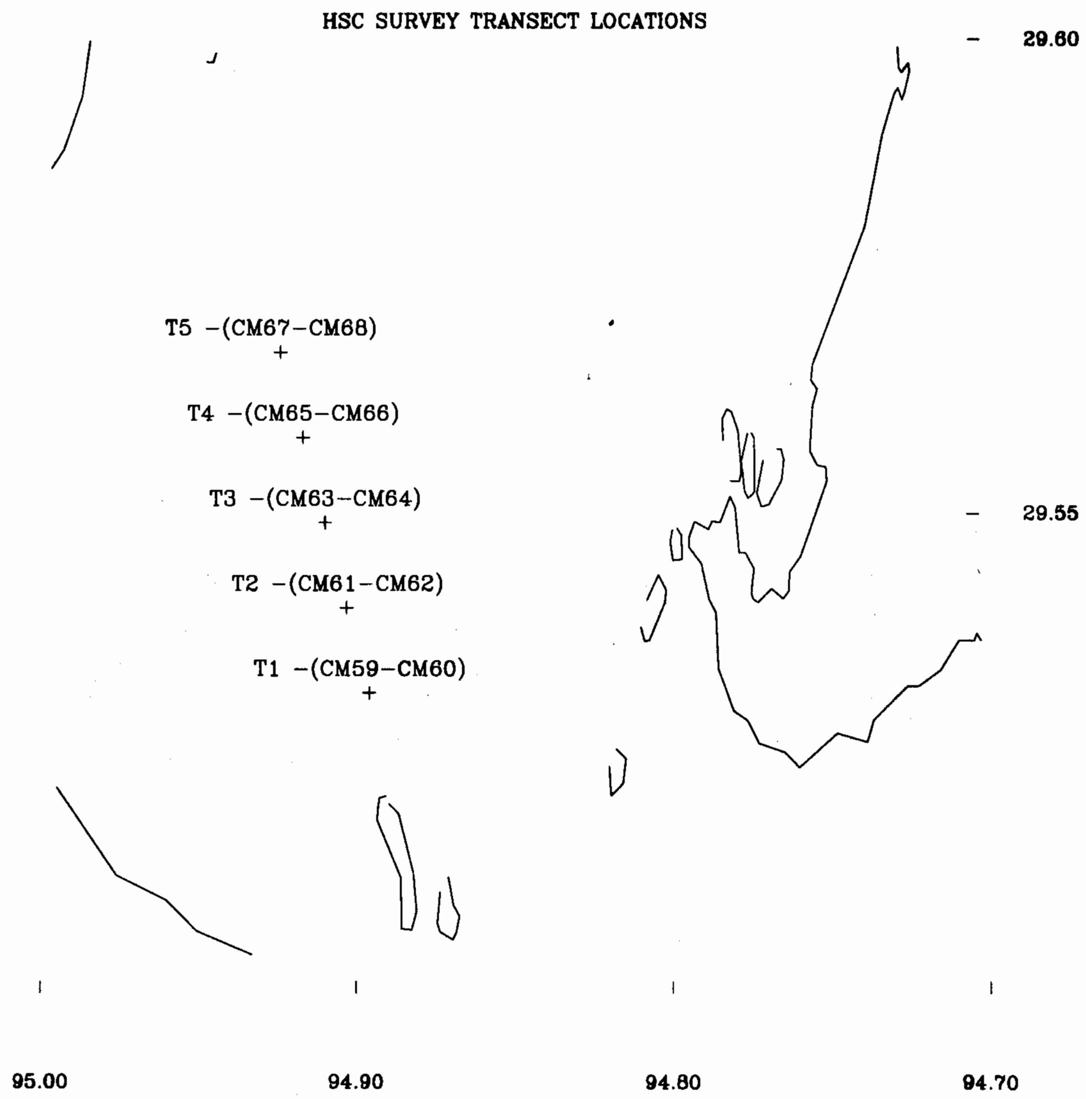


Figure 2.1 Houston Ship Channel Survey Transect Locations
Note T5 - (CM67-CM68) denotes transect 5 proceeds from west to east from Channel Marker 67 to Channel Marker 68. At map scale, the transects plot as a single point denoted by +.

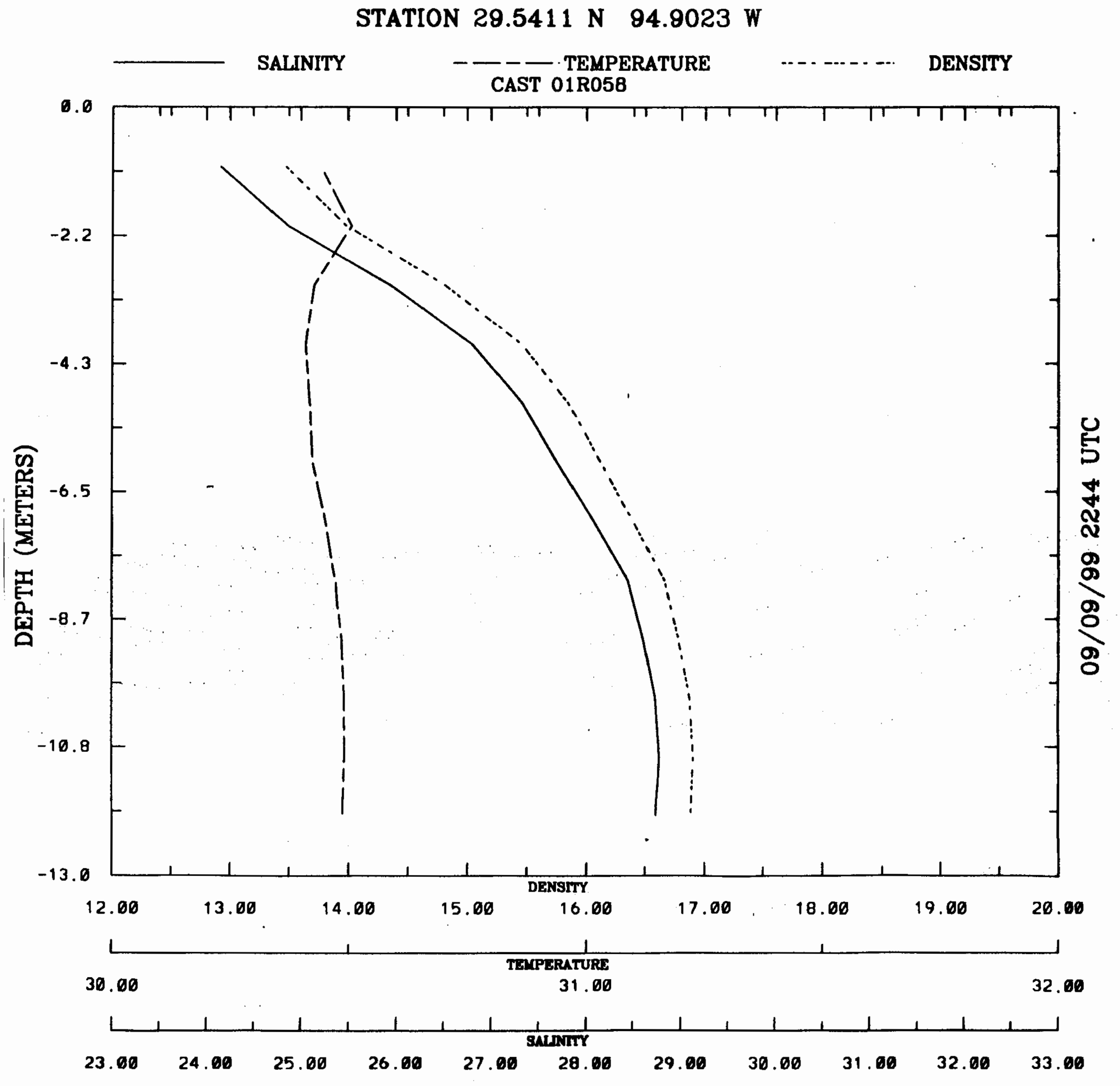


Figure 2.2 HSC T2 Temperature/Salinity/Density Profile: Peak Flood
Note Cast 01R058 denotes Cast Sequence # 58 associated with transect 2 in Table 2.1.

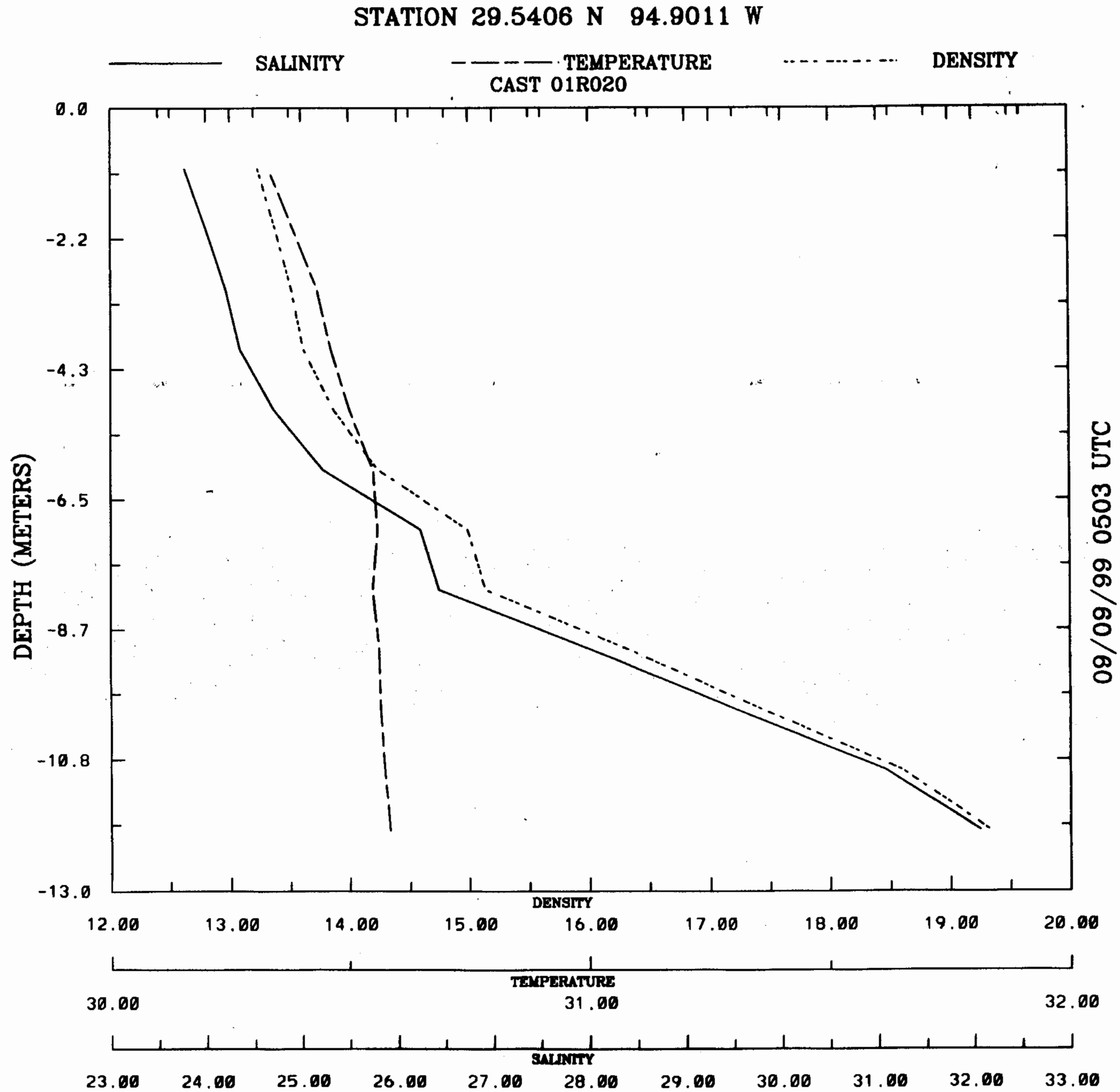


Figure 2.3 HSC T2 Temperature/Salinity/Density Profile: Peak Ebb
Note Cast 01R020 denotes Cast Sequence # 20 associated with transect 2 in Table 2.1.

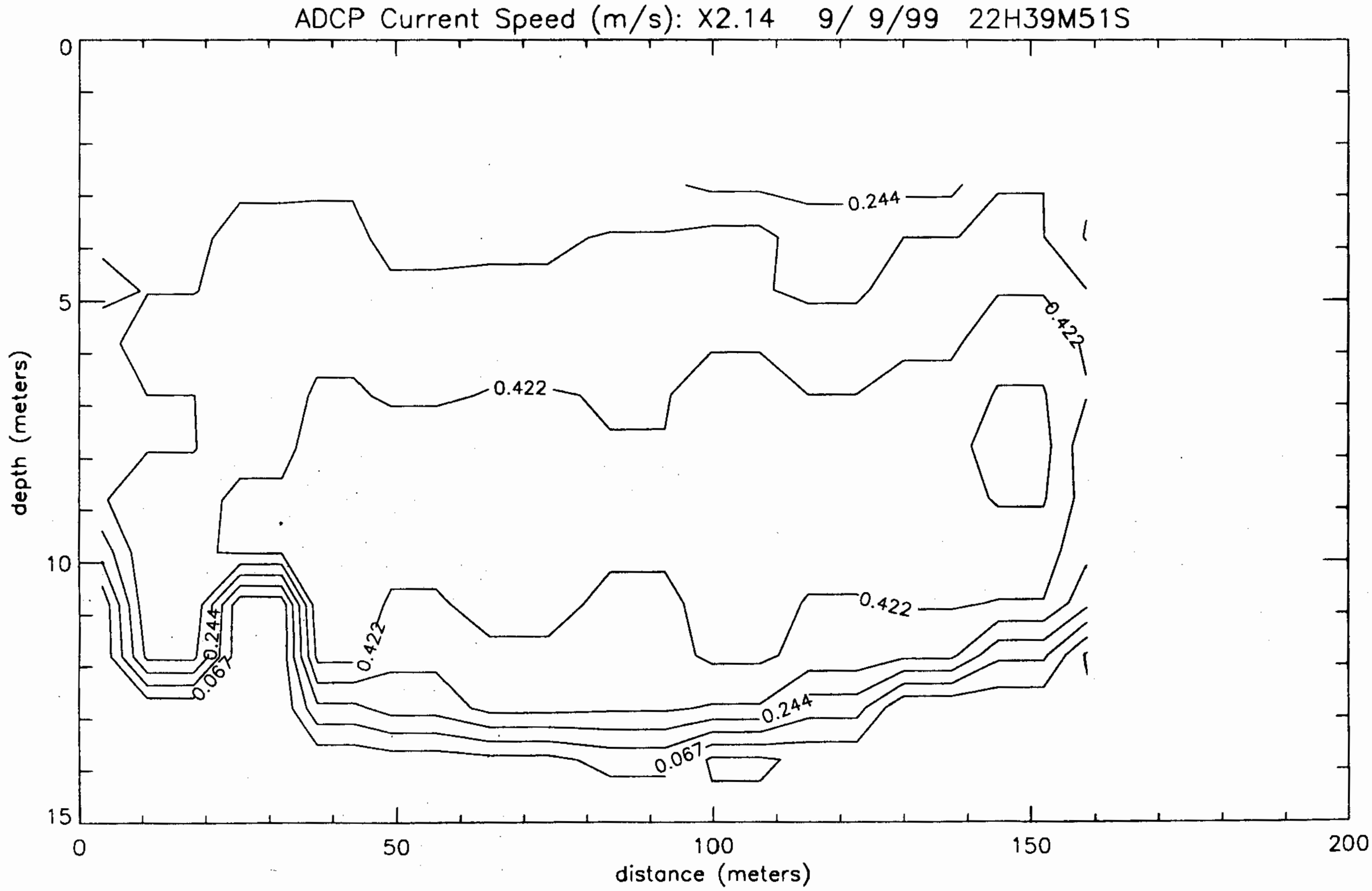


Figure 2.4 HSC T2 Normal Velocity Contours: Peak Flood

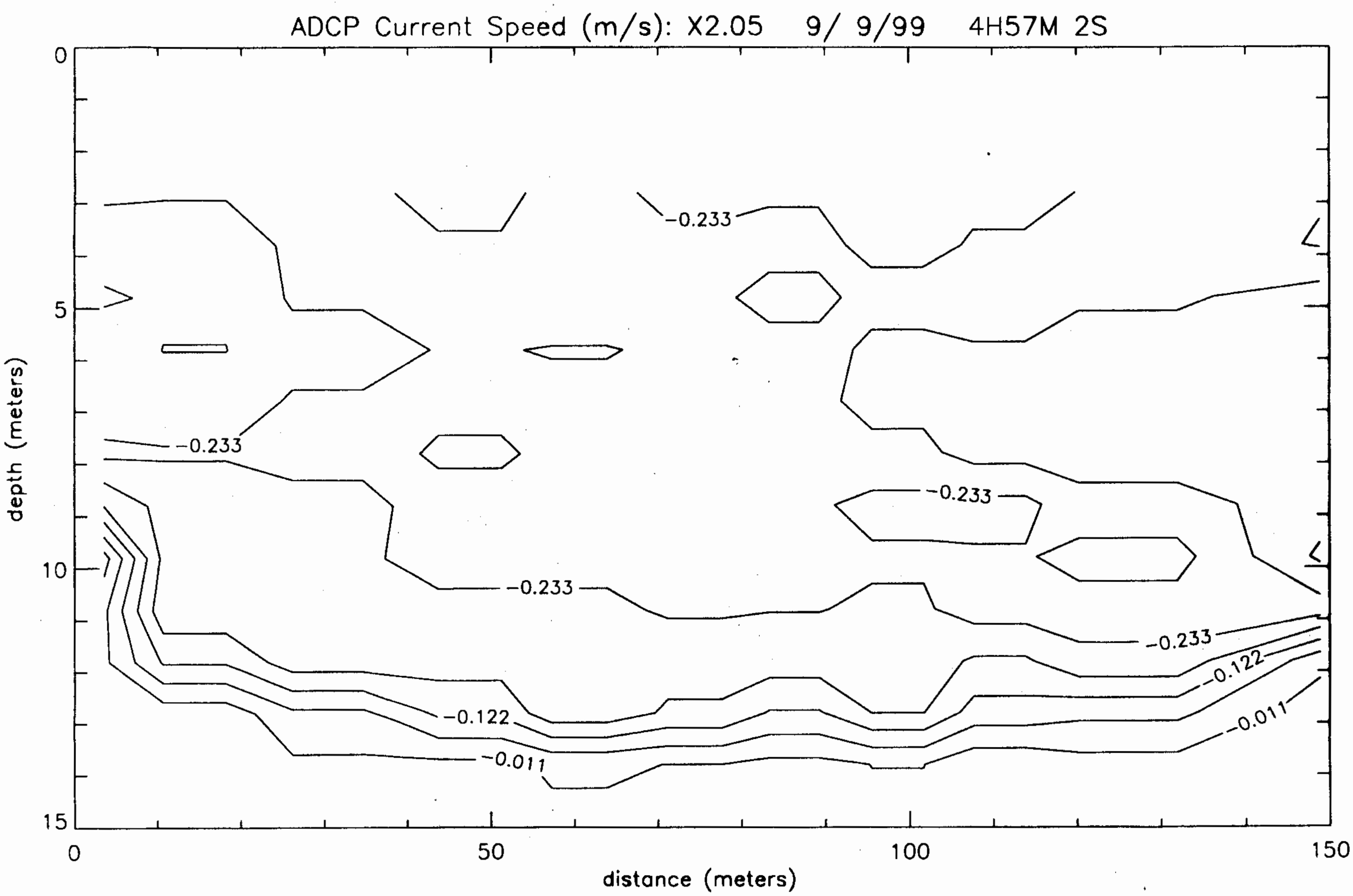


Figure 2.5 HSC T2 Normal Velocity Contours: Peak Ebb

3. GALVESTON BAY NOWCAST/FORECAST SYSTEM DESCRIPTION

The nowcast/forecast system consists of a data delivery system, hydrodynamic models, as well as appropriate input/output linkages and display graphics. We briefly touch on each of these components but focus on the bay and channel hydrodynamic models. Of particular concern, is the design of the steps used to provide their necessary inputs and describe their outputs. An essential element is the provision for missing data and the assurance procedures to eliminate bad data input from corrupting the system.

3.1. Data Delivery System

The data delivery system consists of an Semi-Operation Data Acquisition and Archival System (ODAAS) maintained by the NOS Coast Survey Development Laboratory (CSDL) in which NWS Aviation Model wind/pressure fields are automatically downloaded to CSDL machines. Additional scripts decode NWS Techniques Development Laboratory (TDL) storm surge water levels at Galveston Pleasure Pier. The NWS Western Gulf River Forecast Center (WGRFC) uploads to CDSL anonymous ftp three-day 6 hour interval forecasted river flow and stage for the Trinity River at Liberty , Texas and Lake Houston Dam near Sheldon, Texas, respectively. In addition, the previous day's hourly discharges at Liberty, Texas on the Trinity River and at Piney Point, Texas on Buffalo Bayou and stage for Lake Houston Dam near Sheldon, Texas are uploaded. A decode script accesses and decodes the Houston/Galveston PORTS Universal Flat File Format (PUFFF) files every 6 minutes and stores daily station files. A sample PORTS screen created from a typical PUFFF file is shown in Figure 3.1.

3.2. Hydrodynamic Model Description

The hydrodynamic component consists of a three-dimensional sigma coordinate Galveston Bay and near shelf model (GBM) based on a version of the Blumberg and Mellor (1987) model extended to orthogonal curvilinear coordinates by Blumberg and Herring (1987). The GBM computational grid in Figure 3.2 consists of 181x101 horizontal cells (dx = 254-2482m, dy= 580-3502m) with 5 levels in the vertical. The model was originally developed to provide tidal epoch MLLW in support of NOS Differential Global Positioning System hydrographic surveying (Schmalz, 1996). For nowcasting/forecasting, the model has been extended to include a modified version of the drying/wetting scheme developed by Hess (1994) in Tampa Bay as well as a shallow water modified version of the flux-corrected transport scheme reported by Lin et al. (1994). SST is prescribed in lieu of heat flux.

To simulate currents within the Houston Ship Channel (HSC), a fine resolution channel model (HSCM) was developed. The refined channel grid was developed in three sections based on the Wilken (1988) elliptic grid generation program patterned after Ives and Zacharais (1987). Each grid section was linked in order to develop the final composite channel grid (See Figures 3.3 and 3.4) consisting of 71 x 211 horizontal cells (dx=63-1007m, dy=133-1268m) with the same 5 sigma levels as in the GBM. In both models, bathymetry is based on historical hydrographic surveys (NGDC, 1997). In this study the bathymetry has been updated to include NOS 1988 hydrographic survey data. However, the HSC bathymetry was incorporated into the HSCM grid based on USACE channel survey data given on nautical charts. The two models were then nested in a one-way coupling scheme, wherein GBM water surface elevation, salinity, temperature, turbulent kinetic energy, and turbulent length scale time histories were saved at 6-minute intervals to provide boundary conditions to drive the HSCM.

3.3. Nowcast/Forecast System Design

The design of a prototype nowcasting/forecasting system is modular in concept, such that refined hydrodynamic models can be readily substituted for the initial models. To this end, a separate nowcast/forecast program has been developed to establish hydrodynamic model forecast inputs. The program utilizes the following ten step procedure:

1)Setup 24 hour nowcast and 36 hour forecast time periods,
2)Predict astronomical tide,
3)Predict astronomical currents,
4)Read PUFFF files and develop station time series,
5)Develop GBM subtidal water level signal,
6)Assimilate PORTS salinity and temperature data into GBM and HSCM initial conditions,
7)Establish GBM and HSCM salinity and temperature boundary conditions,
8)Establish GBM and HSCM SST forcings,
9)Establish USGS observed and NWS/WGRFC forecast freshwater inflows, and
10)Establish PORTS based and Aviation Model wind and pressure fields.

Time series files for predicted water surface elevation, and principal direction prediction depth currents are generated as well as PORTS time series data files for water levels, currents, salinity, temperature, wind, and atmospheric pressure. Time series analysis programs to plot nowcast and forecast results in conjunction with the above time series files for both models have also been incorporated within the system. Each step is reviewed in turn below.

Step 1: Presently a 24 hour nowcast is used to spin up both models from rest. Based on PORTS data realistic initial density fields are established. Due to the processing time (6 hr for Aviation Model and TDL Model and 6 hr for GBM and HSCM) a 36 hour forecast is made in which the first 12 hours embrace the processing time. Thus, timelines are set-up for the 24 hour nowcast and 36 hr forecast using the CST time reference frame. Next the angles of Bay and HSC grid cell x-directions relative to East are determined. Mid-year node factor and beginning year equilibrium arguments are next determined for use in steps 2 and 3. Note the algorithm handles year crossings and was fully Y2K compliant.

Step 2: Astronomical tides are predicted at five locations along the GBM boundary and at internal locations of both models over the 60 hour simulation period using the prediction method of Schureman (1958).

