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TECHNICAL NOTE

Results from Phase 1 of the Coastal Marine Demonstration Project: The Coastal Ocean

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TABLE OF ABBREVIATIONS

AVHRR - Advanced Very High Resolution Radiometer
AVN - Aviation weather forecast model
CMDP - Coastal Marine Demonstration Project
COFS - Coastal Ocean Forecast System
CSC - NOAA's Coastal Services Center
ECGM - East Coast and Gulf of Mexico wave model
ECW - East Coast Wave model
EMC - Environmental Modeling Center
ERS - Earth Resources Satellite
GIS - Geographic Information System
GOES - Geostationary Operational Environmental Satellite
HPC - Hydrometeorological Prediction Center
HRPT - High-Resolution Picture Transmission (from NOAA's polar-orbiting satellites)
MCSST - Multi-Channel Sea Surface Temperature retrieval algorithm
MIM - Marine Interpretation Message
MPC - Marine Prediction Center
NWS - National Weather Service
NCEP - National Centers for Environmental Prediction
NDBC - National Data Buoy Center
NESDIS - National Environmental Satellite Data ans Information Service
NOAA - National Oceanic and Atmospheric Administration
NODC - National Oceanographic Data Center
NOPP - National Ocean Partnership Program
NOS - National Ocean Service
NWGS - North Wall (of) Gulf Stream
OAR - NOAA's Office of Oceanic and Atmospheric Research
OFA - Navy's Ocean Feature Analysis
OMB - Ocean Modeling Branch
OSPD - Office of Satellite Data Processing and Distribution
SAB - Satellite Applications Branch
SSH - Sea Surface Height
SST - Sea Surface Temperature
TASC - The Applied Sciences Corporation
UTC - Universal Time Constant
WAM - Wave Model, presently operational at the NWS/NCEP
WSI - Weather Services International Corporation
XBT - expendable bathythermograph

1. Introduction

The Coastal Marine Demonstration Project (CMDP) is a joint activity involving a number of partners for the purpose of demonstrating the state-of-the-art in coastal marine forecasting. The CMDP is sponsored by the National Ocean Partnership Program and administered by the Office of Naval Research. This demonstration is limited to a small group of users which includes commercial shipping, Chesapeake Bay pilots, commercial fishermen, recreational boaters, the U. S. Navy, and the U.S. Coast Guard. A set of selected marine products has been distributed providing forecasts out to 24 hours for some products and longer for other products. The project is composed of two demonstration phases. The first phase took place between 16 June and 30 July 1999, and the second phase will take place during February and March 2000. The demonstration area covers a region off the U.S. East Coast from 32 to 42°N and out to 70°W, and includes the Chesapeake Bay. The partners involved in this project are Princeton University, the University of Rhode Island, the University of Maryland at Horn Point, The Applied Sciences Corporation (TASC), Weather Services International Corp.(WSI), and within NOAA, the National Ocean Service (NOS), the National Weather Service (NWS), the Office of Oceanic and Atmospheric Research(OAR), and the National Environmental Satellite Data and Information Service (NESDIS). Three NOAA organizations, NOS, NWS, and OAR, are responsible for producing the selected set of marine products which form the basis for this demonstration. These products include surface winds, precipitation, fog and visibility, water levels, waves, currents, sea surface temperature, surface salinity, and satellite-based ocean feature analyses. Most of these products take the form of forecasts which are produced by models. In some cases these models have been developed only recently and have not had the opportunity of being evaluated for extensive periods. The National Centers for Environmental Prediction (NCEP) of the NWS have the responsibility to provide product coverage of the coastal region whereas it is the responsibility of NOS and OAR to provide product coverage for the Chesapeake Bay. The products from NCEP that were selected for distribution during the first phase of this demonstration were surface waves, fog and visibility, sea surface temperature (SST), surface salinity, and surface currents. The models were developed and/or implemented within NCEP and are maintained by the Ocean Modeling Branch(OMB) of the Environmental Modeling Center. Quality control for these products for both phases of the demonstration was, and will be, provided by NCEP's Marine Prediction Center. This activity is discussed in section 7 of this report.

The university participation is to provide new improvements in ocean modeling which can be incorporated into the models which are being used in this demonstration. For the coastal ocean, the university contributions are related to developing new methodologies for ocean data assimilation for the Coastal Ocean Forecast System(COFS). In particular, Princeton University has developed a new method for assimilating surface elevation data from TOPEX and Gulf Stream path information from the Navy into COFS. This assimilation package was implemented at NCEP for the first demonstration and preliminary results using this assimilation software are discussed in this report in section 4. The private sector which includes TASC and WSI has the major responsibilities for project coordination, product distribution, and collecting and evaluating feedback from the users. Finally, the block diagram in Figure 1 summarizes the activities that took place during phase 1 by showing the flow of information from product generation, including product evaluation, to archiving and distribution of the products at the National Oceanographic Data Center (NODC), and then to WSI for final distribution to the users. Note that although this project is primarily based on providing model-based forecast information to the users, observations from a variety of sources were also acquired by WSI for distribution to the users. The loop will be closed when feedback from the users is received, summarized, and used as basis for making new improvements to the models and how the products are distributed.

2. System Reliability (Balasubramaniyan and Breaker)

NCEP's responsibility to the CMDP involved both product generation and product quality control. Timely product generation requires that the computer systems on which the participating models run be operating on schedule. Unfortunately this was not always the case, and system down time on several occasions resulted in CMDP products not being available for delivery on schedule. The models involved are the Eta model, the Fog and Visibility model which runs as part of the Eta model run, the Regional Wave Model, and the COFS which all run on NCEP's Cray C90 computer.

During the first phase a log was maintained that documented the performance of the computer systems which provided support for the CMDP. From that log the following problems were noted. During the first phase, major system failures were experienced by the C90 on June 22 and 25, and on July 28, 1999. Lesser delays related to the C90 occurred involving a power surge in one case and a disk crash on Cray4 in another case. Cray4 serves as a file server for the C90 for COFs and so problems with Cray4 frequently impact COFS. Overall, on at least 12 occasions, the COFS runs were completed later than scheduled resulting in delays of several hours or longer in each case in getting the products transmitted to NODC which served as the focal hub for the demonstration. During the first demonstration, a change was made to the operating schedule for COFS on July 8th which resulted in marine forecasters being able to access the forecasts from COFS several hours earlier each day. These forecasters provided the important function of quality control for the various CMDP products issued by NCEP. Overall, model operations ran more smoothly as experience accrued over the six-week period of the demonstration.

It is important to note that problems during the demonstration in getting products to the users on schedule were not limited to computer problems at NCEP. On July 29th, the file server at NODC went down for several hours causing major delays in posting all of the CMDP products at the WSI web site, and on a number of occasions, WSI was late in posting various products for the demonstration on their web site.

3. The Eta Model (Breaker)

All of the forecast models used in this demonstration require input directly or indirectly from the Eta high-resolution atmospheric forecast model (Black, 1994). Figure 2 shows the various models in the CMDP that depend on the Eta model for input. The Eta model provides surface momentum flux for the Regional Wave Model, moisture parameters for the Fog and Visibility Model, and momentum, heat, and moisture fluxes for the Coastal Ocean Forecast System. The remaining models are run at NOS but also require information from the Eta model.

The current version of the Eta model has 45 levels in the vertical and 32 km horizontal resolution. The vertical coordinate system is similar to the terrain-following sigma coordinate system but with certain improvements in the vicinity of steep topography. Of particular interest for ocean model applications, the bottom boundary layer is well-resolved with the thickness of the lowest layer being only 10 meters. The primary prognostic variables in the model are temperature, the u and v wind components, specific humidity, surface pressure, and turbulent kinetic energy. At the present time, forecasts are made out to 48 hours. The radiation package has been significantly improved over the past five years yielding major improvements in our calculation of surface heat fluxes.

4. Evaluation of COFS (Thiebaux and Breaker)

a. Short-term coastal ocean forecasting for the North Atlantic with real-time data assimilation

As mentioned earlier, it was NCEP's responsibility to provide forecasts of surface waves, fog and visibility, and sea surface temperature (SST), surface salinity, and surface currents during phase 1 of the CMDP. Forecasts of sea surface temperature (SST), surface salinity, and surface currents, in particular, were produced by the Coastal Ocean Forecast System. The COFS has been under development at NCEP since 1993 and is based on the Princeton Ocean Model (Blumberg and Mellor, 1987). This model uses a curvilinear orthogonal grid in the horizontal to better approximate the coastline and a terrain-following sigma coordinate in the vertical. The model's horizontal resolution varies between 20 km offshore and 10 km near the coast. In the vertical the model has 19 levels. The model is run daily to produce a nowcast and a 24-hour forecast of coastal ocean conditions (three-dimensional fields of temperature, salinity, and currents), using surface wind and thermal forcing from NCEP's high resolution, regional atmospheric Eta model (Black, 1994). COFS has been running with routine assimilation of sea surface temperatures (SSTs) from the AVHRR, ships, and buoys, using an algorithm that produces a temperature correction field for the top model level and corrections through the mixed layer by extrapolation of the surface correction field (Kelley and Behringer, 1999).

As part of the CMDP, a new data assimilation package developed at Princeton University for the ingestion of data locating the north wall of the Gulf Stream (NWGS) and TOPEX altimeter data (Mellor, Ezer and Kim, 1998) was added to existing surface-temperature-assimilation software. Gulf Stream north-wall-location data were provided by the Naval Oceanographic Office and quality-controlled TOPEX data were provided by NOAA's Satellite Altimetry Lab. These are assimilated with an algorithm based on correlations of SST and sea surface height (SSH) anomalies with subsurface temperatures and salinities taken from the Princeton Ocean Model itself, and run just prior to the assimilation of surface temperature data.

In order to study the impact of the addition of altimeter and NWGS data, two model runs were made daily, beginning May 1, 1999: a control run with the model using surface forcing and SST data assimilation only, and a parallel run with the addition of the altimeter and Gulf Stream location data. In each case, the models produced nowcasts and 24-hour forecasts of temperature, salinity and current fields. Evaluations of the surface and subsurface temperatures from the models have been made by comparing model output to data obtained from buoys and expendable bathythermographs (XBTs).

b. The impact of assimilating ocean data

Assimilation of the additional data including the north wall of the Gulf Stream and the SSH anomalies from the TOPEX altimeter, has shown significant change in the level of agreement with temperature profiles obtained from XBTs. As cases in point, Figs.3a and 3b show co-located temperature profiles from XBTs and virtual profiles created from model fields with SST data assimilation-only(COFS3.2), and with the addition of the TOPEX altimeter and Gulf Stream path assimilation (COFS3.4). In Fig. 3a, the virtual profile created using COFS3.4 is somewhat closer to "reality" than COFS3.2 at least for depths between about 30 and 50 meters. In Fig. 3b, the COFS3.4-generated profile is clearly closer to reality from just below the surface down to almost 1000 meters except for the region between about 20 and 50 meters.

The agreement between COFS' surface temperatures and SST reports from moored buoys in the model domain, as shown by a comparison of time series plots and statistical calculations, using independent data sources, did not change significantly for COFS3.2 and 3.4. This result is consistent with our expectation that the primary impact of assimilation with COFS3.4 should be at depth because the SSH anomaly vs T(z) and SSH anomaly vs S(z) correlations are much greater at depth than they are near the surface. During a parallel test run with the addition of the NWGS data only, differences with the fields produced with SST data assimilation only were indiscernible, clearly implying that the major impact from COFS3.4 is due to the altimeter data from TOPEX.

The most profound impacts of the combined ingestion of SST, SSH anomaly, and NWGS data, are evident in the appearance of eddies in COFS nowcast and forecast temperature and velocity fields. These were evaluated by visual comparison with AVHRR and GOES images. Figs. 4a and 4b show velocity fields for the two versions of the model: Fig. 4a shows the 1-meter velocity field produced by the control run with temperature-only assimilation, and Fig. 4b, the product of the run including assimilation of TOPEX altimeter and NWGS data. The surface velocity field from inclusion of the TOPEX and NWGS data reveals an anticyclonic eddy just north of the Gulf Stream, centered at 39.5N and 65W, which is not present in the control-run velocity field. Fig. 5, which shows independent data from the imager on the GOES-8 satellite, depicts the eddy as a meander about to pinch off from the Gulf Stream. Profiles of salinity (Fig. 6) taken from COFS3.2 and 3.4 at the eddy location (39.5 N and 65 W) clearly show the impact of the altimeter data assimilation at depths from just below the surface down to almost 700 meters. Salinities are as much as 0.5 ppt higher inside the eddy identified using COFS3.4.

c. Quality of the COFS-generated forecast fields

SST, surface salinity, and surface current forecasts were produced by COFS as part of the CMDP. The quality of the SST forecasts was generally acceptable. But problems are encountered with locating the Gulf Stream boundaries correctly, which is not an unexpected finding. This topic is discussed in more detail in section 8 of this report. Gulf Stream path assimilation apparently did not correct this problem although it may have helped in areas beyond the project domain. Surface salinity forecasts, of course, could not be verified . However, based on reports from the MPC, surface salinities did portray the major plumes that emanate from New York Harbor, and Delaware and Chesapeake Bays, and they did respond rather realistically to surface wind forcing on several occasions. Unfortunately, no major precipitation events occurred during the demonstration and so essentially no changes in surface salinity away from the coast could be, or were, observed. With respect to the surface currents, more serious problems were detected, particularly over the continental shelf between Cape Hatteras and Long Island. In this region, the prevailing surface flow is to the south out to the shelf margin and beyond into the Slope Water region. Figure 7 shows a surface current forecast for the CMDP area for July 15, 1999. In the area between Cape Hatteras and New York, the shelf flow is clearly depicted as being to the northeast all the way from the coast out to the Gulf Stream. In the absence of strong surface wind forcing from the southwest this flow pattern is definitely at odds with the expected circulation in this area. A number of possible explanations for this important discrepancy are being explored which include (1) the impact of freshwater discharge from the coast, (2) dominance of the Gulf Stream circulation in the region, and (3) sensitivity of the shelf and Slope Water circulations to the specification of boundary conditions along the open eastern boundary at 50°W.

d. Conclusions

Successful prediction of ocean state with a numerical model has lagged far behind weather prediction despite the availability of satellite measurements and imagery of ocean surface conditions. At depths below the surface, ocean data suitable for real-time assimilation are sparse, indeed. During the CMDP, technology for assimilating satellite-derived surface observations with *in situ* observations has been successfully tailored to a model that integrates the state of the ocean, for routine production of real-time nowcasts and forecasts. This project has provided the opportunity to demonstrate that the assimilation of data available in real-time, can produce ocean fields that are in good agreement with independent observations. Although assimilation of sea level heights derived from TOPEX altimeter reports, in particular, has contributed significantly to the modification of the subsurface model temperature and salinity structures, the track spacing of adjacent TOPEX orbits(~ 300 km) is too coarse to capture many of the major features associated with the Gulf Stream. Future plans for altimeter data assimilation will include ERS-2 data, which will give more complete coverage of the Gulf Stream System. Finally, both improvements in specifying the boundary fluxes as well as in data assimilation will be required in order to make significant improvements in model performance.

5. Evaluation of the Regional Wave Model (Chao)

The wave model which produces wave forecasts for the CMDP is the current NCEP operational East Coast and Gulf of Mexico wave model (ECGM). The model is based on the WAM model Cycle-4 version. The model solves the energy balance equation for the frequency-direction ocean surface wave spectrum. We have ignored the effects of currents such as the Gulf Stream due to lack of data or model output at the required resolution. The domain of the model extends from 98 to 65 W, and from 15 to 45 N. The grid resolution is 1/4 deg. by 1/4 deg. The boundary input wave data are provided by a separate model which covers the Atlantic Ocean with a grid resolution of 1 deg. by 1 deg.

