The GoMOOS nowcast/forecast system

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Abstract

A circulation nowcast/forecast system has been developed for the Gulf of Maine as an integral component of the Gulf of Maine Ocean Observing System (GoMOOS). It has been used daily since 2001 to produce short-term forecasts of the circulation and hydrographic properties in the Gulf of Maine. One of the expectations is that the nowcast/forecast system can provide consistent SST to fill in AVHRR data gaps and eventually produce reliable 3D temperature and flow fields for fisheries and other applications.

The framework of the nowcast/forecast system is presented, including an algorithm for assimilating satellite-derived SST. Comparisons between the predicted and the observed temperature (both in situ and satellite-derived) and velocity are discussed. In general, the assimilation algorithm is stable and produces robust SST patterns. Seasonal variations in temperature and the coastal current are reasonably reproduced. Correlation between the modeled and observed fields in the synoptic band is summarized for individual buoys in monthly bins. The Root-Mean-Square (RMS) errors for the M_2 tidal ellipse are estimated at 1.9 and 1.2 cm s^{-1} for the major and minor axis, respectively, while the RMS error in ellipse orientation is at 11^\circ.

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1. Introduction

The Gulf of Maine is a biologically productive, marginal sea (Fig. 1). Its exchange with the open ocean is largely controlled by the geometry of banks and channels that characterize its open boundary. Inside the Gulf there are three basins separated at the 200 m depth, namely the Jordan Basin and the Georges Basin in the Eastern Gulf of Maine and the Wilkinson Basin in the Western Gulf of Maine. A circulation schematic based on satellite-tracked drifters and hydrographic observations delineate two distinct cyclonic gyres centered over the two basins in the eastern Gulf of Maine and a complex and well-developed cyclonic coastal current system encompassing the gyre pair (Pettigrew et al., 2005).

It has been documented repeatedly that the Gulf-wide circulation is strongest and most coherent in the summer, but lacks a well-defined pattern in the winter (e.g., Bumpus and Lauzier, 1965; Vermersch et al., 1979; Brown and Irish, 1992), most likely related to the evolving density structure as suggested by Brooks and Townsend (1989) and Brown and Irish (1992). Processes that influence the density distribution inside the Gulf of Maine include surface heat flux,

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tidal mixing, river runoff, and the inflow of the Scotian Shelf Water (SSW) and the inflow of the Slope Water through the Northeast Channel. The Gulf of Maine and Bay of Fundy system is well known for its nearly resonant semi-diurnal tidal responses, and the associated vigorous tidal stirring keeps the water vertically well-mixed over Georges Bank, the western shelf of Nova Scotia (Loder and Greenberg, 1986), and the eastern Maine coast (Pettigrew et al., 1998). The thermohaline structure in the eastern Gulf of Maine is also substantially modified by the cold and less saline SSW (Pettigrew et al., 1998). While the principal repositories of slope water in the GOM are Georges Basin and Jordan basin, water mass analysis of deep-water properties in Wilkinson Basin also show the influence of slope water inputs. Brooks (1990) observed that the slope water spread over Lindenkohl sill (in the vicinity of 67.75 W, 42.45 N) from Georges Basin toward Wilkinson Basin. It has been shown that the surface heat flux plays an important role in regulating the annual cycle of the circulation in the Gulf of Maine by eroding the stratification in the upper water column due to winter cooling and reestablishing the stratification due to summer warming (Xue et al., 2000). Based on a close examination of shipboard and moored observations obtained in February 1987, the free convection initiated the deepening of the mixed layer in Wilkinson Basin, while the deepening was also enhanced by the colder and denser water fed from the coastal regions in the western Gulf of Maine (Mupparapu and Brown, 2002).

It is not the aim of this paper to investigate the intriguing dynamics of the Gulf of Maine. Our objectives are, however, to introduce a Gulf of Maine nowcast/forecast system as a part of the Gulf of Maine Ocean Observing System (GoMOOS) initiative, to discuss the issues involved in developing such a system, and to advocate for a quantifiable measure of such a system. It is recognized by the National Ocean Research Leadership Council that models play critical roles in the Integrated Ocean Observing System (IOOS) (Ocean US, 2003). Models can be used to fill the gaps of the undersampled field observations and extrapolate and interpolate them to a full 4D synoptic view. As well, they can be used to estimate quantities that are not observed directly and make predictions. An important issue associated with IOOS is the synergy between monitoring and modeling. Monitoring provides a critical incoming data stream for models as forcing, in assimilation, and in skill assessment. To this end, models act as passive receivers. A more active role would be for models to suggest to the monitoring system in terms of critical variables and locations to be monitored. Recognizing that operational coastal ocean forecasting is still in its infancy, many issues need to be explored, which include standardization of incoming/outgoing data streams,
state-of-the-art technology versus mature operational technologies, model efficiency, assessment of predictive skills, consistency of model performance, system errors and operational criteria. Some of the issues (e.g., efficiency) would be better handled independently due to the limitation of facilities and resources. Others (e.g., consistency) would need time and sustained operation. Nevertheless, models at a minimum should be robust (say, capable of year-round integration), efficient (say, one to two orders of magnitude faster than clock time to produce forecasts), and routinely provide error and uncertainty statistics so that users can refer to the model results intelligently.