Step 3: Principal component direction current predictions are made using the Schureman (1958) prediction formula based on 29 day harmonic analysis.

Step 4: PUFFF file data are accessed over the last two days covering the nowcast period. Water level, current speed and direction, surface salinity, and surface and bottom temperature, wind speed and direction, and atmospheric pressure data are available for each of the six PORTS stations. Times series at stations within the Galveston Bay and Houston Ship Channel model domains are written for subsequent model/data intercomparison. The most recent surface salinity and surface and bottom temperatures are saved at Morgans Point and Bolivar Roads. The most recent surface temperatures are saved at Galveston Pleasure Pier and Eagle Point, while the latest bottom temperature is saved at Redfish Bar. The latest surface salinity is saved at Eagle Point. These most recent PORTS station salinity and temperature values are used in step 6.

Step 5: During the 24 hour nowcast period, subtidal water level is developed by subtracting the predicted tide from PORTS water level data at Galveston Pleasure Pier. First the predicted astronomical tide file from step 1 and measured water level file from step 4 at Galveston Pleasure Pier are accessed. Next the predicted water levels are subtracted from the observed water levels to obtain the nowcast period water level residuals. During the forecast period, the predicted TDL Extratropical Storm Surge Model subtidal water levels are used. The residual/subtidal water level Galveston Bay Model boundary file is smoothed using a three-point box filter before written for subsequent use.

Step 6: The most recent PORTS station surface salinity and surface and near bottom temperature data determined in step 4 are used to modify seasonal salinity/temperature fields based on Bay climatology (Orlando et al., 1993) and near shelf measurements (Temple et al., 1977) in the following manner. First, the GBM restart file (written at 12hr into nowcast cycle) and then the HSC restart file (written at 12hr into nowcast cycle) are read. Next SST and SSS data model differences ($\Delta S, \Delta T$) and T and S stratification data model differences ($\Delta S_s, \Delta T_s$) at PORTS locations are developed. Along the Bay model open boundary at cells (3,2), (180,32), and (180,2) surface salinity and temperatures are determined based on table look-up at Port Bolivar and interpolation associations. Coast values at (3,2) and offshore values at (180,2) are assigned to boundary cells (60,2) and (120,2), respectively. Salinity and temperature stratification at the five boundary cells is based on monthly climatological values. A nine point $1/r^2$ spatial interpolation based on Galveston Pleasure Pier (near Shelf), Bolivar Roads (Lower Bay), Redfish Bar (Middle Bay), and Morgans Point (Upper Bay) plus the five boundary cells is used to develop GBM surface difference and stratification difference fields. Next adjusted T and S fields are computed at each sigma level based on adjusted surface and sigma level interpolated stratification. Note, the sigma level interpolation is not strictly valid. Rather synthetic two-point CTD casts should be constructed to develop a depth dependent interpolation evaluated at each sigma-level in each cell. The present approach is reasonably accurate for the modest bottom slopes and stratification values found within Galveston Bay and the near Shelf. Finally, the adjusted T and S Bay fields are written onto restart file replacing original T and S fields. The adjusted T and S Bay fields are interpolated to HSC grid in the horizontal using nearest neighbor and in the vertical by using a sigma-depth-sigma correspondence. The adjusted T and S HSC fields are then written onto the HSC restart file replacing the original T and S fields. Note this approach does not explicitly handle salinity stratification in the navigation channels, since no PORTS data are presently available to determine this. The present scheme limits the salinity stratification to 4.5 PSU and the temperature stratification to 3.5 °C, respectively. Both these limits are reasonable everywhere except for salinity stratification within the navigation channel. The impact of this data deficiency on simulated nowcast/forecast salinities within the navigation channels is addressed in Chapter 4.

Step 7: Boundary conditions are established for Julian start date minus one and Julian end date plus two of the nowcast. River inflow salinities are set to zero. Along the open boundary the surface salinity may be adjusted based on a user specified K1 period amplitude and phase. Both are set to zero. Surface temperature is based on a user specified S2 period amplitude and phase. The amplitude is specified in the range of 0.3-0.5 deg C. Boundary conditions are set such that they are compatible with the adjusted T and S fields in step 6 and are assumed time invariant. Thus, the GBM offshore boundary data are developed based on a persistence of the initial conditions along the open boundary developed in Step 6. At present this approach appears to be robust.

Step 8: Bay and HSC model SST forcings are established. The SST over Bay domain is set to level 1 of the adjusted T field. Next, we use a nearest neighbor horizontal interpolation to determine the HSC model SST field. Finally, both fields are written to SST boundary files. Initial SST fields are persisted over the 60 hour simulation period. This approach appears to be reasonably robust.

Step 9: River inflows are established by first accessing the San Jacinto, Trinity, and Buffalo Bayou USGS stage/discharge data, which are supplied via ftp by the NWS/WGRFC on a daily basis. The latest discharge data are used for nowcast period. Note the USGS developed stage discharge curve for Lake Houston is used to obtain discharge from lake level stage. Next, 48 hour persistence forecasts are developed from nowcast values. These forecasts are overridden for San Jacinto and Trinity Rivers based on availability of three day duration 6 hour interval forecasts issued by the NWS/WGRFC.

The expansion of the City of Houston has lead to additional runoff and very flashy rainfall/runoff hydrographs (Liscum and East, 1995) and a real time streamflow measurement system has been developed by Harris County. As a result NWS/WGRFC does not at present forecast Buffalo Bayou flows. Presently a persistence of the previous day average daily flow is used in the forecast. It may be necessary in the future to work with Harris County to develop refined flowrates as the City of Houston continues to expand.

Step 10: During the nowcast, PORTS wind station data at four met stations (Galveston Pleasure Pier, Morgans Point, Eagle Point, and Bolivar Roads) are used to produce winds and pressure fields. Galveston Pleasure Pier values are assigned to C-MAN station SRST2 at Sabine Pass and to NDBC Buoy 42035 off Galveston to aid the interpolation. See Figure 3.5 for station locations. Hourly two-step Barnes (1973) interpolation over the Bay grid is performed in which PORTS winds are assumed to represent 10-m overwater values. A nearest neighbor horizontal interpolation is used to determine HSC model wind/pressure fields from Bay model wind/pressure fields.

For the forecast period the NWS/AVN 10-m winds and sea-level pressure fields are accessed. A 25 point cluster $1/r^2$ interpolation is used to set the AVN values at PORTS meteorological station locations. The same two-step Barnes interpolation at 3 hr intervals over the AVN 48 hour forecast period is used to develop the fields. Note the Bay model grid land/water mask were originally used to determine where to adjust AVN overland values to Bay grid overwater values. The adjustment is based on a method developed by Hsu (1988). In this study, no overwater adjustment is made. Next a nearest neighbor horizontal interpolation is used to determine HSC wind/pressure fields from Bay wind/pressure fields. Finally, the Bay and HSC model wind/pressure files are written.

```
          Houston/Galveston PORTS, National Ocean Service/NOAA
                 at  9:36 am CST  March 29, 2000
.........................................................................
             TIDES                :              CURRENTS
Morgans Point        0.3 ft.      : Morgans Point       *******************
Eagle Point          0.6 ft.,Rising : Bolivar Roads       0.2 kts.(S), 284°T
Pier 21              1.2 ft.,Rising :
Bolivar Roads        1.4 ft.,Rising : (F)lood,(S)lack,(E)bb,towards °True
Pleasure Pier        1.9 ft.,Falling:.....................................
                                  :                  Salinity   S.G.  W.Temp
                                  : Morgans Point    15.1 psu  1.009   77°F
                                  : Eagle Point      ***************   66°F
                                  : Bolivar Roads    ***************   72°F
                                  : Pleasure Pier                      74°F
..................................:......................................
   METEOROLOGICAL       Wind Speed/Dir               Air Pressure    Air Temp
Morgans Point      4 knots from SE , gusts to  5   1007 mb,Falling    77°F
Eagle Point        6 knots from E  , gusts to  7   1007 mb,Falling    75°F
Bolivar Roads        Calm                          1007 mb,Falling    76°F
Pleasure Pier      8 knots from ESE, gusts to  9   1006 mb,Steady     74°F
.........................................................................
**** - Data not displayed as a result of quality control monitoring. For more
information, go to http://www.opsd.nos.noaa.gov/corms_status.html
```

Figure 3.1 PORTS screen

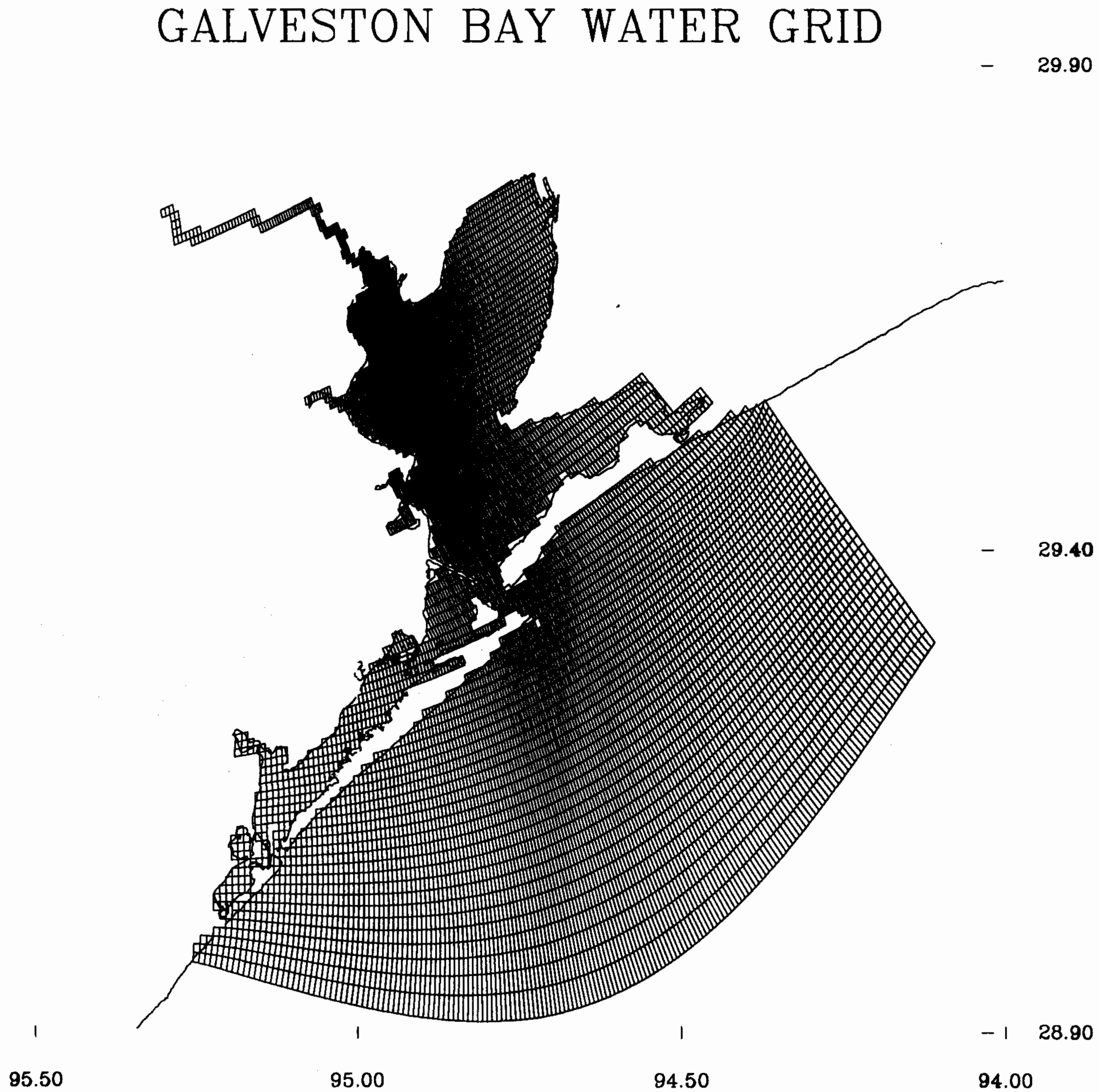


Figure 3.2 Galveston Bay Model Grid

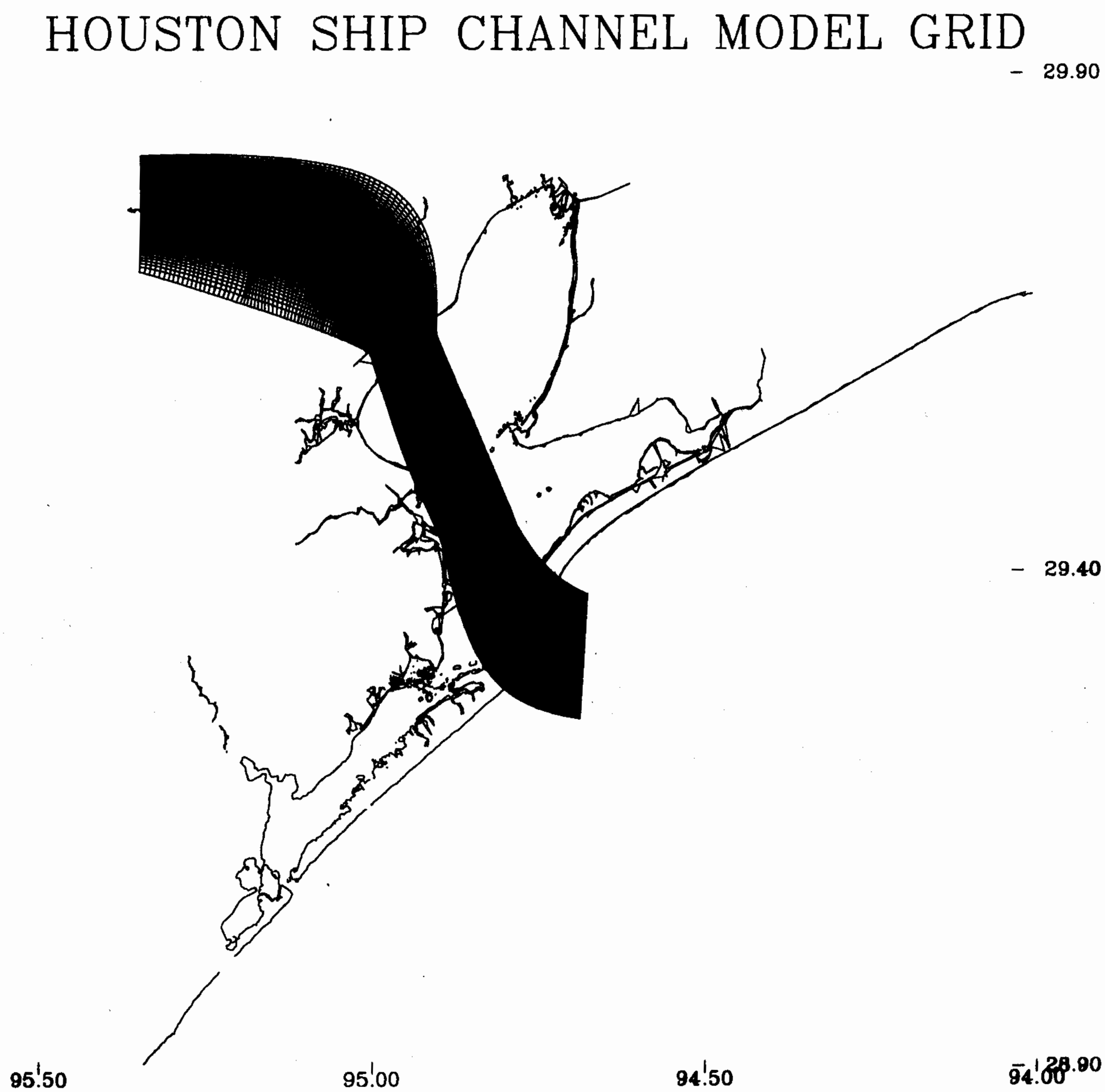
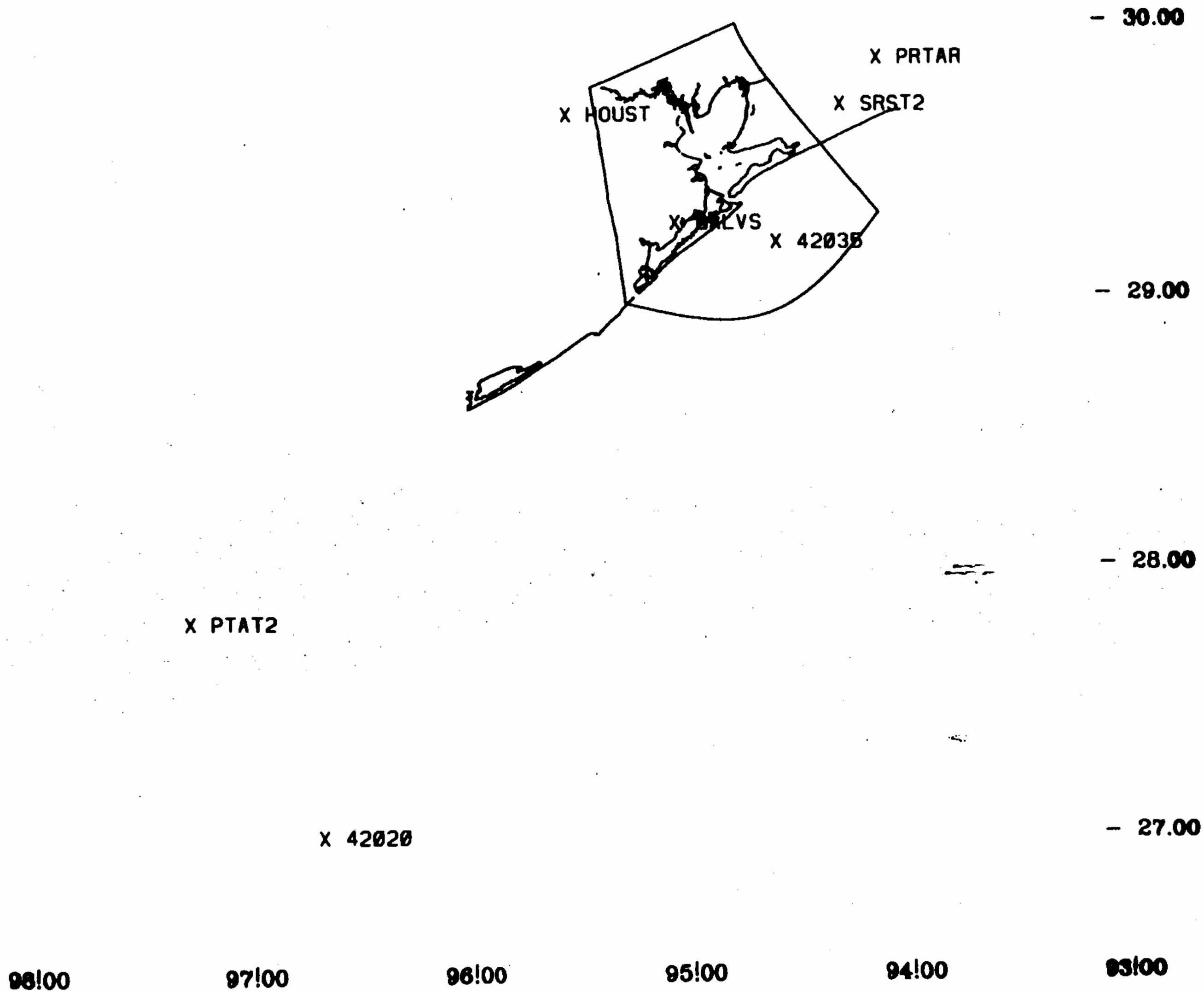


Figure 3.3 Houston Ship Channel Model Grid

Figure 3.4 Houston Ship Channel Model Grid near Galveston Entrance



Note Galveston Bay Model grid boundary is outlined.

Figure 3.5 Meteorological Observation Station Locations

4. SURVEY DATA VERSUS MODEL RESULT COMPARISONS

The prototype nowcast/forecast system was initialized from climatological conditions for the 8 September 1999 nowcast/forecast cycle; e.g., the system started from rest at 1800 CST on 6 September 1999. The nowcast results were saved at 1800 CST on 7 September to initialize the 9 September 1999 nowcast/forecast cycle. The nowcast results for this cycle were then used to initialize the 10 September 1999 nowcast/forecast cycle. The 10 September 1999 nowcast cycle results over the period 1800 CST 8 September to 1800 CST 9 September were compared to ADCP/CTD measurements taken during the survey as well as to the PORTS measurements. In addition, the first 24 hours of the 36 hour forecast for the 9 September 1999 nowcast/forecast cycle (which correspond to the nowcast period of the 10 September nowcast/forecast cycle) were also compared to the PORTS measurements. To place the survey data versus nowcast comparisons in perspective, we first consider the nowcast/forecast comparison versus PORTS data.

4.1. PORTS Data Comparisons

The 24-hr nowcast period extends from 6 pm CST on 8 September to 6 pm CST on 9 September. The initial velocity field is set to the results at the end of the previous nowcast cycle. The Bay climatological density field is adjusted based on the latest salinity and temperature conditions measured with the PORTS over the nowcast period to represent the initial density field. A SST specification is used. The initial density conditions on the boundary are persisted over the entire nowcast/forecast period. Bay model water surface elevation conditions include both the astronomical tide as well as the subtidal signal. The Bay model is used to directly drive the finer resolution Houston Ship Channel model. During the forecast period of the previous nowcast/forecast cycle from 6 pm CST on 8 September to 6 am CST on 10 September, the NWS/AVN forecast atmospheric wind and sea-level pressure fields, the NWS/TDL forecast subtidal water level at Galveston Pleasure Pier is applied to the Bay model boundary in conjunction with the predicted astronomical tide, and the NWS/WGRFC forecast flows are used. Comparison results for the nowcast/forecast period time series are given in Table 4.1 for water level, in Table 4.2 for prediction depth currents, in Table 4.3 for prediction depth principal component direction current speed, in Table 4.4 for near-surface salinity, in Table 4.5 for temperature, in Table 4.6 for wind and sea-level atmospheric pressure. Comparisons are expressed in terms of root mean square error (RMSE) and the Willmott et al. (1985) dimensionless relative error with 0 corresponding to complete shape agreement and 1 corresponding to no agreement in shape. In the figures, an indicator of agreement (IND AGRMT) equal to one minus this dimensionless relative error is given. Note model grid values nearest to the observation locations were used for all quantities with the exception of the currents, where cell-face averages were used to determine grid cell current speed and direction.

Water Level

Nowcast/forecast water level time series are compared in Figures 4.1-4.8. At Galveston Pleasure Pier (Figures 4.1-4.2) the model water levels exhibit no major oscillations and are relatively smooth. This has been accomplished by smoothing the subtidal water level boundary signal. Inside the Bay at Bolivar Roads (Figures 4.3-4.4), at Eagle Point (Figures 4.5-4.6), and at Morgans Point (Figures 4.7-

4.8) the amplitude of the simulated water level signals are significantly reduced due to bottom friction in agreement with observed water levels. Nowcast water levels agree with measurements order 7 cm both outside and within the Bay. Forecast water level agreement is degraded by 3 cm to order 10 cm outside and within the Bay.

Prediction Depth (4.6m) Currents

Nowcast and forecast currents at prediction depth at Bolivar Roads generated from the GBM are considered in Figures 4.9 and 4.10, respectively. Nowcast and forecast rms current speed errors are order 20 cm/s with rms direction errors of order 35 and 75 degrees, respectively. Note the direction errors are calculated independent of observed current strength and are much larger than those obtained by neglecting comparisons where observed currents are below 0.5 knots. Nowcast times of slack water are in agreement with observations to within 20-30 minutes but are degraded to over 1 hour in the forecast. At Redfish Bar (Figures 4.11-4.12) no PORTS current measurements are available, since the ADCP previously installed has been removed. Peak nowcast and forecast currents generated from the HSCM are order 50 cm/s, which is somewhat less than peak survey measurements of order 60 to 70 cm/s. Note the astronomical tidal current predictions suggest a peak flood strength of order 90 cm/s. The HSCM predicts a flood/ebb asymmetry with slight stronger currents on ebb. This is consistent with NOS astronomical tidal current predictions. At Morgans Point (Figures 4.13-4.14) nowcast and forecast currents from the HSCM are in excellent agreement with PORTS observations. Rms speed and direction errors are order 10 cm/s and 45 degrees, respectively. Note the direction errors are determined independent of observed current strength. Peak flood/ebb currents in both nowcast and forecast are order 30 cm/s.

Salinity

Near-surface salinity at Bolivar Roads (Figures 4.15-4.16) shows some evidence of the advection of a strong horizontal salinity gradient on ebb but not on flood. This is not reproduced in the GBM nowcast and forecasts, in which rms errors are order 2 PSU and degrade to 4 PSU, respectively. At Eagle Point (Figures 4.17-4.18), in the vicinity of the HSC survey, near-surface salinity rms errors are 2 PSU in both HSCM nowcast and forecast. Similar HSCM errors occur at Morgans Point (Figures 4.19-4.20).