Wind data derived from NCEP's Aviation atmospheric model(AVN) are used to drive the Atlantic model, and the meso-Eta model (Eta32) winds are used to drive the ECGM model. The model runs twice daily at 00 and 12 UTC. Each cycle produces forecasts out to 48 hours at three-hour intervals(Chao,1997).

For the evaluation of model(ECGM) performance in the CMDP area during June and July 1999, the significant wave heights, wind speeds, and directions produced by the model are used together with buoy measurements by means of time series and monthly statistics. Figure 8 shows the locations of NDBC buoys used in the evaluation.

Figures 9(a) and 9(b) show time series plots of buoy measurements and 24-hour model forecasts for June 1999 at NDBC buoy stations 44004 and 44014, respectively. Buoy 44004 is located offshore in deep water at 70.7 W, 38.5 N and 44014 is located off Virginia Beach in a relatively shallow depth of about 50 meters at 74.8 W, 36.6 N. In general, the forecast wave heights agree well with the observed trends. However, the variation of forecast wave height in time is not dynamically sensitive as shown by the measured data, i.e., the forecast wave height does not rise or fall as fast as the observations. Similar results can also be seen in the time series for July 1999, shown in figures 9(c) and 9(d).

Scatter plots and error statistics for buoy vs model differences are presented for two regions. One region consists of deep water buoys 41001, 41002 and 44004. The other region include buoys in coastal waters at depths of less than 130 meters. Figures 10(a) and 10(b) are scatter plots and error statistics of the 24-hour model forecasts for June 1999 for the deep water region (denoted as CMDPd in Fig. 10(a)) and for the coastal region (denoted as CMDPs in Fig. 10(b)), respectively. As shown by the wind speed and direction plots, the wind input to the wave model contains substantial errors. In the deep water region, wind speed is generally overpredicted (positive bias), while in the coastal region, it is slightly underpredicted (negative bias). In contrast, the wave heights in both regions show considerable negative bias. The problem of model's under-prediction of wave heights becomes more notable when measured wave heights are higher than 1.5 meter or so. It can also be observed from these figures that in deep water, a positive bias in wind speed is followed by a less negative bias in wave height while in the coastal waters, a negative bias in wind speed increases the negative bias in wave height. Similar results also are shown in July 1999 plots (Figures 10(c) and 10(d)).

The results of the evaluation indicate that better wind input to drive the wave model is required. Also improvements in the wave model physics to provide a more rapid response to the wave height variation in time is desirable. A new wave model which has been shown to have an overall improvement in numerical prediction has been developed and will be operationally implemented (Chao et.al, 1999). It is expected that better performance in producing wave forecasts will occur with the new model during phase two of CMDP.

6. Evaluation of the Fog and Visibility Model (Brown and Burroughs)

During the CMDP, the Satellite Analysis Branch (SAB) of NESDIS collected data which included:

- GOES-8 visible satellite imagery at 1215 and 1815 UTC with current weather observations, cloud ceilings and visibility overlaid.
- Copies of the National Weather Service coastal visibility products from the Internet.
- The 1800 UTC surface analysis.

The SAB of NESDIS and the OMB of NCEP are in the process of analyzing the imagery for obstructions to visibility such as fog, haze, etc. A comparison will be made of computer generated fog and visibility guidance products with a view to developing statistics to determine how well the products performed. In this report, we present two examples: the first case represents what we consider to be a good Fog and Visibility forecast, and the second case represents a forecast of lower quality.

The first case is from July 2, 1999. Figure 11 shows the Eta visibility product for the NOPP demonstration area for the 12-hour forecast from the 0000 UTC model run on 2 July 1999. Patches of lowered visibility can be seen south of Long Island and along the Delmarva Peninsula. The outer contour on the figure is 7 n. mi, while the inner contour corresponds to 3 n. mi. A satellite image from 1215 UTC (Fig. 12) showed considerably more fog and lowered visibility[1]. Fog patches can be seen over Long Island Sound, along the entire southern coast of Long Island, along the entire coast of New Jersey, over Delaware Bay, and over portions of Chesapeake Bay. Hence, even though the aerial extent of fog has been underestimated, the model showed the potential of providing guidance for areas with low visibility conditions. This assessment is corroborated by the Marine Interpretation Message from 0900 EDT from the Marine Prediction Center.

The second case is from July 16 -17,1999, which is the time surrounding the crash of John F. Kennedy, Jr's plane in the waters near Martha's Vineyard, Massachusetts. The

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[1]Light fog corresponds to a visibility of 3 n.miles whereas dense fog has a visibility of 0.5 n.miles (or less).

1815 UTC GOES-8 visible satellite analysis from July 16 showed fog and haze extending from the New Jersey coast to the coastal areas of Long Island and Cape Cod. Observed visibilities were 7 - 10 n mi (Fig. 13). The next morning the haze was more dense with low level clouds present. The visibility had been reduced to 5 - 10 n mi. The Eta visibility products (not shown) verifying at 1800 UTC July 16 and at 1200 UTC July 17 showed no reduction in the visual range at either time anywhere in the CMDP area.

7. Marine Prediction Center Evaluation of the Coastal Marine Demonstration Project (Vukits and Kelly)

During the period of the CMDP, the Marine Prediction Center (MPC) evaluated five forecast fields:

- Regional Waves from the East Coast Wave Model (ECW)
- Visibility from the Fog/Visibility Model
- Sea Surface Temperature from the COFS
- Sea Surface Currents from the COFS
- Sea Surface Salinity from the COFS

The MPC staff wrote brief subjective evaluations of each parameter that were summarized and included in the daily 1300 UTC Marine Interpretation Messages (MIMs), which were disseminated to the field.

a. Regional Waves

Overall, the East Coast Wave model (ECW) forecast wave heights, wave periods, and swell directions off the mid Atlantic coast were very comparable to those forecast by the NCEP NOAA WAM and WAVEWATCH III models. The biggest discrepancy between these models was likely a direct result of the fact that the ECW waves are generated from Eta model winds while the WAM and WAVEWATCH III wave forecasts are generated from AVN model winds. With the CMDP taking place during the early summer, the number of significant (gale force or higher) weather events was very limited. The most significant weather was related to moderately strong warm frontal passages. The most persistent ECW trend noted in the MPC evaluation was that in warm air advection scenarios (south to southwest surface winds), the ECW had a bias, versus the WAM and WAVEWATCH III, towards under forecasting the wave heights. Also, with low seas initially, the ECW was often slow to respond and to forecast increasing waves when the surface pressure gradient and associated winds were forecast to increase. For example, from the 2 July 1999 MIM,

- IN THE MODERATELY STRONG (25-30 KT) S-SW GRADIENT NOW OFF THE MID ATLANTIC COAST THE ECW MODEL HAS INITIALIZED THE SEAS TOO LOW. THEN VERSUS THE 00Z NOAA WAM AND WAVEWATCH II MODELS THE ECW...LIKELY DUE TO THE INITIALIZATION...APPEARS TO BE UNDER FORECASTING THE SEAS ESPECIALLY THROUGH THE FIRST 36HRS. THE ECW WAVE PERIOD AND DIRECTION FORECASTS LOOK REASONABLE.

Similar to the NOAA WAM and WAVEWATCH III models, it was found that the ECW tends to under forecast wave heights when northeasterly surface winds set up counter to the Gulf Stream. For example, from the 23 June 1999 MIM,

- THE ECW DID A GOOD JOB IN THE NORTHERN CANYONS WITH THE SEAS BUT MISSED THE COUNTER CURRENT HIGHER SEAS OVER THE GULF STREAM IN THE S CANYONS AND OVER WATERS E AND S OF 1000 FMS...NE OF CAPE HATTERAS. THE ECW FORECAST 3 TO 4 FT BUT OBSERVED SEAS WERE 6 TO 9 FT NEAR THE GULF STREAM AND 5 TO 6 FT IN THE CANYONS. THE ECW SWELL DIRECTION AND PERIOD FORECASTS LOOKED OK.

This is likely a direct result of the mesoscale nature of the instability in the vicinity of the Gulf Stream not being accounted for in the form of higher Eta surface winds.

In short, the ECW model behaved well. The bias was toward low values, both in the initialization and in the forecast. With light seas initially, the model was slow to respond to increasing conditions associated with fronts late in the forecast period. This was particularly noted between July 21-24. Comments that the values were reasonable, but on the low side, were common.

b. Fog/Visibility

The MPC found the Fog/Visibility Model far superior to the OMB's Statistical Fog and Visibility Model. This comparison may not be fair since the statistical model is not applicable to the coastal areas. The Fog/Visibility Model's accuracy versus the GOES-8 3.9-11.0 micron imagery and surface observations, and its method of display, made it much more useful to the operational forecasters than the statistical model. The following are some of the tendencies of the Fog/Visibility Model:

- The model tended to over forecast the areal extent of reduced visibilities south of 35N.
- The model tended to forecast visibilities that were too high in the vicinity of frontal boundaries and areas of precipitation.
- Under strong warm air advection, with moderate to strong southwest winds and high surface dew points, the model tended to under forecast the areal extent of reduced

visibility over the northern most portion of the domain. For example, from the 2 July 1999 MIM,

- LATEST 11-3.9 MICRON IMAGERY INDICATES A NARROW BAND OF FOG EXTENDING E FROM NANTUCKET ACROSS GEORGES BANK. THE FOG/VISIBILITY MODEL DOES FORECAST FOG IN THIS AREA BUT DOES NOT HAVE THE AREAL EXTENT LARGE ENOUGH. OTHERWISE THE MODEL FORECASTS COASTAL FOG FROM NEW JERSEY NORTHEASTWARD DURING THE NIGHT TIME HOURS THRU 48HRS WHICH LOOKS VERY REASONABLE BASED ON THE EXCEPTIONALLY HIGH SURFACE DEW POINT FORECASTS.

In general, the Fog/Visibility Model picked up restrictions to visibility associated with precipitation more reliably than restrictions associated with warm air advection over the cooler waters. The model's forecast values were seldom extremely low (1 nm or less) and the conclusion would be that extremely low visibility does not occur in the summer, or that the model does not pick up that feature. Since the model frequently picked up features generating 3 nm visibility, either the resolution of the model blends the values too much, or statistically there is an insufficient database to forecast the lower visibilities. In either event, it is the lowest visibility conditions that are the most significant for mariners, so this is an important issue to resolve.

For future trials, the MPC would like to see the New England waters included in the testing of this parameter in particular. The sea surface temperatures in the Gulf of Maine and Georges Bank areas are significantly lower than in the waters south of 40N, and hence the warm air advection scenarios would be more frequent and significant. New England summer fogs are often notoriously dense.

c. Sea Surface Temperature

Early in the demonstration, anomalously high sea surface temperatures (SST) were consistently being forecast by the COFS in the waters off Narragansett Bay. There was also an anomalous bulge with higher SST along the left side of the Gulf Stream near 75 W. Another feature which developed toward the end of July was the weakening of the temperature gradient on each side of the Gulf Stream. Observational data in the vicinity of the stream was inadequate to be sure if this was a model problem, or perhaps reality.

Overall, compared to the Navy's Oceanographic Features Analysis (OFA), the COFS SSTs were very representative. The COFS SSTs did tend to run higher than the Navy's OFA northwest of the Gulf Stream to the coast. The COFS SSTs were much higher near the coast than the Navy's OFA, but this is probably due to the higher resolution of the COFS. For example, from the 27 June 1999 MIM,

- THE COFS SSTS IN THE VICINITY OF THE GULF STREAM LOOK REASONABLE COMPARED TO THE LATEST NAVY OFA ANALYSIS. N OF GULF STREAM THE COFS HAS HIGHER SSTS...ESPECIALLY NEAR THE COAST...THAN THE LATEST OFA. THE COFS IS ALSO STILL FORECASTING AN ANOMALOUSLY HIGH PLUME OF SSTS OUT OF NARRAGANSETT BAY.

d. Sea Surface Currents

With a general lack of observational data, evaluating the COFS surface currents was difficult. What general conclusions that could be drawn include the following. The flow associated with the Labrador Current, bringing a flow from the northeast of cooler water into the mid Atlantic waters north of 35N, was not generally apparent. This is another example of where expanding the area of the study to include the New England waters might have enabled us to track the origin and the behavior of that current. The prevailing winds in June and July were from the southwest, so perhaps the weak outgrowth of the Labrador Current was overridden by the wind generated currents, but it is difficult to verify in the absence of data.

The prevailing southwest winds during the project may also explain why the COFS surface currents were predominantly from southwest to northeast between Cape Hatteras and Long Island, which was opposite to the expected prevailing current. There was also a general feeling that the COFS currents associated with the Gulf Stream were underestimated, but, again, ground truth data were lacking to verify this impression.

e. Sea Surface Salinity

With no sea surface salinity observations available for comparison, the MPC was limited to observing how the plumes of low salinity water (from the bays and rivers) behaved in the ocean environment. Generally the plumes were advected by the surface winds as expected, but sometimes the growth was not consistent with the wind direction forecasts. For example, from the 20 June 1999 MIM,

- THE COFS SEA SURFACE SALINITY FORECAST SHOWS LOWER SALINITY VALUES EXITING CHESAPEAKE BAY AND BENDING SOUTHWARDS TOWARDS CURRITUCK SOUND IN NORTH CAROLINA. HOWEVER...FOR THE SAME FORECAST TIME BOTH THE ETA AND AVN MODEL WINDS ACROSS THIS AREA ARE FROM THE S AND SE...SO WOULD EXPECT THE LOWER SALINITY VALUES TO BE BENDING NORTHWARDS.

Looking at the forecast parameters, from the CMDP, in an operational forecast mode allowed the MPC forecasters to more comprehensively evaluate their value in real time. The MPC contribution was critical in identifying problems before releasing the guidance to the users.

8. Summary of the AVHRR Imagery from the Coastal Services Center (Waters)

a. Background

The role of the Coastal Services Center (CSC) during the Coastal Marine Demonstration Project (CMDP) was to analyze Advanced Very High Resolution Radiometer (AVHRR) imagery and compare the features and SSTs derived from the imagery with the forecasts made by the COFS. The afternoon NOAA-14 AVHRR data were downloaded on CSC's High-Resolution Picture Transmission (HRPT) station and processed to generate SST images each evening. The forecasts from the COFS model gridded output were downloaded from an ftp site each evening and processed for comparison. Two types of comparisons were performed, (1) an automatic point-by-point extraction of SST values from the imagery to match the COFS data points, and (2), a manual examination of the spatial patterns exhibited by the two data sets.

b. Processing

The AVHRR data were converted to SSTs using a multi-channel sea surface temperature retrieval algorithm (MCSST) appropriate for the NOAA-14 sensor. The resulting values were byte-scaled and output as geo-referenced, tagged image file format (geoTIFF) images that could be used in a Geographic Information System (GIS). The images were also produced in lower quality JPEG format and made available to the CMDP project web-site. From the SST imagery, gradient SST images were calculated to aid in feature identification and to quantify how rapidly temperatures changed across thermal fronts. Clouds were flagged using an SST estimation cutoff (below -6°C is cloud), a high channel 2 threshold(above 85 counts is cloud), and a high gradient test for both SST and channel 2.

The COFS data were extracted from the GRIB file format and processed to generate SST contour maps with 1°C intervals. The lines for these contour maps were extracted and put in shapefile format for use in a GIS. In addition the forecasts for the current fields, SST, and salinity were sub-sampled by a factor of 2 and put in a table format that could be read by the GIS system.