The GoMOOS circulation nowcast/forecast system has been developed from the comprehensive Gulf of Maine circulation model of Xue et al. (2000). The goal is to establish an operational numerical prediction system for the Gulf of Maine, which produces forecasts of ocean conditions by coupling with available atmospheric forecasts and makes them available via the World Wide Web in real time. One of the expectations is that the model, as it matures, can provide short- and long-term, three-dimensional temperature variations, which are known to affect the fisheries in the Gulf of Maine. The system now includes assimilation of the satellite-derived SST, and it will also include in the future assimilation of CODAR estimated sea surface velocity, which is undergoing extensive tests and evaluation. In this paper, only the SST assimilation is discussed. The following section describes the present version of the GoMOOS circulation nowcast/forecast system and the SST assimilation scheme. Section 3 discusses the detailed comparisons between the model predicted and moored observations of temperature and velocity. Section 4 summarizes the current status of the GoMOOS nowcast/forecast system and the ongoing and planned activities.

2. The Gulf of Maine nowcast/forecast system

The Gulf of Maine circulation nowcast/forecast system is based on the three-dimensional Princeton Ocean Model (Mellor, 2003) in a curvilinear grid (Fig. 2). It has 22 sigma levels in the vertical (0, −0.0083, −0.0167, −0.0333, −0.0667, −0.1333, −0.2000, −0.2667, −0.3333, −0.4000, −0.4667, −0.5333, −0.6000, −0.6667, −0.7333, −0.8000, −0.8667, −0.9333, −0.9667, −0.9833, −0.9917, −1.0). The horizontal resolution varies from ~3 km nearshore to ~5 km offshore, which limits the external and internal time steps to 8 and 216 s, respectively. The nowcast/forecast system is driven at the surface with the heat, moisture, and momentum fluxes from the National Center for Environmental Prediction (NCEP)’s Eta mesoscale atmospheric forecast model (http://www.emc.ncep.noaa.gov/mmb/mmbpll/etaop/) with a spatial resolution of 32 km and a temporal resolution of 3 h. Boundary forcing includes daily river outflows from St. John, Penobscot, Kennebec, Androscoggin, Saco, and Merrimack, tidal (M2, S2, N2, K1, O1, ...
and $P_1$) and subtidal forcing from the open ocean, which is interpolated from the daily nowcast of the NCEP Regional Ocean Forecast System (ROFS—http://polar.wwb.noaa.gov/cofs/Welcome.html).

2.1. Operational procedure

The daily operation, which starts everyday at 0600 Eastern Standard Time, includes three consecutive jobs: pre-processing, model integration, and post-processing. Pre-processing consists of a series of automated scripts, which download the river discharge, AVHRR, Eta and ROFS forecasts, and interpolate them to the Gulf of Maine model grid (see Fig. 2). Handling missing data is a critical step. For short-term disruption of river discharge data, the last valid number is carried forward. Climatological monthly mean values are used during the extensive ice period in winter. For AVHRR, a daily composite is formed to minimize the effects of cloud cover. Missing ROFS data are usually substituted using the ROFS output from the last available date with tidal correction, which works well for interruptions of up to a week. Similarly, the last available Eta forecast is used to substitute for missing Eta data. This procedure, however, can result in considerable errors.

Upon the completion of pre-processing, which supplies necessary surface and side open boundary conditions, the automated daily procedure calls for the model integration session (Fig. 3). A 24-h nowcast cycle assimilates the satellite SST (see details in the following section) and updates the initial condition for the next 48-h forecast.

Post-processing includes archiving the model results and updating the graphical output on the web. Model output of every 3 h has been archived since 1 January 2001, and daily restart files have been saved incrementally for hindcasts of specific events. Temperature, salinity and velocity at three levels and surface elevation are shown graphically on the Web at a 3-h interval (http://gomoos.org). The GoMOOS circulation forecast system is currently running on both an SGI Origin 3200 and a dual processor PC. The daily procedure takes about 20 min on the SGI and about 2 h on the PC. The system is robust, and has seldom needed human intervention over the past 3 years.

2.2. SST assimilation

For a model to produce SST correctly, it is essential to have the exact heat balance at the surface. The Eta heat fluxes appear to contain significant errors as suggested by the discrepancy between the observed and the predicted air temperature. Consider as an example, the monthly mean of the observed and modeled surface air temperature in 2003 at National Data Buoy Center (NDBC) buoy 44007 (43.53 N, 70.14 W) (Fig. 4). Differences vary from month to month with the Eta predicted air temperature being about $2^\circ$C colder in winter to about $0.6^\circ$C warmer in early summer. Similar biases are found in years 2001 and 2002 and for all GoMOOS and NDBC buoys in the Gulf of

Fig. 3. Schematic of the daily nowcast/forecast procedure.