Temperature

Near-surface temperature and stratification are considered at Bolivar Roads in Figures 4.21-4.22, at Eagle Point in Figures 4.23-4.24, and at Morgans Point in Figures 4.25-4.26, respectively. The observed stratification at Bolivar Roads of order 2 deg C is not observed at either Eagle Point or Morgans Point, where stratification is order 0.5 deg C. The observed stratification at Bolivar Roads is not reproduced in the GBM. The observed stratification in both nowcast and forecast at both Eagle Point and Morgans Point is closely reproduced in the HSCM results. Agreement in surface water temperature between the GBM and HSCM and the PORTS observations is order 1 deg C. This suggests that the persistence of the initial nowcast SST appears to be a reasonable approach.

10m Winds

Nowcast 10-m wind forcing is considered at Bolivar Roads in Figure 4.27 and at Eagle Point in Figure 4.29 during the nowcast period. The two-step Barnes interpolation procedure is used to determine the nowcast windfield each hour. The interpolation method represents the only source of disagreement, since no land/water adjustments are made to the observations. However, it should be noted for the nowcast winds at time points not on the hour, a linear interpolation is made to compare with the 6 minute interval PORTS wind data. Agreement in wind speed is order 2 m/s and in wind direction is order 30 degrees. Corresponding NWS/AVN forecast 10-m wind forcings computed at 3-hr intervals are compared with observations in Figure 4.28 at Bolivar Roads and in Figure 4.30 at Morgans Point. Forecast windspeeds are degraded by order 1.0-2.0 m/s with forecast wind directions degraded by order 30 degrees.

Sea-level Atmospheric Pressure

Nowcast sea-level atmospheric pressure forcing is considered at Bolivar Roads in Figure 4.31 and at Eagle Point in Figure 4.33 during the nowcast period. The two-step Barnes interpolation procedure is used to determine the nowcast atmospheric pressure each hour. Agreement in atmospheric pressure is within 0.5 mb. Corresponding NWS/AVN forecast sea-level atmospheric pressure forcings computed at 3-hr intervals are compared with observations in Figure 4.32 at Bolivar Roads and in Figure 4.34 at Morgans Point. Forecast pressure fields are degraded by order 2 mb.

4.2. Houston Ship Channel Survey ADCP/CTD Data Comparisons

Within the fine resolution HSCM, the navigation channel is represented by a single grid cell in width and thus cross channel effects are not reproduced within the model. A major objective of this study is to investigate what impact their neglect in the model has on model based current predictions. To this end, the ADCP measurements associated with each CTD cast were averaged to produce a representative velocity profile normal to each transect with the flood or up-estuary direction being considered positive. In addition, the vertical velocity components were averaged to produce a representative vertical profile over the navigation channel at each transect. With respect to salinity and temperature, the CTD profiles were directly compared to the model results for the grid cell representing the appropriate transect location. HSCM and survey comparison results are presented at Transect 4 for salinity, temperature, normal and vertical velocity profiles, in turn. Results at the other transects were similar. Vertical profile comparisons are expressed in terms of an rms error and a stratification index (S.I.), which is equal to the observed stratification minus the model stratification.

Salinity

Simulated near surface salinity (Level 1) is in good agreement with the CTD observations as shown in Figure 4.35. However, near bottom salinities in the HSCM (Level 5) are underestimated by order 4 PSU. Representative comparisons of the vertical structure shown in Figure 4.36 confirm the behavior and demonstrate the inability of the HSCM to maintain the order 8 PSU stratification observed in the navigation channel. The problem is two fold. On the one-hand the initialization/assimilation procedure due to lack of data within the HSC limits the stratifiaction to 4.5 PSU (a reasonable limit outside the channel). A second aspect is associated with the sigma coordinate representation of the abrupt change in topography from 12m (in the navigation channel) to 2m (immediately outside the channel) over a single grid cell length scale.

Temperature

Near surface (Level 1) and near bottom (Level 5) temperatures as shown in Figure 4.37 are underpredicted by approximately 1.5-2 deg C by the HSCM. In Figure 4.38 the first four profiles are shown and one notes that the sign of the stratification in the model is opposite to that in the data.

Normal Velocity

Current speeds normal to Transect 4 are compared at near surface (Level 1) and near bottom (Level 5) in Figure 4.39. Note a plus value designates an up-estuary or flood direction flow. The HSCM is in general agreement in term of flood/ebb direction. Vertical structures are compared in Figures 4.40-4.41. Rms errors range from 8 to 31 cm/s. In general the vertical structure is more pronounced in the data than found in the model.

Vertical Velocity

Vertical velocity magnitudes are contrasted in Figure 4.42. Vertical velocity components are much smaller in the HSCM order 1 mm/s than in the observations order 1-3 cm/s. Vertical structure is non-existent in the model but is definitely seen in the observations as shown in Figure 4.43. There are times (near slack water) when possibly the vertical velocities approach the magnitude of the horizontal velocity components. However, it is possible that the vertical velocity measurements are degraded more significantly than the horizontal velocity measurements due to wake effects. It should be noted that no sample were considered with error velocity greater than 10 cm/s as suggested by Mr. Paul Devine, RD Instruments.

Table 4.1. 8-9 September 1999 Nowcast/Forecast Results: Water Surface Elevation

Station Name	Model Simulation	RMSE(cm)	Relative Error (-)
Galveston Pleasure Pier	Galveston NCST Bay FCST	7 10	0.04 0.08
Bolivar Roads	Galveston NCST Bay FCST	6 7	0.08 0.10
Galveston Pier 21	Galveston NCST Bay FCST	7 9	0.11 0.15
Eagle Point	Houston Ship NCST Channel FCST	4 7	0.24 0.58
Morgans Point	Houston Ship NCST Channel FCST	8 14	0.16 0.36

Table 4.2. 8-9 September 1999 Nowcast/Forecast Results: Prediction Depth (4.55m)
Currents (Speed, Direction)

Station Name	Model Simulation	RMSE (cm/s, deg T)	Relative Error (-, -)
Bolivar Roads	Galveston NCST Bay FCST	(20, 35) (24, 75)	(0.15, 0.04) (0.23, 0.19)
Redfish Bar	Houston Ship NCST Channel FCST	(-, -) (-, -)	(-, -) (-,-)
Morgans Point	Houston Ship NCST Channel FCST	(8, 43) (9, 48)	(0.16, 0.06) (0.31, 0.08)

Table 4.3. 8-9 September 1999 Nowcast/Forecast Results: Prediction Depth (4.55m)
Principal Component Direction Current Speed

Station Name	Model Simulation	RMSE (cm/s)	Relative Error (-)
Bolivar Roads	Galveston NCST Bay FCST	22 27	0.06 0.10
Redfish Bar	Houston Ship NCST Channel FCST	- -	- -
Morgans Point	Houston Ship NCST Channel FCST	15 13	0.46 0.42

Table 4.4. 8-9 September 1999 Nowcast/Forecast Results: Surface Salinity

Station Name	Model Simulation	RMSE (psu)	Relative Error (-)
Bolivar Roads	Galveston Bay NCST FCST	2.2 4.3	0.67 0.63
Redfish Bar	Houston Ship Channel NCST FCST	1.8 2.4	0.81 0.88
Morgans Point	Houston Ship Channel NCST FCST	1.8 1.7	0.50 0.60

Table 4.5. 8-9 September 1999 Nowcast/Forecast Results: Temperature (Near-surface, Stratification)

Station Name	Model Simulation	RMSE (°C, °C)	Relative Error (-, -)
Bolivar Roads	Galveston Bay NCST FCST	(1.2, 1.3) (1.9, 1.3)	(0.57, 0.55) (0.64, 0.56)
Redfish Bar	Houston Ship Channel NCST FCST	(0.9, -) (1.6, -)	(0.59, -) (0.67, -)
Morgans Point	Houston Ship Channel NCST FCST	(1.0, 0.4) (0.7, 0.3)	(0.70, 0.66) (0.62, 0.65)

Table 4.6. 8-9 September 1999 Nowcast/Forecast Results: 10m Wind (Speed, Direction) and Sea-level Atmospheric Pressure

Station Name	Model Simulation	RMSE (m/s, deg T) /(mb)	Relative Error (-, -) /-
Bolivar Roads	Galveston Bay NCST FCST	(1.2, 30)/0.5 (2.6, 106)/1.6	(0.10, 0.05)/0.05 (0.91, 0.46)/0.41
Eagle Point	Houston Ship Channel NCST FCST	(1.0, 35)/0.3 (1.8, 43)/1.9	(0.16, 0.14)/0.01 (0.81, 0.20)/0.42

Note NCST 10m winds and sea-level pressures are obtained from PORTS meteorological stations sampled at 1hour intervals. No height correction is made. FCST 10 m winds and sea-level pressures are obtained from NWS/AVN 10m wind and pressure fields $1/r^2$ interpolated to PORTS meteorological stations at 3 hour intervals. These winds and pressures are compared with 6 min PORTS meteorological observations.

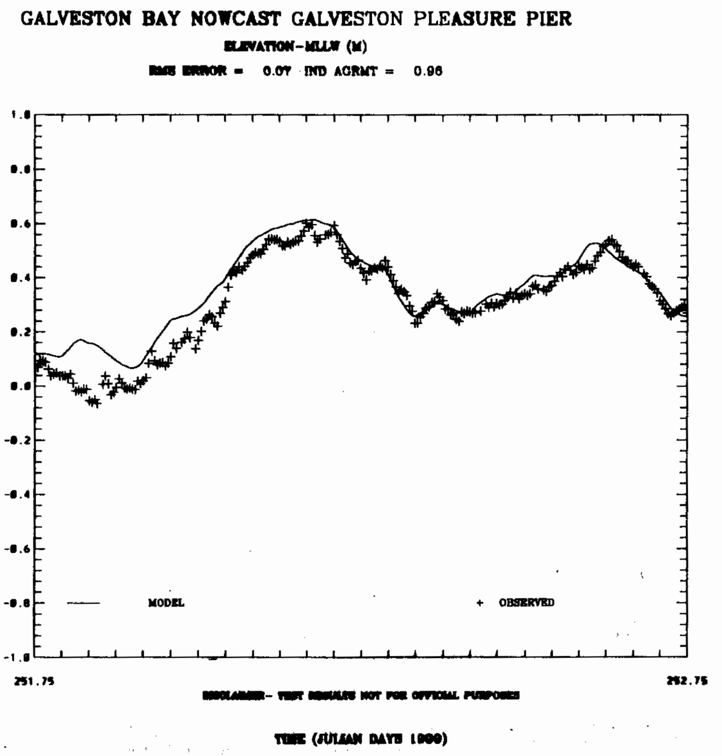


Figure 4.1 Water Surface Elevation Nowcast: Galveston Pleasure Pier

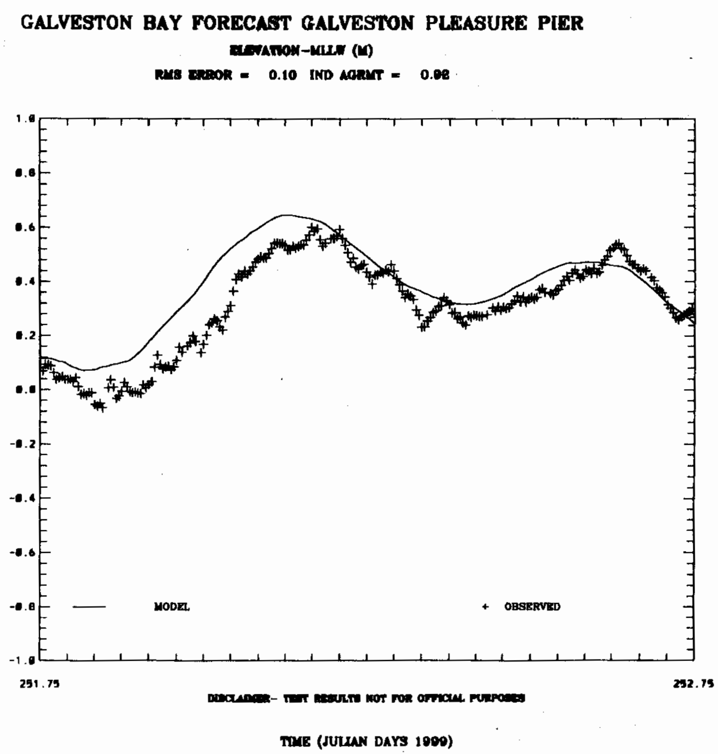


Figure 4.2 Water Surface Elevation Forecast: Galveston Pleasure Pier

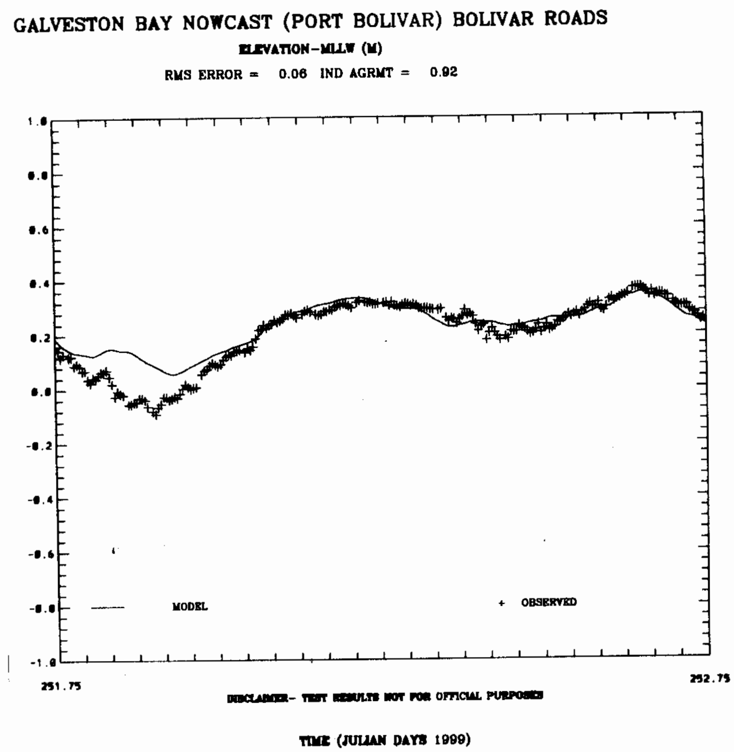


Figure 4.3 Water Surface Elevation Nowcast: Bolivar Roads

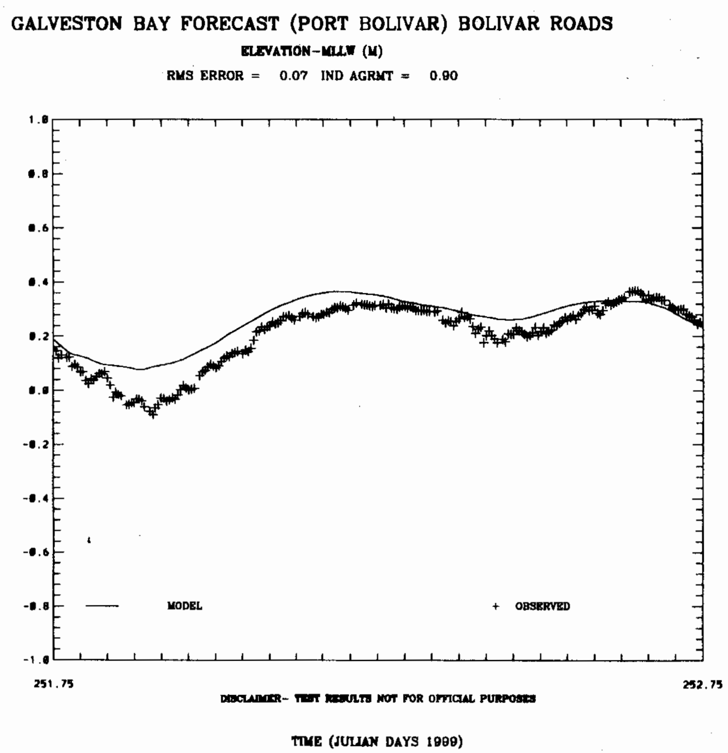


Figure 4.4 Water Surface Elevation Forecast: Bolivar Roads

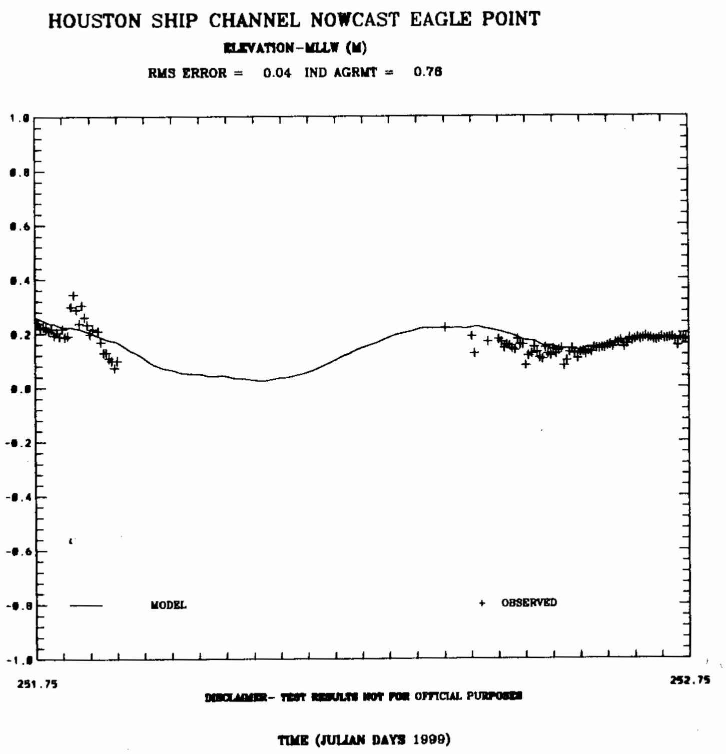


Figure 4.5 Water Surface Elevation Nowcast: Eagle Point

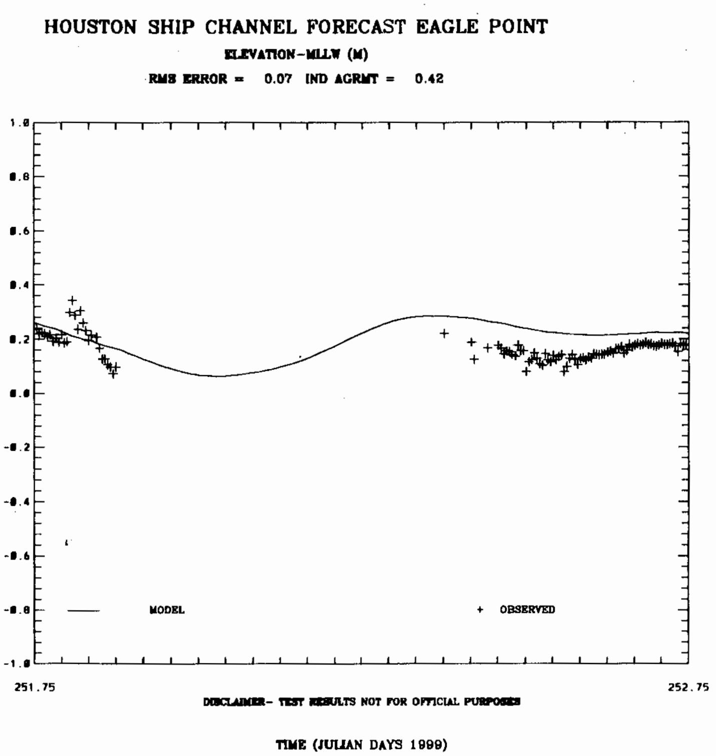


Figure 4.6 Water Surface Elevation Forecast: Eagle Point

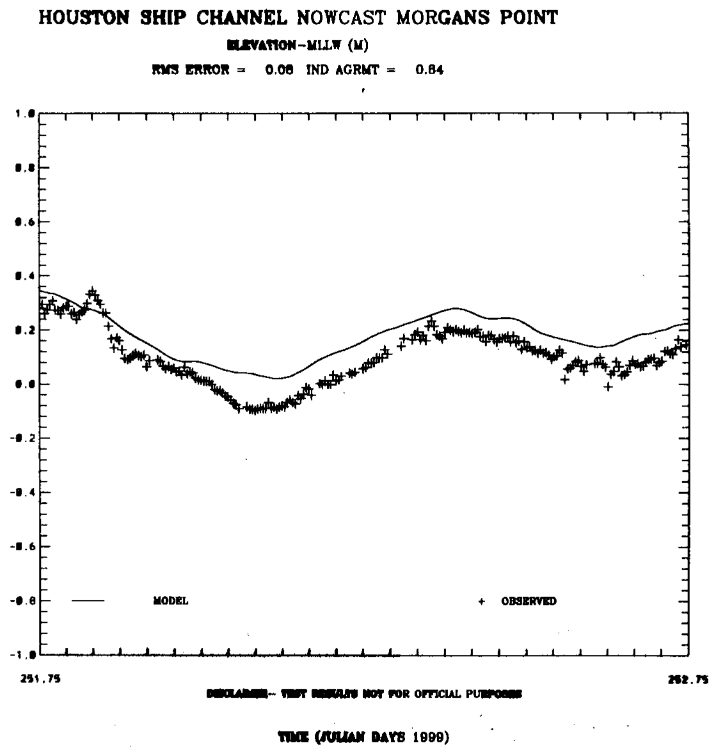


Figure 4.7 Water Surface Elevation Nowcast: Morgans Point

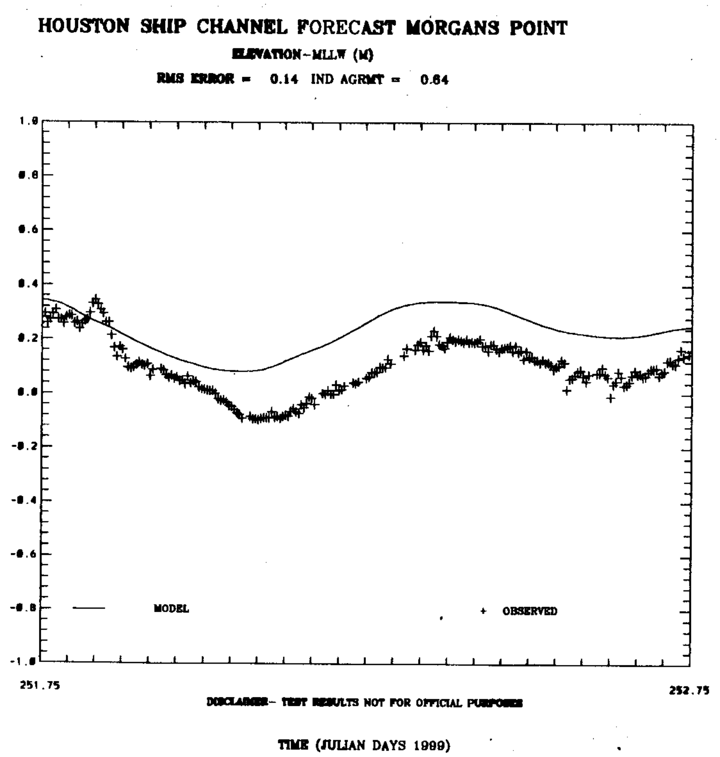
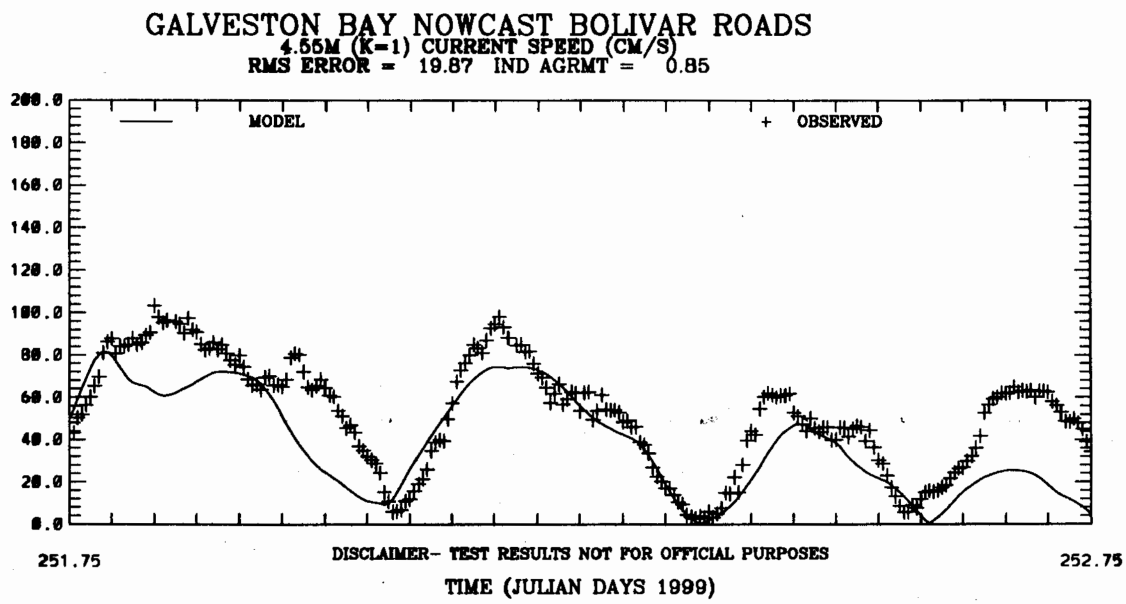