Moored-buoy data from NDBC provided an additional check on the SSTs to compliment the AVHRR imagery. These data were downloaded from NDBC's internet site each night and processed to provide data points matching the time of the AVHRR overpasses.

A program was written to extract the SST values at the COFS locations from the geoTIFF files for statistical comparisons. For each point, the average of the nine pixels nearest the COFS location was calculated. If any of these nine points was flagged as a cloud or land, an invalid retrieval was returned. Despite the cloud flagging routines, there were many cases of cloud contaminated pixels with low SST values that were not flagged and therefore some of the AVHRR data in these comparisons will be inaccurate. As a result, some type of filtering will need to be applied to the comparison files before useful statistics can be derived.

c. Procedures

Each day(excluding weekends), the COFS data and SST imagery were compared in a GIS-like system. The system was written in JAVA to allow platform independence and was designed to allow the representation of vector fields. The user can pan and zoom interactively and display the image-based SSTs at any point by simply moving the mouse. A typical session would begin with loading the SST image, turning on a graticule (lat-lon lines), turning on the SST contour lines and looking for features that did or did not match. Notes were made on features such as bulls eyes in the COFS contours where the AVHRR was uniform, mismatches on the path of the Gulf Stream, sharpness of the Gulf Stream boundaries, eddy locations, and general temperature agreement.

With the experience gained from the evaluations, routine comparisons of the COFS forecasts with the SST retrievals from the AVHRR were initiated. This became particularly important as the ocean warmed and it became difficult to see the eddy features adequately from the 1 °C contours. The currents were helpful in identifying the forecasted eddies.

In addition to performing the analyses, an image of the composite information was saved in the JAVA GIS that formed the basis of the analysis. The written descriptions and the saved images were provided to the CMDP, enabling other project participants to address problems identified in the forecasts.

d. Evaluation

COFS has succeeded in the goal of predicting the general features of the ocean correctly with approximately the right temperatures. While there is room for improvement, as detailed below, the COFS forecasts provided a remarkably good picture of the ocean conditions.

The most serious and persistent problem noted was the inability of COFS to match the high thermal gradient on the north side of the Gulf Stream. The gradient in COFS was often only 1/4 or less than the gradient seen in the AVHRR imagery. Since this is one of the major features in the western north-Atlantic, improvement in this area would do much to build confidence in the forecasts.

We often found that the forecasted path of the Gulf Steam was close, but not identical, to the AVHRR observed path. An example of such a path mismatch is shown in Figure 14 where a bulge in the model-produced Gulf Stream North Wall occurs northeast of Cape Hatteras. Also the weaker gradient in SST mentioned above along the North Wall is clearly evident in the model-generated SST field. Additionally, the eddies were often in the wrong locations. Eddies that are close to the Gulf Stream have an effect on its path, often causing it to turn. If an eddy in the model is in the wrong location, it will not be influencing the Gulf Stream in the right place or direction and the Gulf Stream will not take the same path as seen in the imagery. Without satellite imagery to identify and locate the eddies, it would be very difficult to get them in the correct place in the model. An example of the surface currents from COFS superimposed on an AVHRR image for July 26, 1999 is shown in Figure 15. The core of the Gulf Stream is clearly located too far south in the model in the region just northeast of Cape Hatteras.

9. Conclusions and Recommendations

During the first phase of the CMDP there were no major weather events that could be used as a basis to examine model performance under extreme conditions. Based on the six-week demonstration period from June 16th through July 30th, 1999, the overall reaction to the products generated during the CMDP by forecasters and users alike was generally favorable. However, each of the forecast products from NCEP had certain problems which were identified by the MPC forecasters and analysts from the CSC. With respect to wave forecasts from the Regional Wave Model, there was a tendency to under forecast significant wave heights during periods of warm air advection and when winds from the NE develop in opposition to the Gulf Stream. With respect to the Fog and Visibility Model, there was a tendency to over forecast the areal extent of reduced visibilities south of 35°N. There was also a tendency for the model to forecast visibilities that were too high in the vicinity of frontal boundaries and areas of precipitation. Problems were also encountered with the products from COFS, but due to the lack of data it was often difficult to document the shortcomings in model performance. However the following problems were noted. A persistent problem with the SST forecasts was the inability of COFS to match the high thermal gradient on the north side of the Gulf Stream. Also, an unrealistic "bulge" occurred near 73°W with higher SSTs being forecast between the Gulf Stream and the coast. With regard to the surface currents, flow associated with the Labrador Current extension, which transports cooler, fresher waters from the northeast into the mid-Atlantic Bight north of 35N, were not generally apparent. In this regard, predicted flow on the continental shelf between Cape Hatteras and Long Island was consistently to the North whereas the expected prevailing circulation in this region is to the South. A number of possible explanations for this discrepancy have been proposed and will be examined. Although there was no salinity data available for comparison, the low-salinity plumes off Chesapeake Bay, Delaware Bay, and New York Harbor were often advected by the surface winds as expected, but sometimes their behavior was not consistent with the wind direction forecasts.

The models which have been in use and thus under scrutiny for the longest time fared the best. In this regard, fewer problems with regard to the Regional Wave Model were noted than for either the Fog and Visibility Model or the COFS model. In view of the technical difficulties associated with forecasting the physical state of the coastal ocean it is not surprising that several major problems with the COFS in particular were noted. A number of major technical issues must be addressed before COFS reaches the point where it can be considered ready to become fully operational. One of the biggest problems facing COFS at this point is data assimilation. Although significant progress has been made in this area, much more work still needs to be done. Both the lack of subsurface data and suitable methodologies for ocean data assimilation are pressing issues. The problems which have been identified during the first demonstration will serve as a basis for making improvements to these models in the future. Some of these improvements are expected to be in place by the time the second phase of the CMDP is underway. It is anticipated that improvements in system reliability should, and will, accompany the improvements which are made to the models. Further, the period of the second demonstration takes place during the atmospherically active winter season which will provide additional insights into the performance of the models involved.

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Figure Captions

Figure 1. A block diagram indicating the flow of information from model forecast generation through distribution to the users during Phase 1 of the Coastal Marine Demonstration Project.

Figure 2. A block diagram showing the various models and the inputs they require from the Eta atmospheric forecast model.

Fig. 3. XBT and COFS temperature soundings, in which COFS3.2 is the control, with assimilation of surface temperatures only and COFS3.4 is run with addition of TOPEX and NWGS data.
a. (37.38 N, 52.07 W) on 5/17/99
b. (39.87 N, 52.47 W) on 7/05/99.

Fig. 4a. Velocity field at 1 meter depth, 3 June 1999, produced by COFS with surface temperature assimilation only.
b. Velocity field at 1 meter depth, 3 June 1999, produced by COFS with additional assimilation of surface heights derived from TOPEX altimeter data and the Gulf Stream path location data.

Figure 5. GOES-8 composite temperature image for the NW Atlantic, with June 2 and 3 data. (provided by R. Legeckis, Office of Research and Applications, NESDIS)

Figure 6. Salinity profiles from COFS with SST data-only assimilation (solid curve), and with the addition of the TOPEX altimeter and Gulf Stream path data (dashed–dot curve) created at the center of an eddy located at 39.5 N and 65 W for June 3, 1999.

Figure 7. A surface current forecast from COFS for July 15, 1999 displayed at the WSI website during the CMDP. Direction of predicted flow is indicated by streamlines superimposed on shading which indicates the speeds (the original shading was in color but did not reproduce well in black and white).

Figure 8. Locations of NDBC buoys used in the validation of the Regional Wave Model.

Figure 9a. Time series of winds and wave heights of 24-hr forecasts(* mark) and buoy measurements(solid line) at NDBC station 44004 for June 1999.
b. Time series of winds and wave heights of 24-hr forecasts(* mark) and buoy measurements(solid line) at NDBC station 44014 for June 1999.
c. Time series of winds and wave heights of 24-hr forecasts(* mark) and buoy measurements(solid line) at NDBC station 44004 for July 1999.

d. Time series of winds and wave heights of 24-hr forecasts(* mark) and buoy measurements(solid line) at NDBC station 44014 for July 1999.

Figure 10a. Scatter plots and statistics of winds and wave heights of 24-hr forecasts for CMDP deep water area for June 1999.
b. Scatter plots and statistics of winds and wave heights of 24-hr forecasts for CMDP coastal waters for June 1999.
c. Scatter plots and statistics of winds and wave heights of 24-hr forecasts for CMDP deep water area for July 1999.
d. Scatter plots and statistics of winds and wave heights of 24-hr forecasts for CMDP coastal waters for July 1999.

Figure 11. Eta visibility product. The isolines of visibility are 7 n mi (outer) and 3 n mi (interior).

Figure 12. GOES-8 visual imagery for July 2, 1999 at 1215 UTC. Over laid on the image are lines of analyzed visibility and weather symbols for dense fog and unlimited visibility.

Figure 13. Same as Fig. 12 except 1815 UTC July 16, 1999.

Figure 14. An example of AVHRR imagery is shown with COFS one degree surface temperature contour lines overlain. The white areas are caused by cloud contamination. See text for an interpretation of this comparison.

Figure 15. AVHRR image for July 26, 1999 is shown with surface currents forecast by COFS. Just north of the Gulf Stream an eddy-like feature that is north and east of where the AVHRR image suggests it should be is seen.

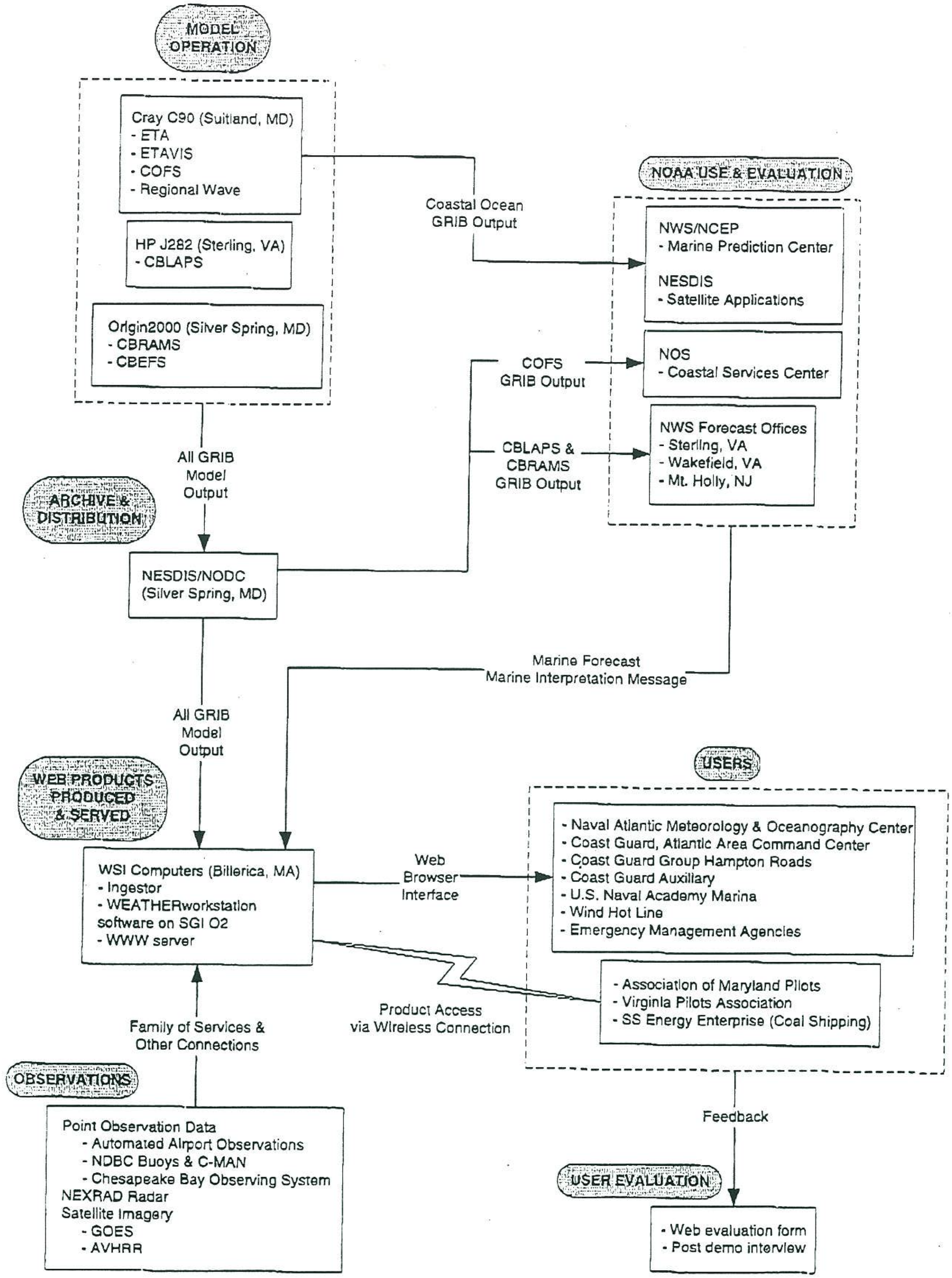

MODEL OPERATION
Cray C90 (Suitland, MD)
- ETA
- ETAVIS
- COFS
- Regional Wave
HP J282 (Sterling, VA)
- CBLAPS
Origin2000 (Silver Spring, MD)
- CBRAMS
- CBEFS
Coastal Ocean GRIB Output
NOAA USE & EVALUATION
NWS/NCEP
- Marine Prediction Center
NESDIS
- Satellite Applications
COFS GRIB Output
NOS
- Coastal Services Center
CBLAPS & CBRAMS GRIB Output
NWS Forecast Offices
- Sterling, VA
- Wakefield, VA
- Mt. Holly, NJ
All GRIB Model Output
ARCHIVE & DISTRIBUTION
NESDIS/NODC
(Silver Spring, MD)
Marine Forecast
Marine Interpretation Message
All GRIB Model Output
WEB PRODUCTS PRODUCED & SERVED
USERS
WSI Computers (Billerica, MA)
- Ingestor
- WEATHERworkstation software on SGI O2
- WWW server
Web Browser Interface
- Naval Atlantic Meteorology & Oceanography Center
- Coast Guard, Atlantic Area Command Center
- Coast Guard Group Hampton Roads
- Coast Guard Auxiliary
- U.S. Naval Academy Marina
- Wind Hot Line
- Emergency Management Agencies
- Association of Maryland Pilots
- Virginia Pilots Association
- SS Energy Enterprise (Coal Shipping)
Product Access via Wireless Connection
Family of Services & Other Connections
OBSERVATIONS
Point Observation Data
- Automated Airport Observations
- NDBC Buoys & C-MAN
- Chesapeake Bay Observing System
NEXRAD Radar
Satellite Imagery
- GOES
- AVHRR
Feedback
USER EVALUATION
- Web evaluation form
- Post demo interview