Figure 4.8 Water Surface Elevation Forecast: Morgans Point



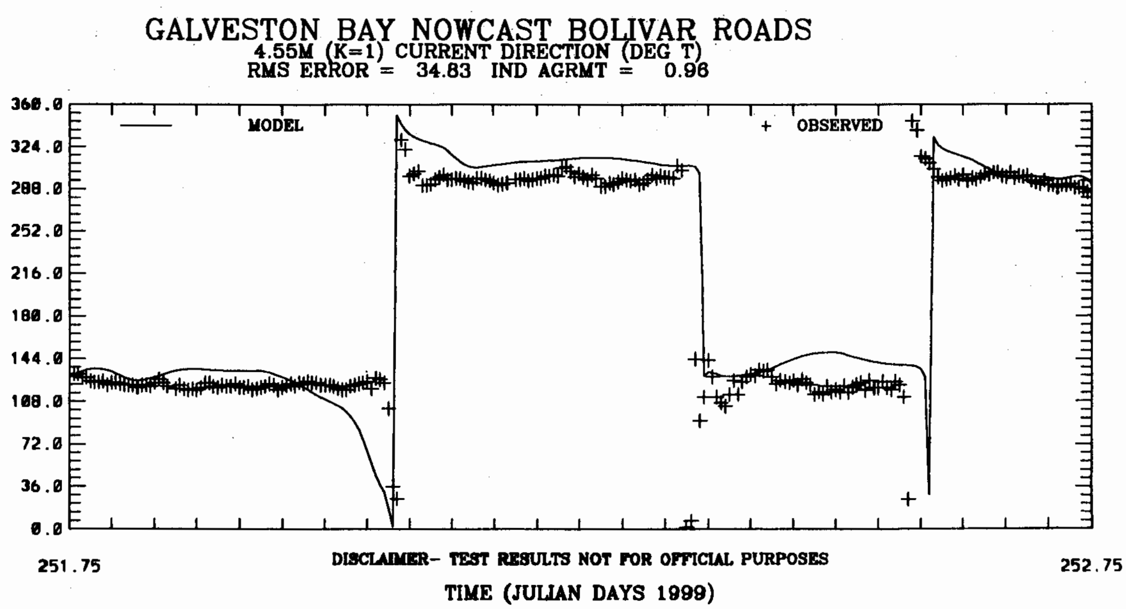
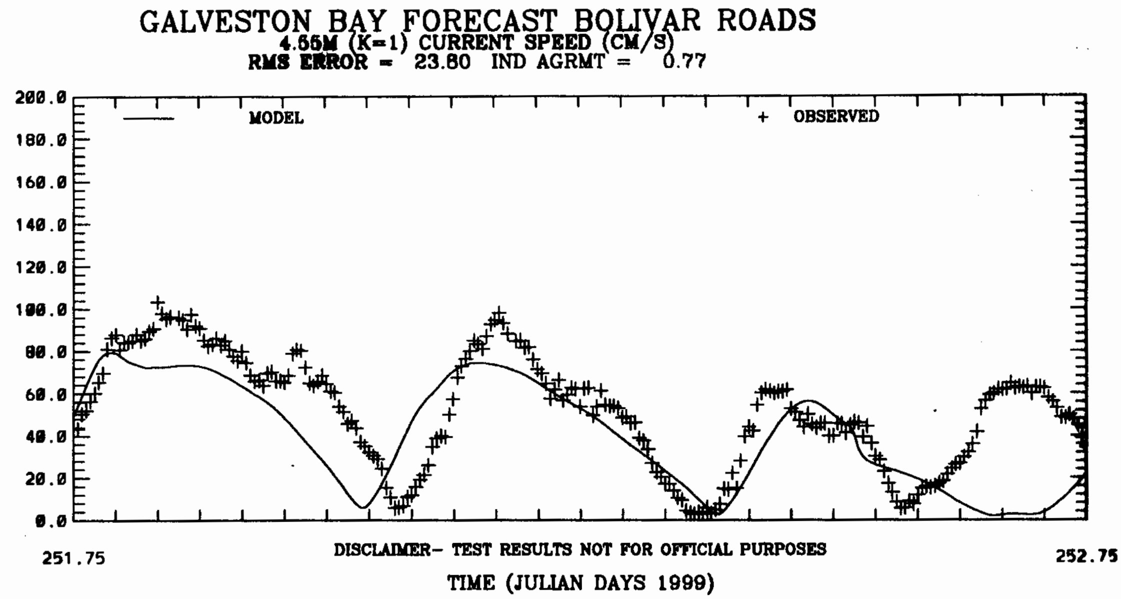


Figure 4.9 Prediction Depth (4.55m) Current Speed and Direction Nowcast: Bolivar Roads



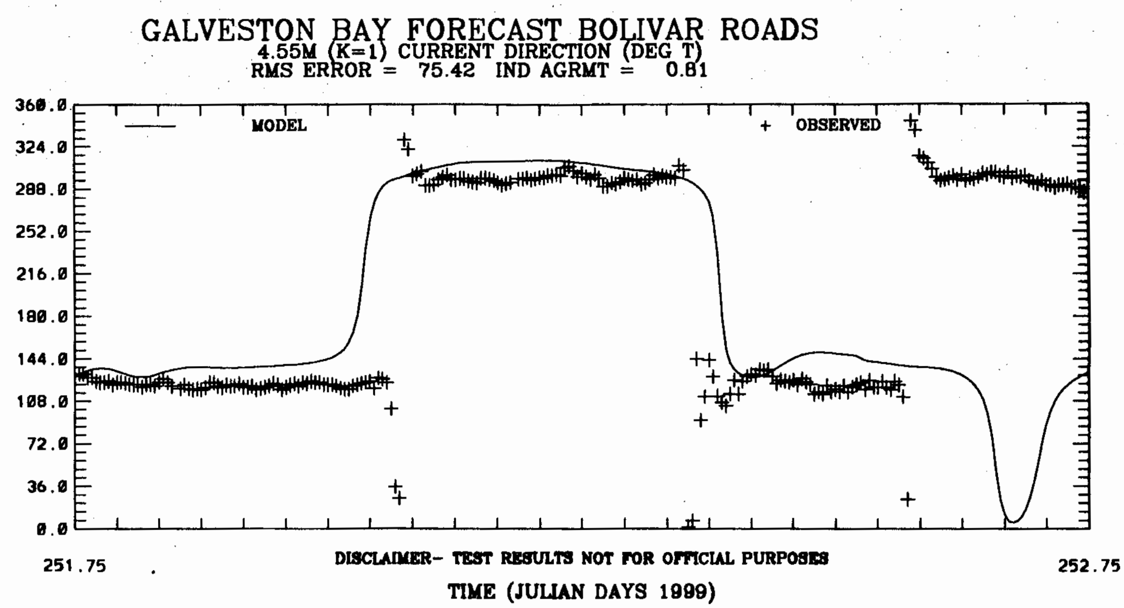
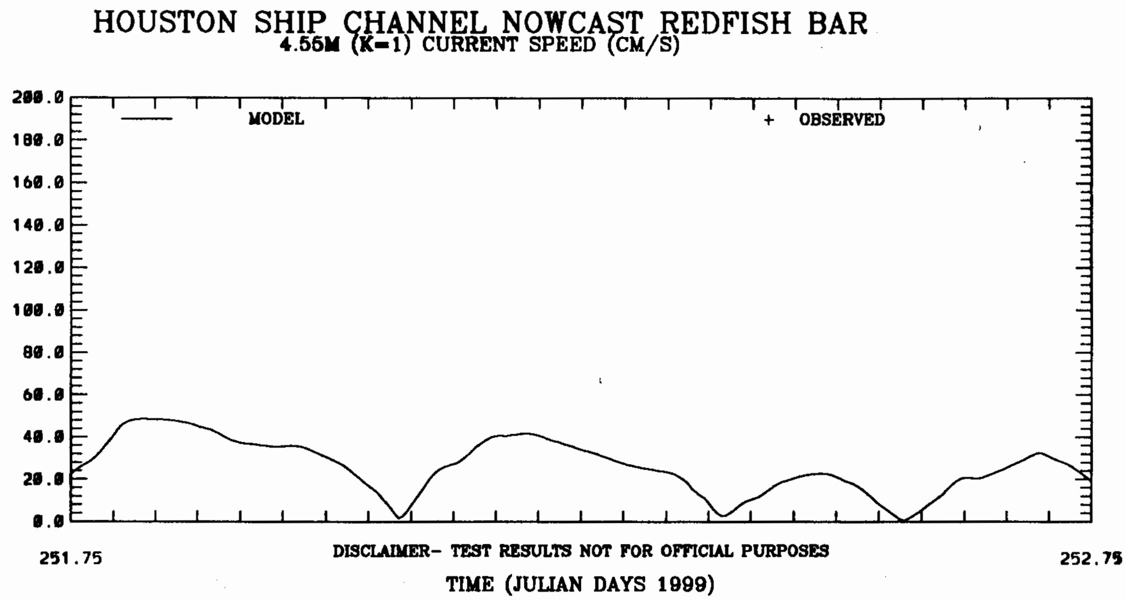


Figure 4.10 Prediction Depth (4.55m) Current Speed and Direction Forecast: Bolivar Roads



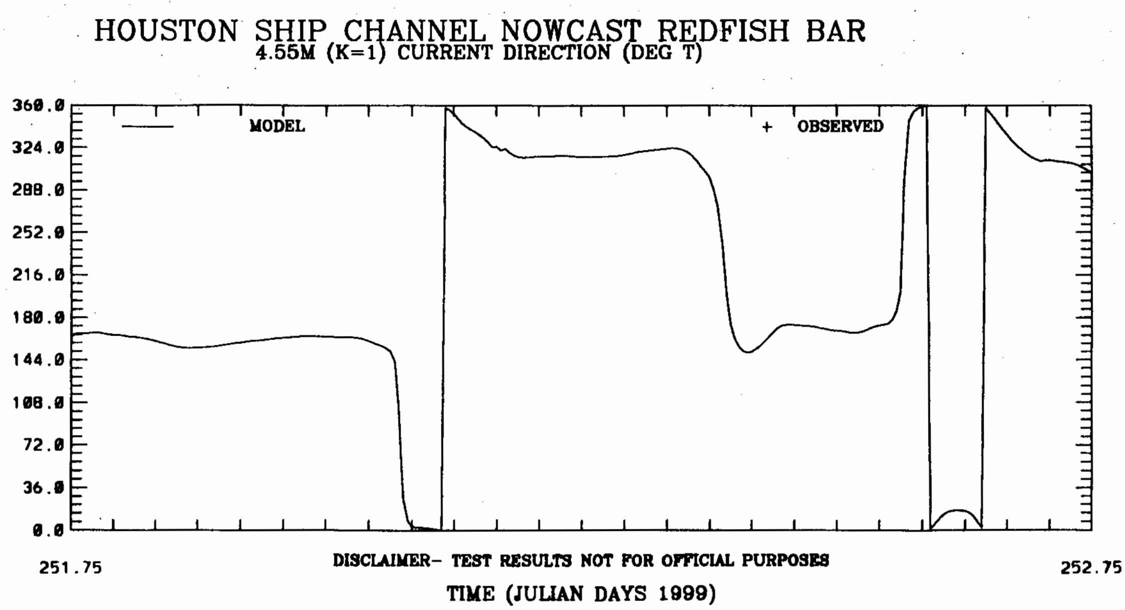
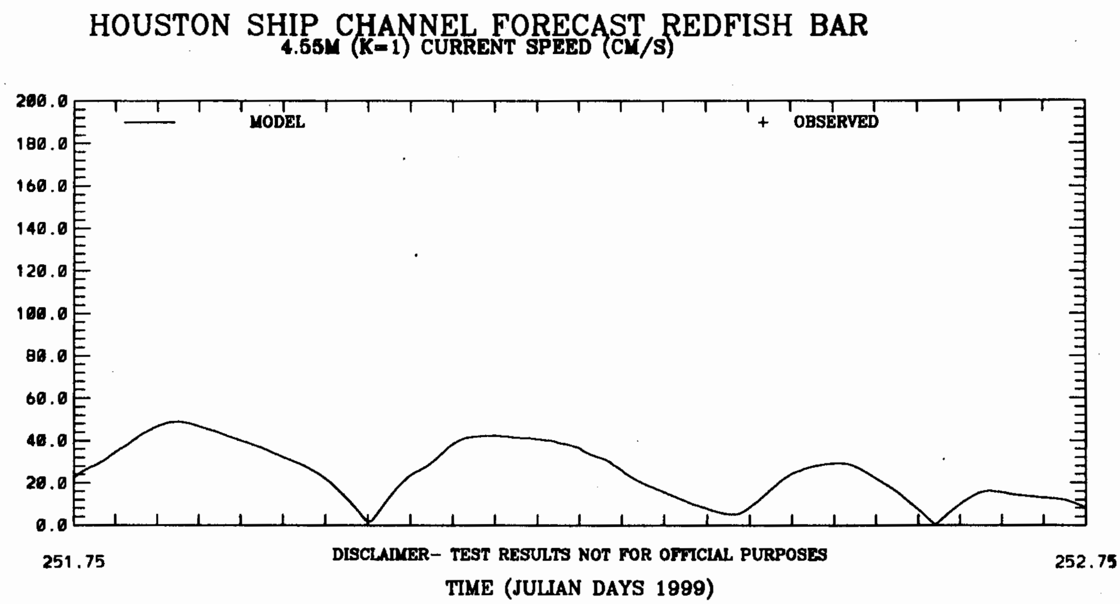


Figure 4.11 Prediction Depth (4.55m) Current Speed and Direction Nowcast: Redfish Bar



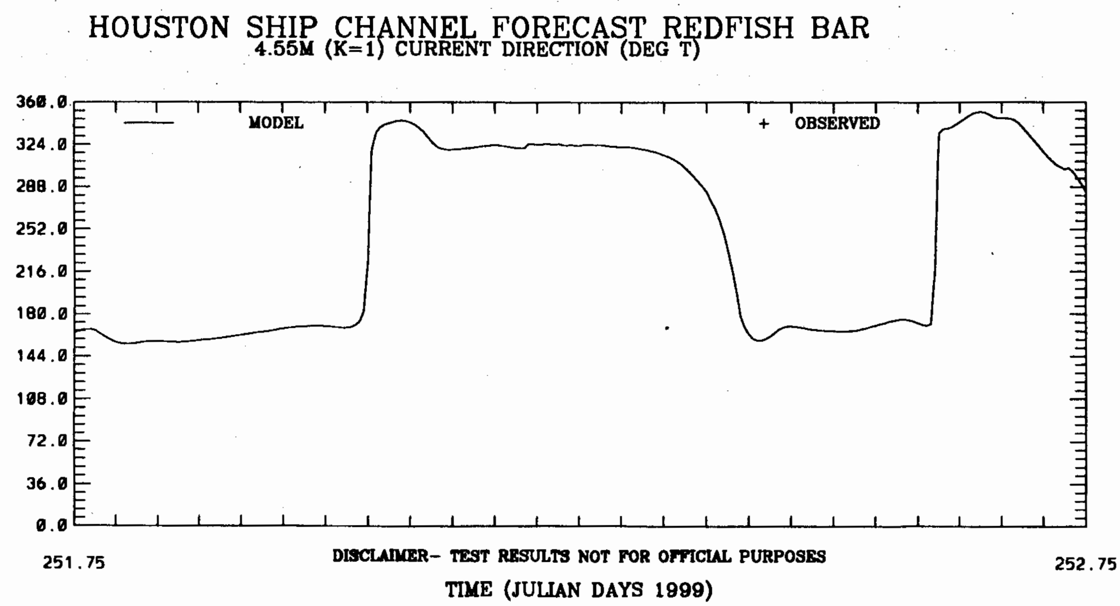
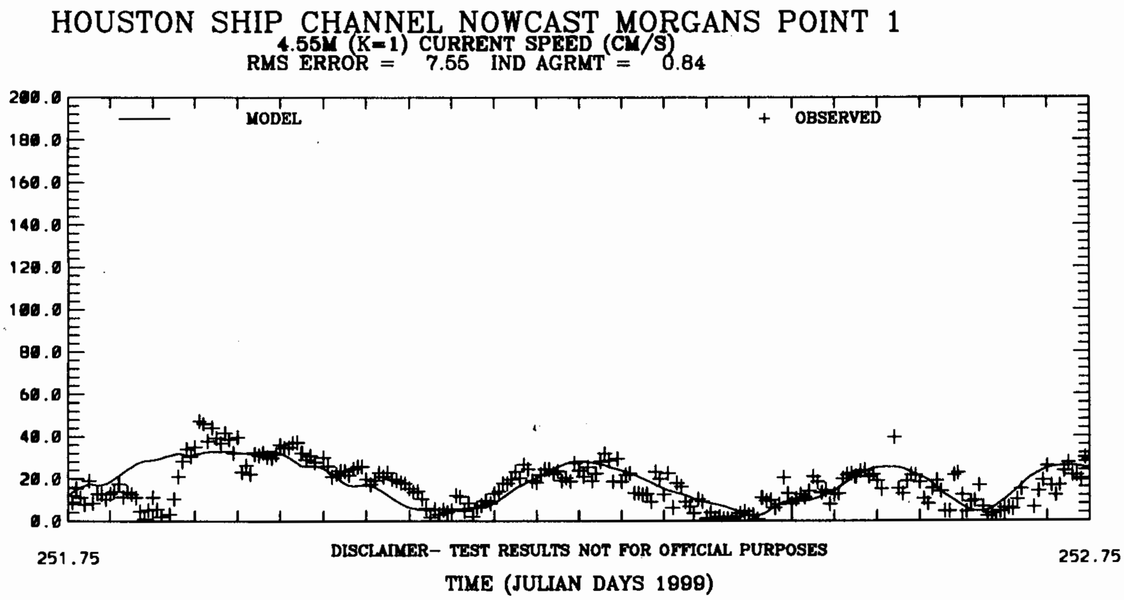


Figure 4.12 Prediction Depth (4.55m) Current Speed and Direction Forecast: Redfish Bar



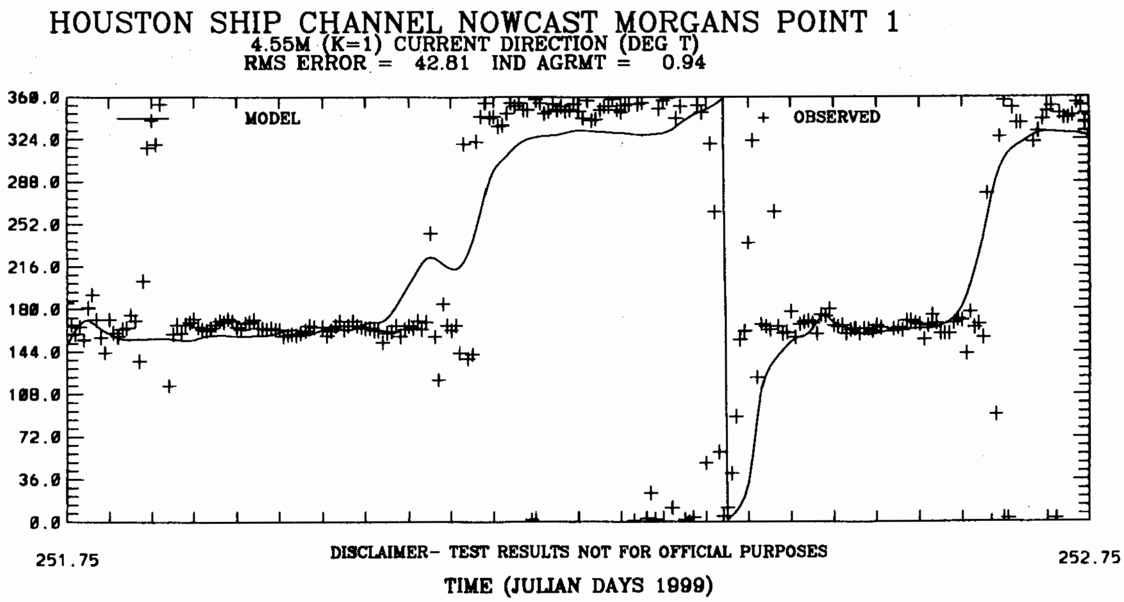
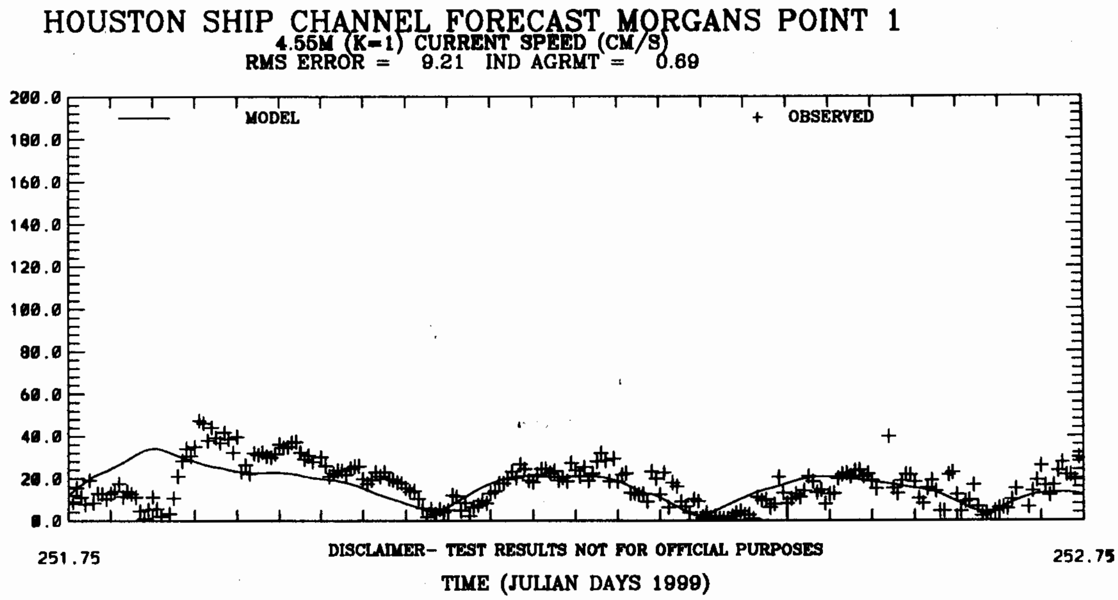


Figure 4.13 Prediction Depth (4.55m) Current Speed and Direction Nowcast: Morgans Point



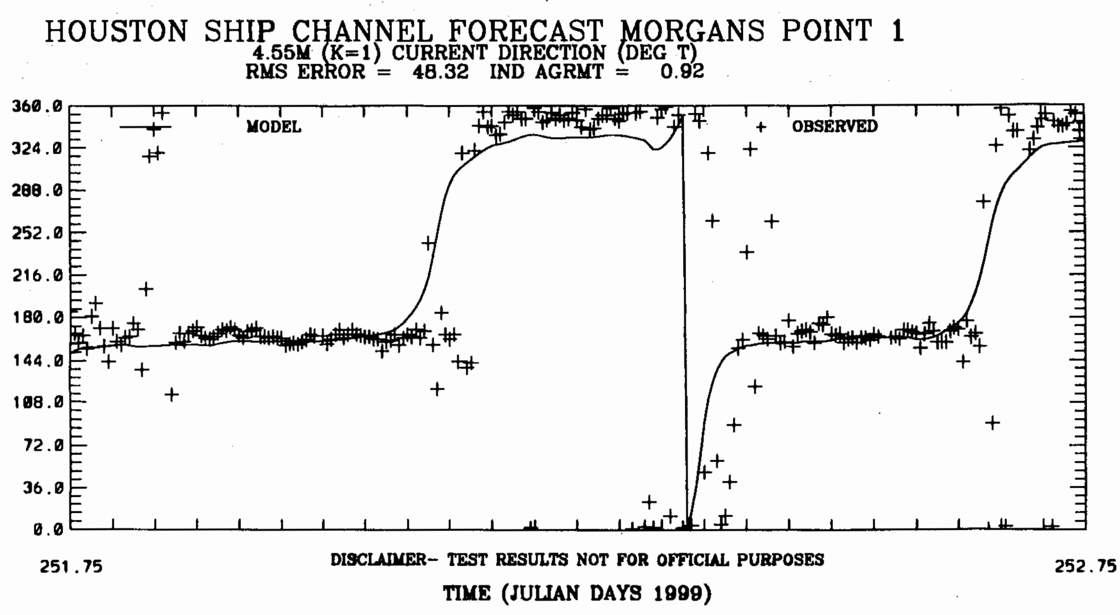


Figure 4.14 Prediction Depth (4.55m) Current Speed and Direction Forecast: Morgans Point