Figure 1

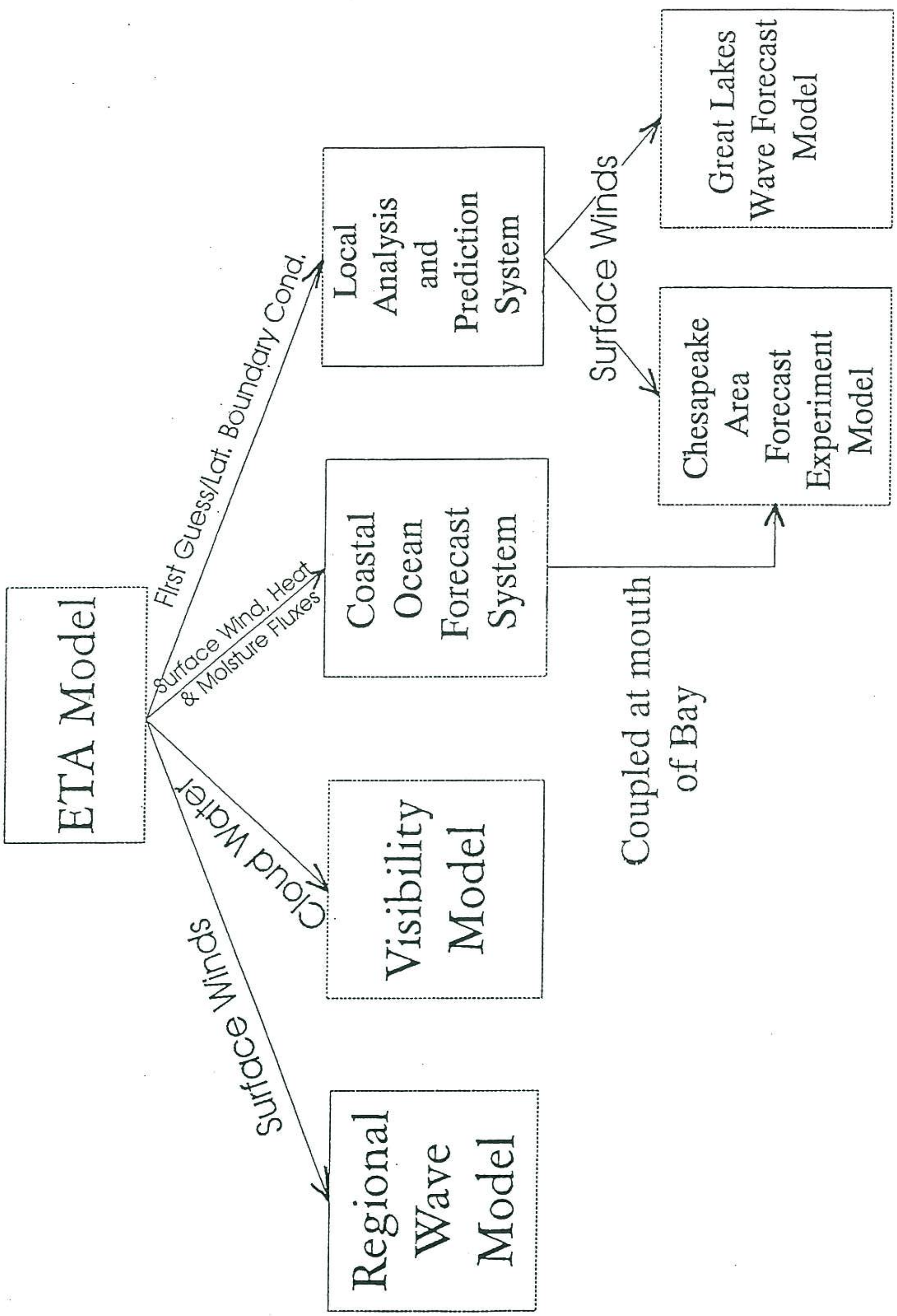
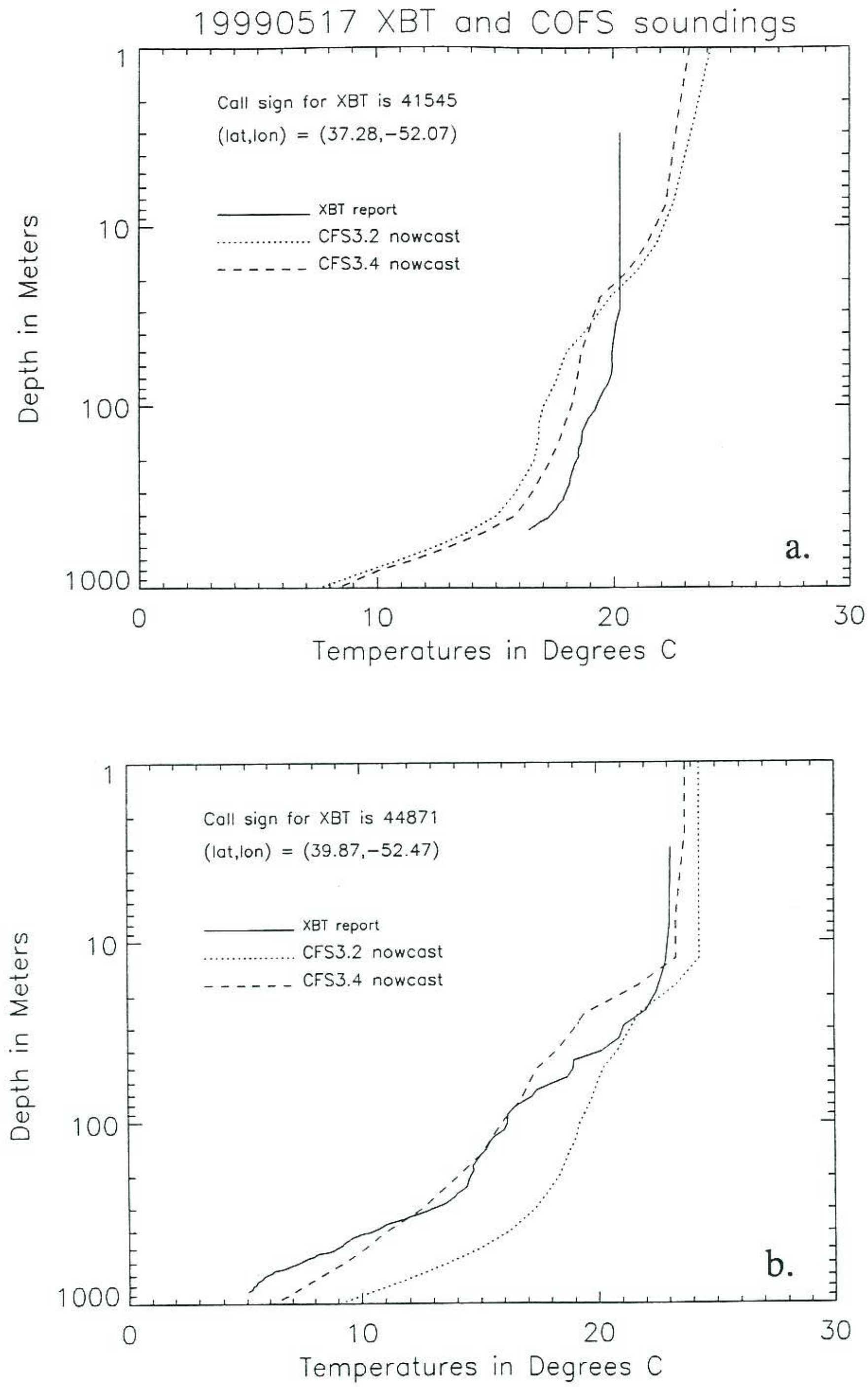


Figure 2. Model Hierarchy

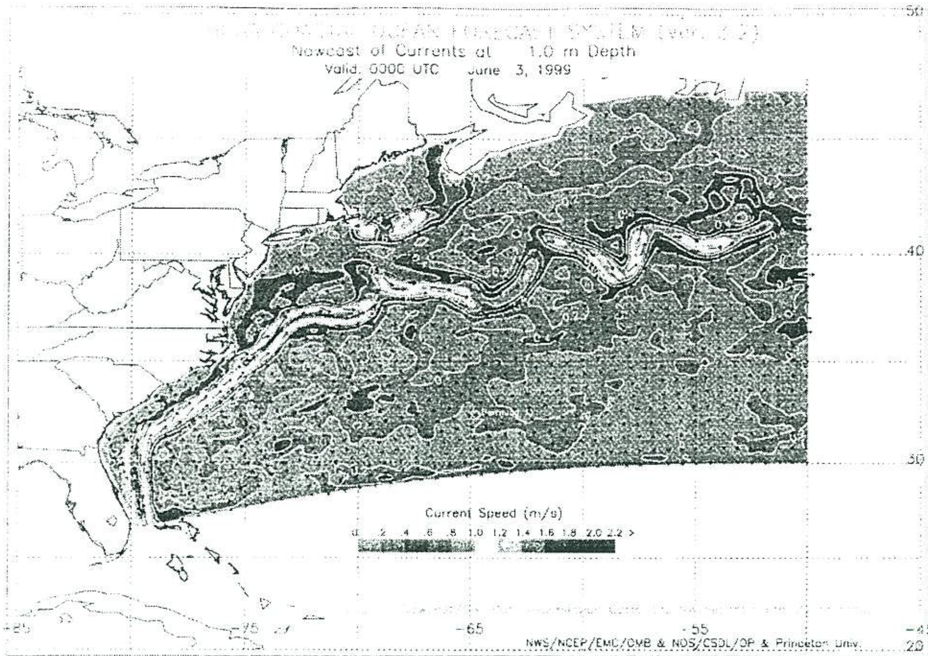
Figure 2



19990517 XBT and COFS soundings
Call sign for XBT is 41545
(lat,lon) = (37.28,-52.07)
XBT report
CFS3.2 nowcast
CFS3.4 nowcast
Depth in Meters
1
10
100
1000
0
10
20
30
Temperatures in Degrees C
a.
Call sign for XBT is 44871
(lat,lon) = (39.87,-52.47)
XBT report
CFS3.2 nowcast
CFS3.4 nowcast
Depth in Meters
1
10
100
1000
0
10
20
30
Temperatures in Degrees C
b.

Figure 3

a.


Nowcast of Currents at 1.0 m Depth
Valid: 0000 UTC June 3, 1999
Current Speed (m/s)
0 .2 .4 .6 .8 1.0 1.2 1.4 1.6 1.8 2.0 2.2 >
50
40
30
20
-85
-75
-65
-55
-45
NWS/NCEP/EMC/OMB & NOS/CSDL/OP & Princeton Univ.

b.

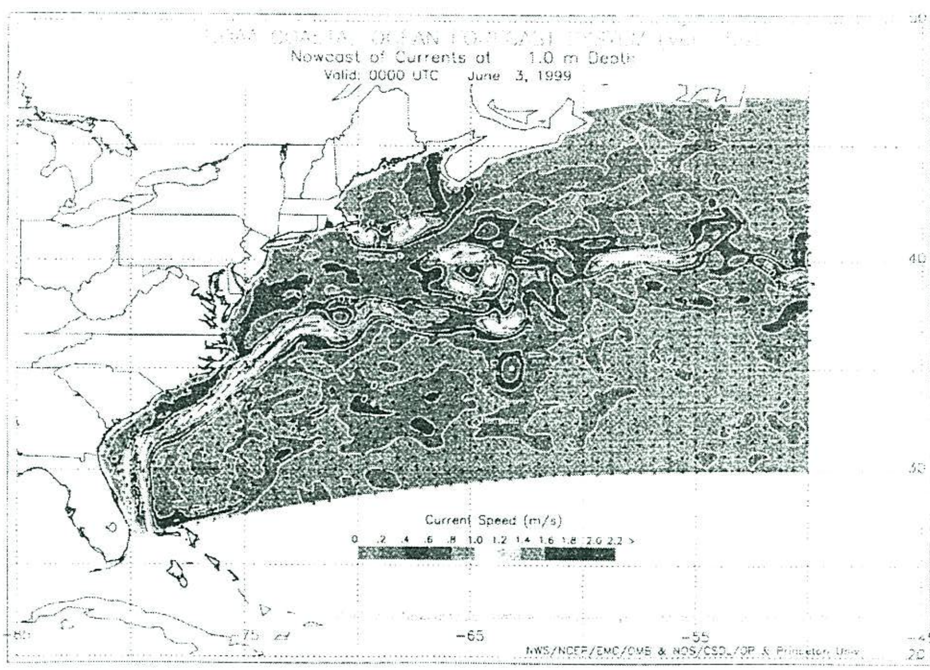

Nowcast of Currents at 1.0 m Depth
Valid: 0000 UTC June 3, 1999
Current Speed (m/s)
0 .2 .4 .6 .8 1.0 1.2 1.4 1.6 1.8 2.0 2.2 >
40
30
20
-75
-65
-55
NWS/NCEP/EMC/OMB & NOS/CSDL/OP & Princeton Univ.