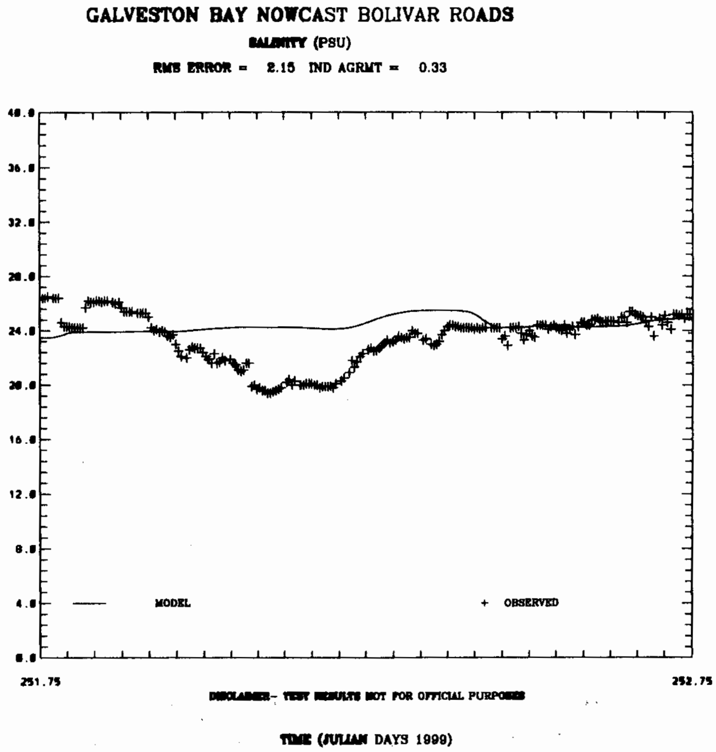


Figure 4.15 Near-surface Salinity Nowcast: Bolivar Roads

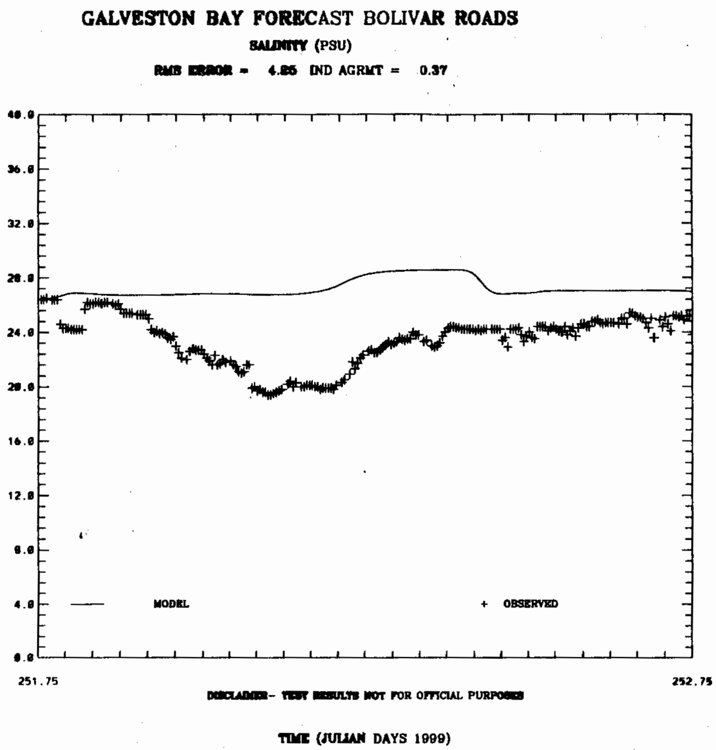


Figure 4.16 Near-surface Salinity Forecast: Bolivar Roads

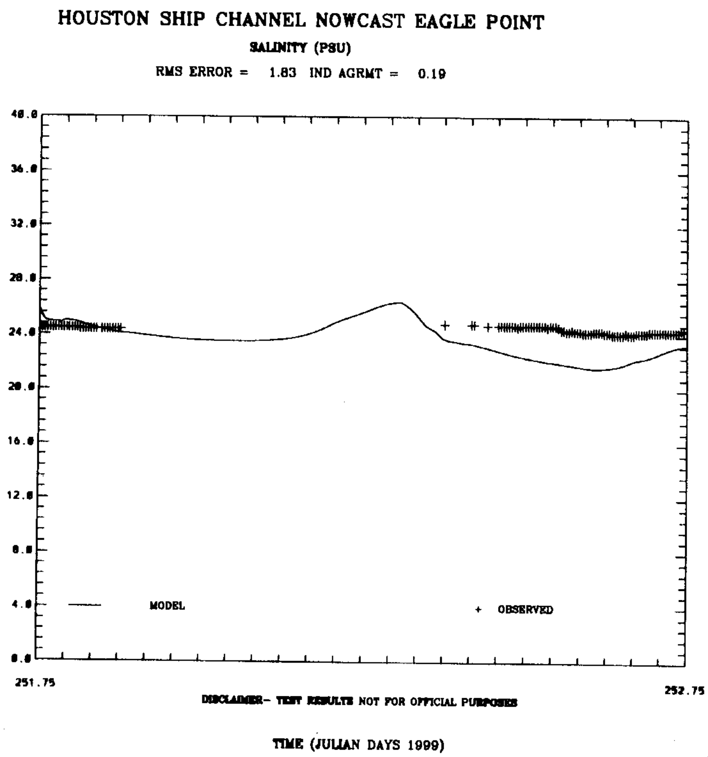


Figure 4.17 Near-surface Salinity Nowcast: Eagle Point

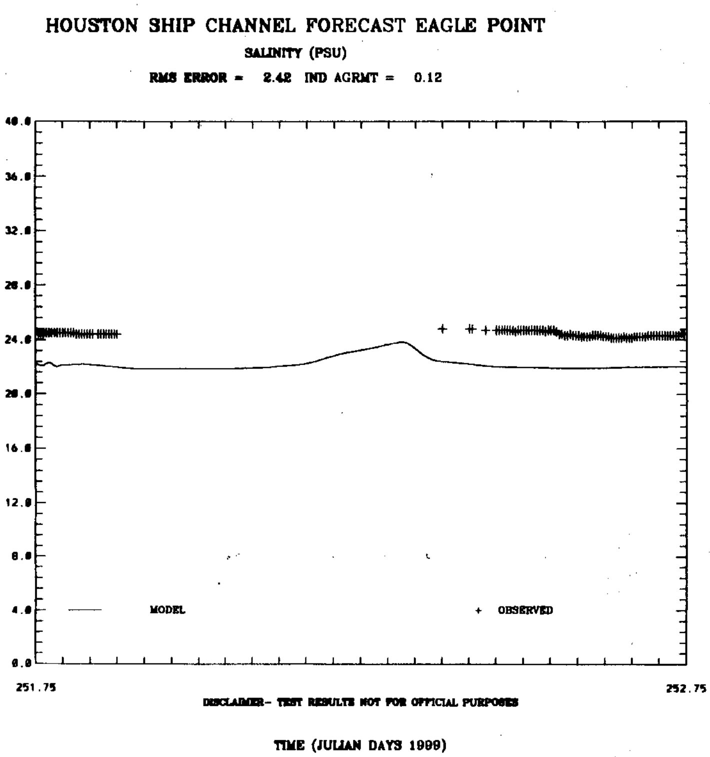


Figure 4.18 Near-surface Salinity Forecast: Eagle Point

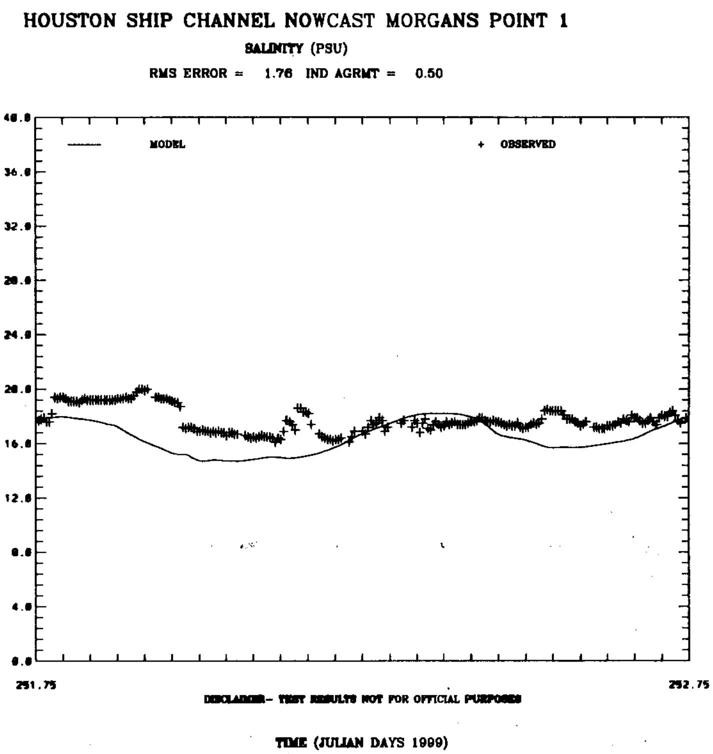


Figure 4.19 Near-surface Salinity Nowcast: Morgans Point

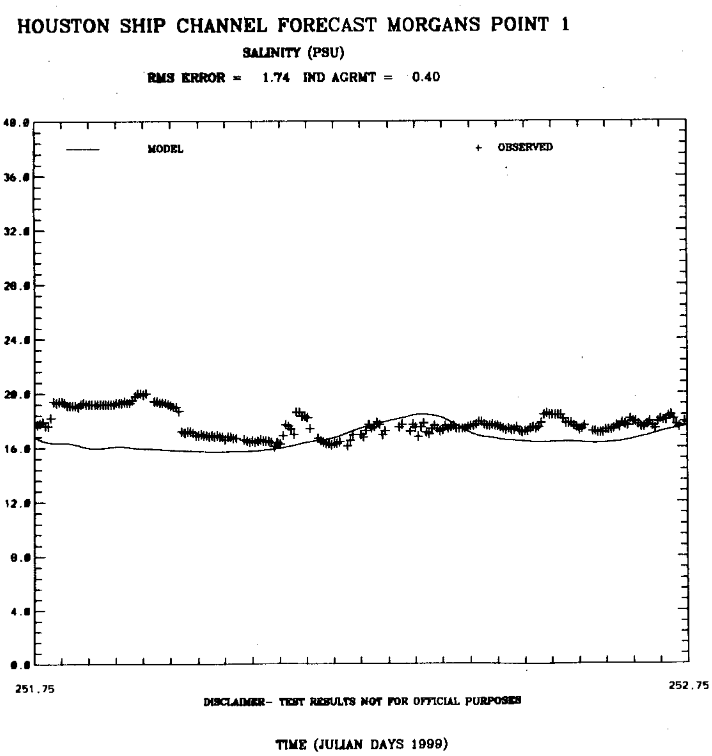


Figure 4.20 Near-surface Salinity Forecast: Morgans Point

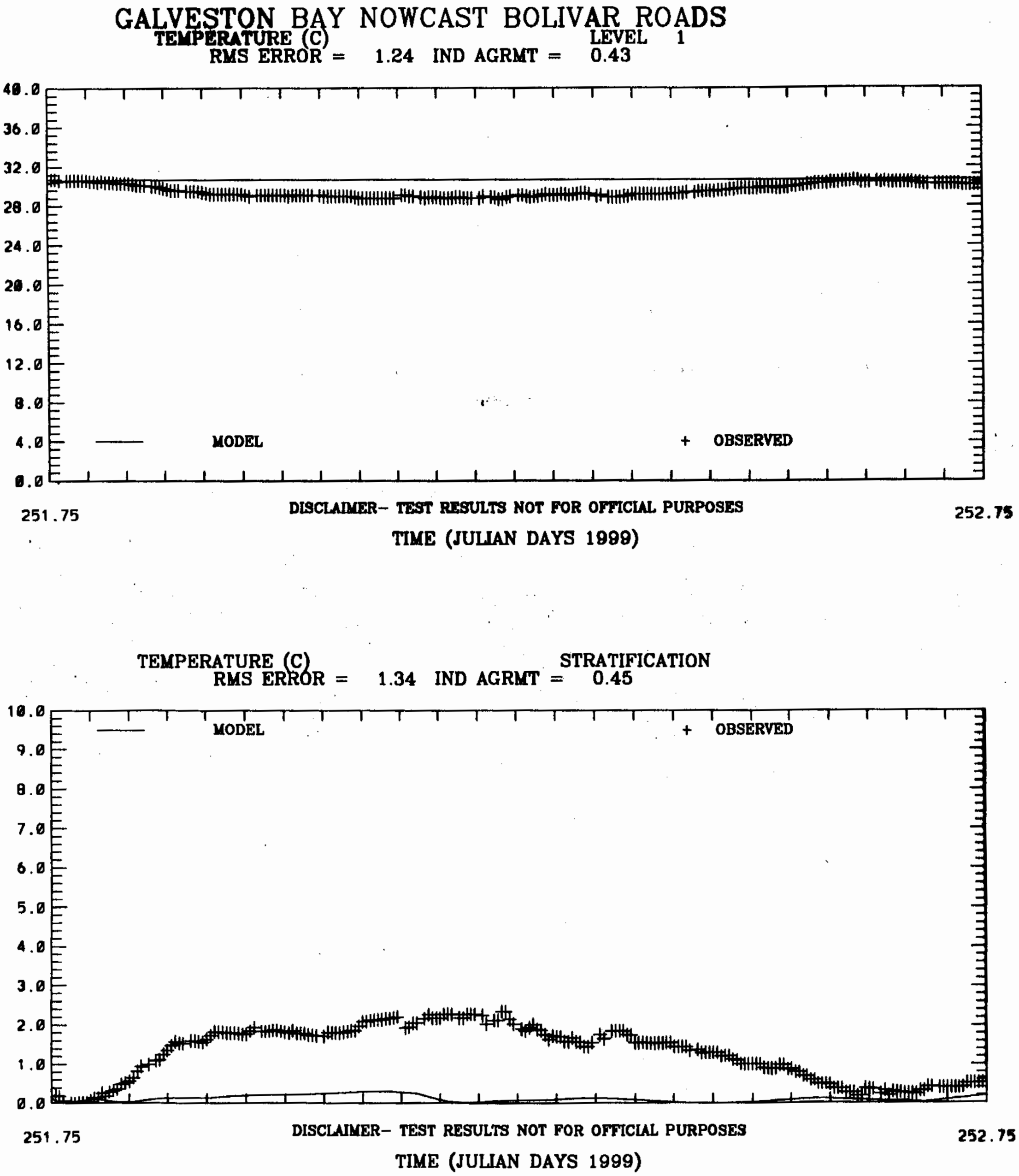


Figure 4.21 Near-surface Temperature and Stratification Nowcast: Bolivar Roads

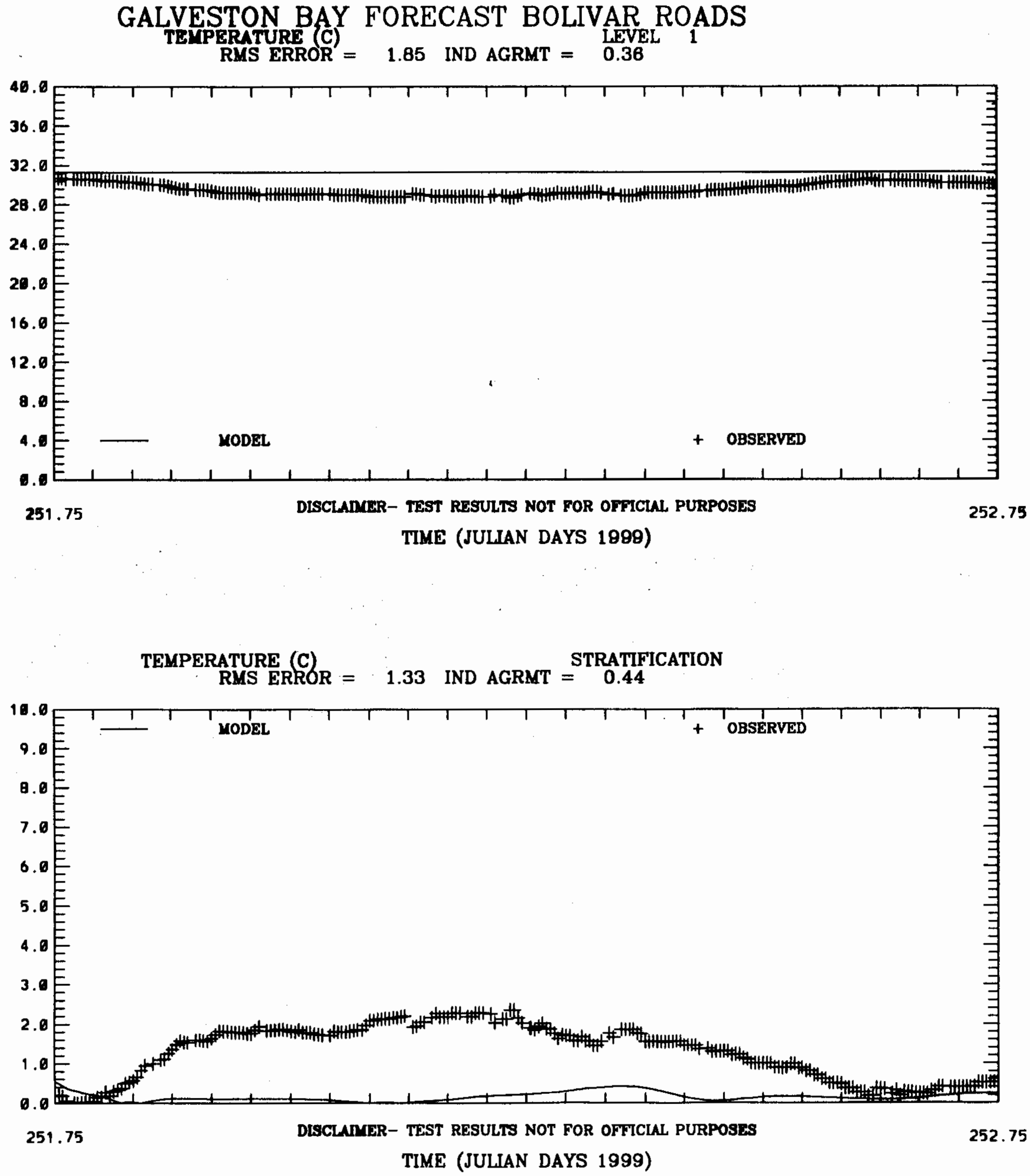
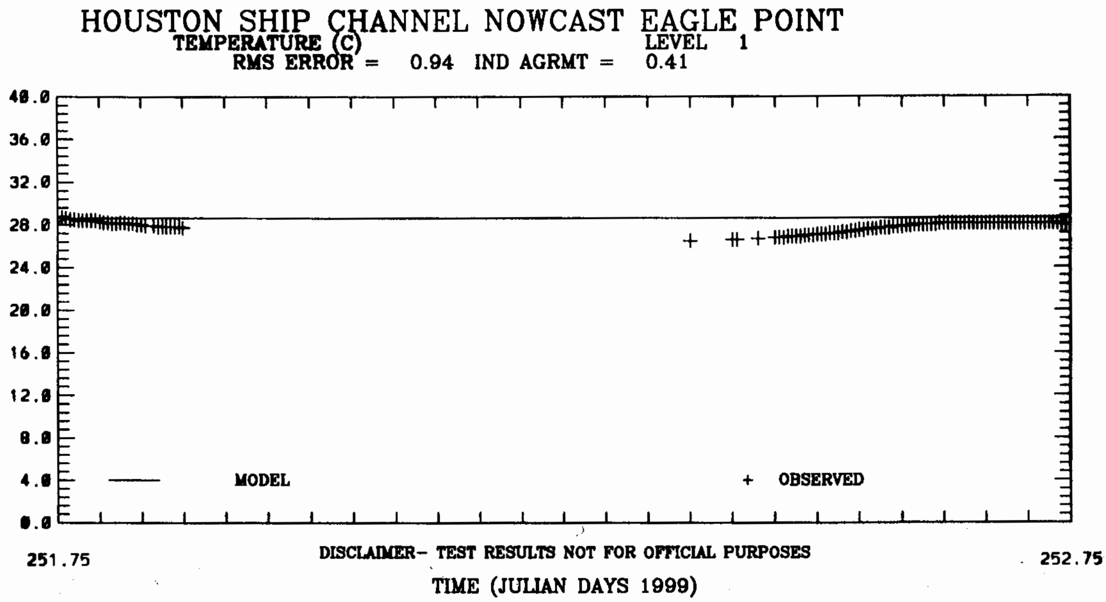


Figure 4.22 Near-surface Temperature and Stratification Forecast: Bolivar Roads



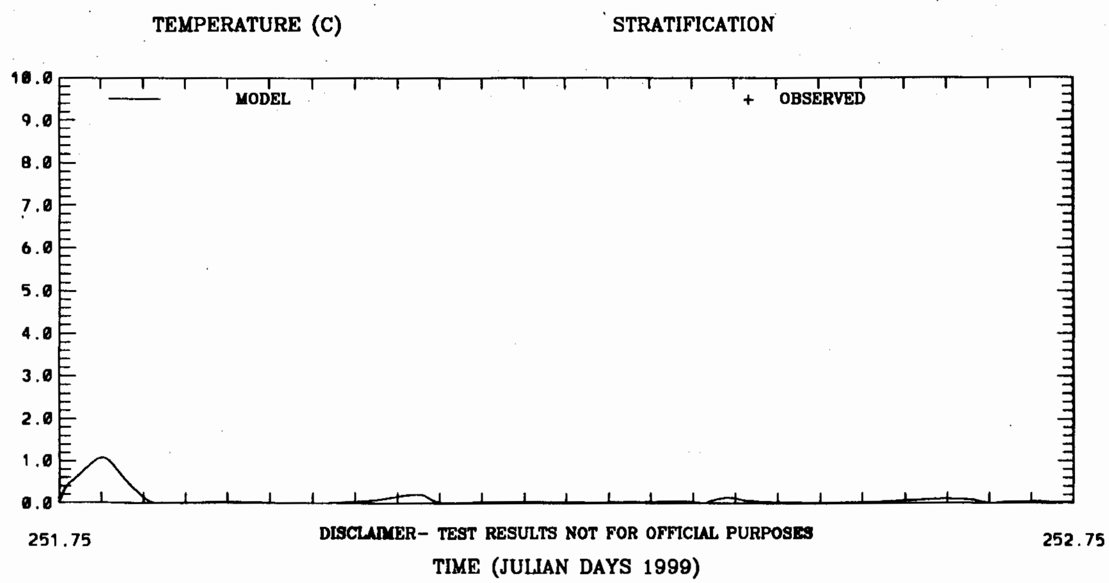
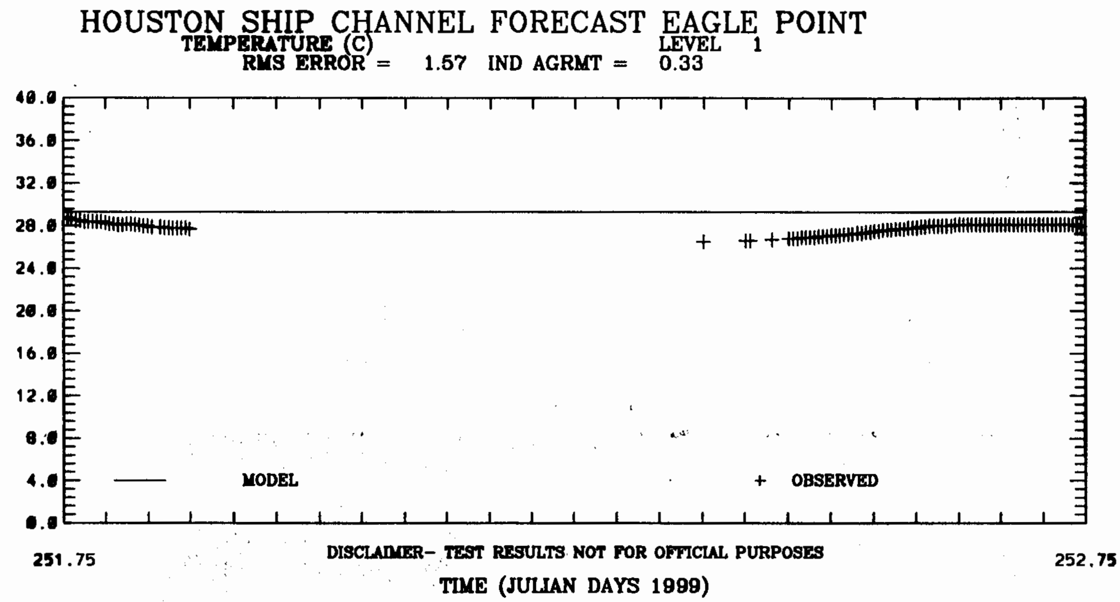