Figure 4

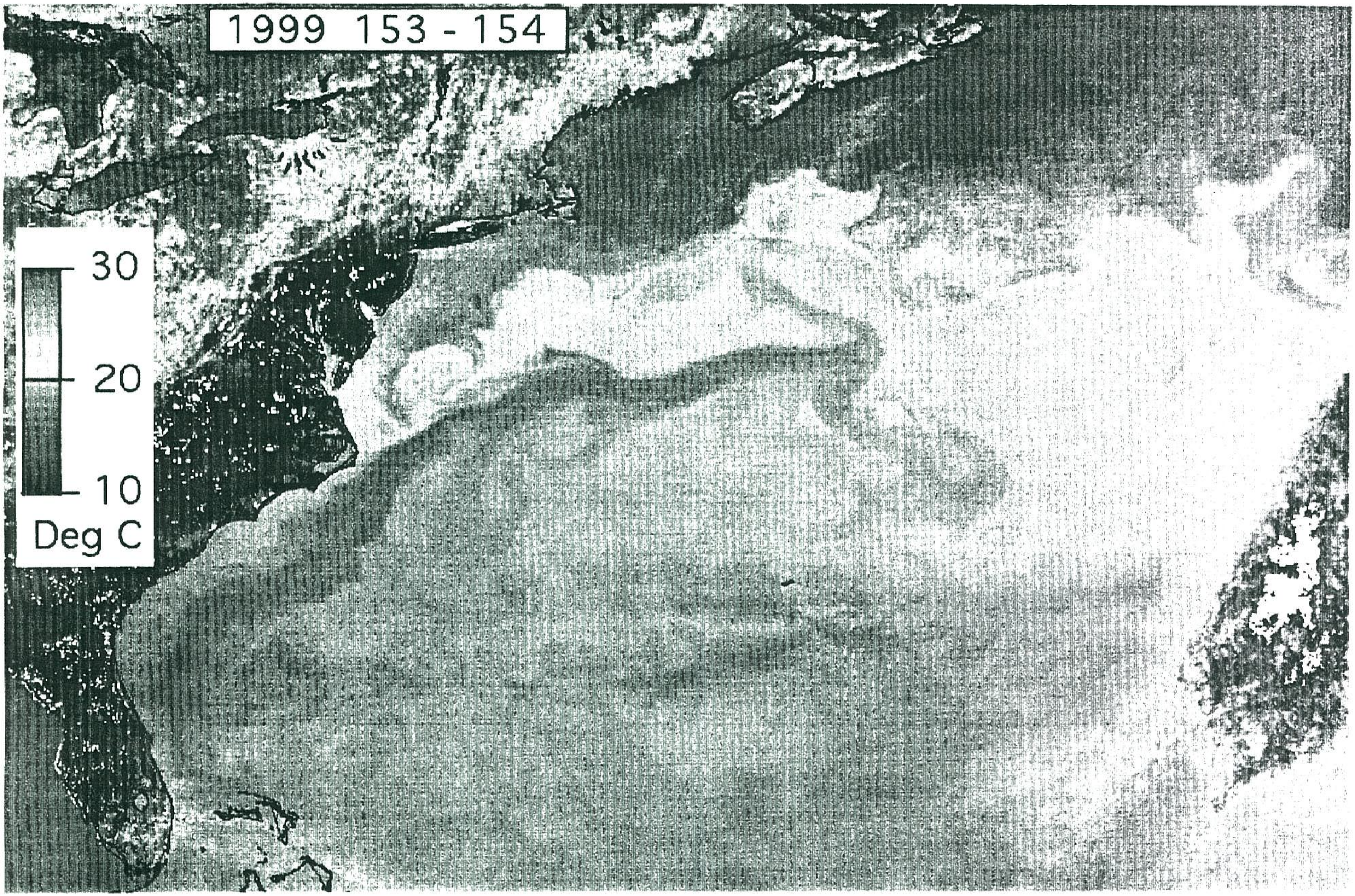


Figure 5

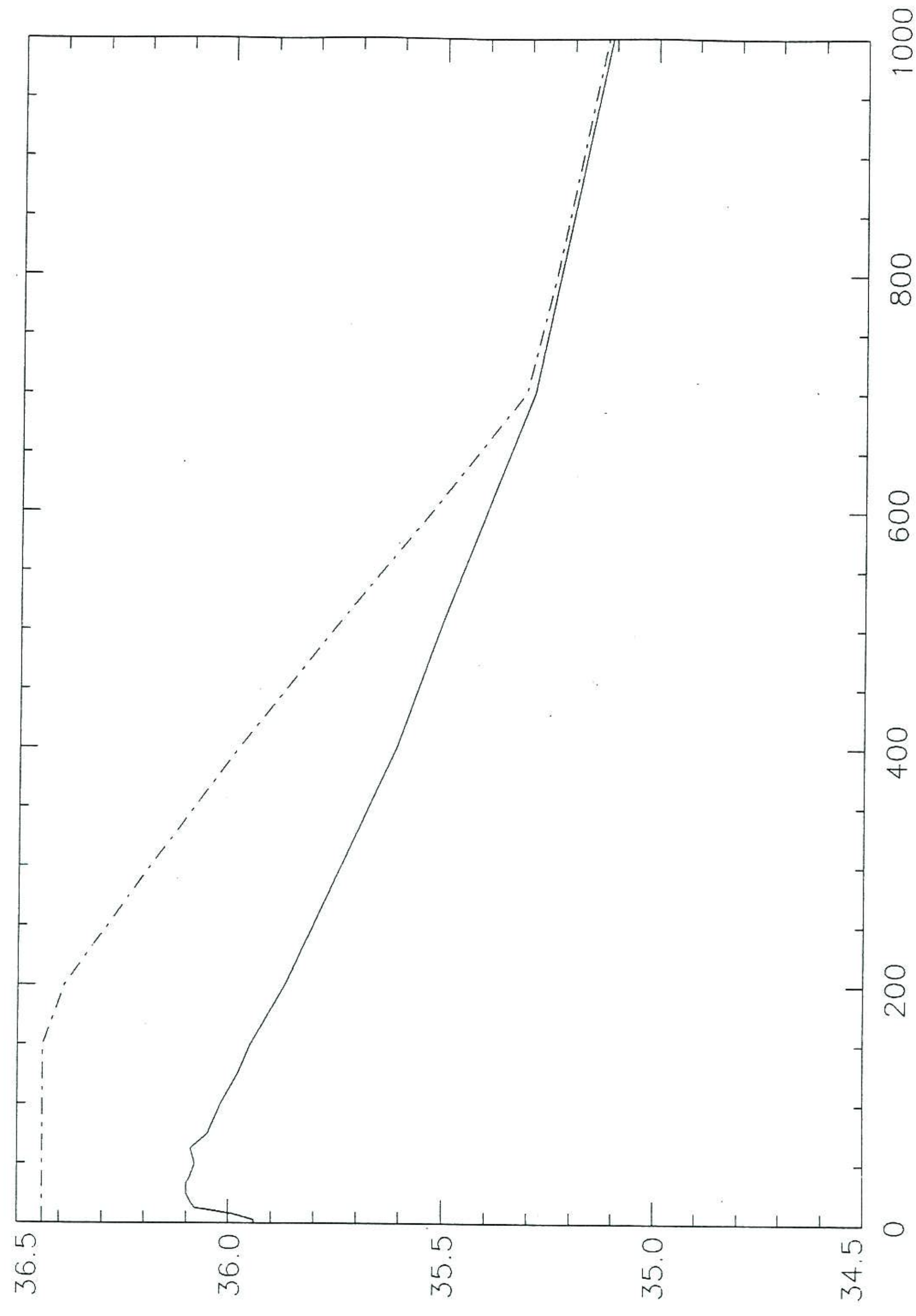


Figure 6

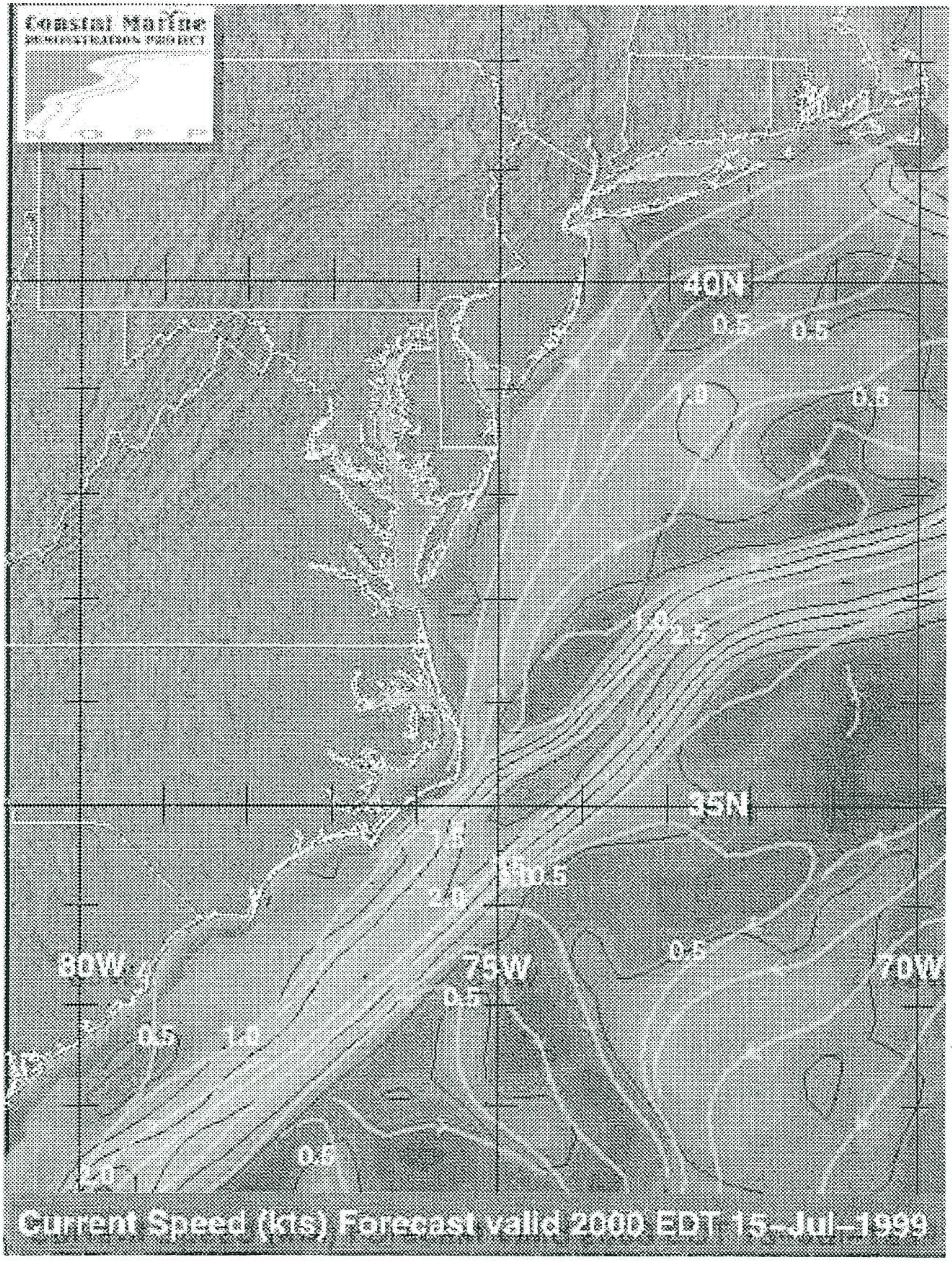

Coastal Marine
DEMONSTRATION PROJECT
40N
0.5
0.5
1.0
0.5
1.0
2.5
35N
1.5
0.5
2.0
0.5
80W
75W
70W
0.5
0.5
1.0
0.5
2.0
Current Speed (kts) Forecast valid 2000 EDT 15-Jul-1999

Figure 7

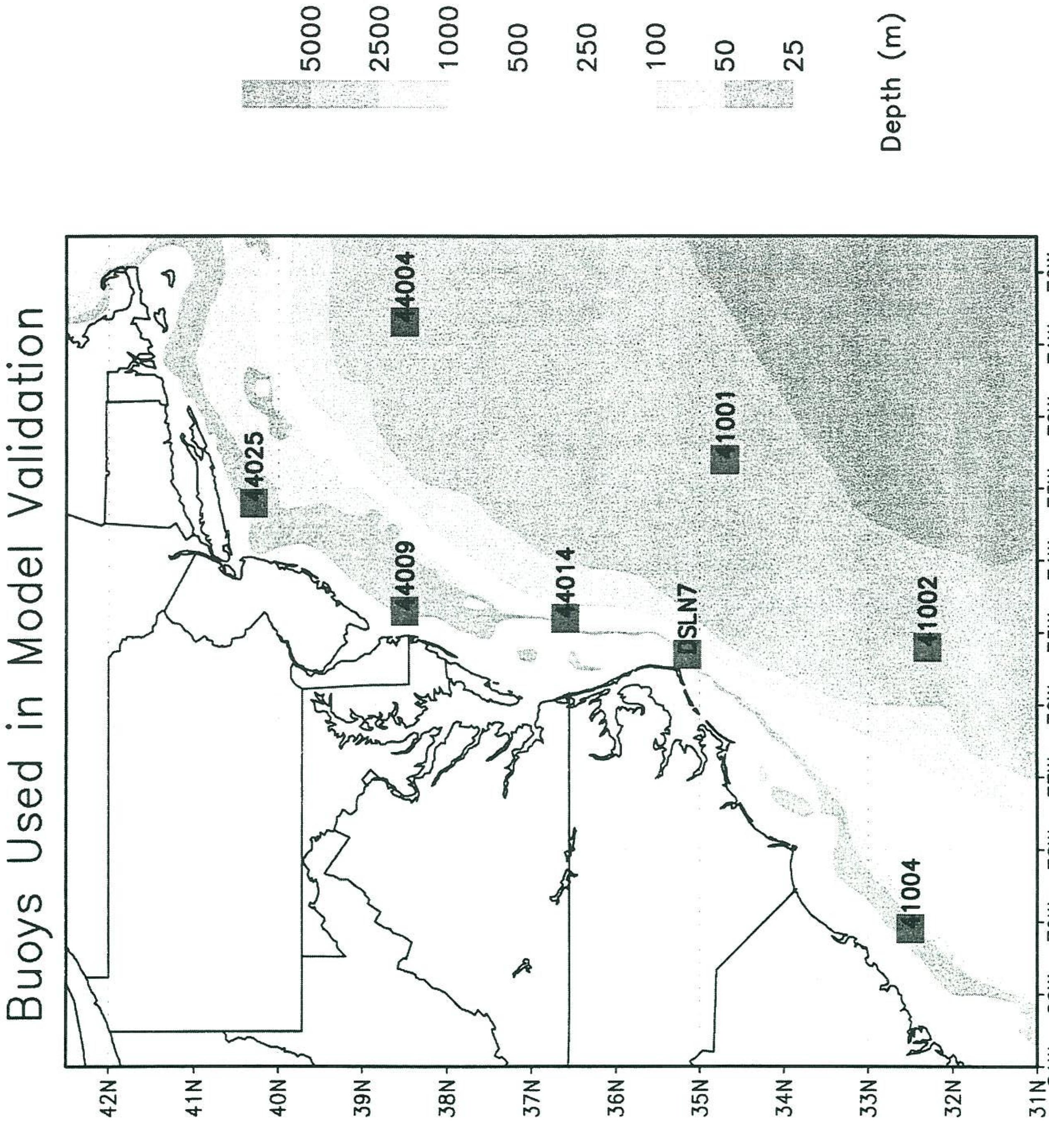
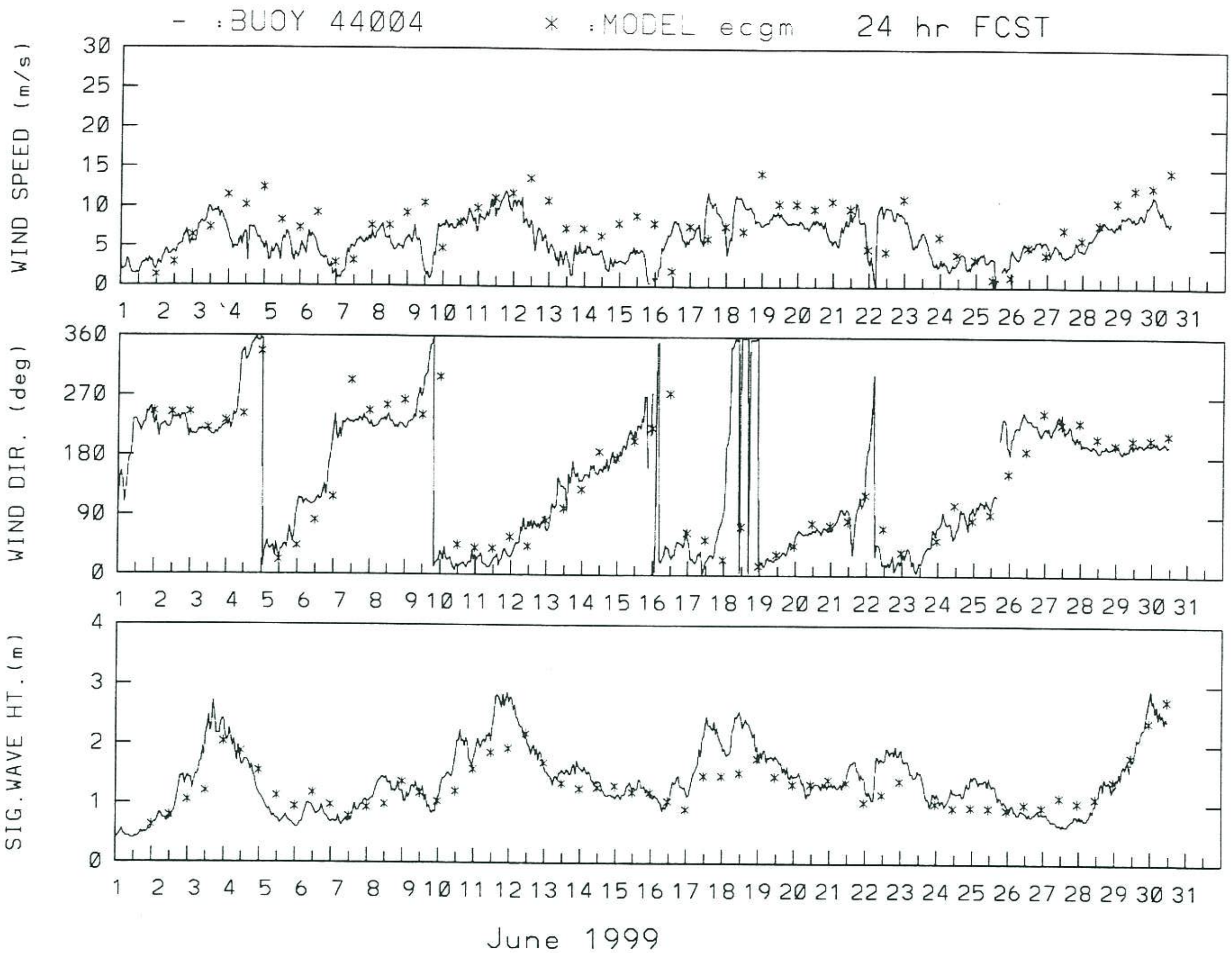
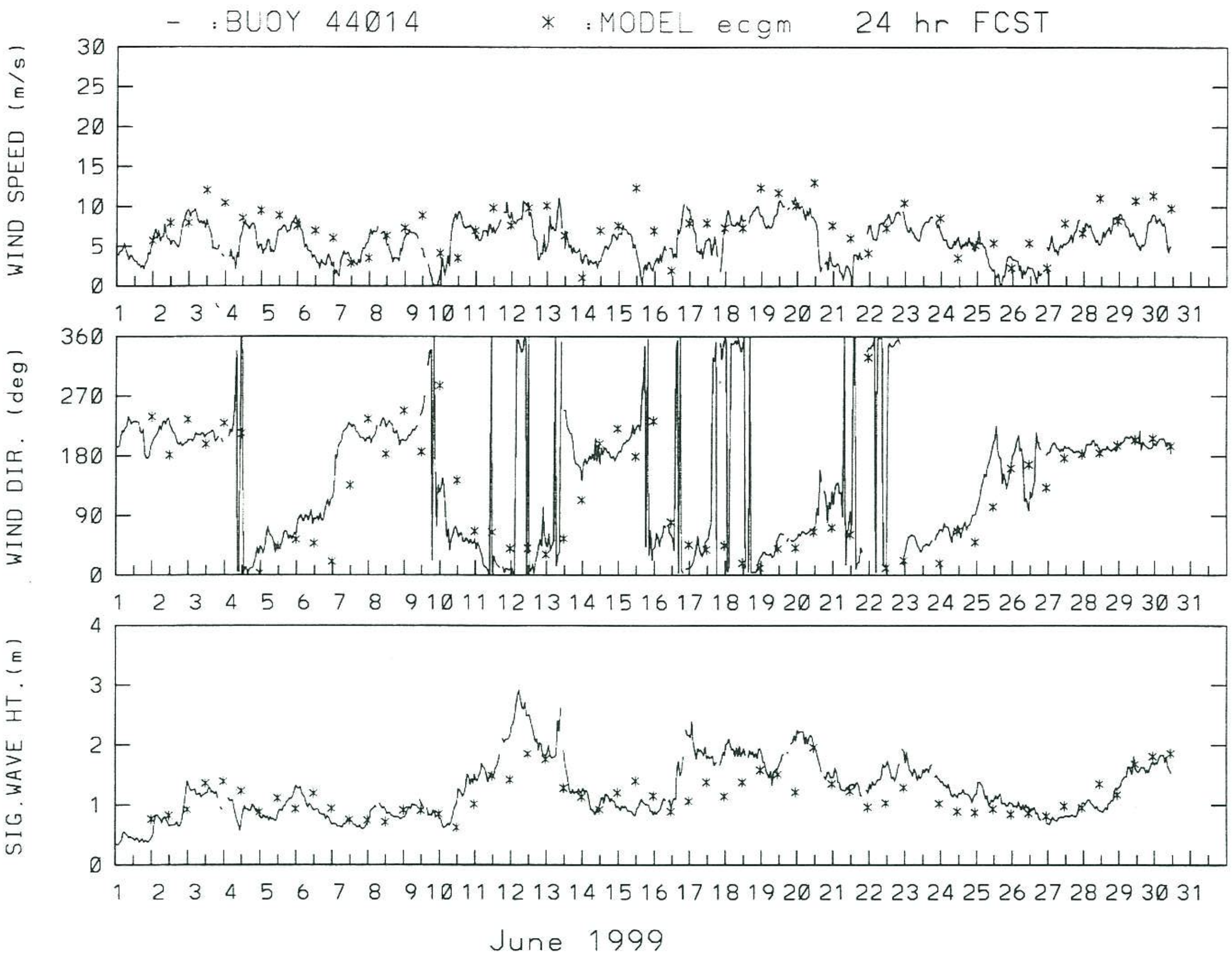

Buoys Used in Model Validation
4025
4009
4004
4014
SLN7
1001
1002
1004
42N
41N
40N
39N
38N
37N
36N
35N
34N
33N
32N
31N
81W
80W
79W
78W
77W
76W
75W
74W
73W
72W
71W
70W
5000
2500
1000
500
250
100
50
25
Depth (m)

Figure 8



- :BUOY 44004
* :MODEL ecgm
24 hr FCST
WIND SPEED (m/s)
30
25
20
15
10
5
0
1 2 3 `4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31
WIND DIR. (deg)
360
270
180
90
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31
SIG.WAVE HT.(m)
4
3
2
1
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31
June 1999

Figure 9a.



- :BUOY 44014 * :MODEL ecgm 24 hr FCST
WIND SPEED (m/s)
WIND DIR. (deg)
SIG.WAVE HT.(m)
June 1999

Figure 9b.

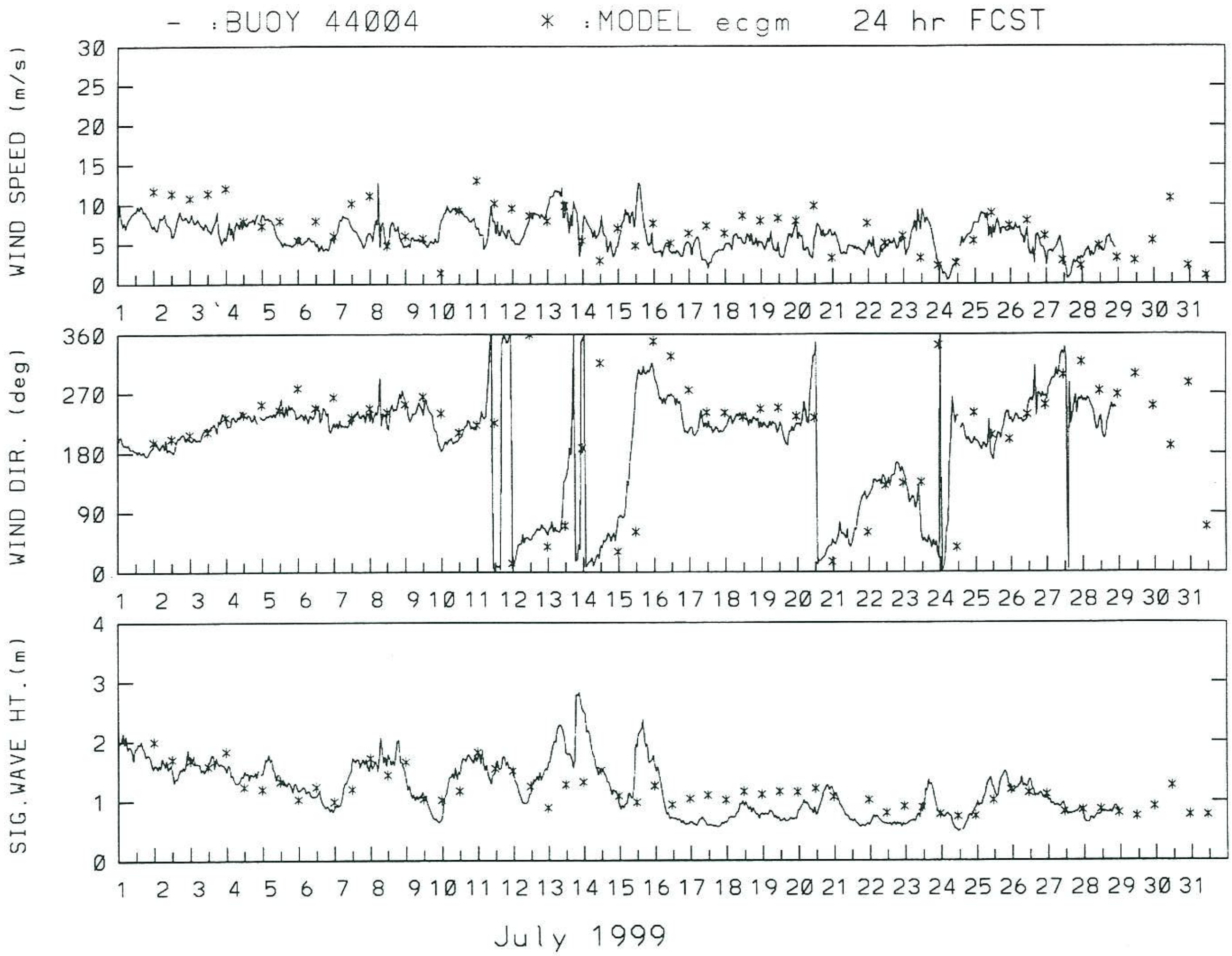
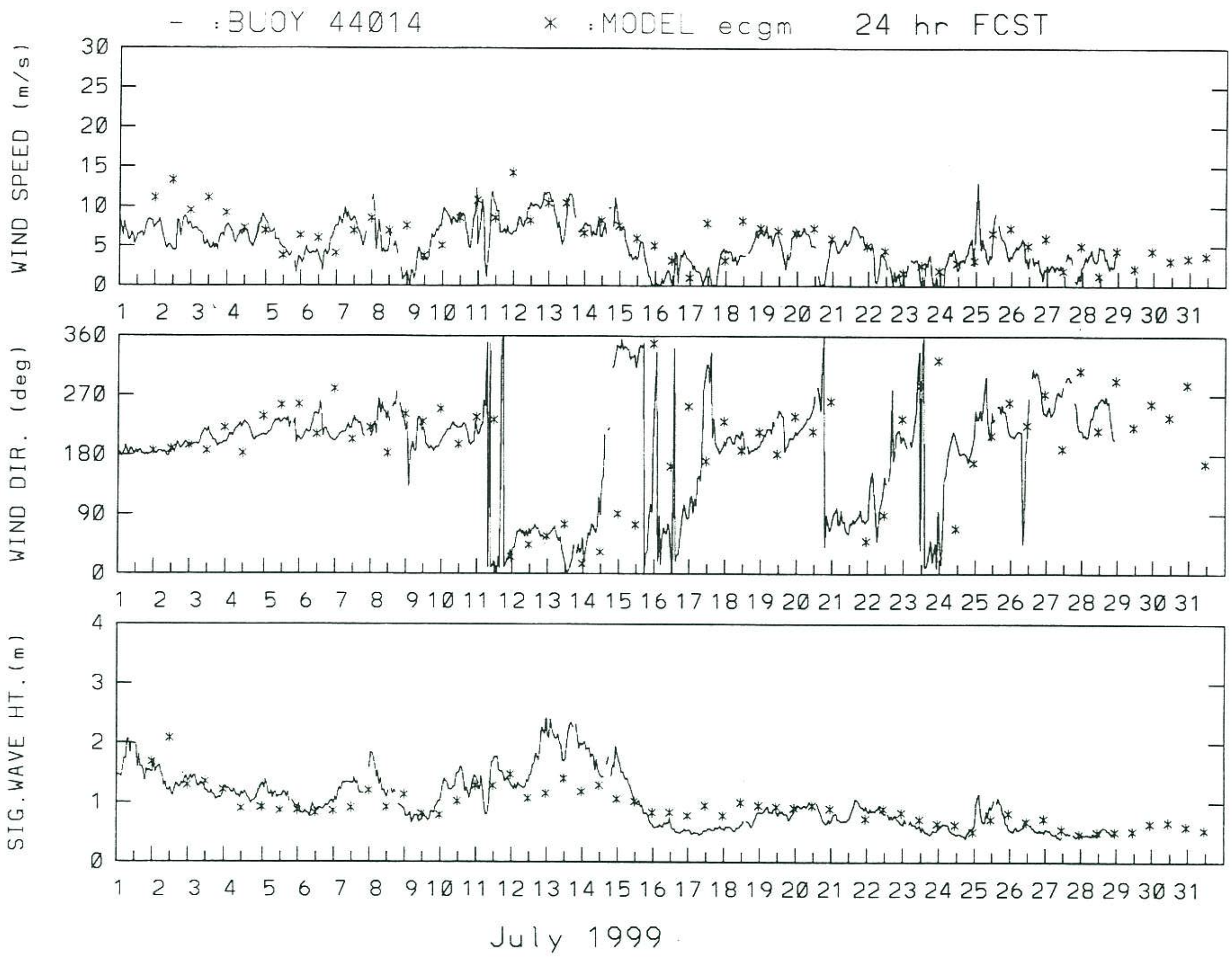
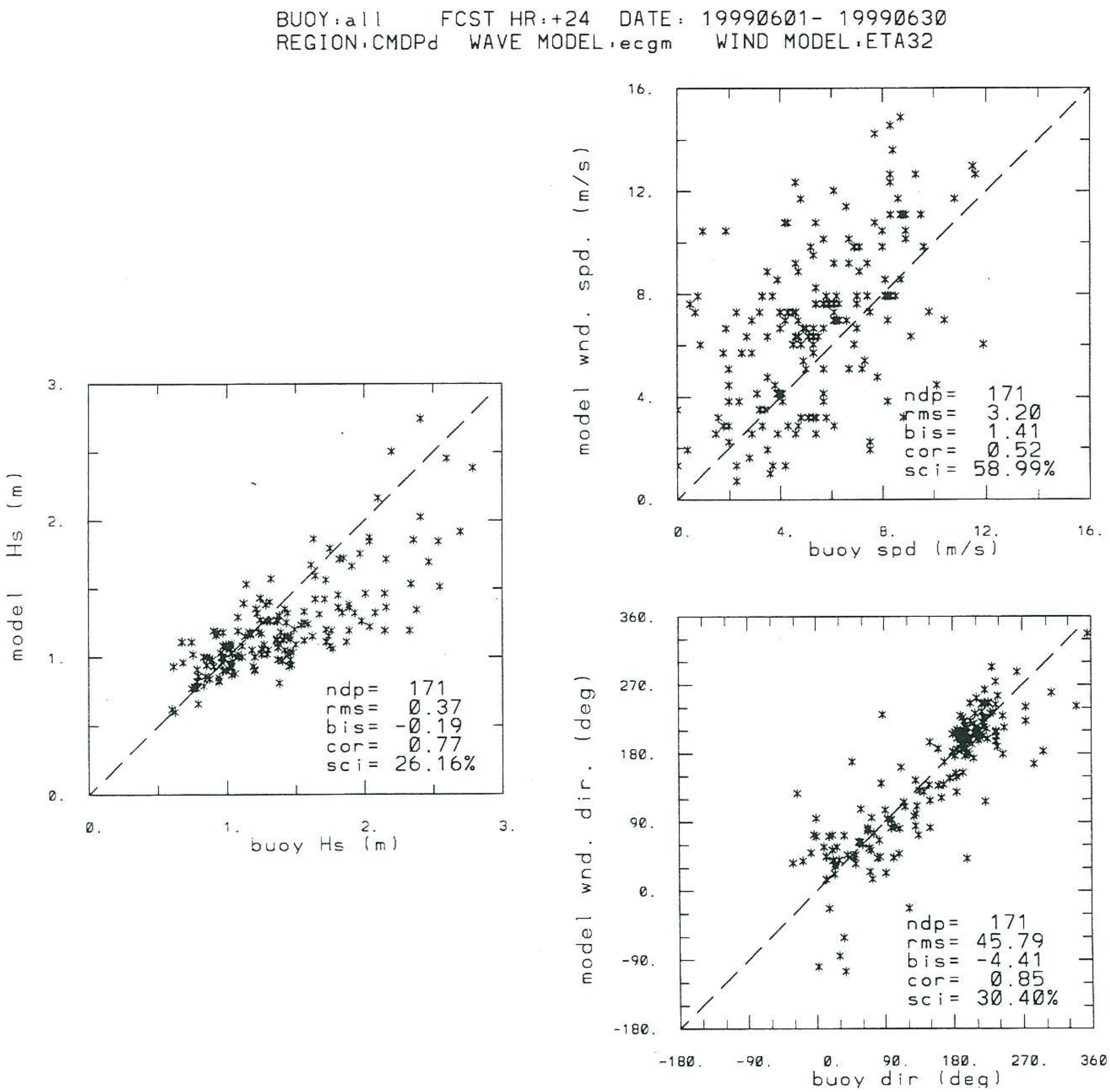

- :BUOY 44004
* :MODEL ecgm
24 hr FCST
WIND SPEED (m/s)
WIND DIR. (deg)
SIG.WAVE HT.(m)
July 1999

Figure 9c.