Figure 4.23 Near-surface Temperature and Stratification Nowcast: Eagle Point



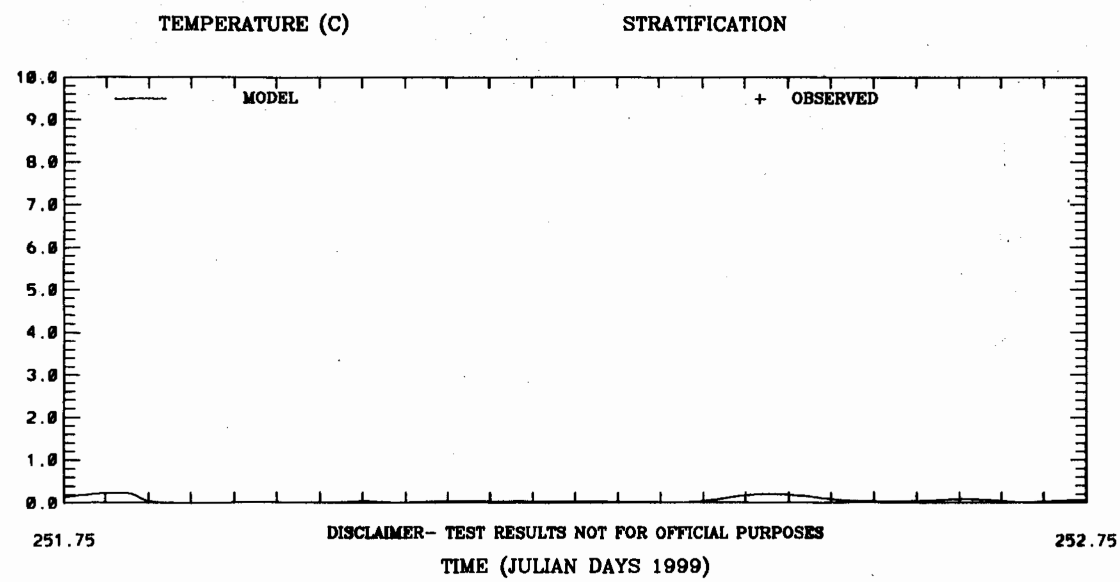
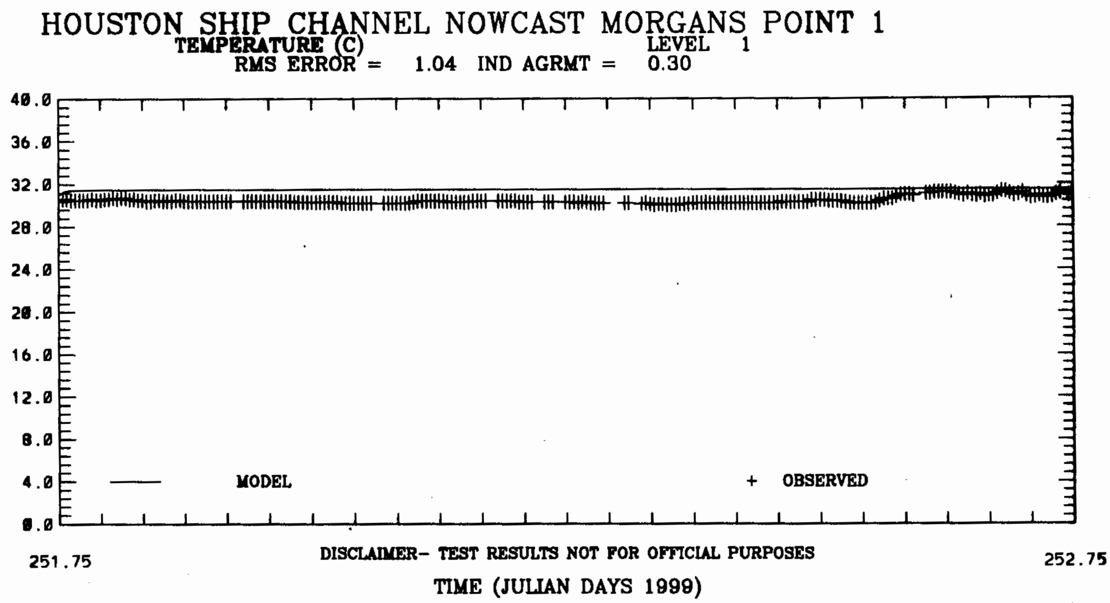


Figure 4.24 Near-surface Temperature and Stratification Forecast: Eagle Point



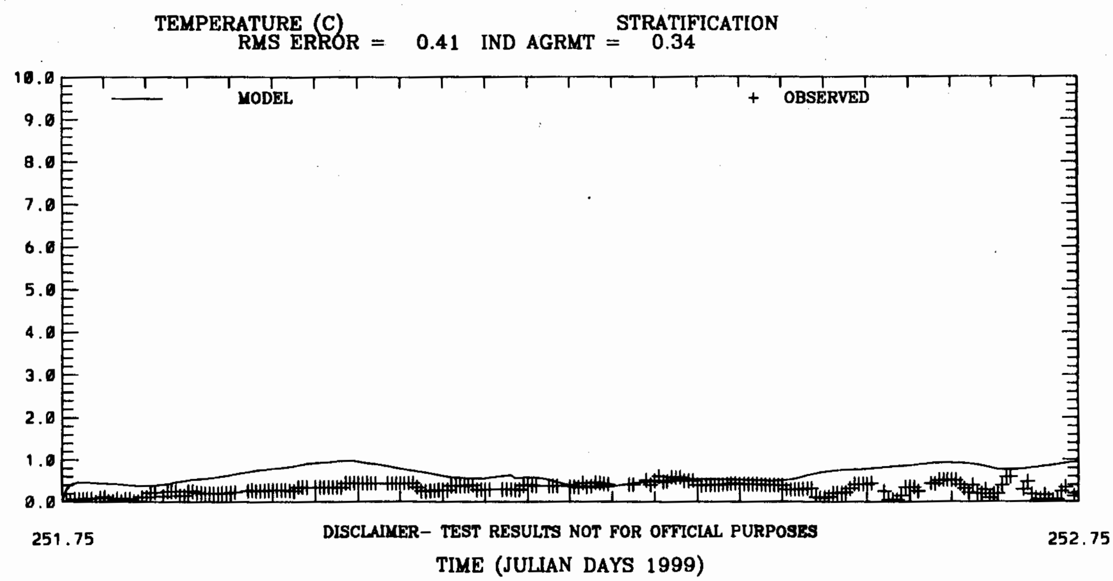
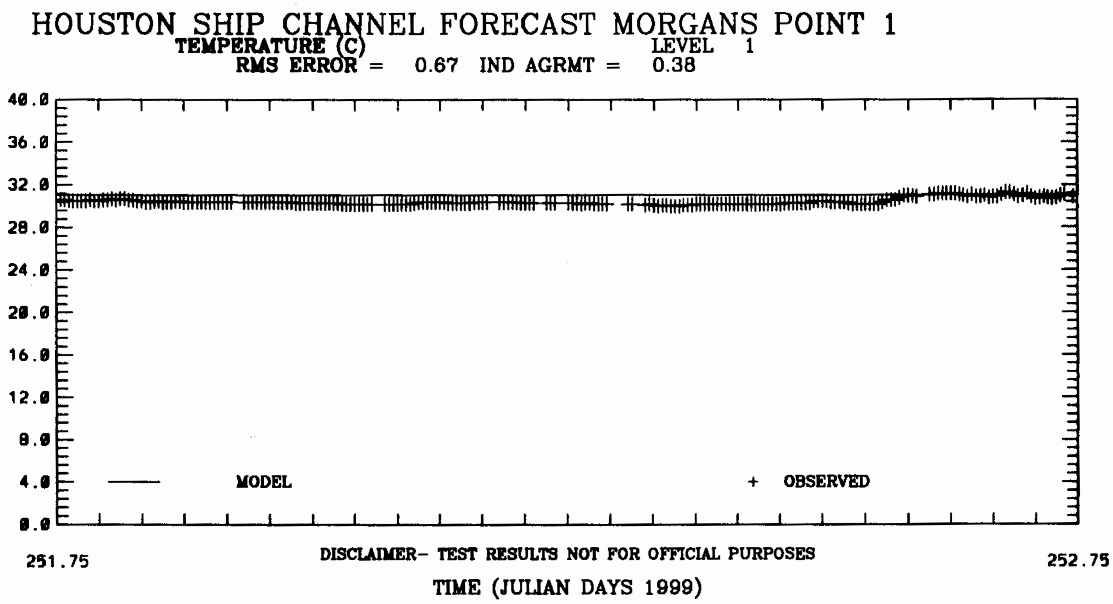


Figure 4.25 Near-surface Temperature and Stratification Nowcast: Morgans Point



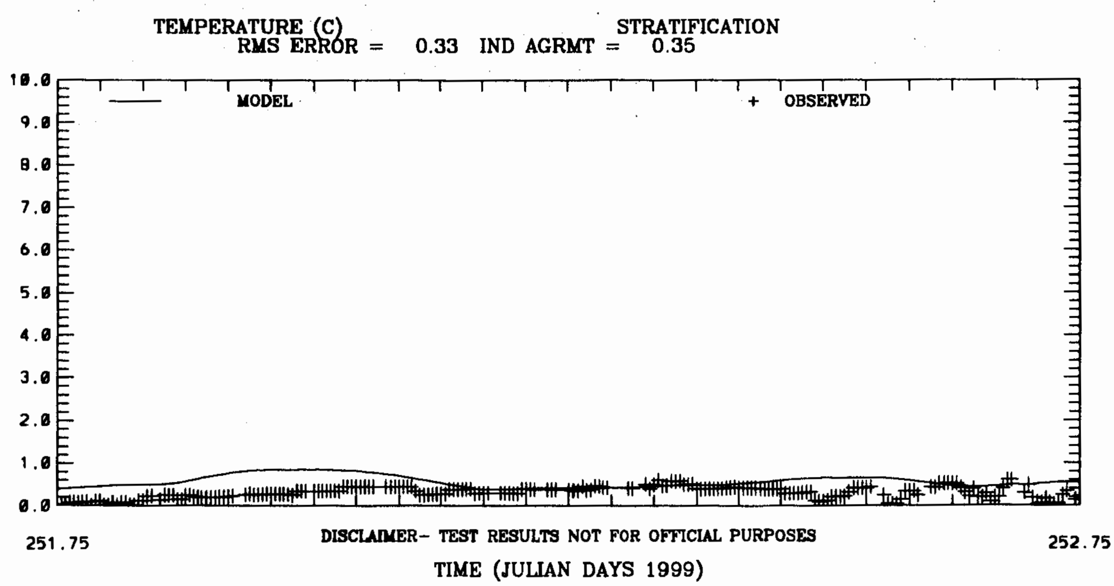
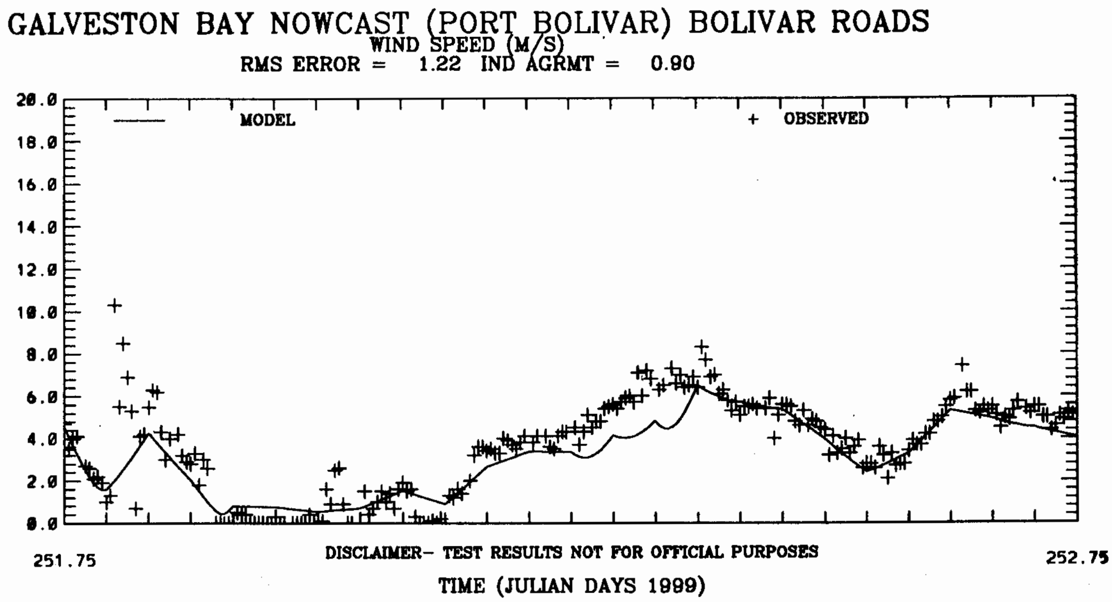


Figure 4.26 Near-surface Temperature and Stratification Forecast: Morgans Point



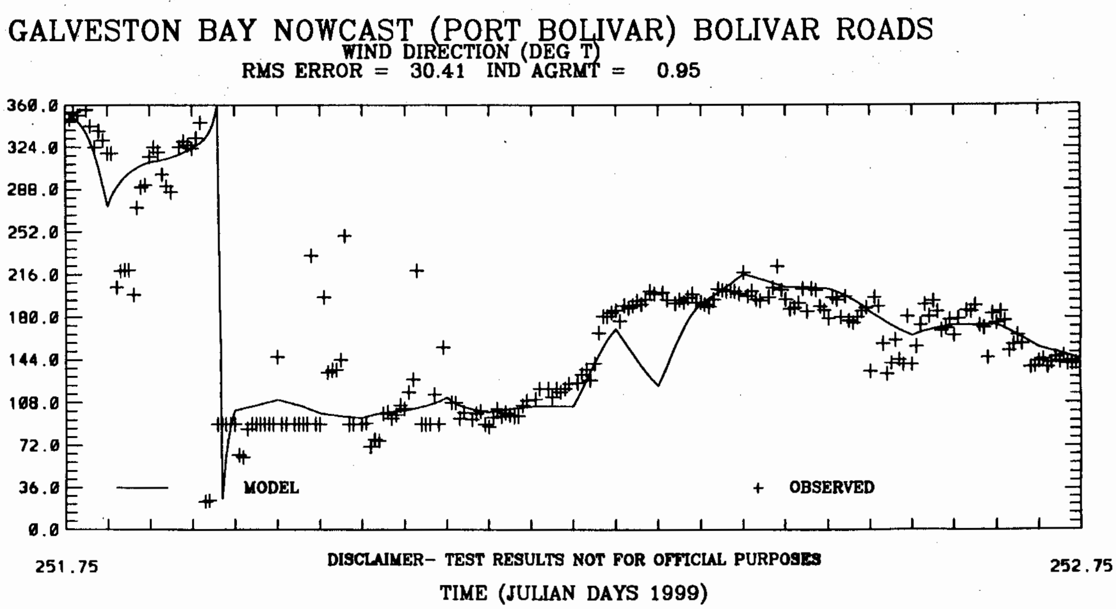


Figure 4.27 PORTS 10m Wind Speed and Direction Nowcast: Bolivar Roads

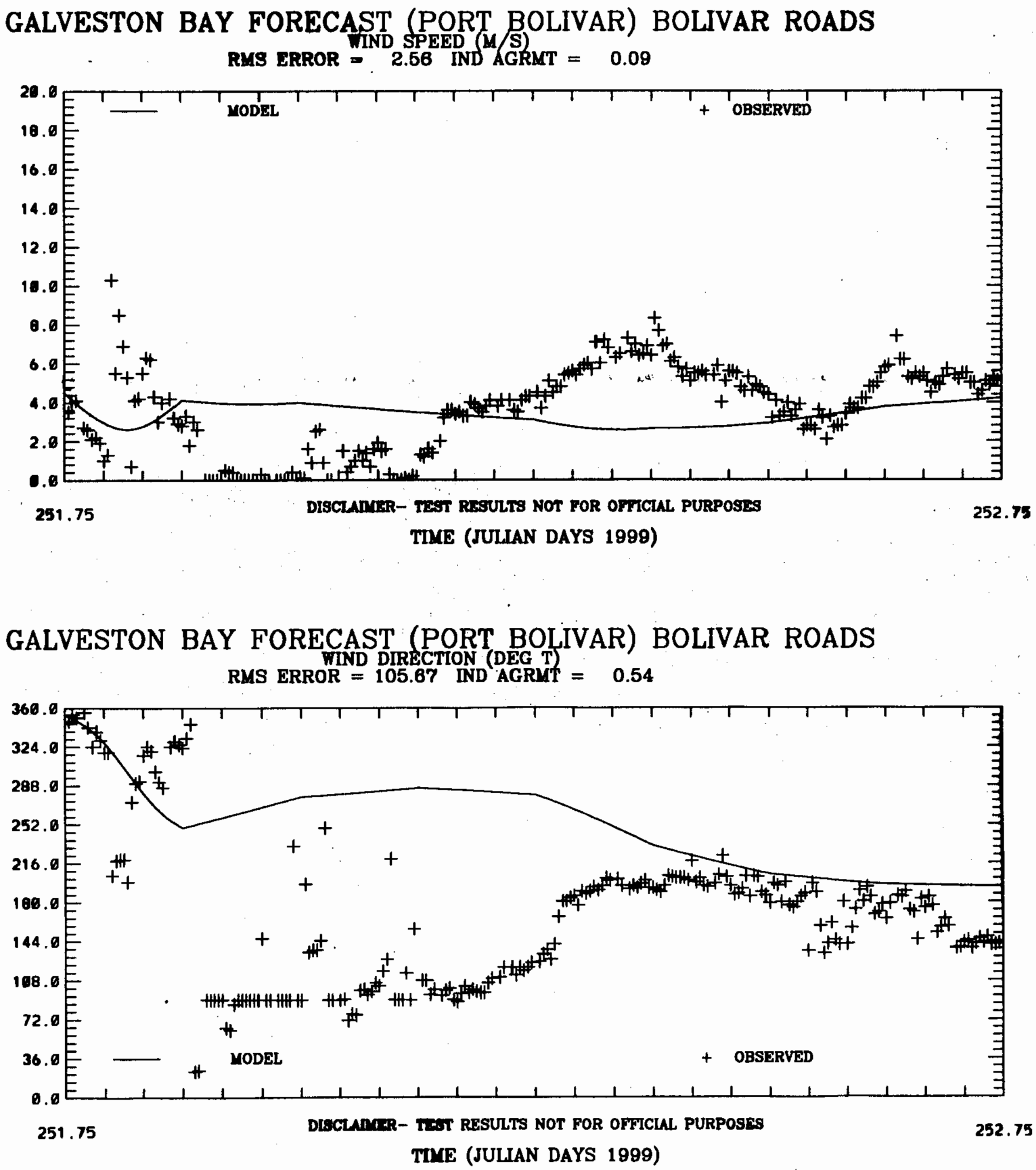
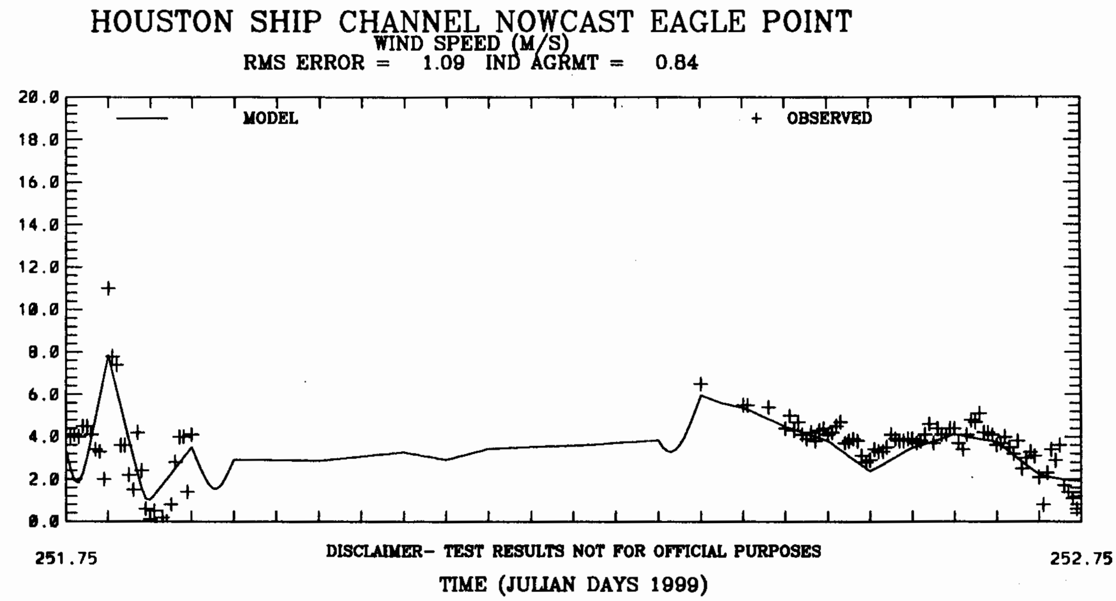


Figure 4.28 AVN 10-m Wind Speed and Direction Forecast: Bolivar Roads



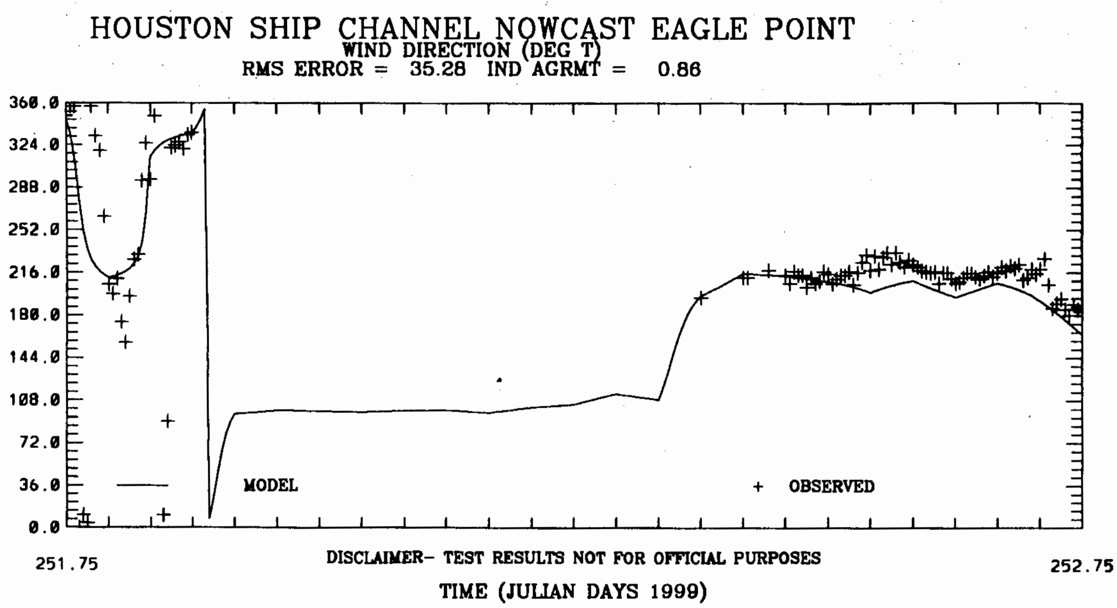
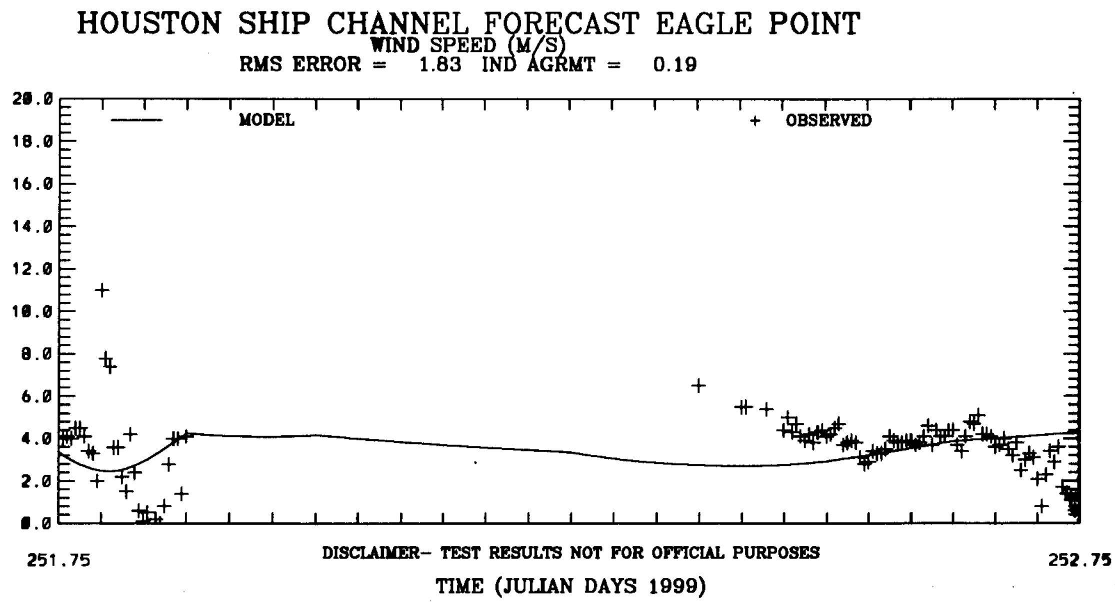