- :BUOY 44014
* :MODEL ecgm
24 hr FCST
WIND SPEED (m/s)
30
25
20
15
10
5
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31
WIND DIR. (deg)
360
270
180
90
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31
SIG.WAVE HT.(m)
4
3
2
1
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31
July 1999

Figure 9d.



BUOY:all FCST HR:+24 DATE: 19990601- 19990630
REGION:CMDPd WAVE MODEL:ecgm WIND MODEL:ETA32
model Hs (m)
buoy Hs (m)
ndp= 171
rms= 0.37
bis= -0.19
cor= 0.77
sci= 26.16%
model wnd. spd. (m/s)
buoy spd (m/s)
ndp= 171
rms= 3.20
bis= 1.41
cor= 0.52
sci= 58.99%
model wnd. dir. (deg)
buoy dir (deg)
ndp= 171
rms= 45.79
bis= -4.41
cor= 0.85
sci= 30.40%

Figure 10a.

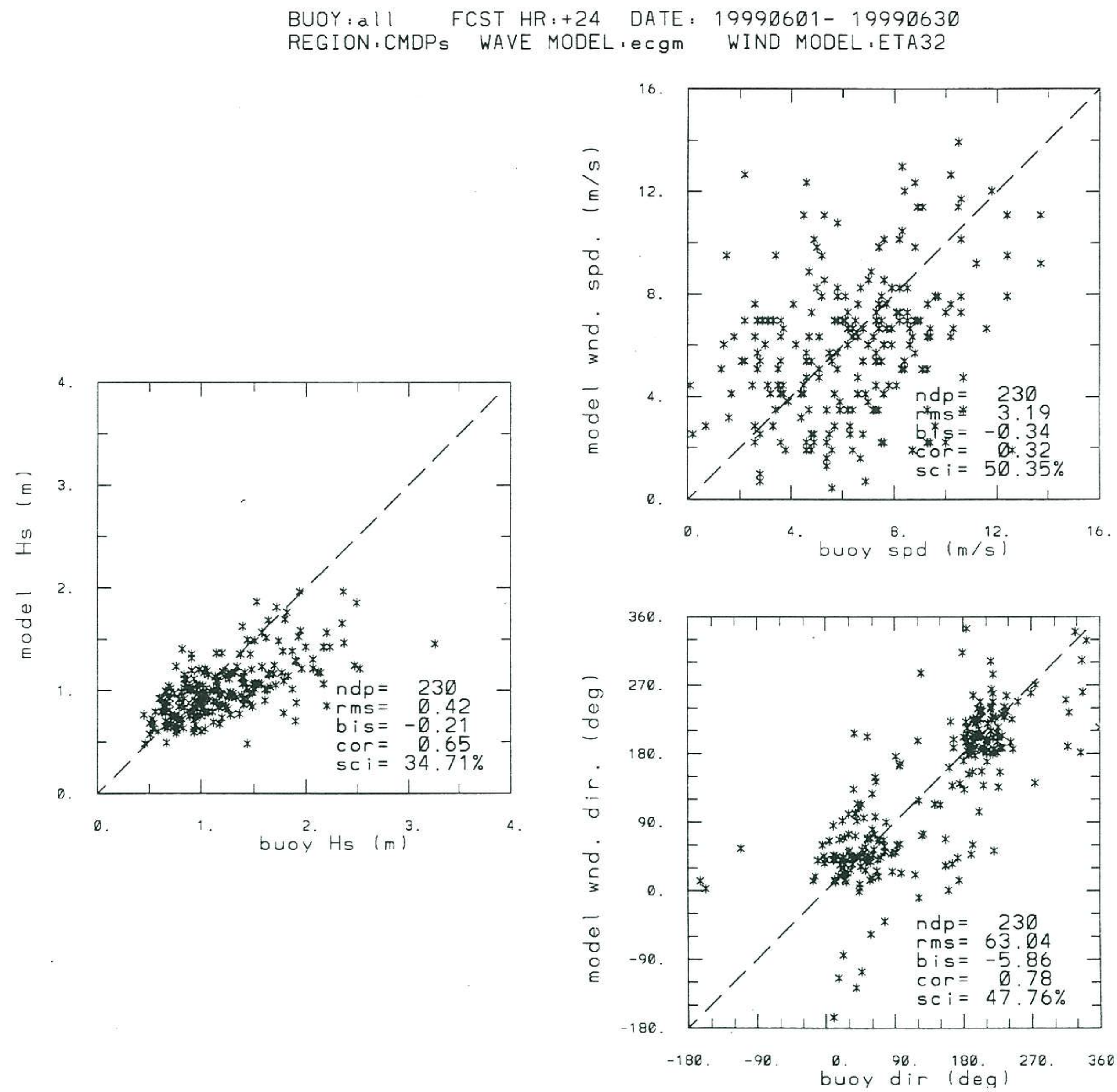
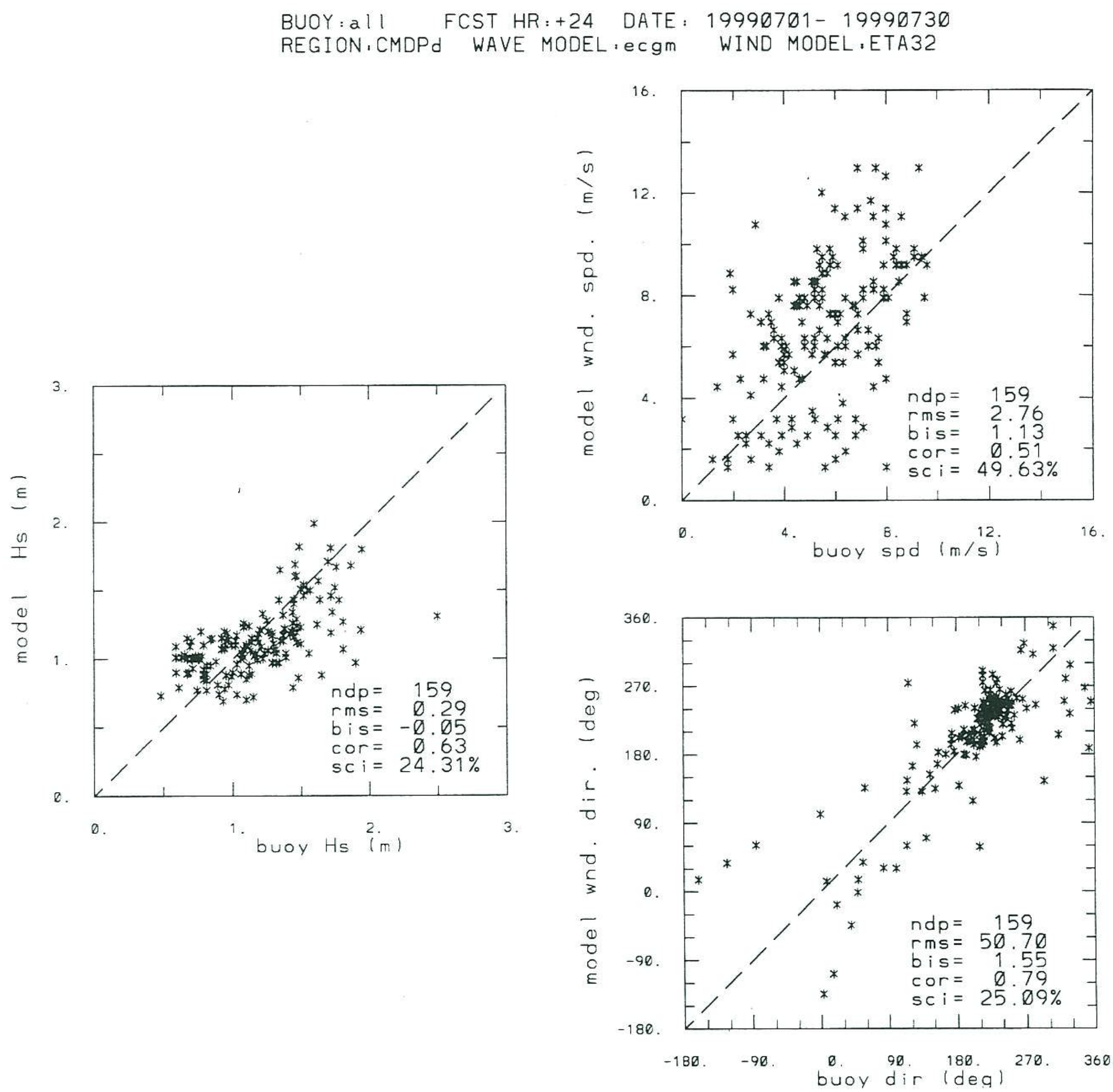
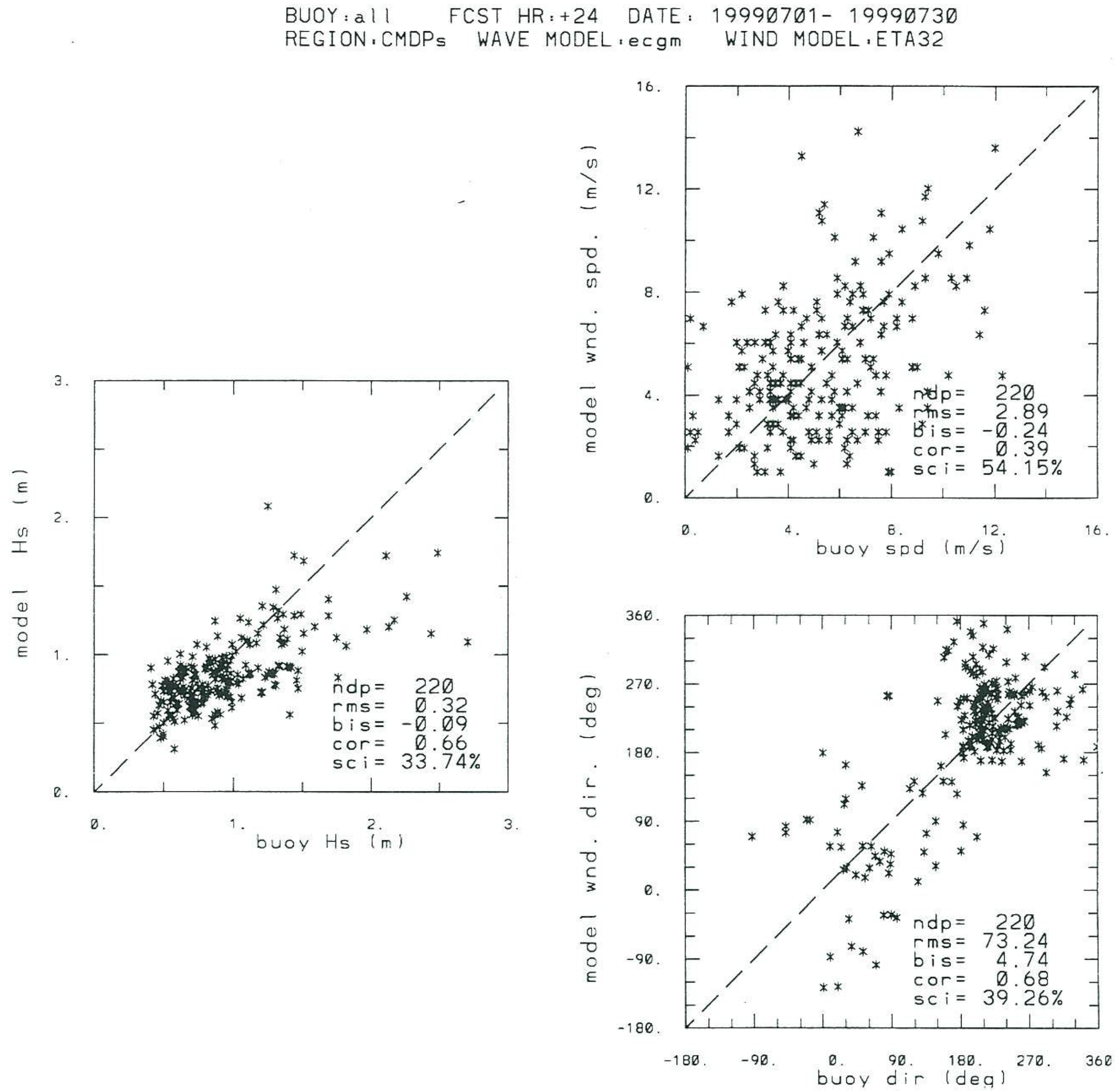

BUOY:all FCST HR:+24 DATE: 19990601- 19990630
REGION:CMDPs WAVE MODEL:ecgm WIND MODEL:ETA32
model Hs (m)
buoy Hs (m)
ndp= 230
rms= 0.42
bis= -0.21
cor= 0.65
sci= 34.71%
model wnd. spd. (m/s)
buoy spd (m/s)
ndp= 230
rms= 3.19
bis= -0.34
cor= 0.32
sci= 50.35%
model wnd. dir. (deg)
buoy dir (deg)
ndp= 230
rms= 63.04
bis= -5.86
cor= 0.78
sci= 47.76%

Figure 10b.



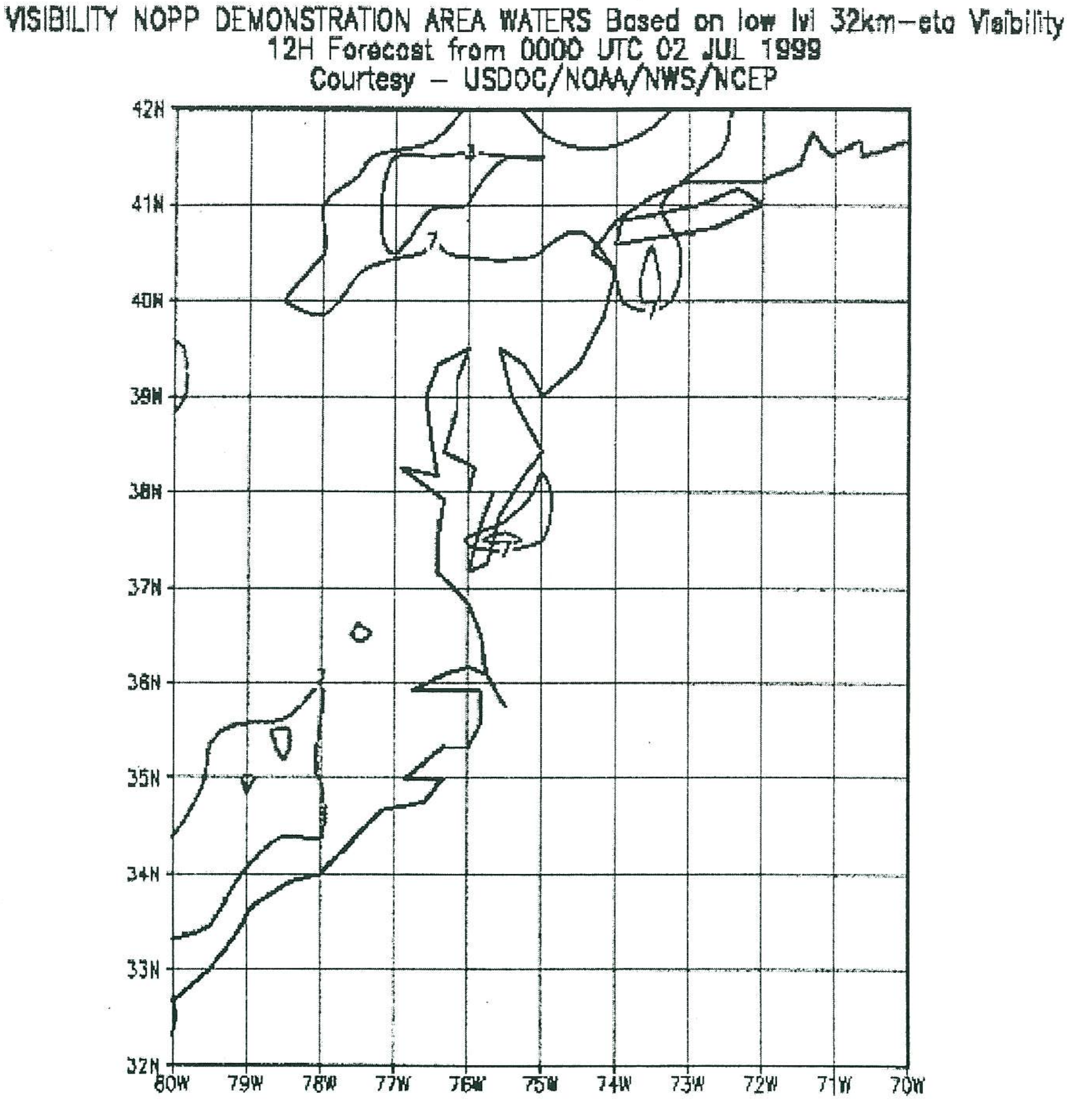
BUOY:all FCST HR:+24 DATE: 19990701- 19990730
REGION:CMDPd WAVE MODEL:ecgm WIND MODEL:ETA32
model Hs (m)
buoy Hs (m)
ndp= 159
rms= 0.29
bis= -0.05
cor= 0.63
sci= 24.31%
model wnd. spd. (m/s)
buoy spd (m/s)
ndp= 159
rms= 2.76
bis= 1.13
cor= 0.51
sci= 49.63%
model wnd. dir. (deg)
buoy dir (deg)
ndp= 159
rms= 50.70
bis= 1.55
cor= 0.79
sci= 25.09%

Figure 10c.



BUOY:all FCST HR:+24 DATE: 19990701- 19990730
REGION:CMDPs WAVE MODEL:ecgm WIND MODEL:ETA32
model Hs (m)
buoy Hs (m)
ndp= 220
rms= 0.32
bis= -0.09
cor= 0.66
sci= 33.74%
model wnd. spd. (m/s)
buoy spd (m/s)
ndp= 220
rms= 2.89
bis= -0.24
cor= 0.39
sci= 54.15%
model wnd. dir. (deg)
buoy dir (deg)
ndp= 220
rms= 73.24
bis= 4.74
cor= 0.68
sci= 39.26%

Figure 10d.



VISIBILITY NOPP DEMONSTRATION AREA WATERS Based on low lvl 32km-eta Visibility
12H Forecast from 0000 UTC 02 JUL 1999
Courtesy - USDOC/NOAA/NWS/NCEP
42N
41N
40N
39N
38N
37N
36N
35N
34N
33N
32N
80W
79W
78W
77W
76W
75W
74W
73W
72W
71W
70W

Figure 11

Figure 12

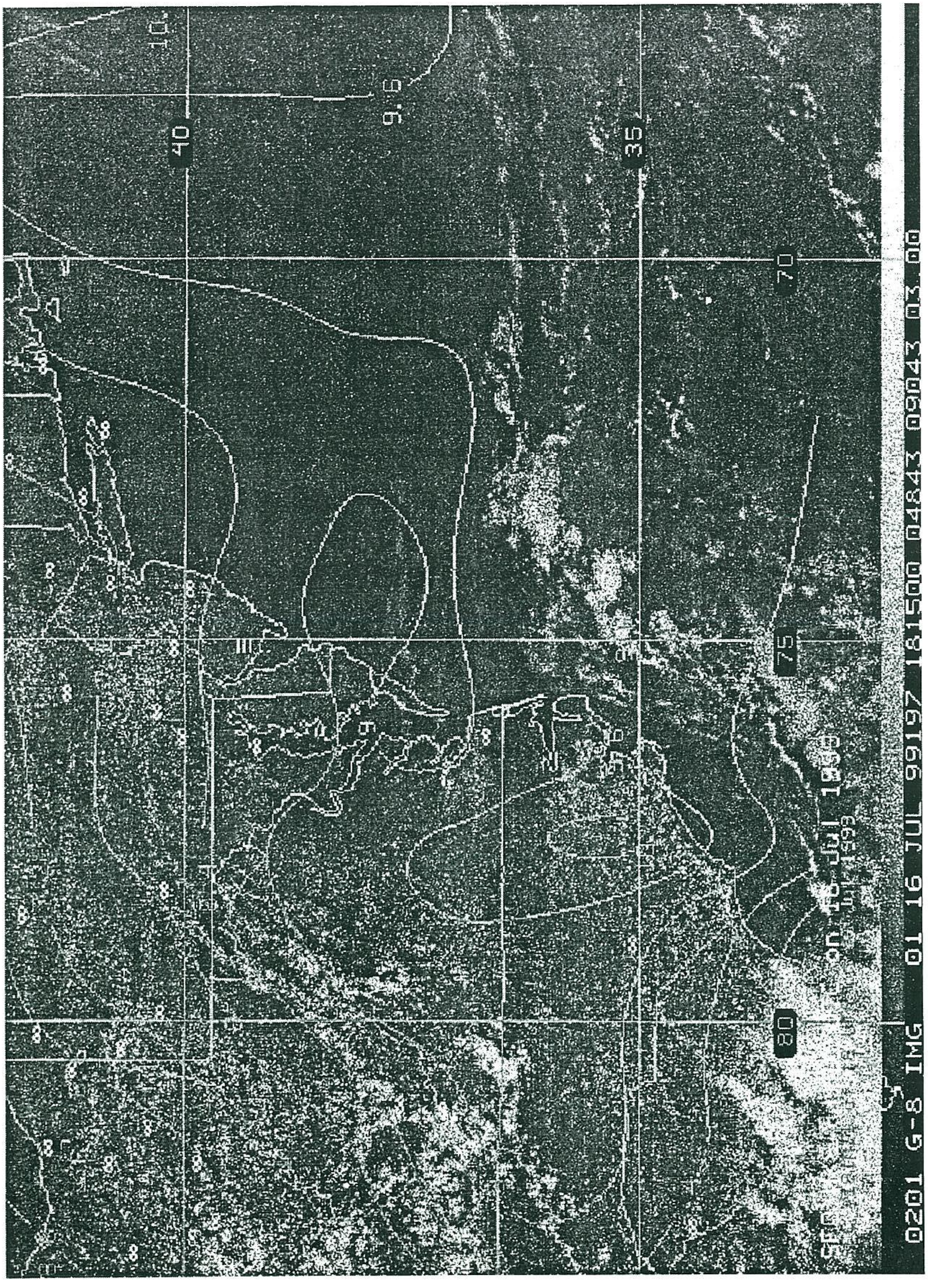
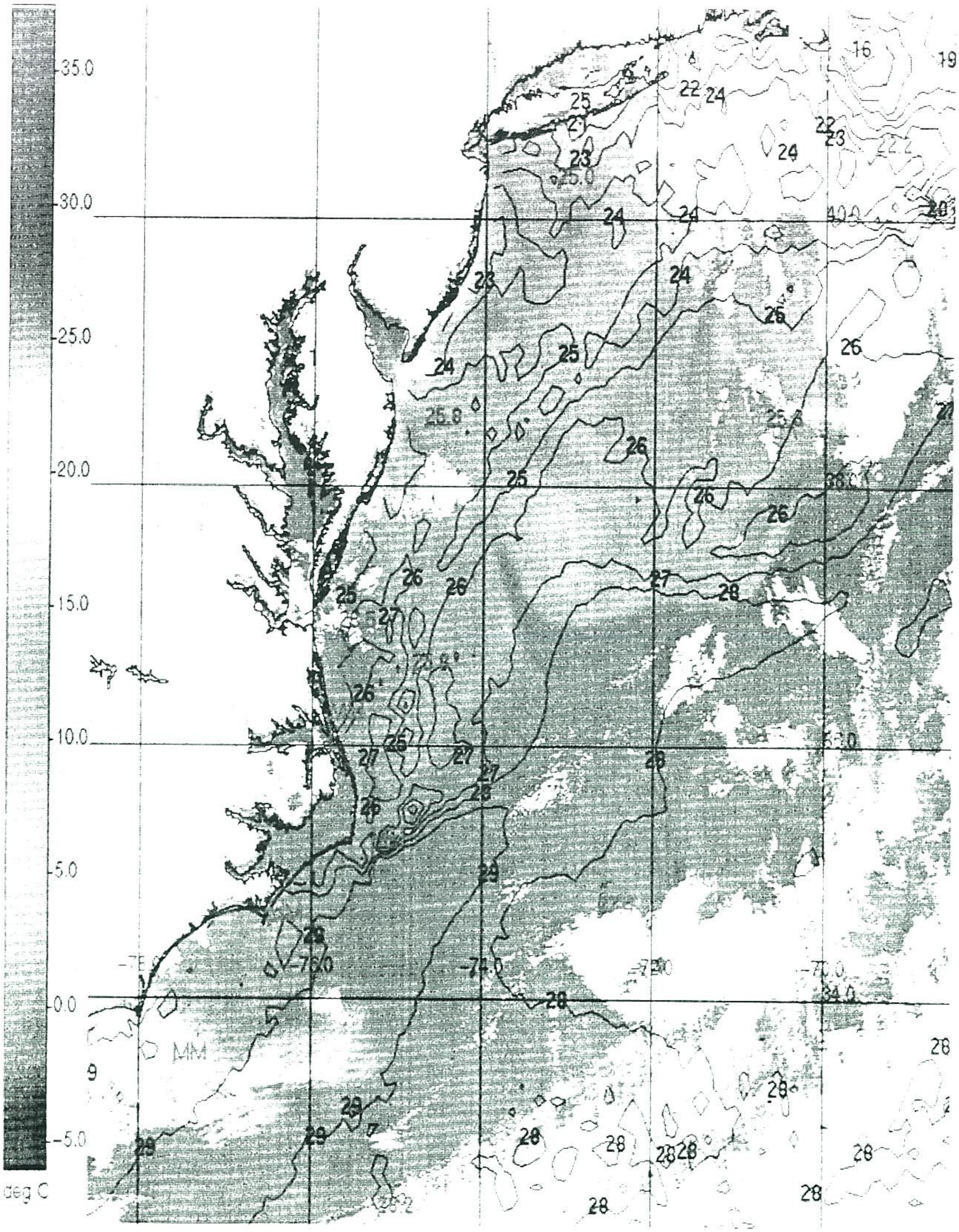

0201 G-8 IMG 01 16 JUL 99197 181500 04843 09043 03.00
40
35
70
75
80
9.6
10

Figure 13



35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
-5.0
deg C
-76.0
-74.0
-72.0
-70.0
40.0
38.0
36.0
34.0

Figure 14

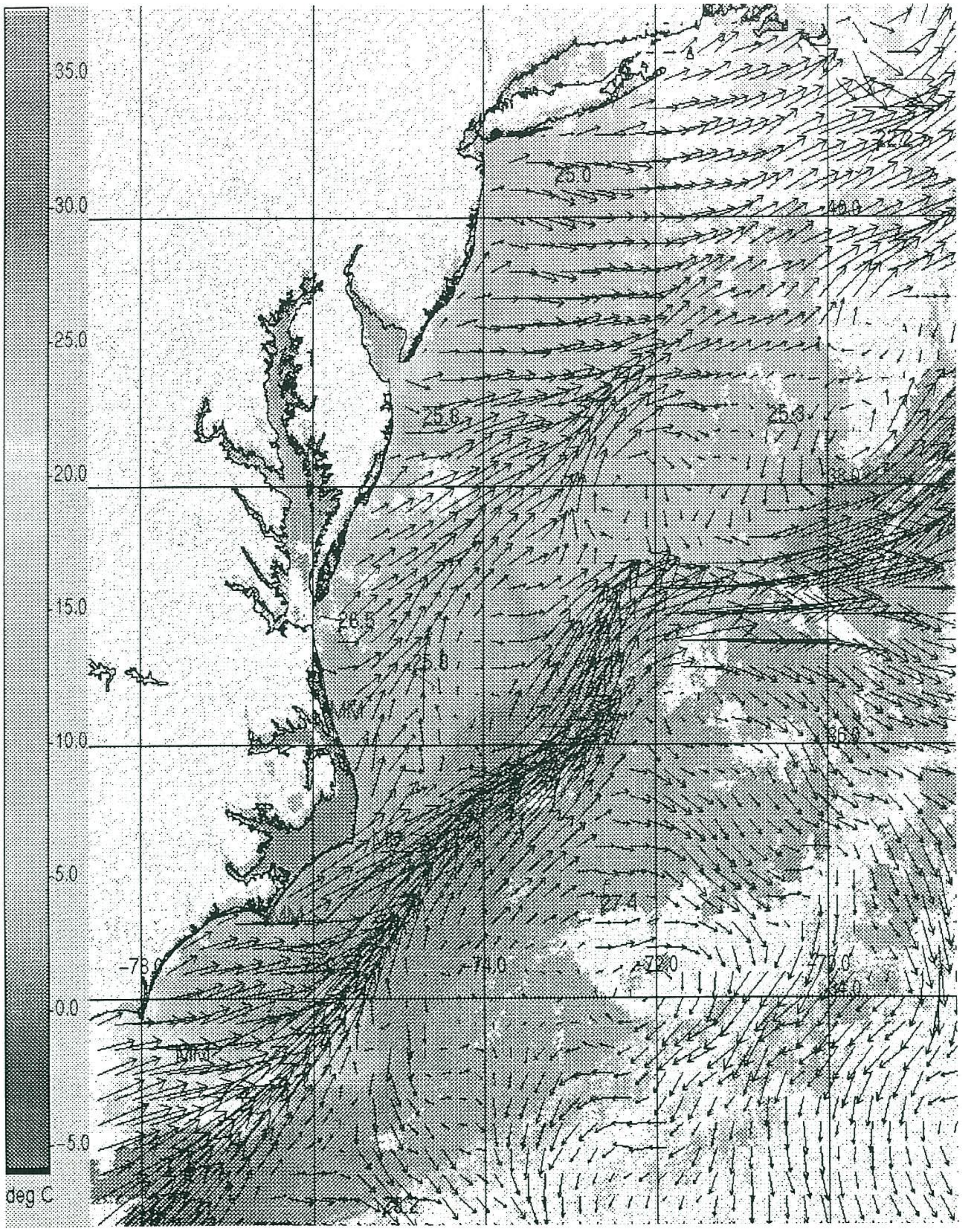

35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
-5.0
deg C
25.0
40.0
25.8
25.3
26.5
27.4
-74.0
-72.0
-70.0
34.0

Figure 15

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