Figure 4.29 PORTS 10m Wind Speed and Direction Nowcast: Eagle Point



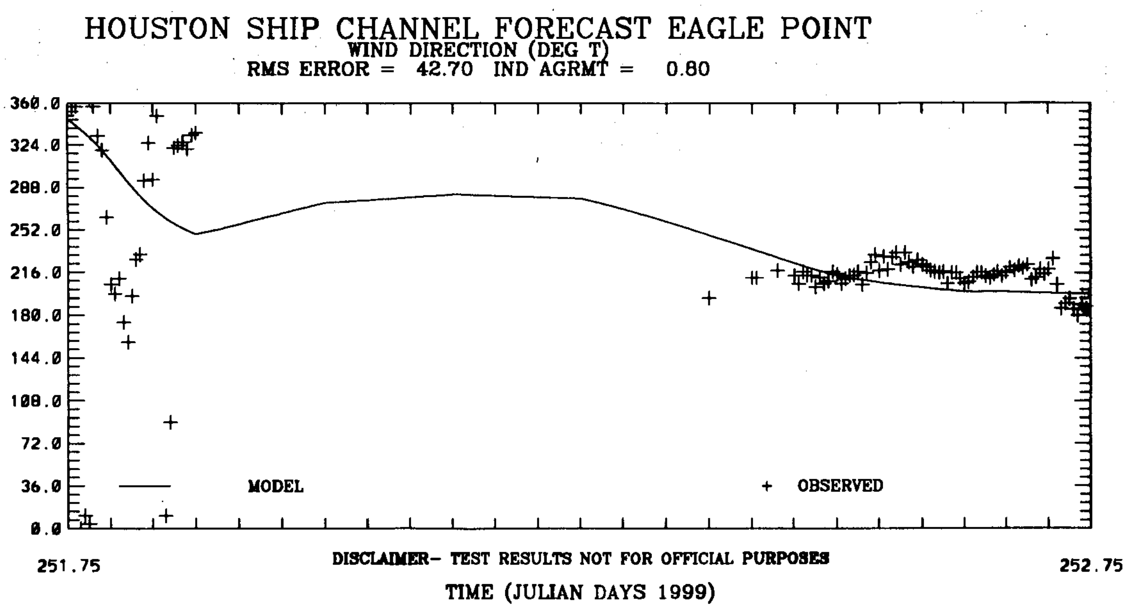


Figure 4.30 AVN 10-m Wind Speed and Direction Forecast: Eagle Point

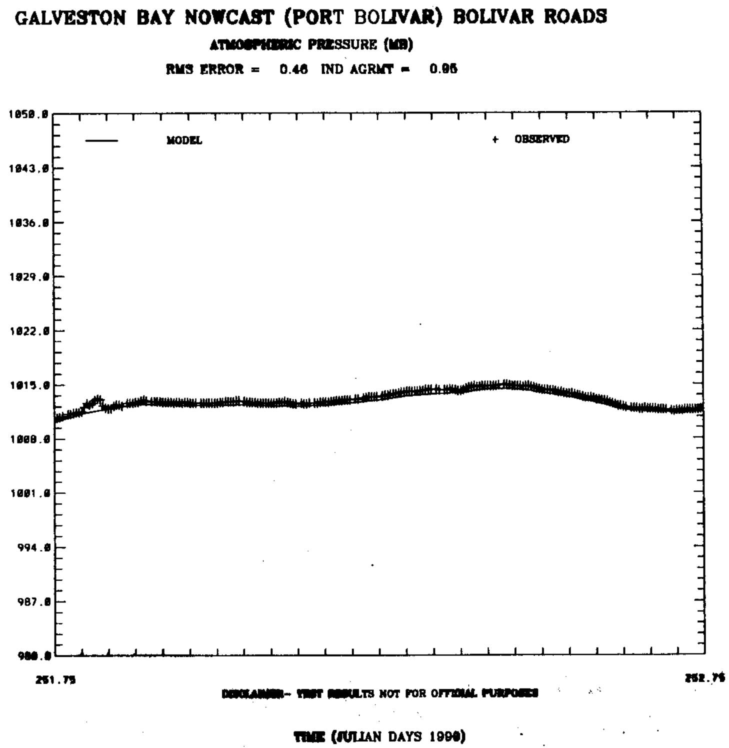


Figure 4.31 PORTS Sea-level Atmospheric Pressure Nowcast: Bolivar Roads

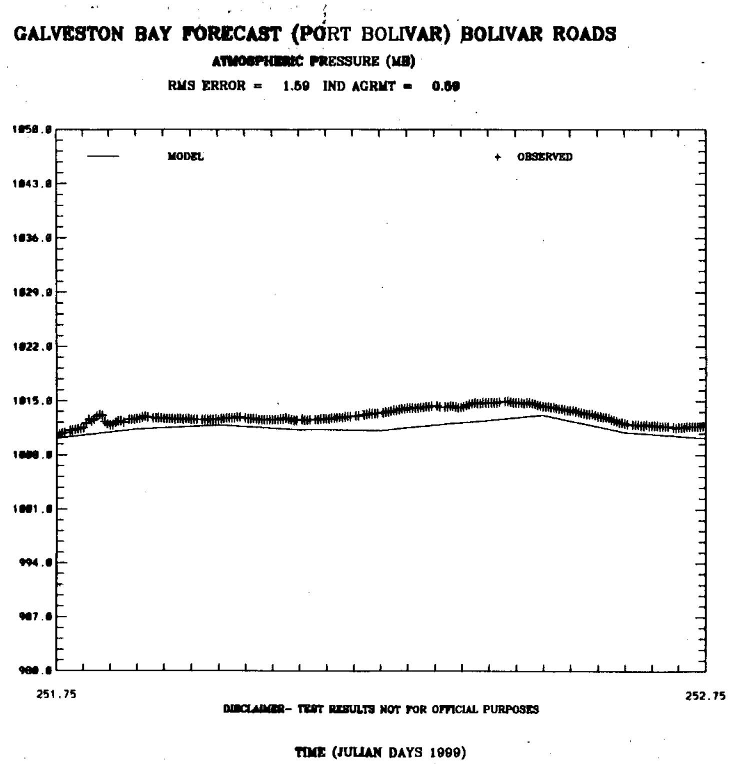


Figure 4.32 AVN Sea-level Atmospheric Pressure Forecast: Bolivar Roads

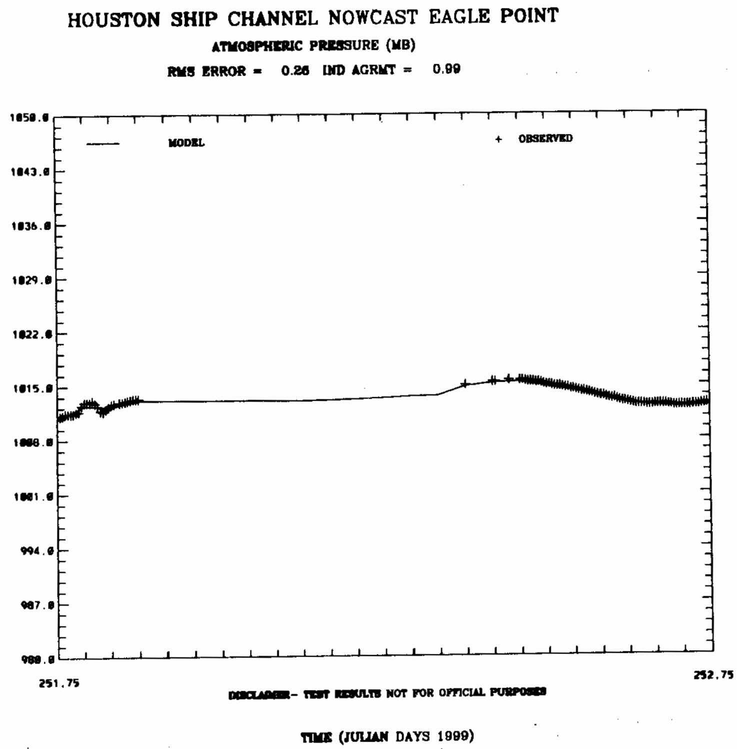


Figure 4.33 PORTS Sea-level Atmospheric Pressure Nowcast: Eagle Point

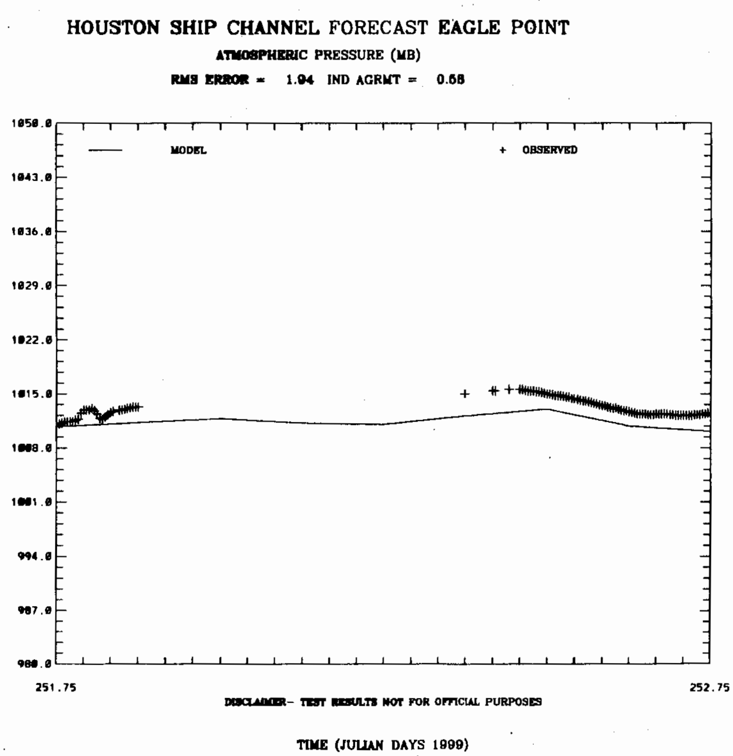
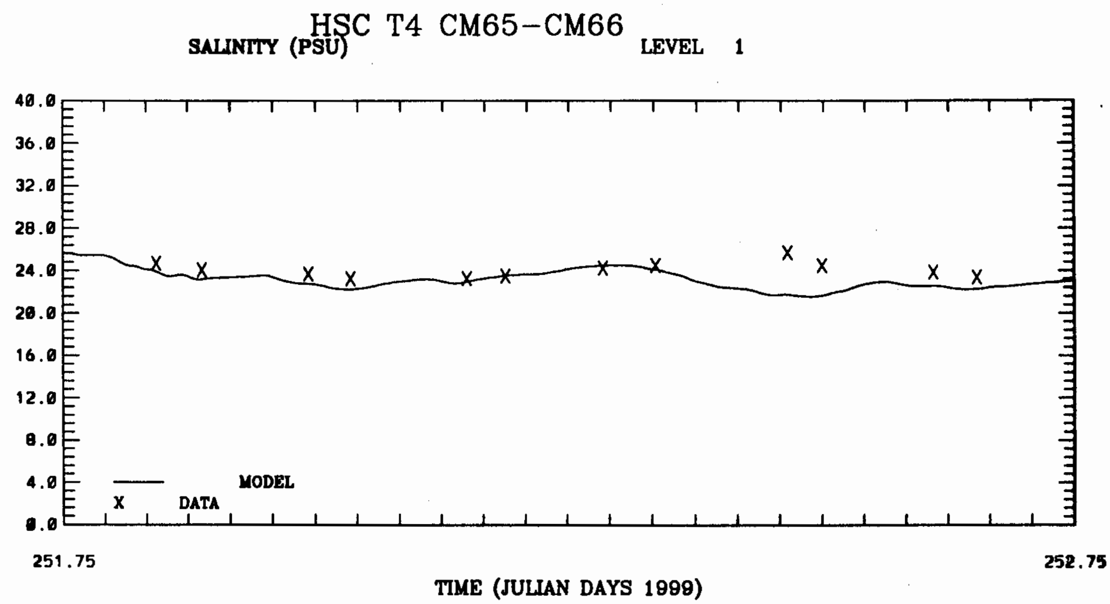


Figure 4.34 AVN Sea-level Atmospheric Pressure Forecast: Eagle Point



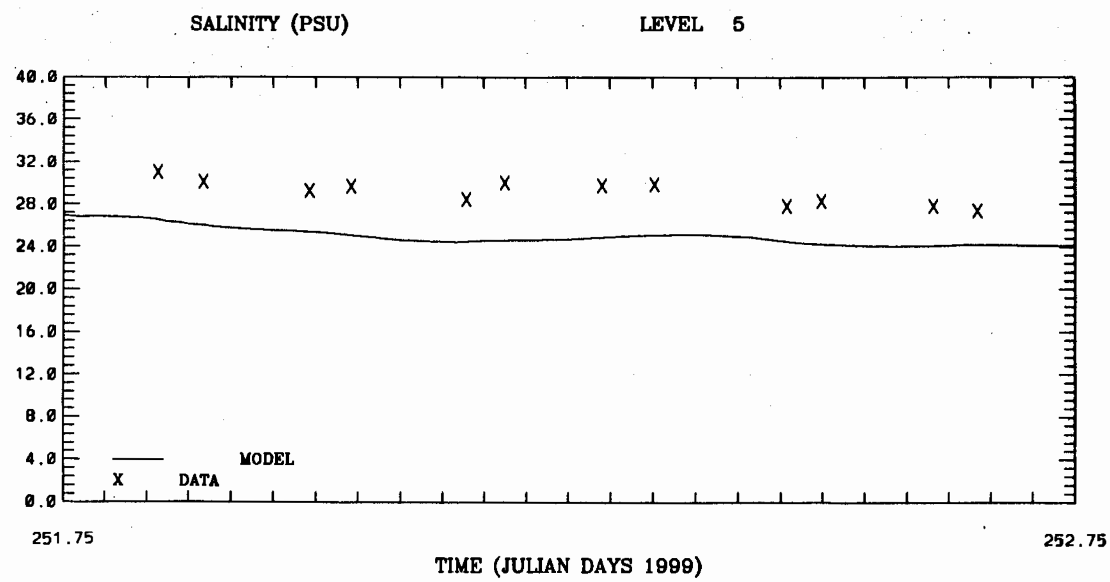
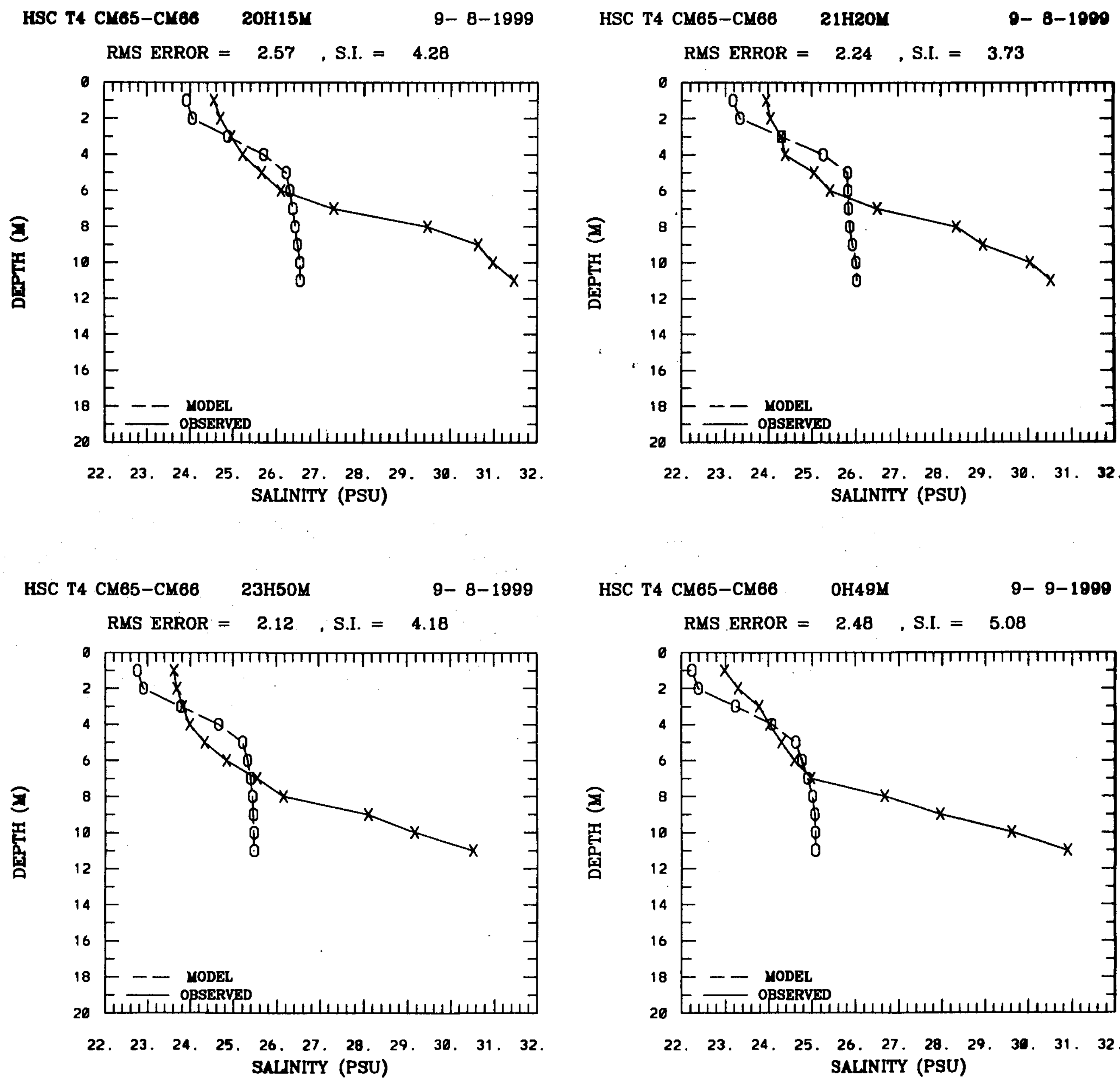


Figure 4.35 HSC T4 Salinity Level 1 and Level 5 Nowcast



Model dashed line marked by 0
Observation solid line marked by X

Figure 4.36 HSC T4 Salinity Profile Set Nowcast

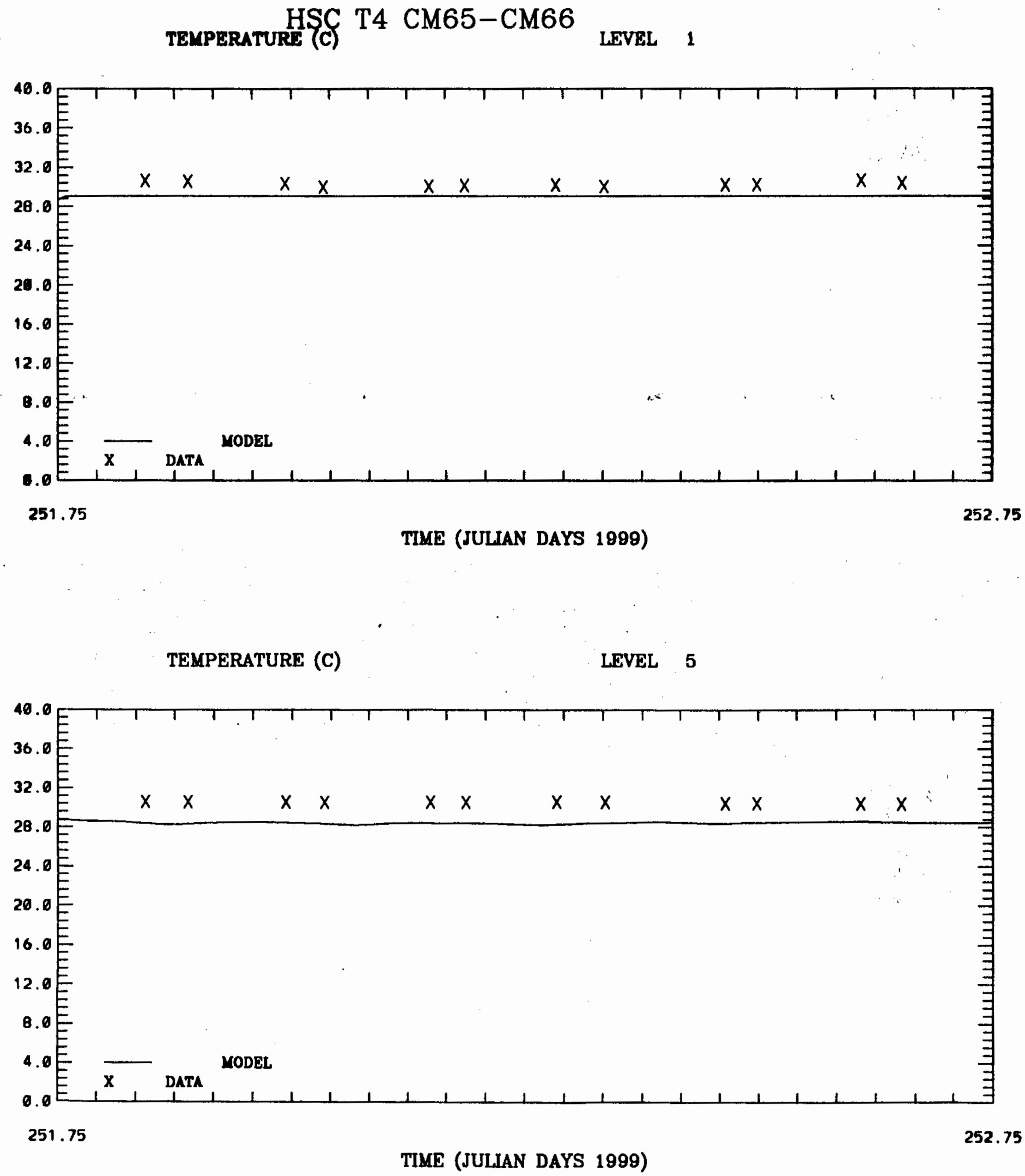


Figure 4.37 HSC T4 Temperature Level 1 and Level 5 Nowcast

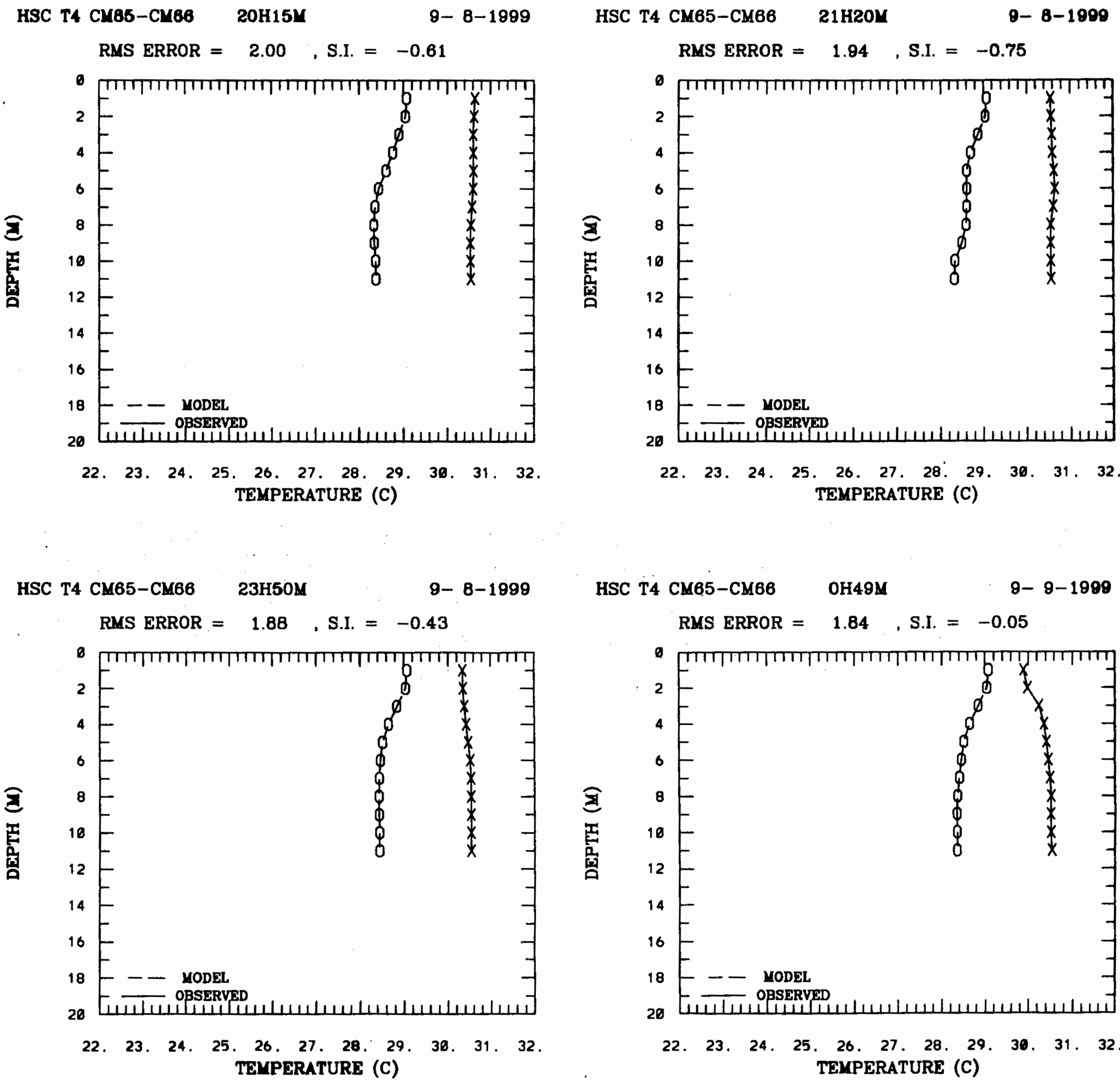


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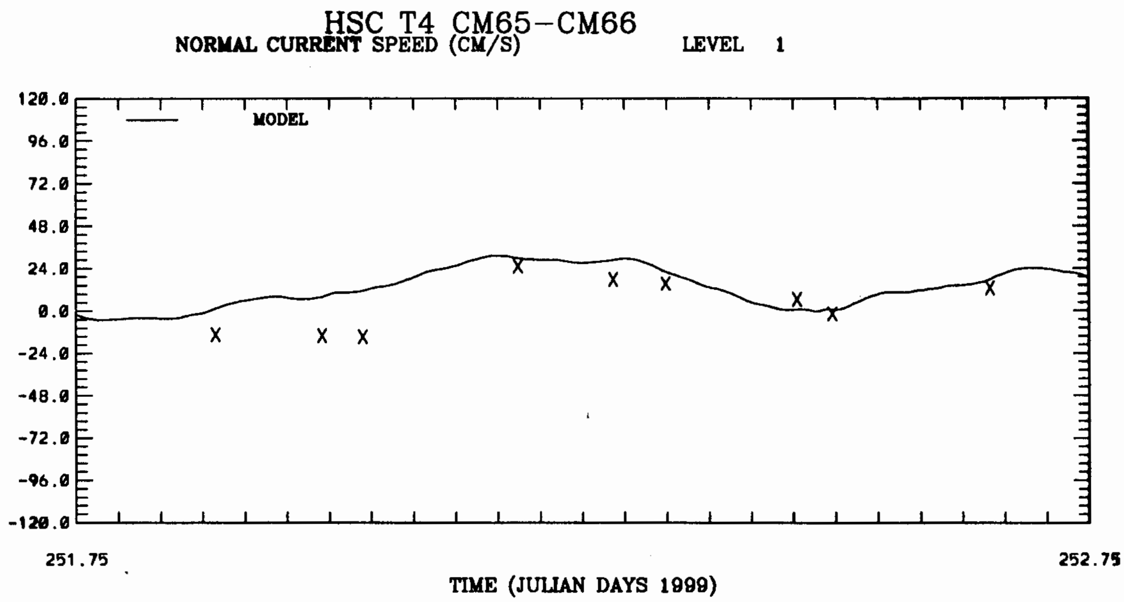
Figure 4.38 HSC T4 Temperature Profile Set Nowcast



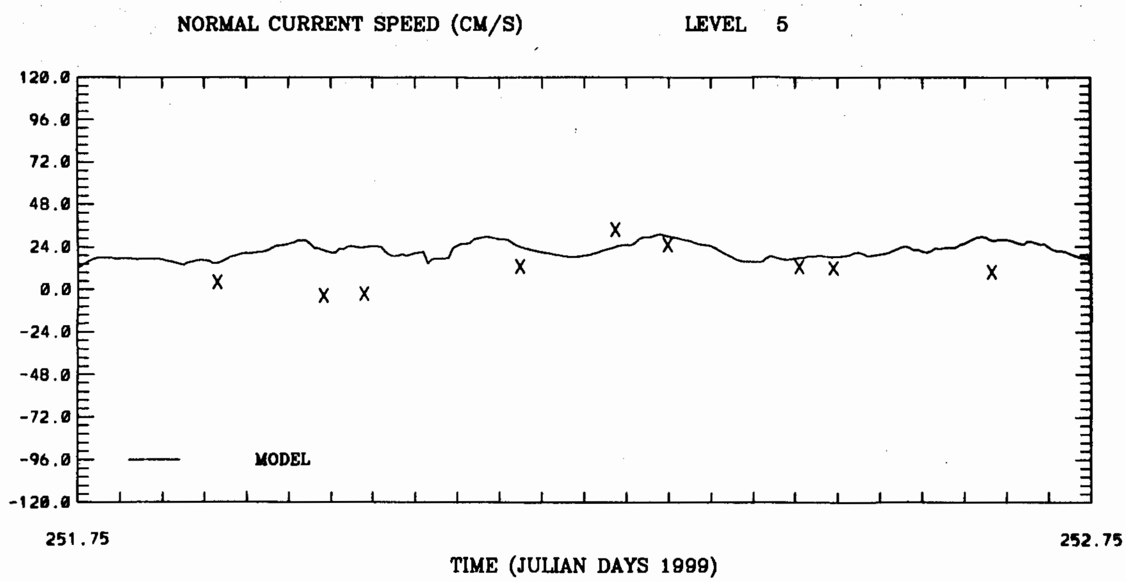
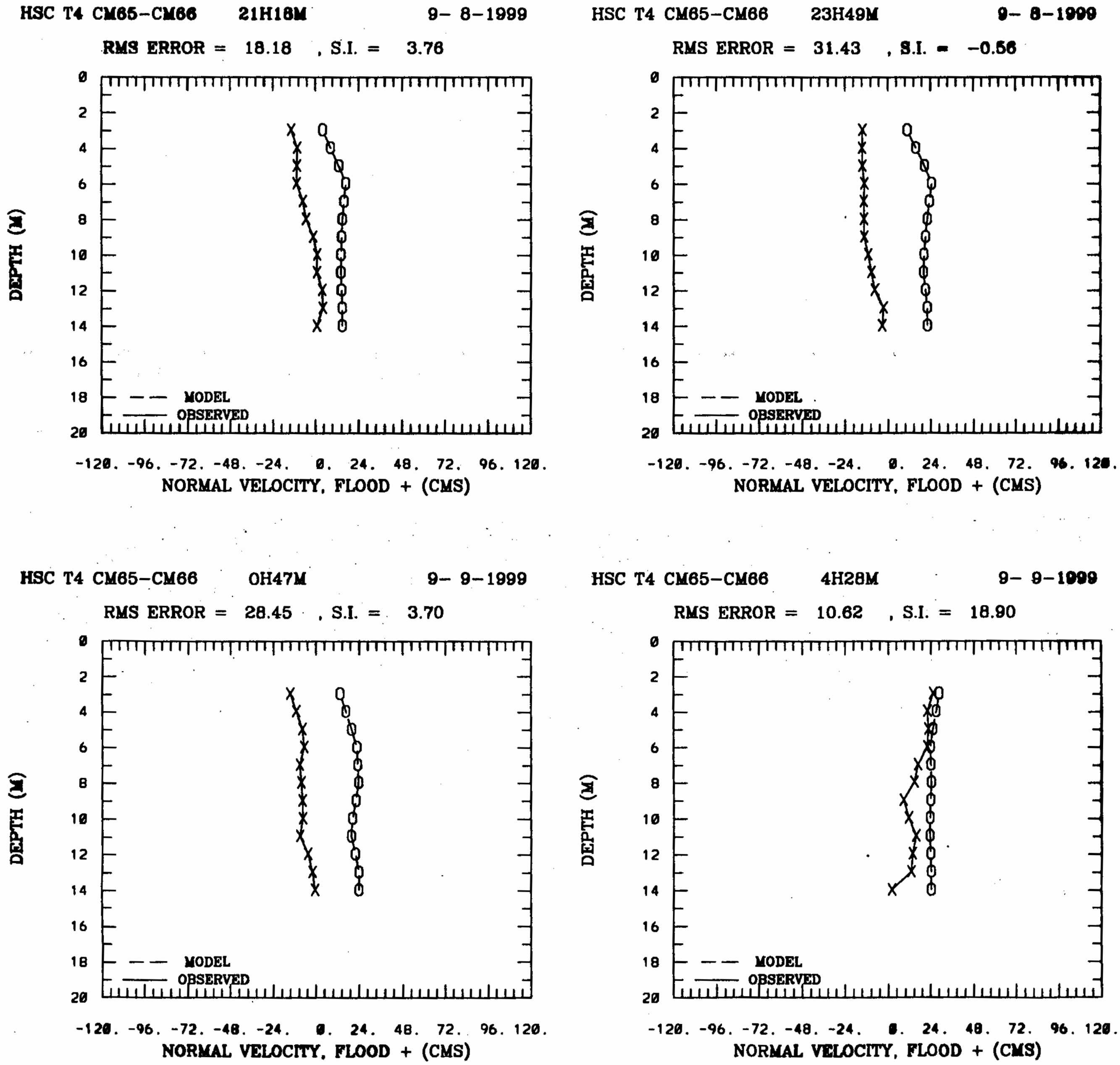


Figure 4.39 HSC T4 Normal Current Speed Level 1 and Level 5 Nowcast



Model dashed line marked by 0
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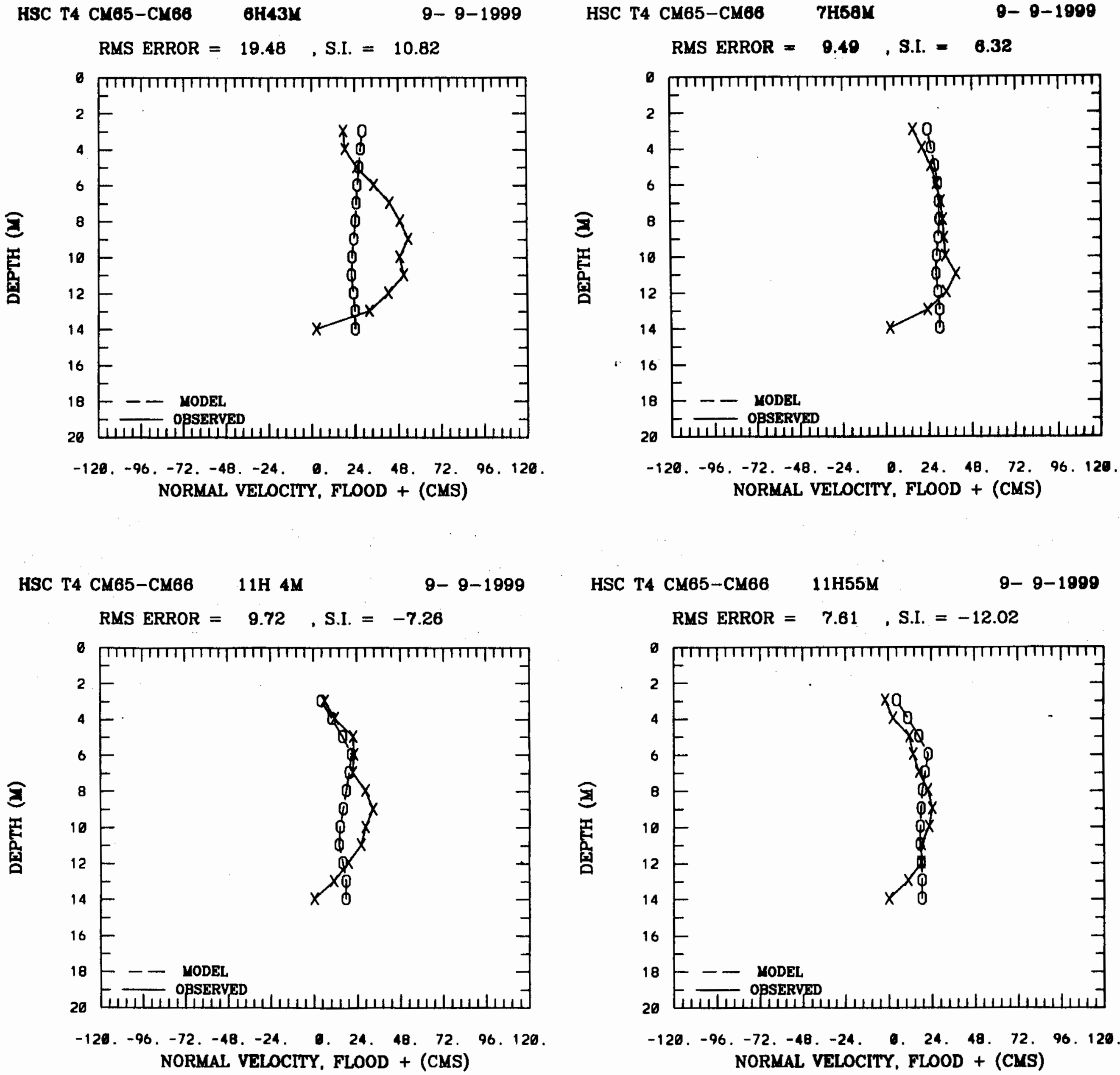
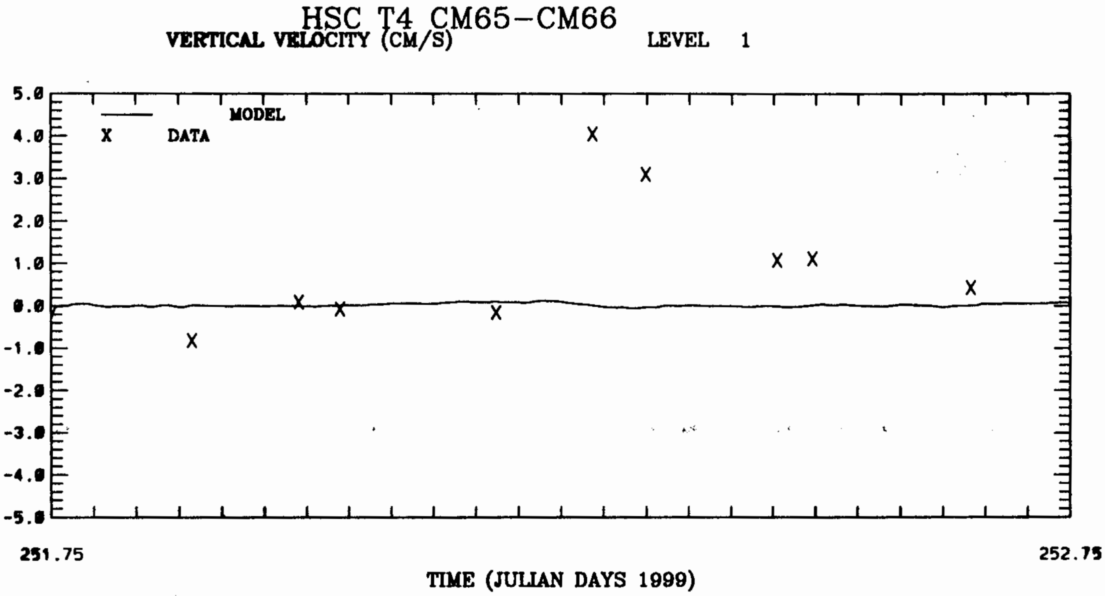
Figure 4.40 HSC T4 Normal Current Profile Set 1 Nowcast



Model dashed line marked by 0
Observation solid line marked by X

Figure 4.41 HSC T4 Normal Current Profile Set 2 Nowcast



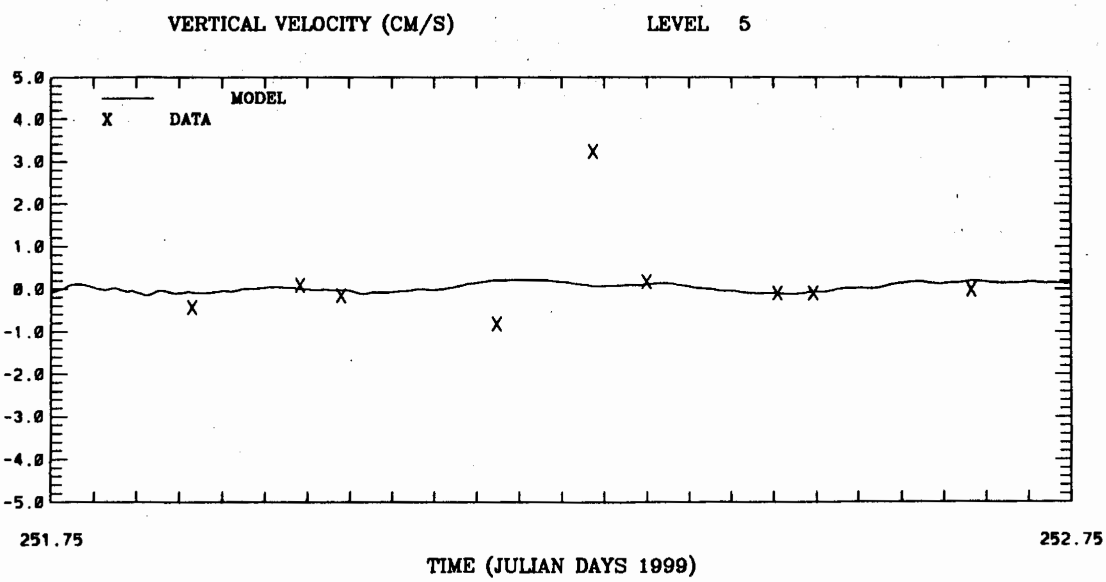
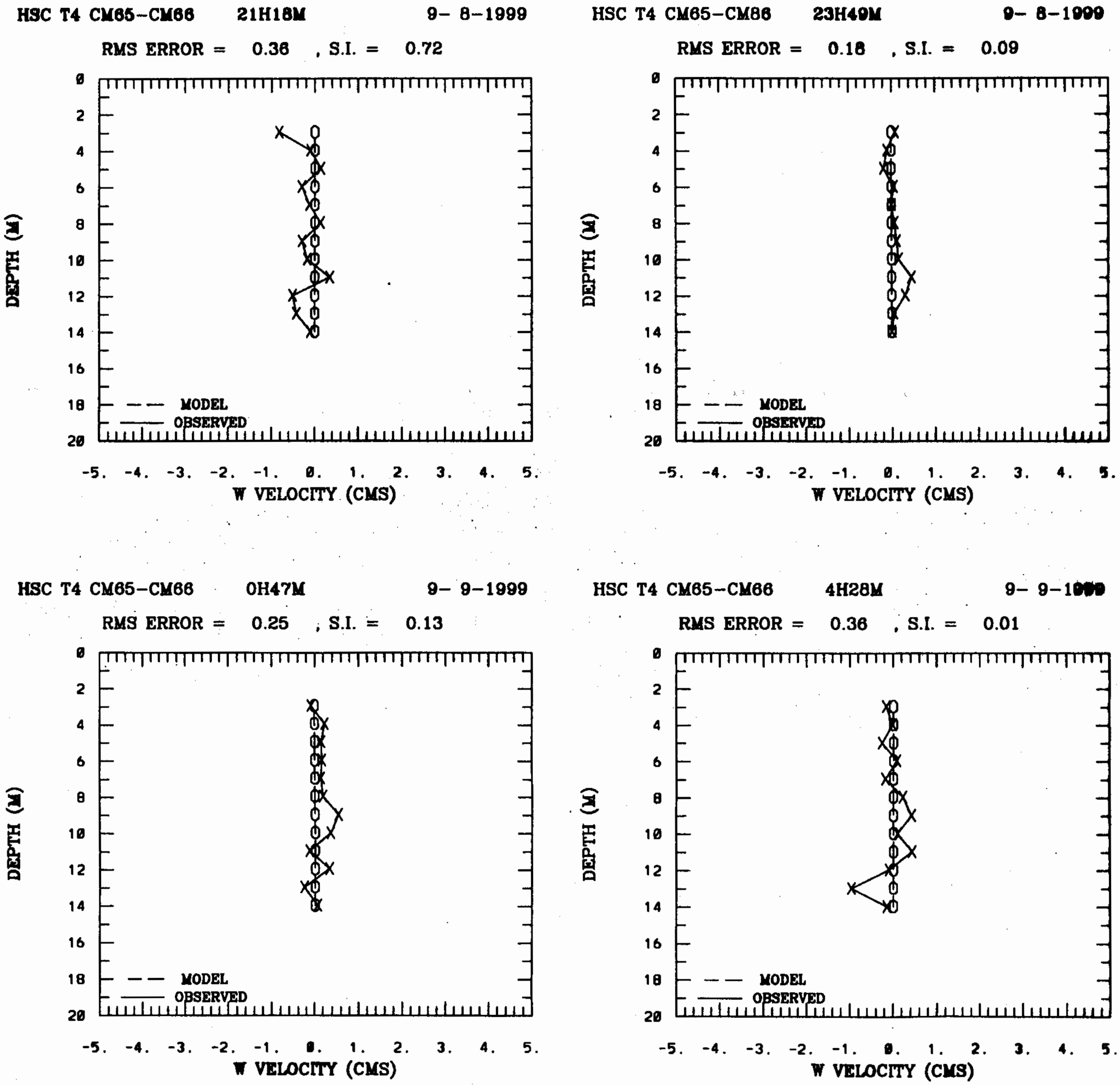


Figure 4.42 HSC T4 Vertical Velocity Level 1 and Level 5 Nowcast



Model dashed line marked by 0
Observation solid line marked by X

Figure 4.43 HSC T4 Vertical Velocity Profile Set Nowcast

5. CONCLUSIONS AND RECOMMENDATIONS

The high-resolution ADCP/CTD survey of a section of the Houston Ship Channel was performed with respect to tight timelines and schedules. To complete the study, it was necessary to develop several ADCP processing programs. Successful processing of towed ADCP data can now be accomplished in a greatly reduced time frame through the use of these programs. ADCP data analysis can now be completed within weeks rather than months after the completion of future surveys. The separation of the ADCP and CTD transects appears to have been not necessary. It is recommended in future transects that a combined ADCP/CTD transect be performed as was done on the CTD pass. The wooden ADCP mounting bracket appeared to work reasonably well but some strumming was noted near the end of the survey. It is recommended that a metal ADCP mounting bracket be used in subsequent surveys. The 1 s ensemble used in this survey results in a tremendous volume of data, which must subsequently be averaged. It is recommended that a 6 s ensemble averaging scheme be used during data collection.

It is recommended that additional surveys be performed at one-month intervals to further study Houston Ship Channel hydrodynamics. It is suggested that the vessel operate out of Galveston and proceed up to Morgans Point and return in one 8 hour survey period; thereby, occupying 5 - 10 equally spaced transects order 4-5 nautical miles apart. This would allow for monthly determination of the salinity distribution along the channel and provide additional velocity data for model validation.

Model results indicate that the stratification in salinity within the channel cannot be captured using the present initialization/assimilation scheme within the present grid and sigma coordinate scheme. Additional study is needed to confirm this model behavior, since the salinity stratification within the navigation channels had to be initialized and adjusted based on data outside the navigation channels due to lack of PORTS data within these areas. Methods for separate consideration of the navigation channel in the initialization and data assimilation procedures need to be considered. Ideally, additional bottom salinity measurements would be incorporated within the PORTS system. However, as an interim measure, the salinity adjustment should not be performed within the channel; e.g., the model should be allowed to develop the stratification in the absence of within channel data. The model developed salinity structure might be adjusted using a climatologically derived structure based on seasonal freshwater inflows. Several numerical remedies should also be investigated. One remedy would involve the use of a mixed level system as recently reported by Mellor et al. (1999) perhaps in conjunction with the use of high order compact difference schemes developed by Chu and Fan (1998). Alternatively, one might investigate the development of a partial barrier along channel boundaries within the internal mode of the HSCM. Of concern here would be the compatibility between the external mode and internal mode computations. With respect to water levels and overall current strengths and directions, the present system appears to produce reasonable results. If the salinity stratification problem can be reduced, it is anticipated that water level and current comparisons would also benefit. The further investigation of the vertical velocity issue in the context of further measurements and the consideration of a non-hydrostatic HSCM is warranted.

In the longer term, the development of an ongoing nowcast system, which would directly provide the initial conditions for many daily forecasts, more efficiently conducted with reduced processing time and more robust automated quality control of a PORTS expanded to include current, salinity, and temperature measurements off the entrance onto the near shelf, is recommended. The system should also include a monthly ADCP/CTD sampling strategy for the Houston Ship Channel.

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