Fig. 4. Comparison of the monthly mean and standard deviation of the observed and Eta surface air temperature in 2003 at NDBC buoy 44007 located at the mouth of Casco Bay (observed—light; predicted—dark).
Maine. As a result, the modeled SST without assimilation (not shown) is considerably higher in summer months, and it does not exhibit the typical east–west contrast often seen in the AVHRR. It is anticipated that, by assimilating satellite-derived SST, the model can establish a more realistic heat budget at the surface. Furthermore, heat fluxes affect not only the SST in the model, but also the subsurface temperature and the circulation, especially when and where strong mixing or strong heat storage occurs. The second reason for SST assimilation is that the model is expected to act as a dynamically consistent interpolator to help fill the gaps in the satellite AVHRR data.

To assimilate satellite AVHRR data into the model, an algorithm similar to that of Kelley et al. (1999) has been incorporated into the GoMOOS nowcast/forecast system since June 2001. The algorithm, chosen mainly because of its computational efficiency, consists of three elements: an optimal interpolation scheme based upon Derber and Rosati (1989) and Behringer et al. (1998); a mixed-layer adjustment (Chalikov et al., 1996); and successive correction during the nowcast cycle.

The first task of the SST assimilation is to produce a daily composite of the surface temperature. There are generally four passes per day including both ascending and descending tracks of n12 and n14 (n16 replaced n14 starting October 2001 and n15 replaced n16 starting March 2004). Data from all passes in the same day are combined to form a daily composite of AVHRR. It is common for daily AVHRR composites to have a considerable amount of cloud cover. For example, examine the composite on 9 June 2002 (Fig. 5a). In addition, an apparent artifact is the exceptionally cold temperature associated with cloud shadows, i.e., the blue areas adjacent to the white areas (clouds). To minimize its effect on the model prediction, the daily composite of AVHRR is compared with the

![Figure 5](image_url)

Fig. 5. (a) The daily composite of AVHRR on 9 June 2002. White areas over the water indicate cloud cover. (b) The SST correction field resultant from OI. (c) The model SST at the end of the nowcast cycle, which serves as the initial condition for the forecast cycle on 10 June 2002. (b) uses the color scale above the color bar, whereas (a) and (c) use the color scale below the color bar.
daily averaged surface temperature from the last forecast cycle, and the differences are limited to \( \pm 2^\circ C \) (equivalent to a correction of \(~10 \text{ Wm}^{-2}\) in the net heat flux). For areas covered by clouds, the last cloud-free day in the past 4 days is used to patch up. If there is no cloud-free day in the past 4 days, two different approaches have been used to fill in the sea surface temperatures. One is to use the climatological 8-day composite that is virtually cloud free, and another is to use the modeled SST. The latter is used in the present version of the GoMOOS nowcast/forecast system.

After deriving the daily composite SST field (designated as the observed field, \( T_o \)), the optimal interpolation procedure is to determine a correction field for the model’s top layer temperature by simultaneously minimizing two difference fields. One is the difference between the corrected temperature field (\( T_c \)) and the model temperature field (\( T_m \)), and the other is between the corrected temperature field and the observed field (\( T_o \)).

\[
I = (T_c - T_m)^{\text{obs}}(T_c - T_m) + (8T_c - T_o)^{\text{corr}}(8T_c - T_o),
\]

where the superscript, \( \text{obs} \) and \( \text{corr} \) are the transpose matrices for the model data and the observations, respectively. Following Kelley et al. (1999), \( \text{corr} \) is a diagonal matrix (assuming the observational errors are uncorrelated). The trace of the diagonal elements of \( \text{corr} \) is the total observational error variance. A time factor is incorporated into \( \text{corr} \) such that more weight is placed on the observations with time closer to the assimilation date. The model error covariance is approximated, for any two grid points, as

\[
\mathcal{R}_{ij} = a \exp[-(r_{ij}/b)^2],
\]

where \( r_{ij} \) is the horizontal distance between two model grid points, \( a \) is the first guess error variance, and \( b \) is the estimate of the correlation spatial scale of the model error, which are set to 0.50 \( \text{C}^2 \) and 60 km, respectively. \( \mathcal{R} \) is the transformation matrix that converts values at the model grid points to the observation locations. Minimization is achieved by using a pre-conditioned conjugate gradient algorithm (Gill et al., 1981; Golub and Van Loan, 1989), which finds the solution iteratively. The corresponding correction field is displayed (Fig. 5b).

SST, however, is not a strong dynamical constraint. Temperature below the surface needs to be adjusted accordingly. A simple procedure is currently employed in the GoMOOS nowcast/forecast system such that when the corrected surface temperature is warmer than the model surface temperature, the correction is applied to the top 100 m with the magnitude decreasing downward linearly, while when the corrected temperature is cooler, the corrected temperature replaces the model temperatures down to the depth where they become equal or to 200 m which ever is closer to the surface. Finally, successive correction is employed over the nowcast cycle to slowly apply the 3D correction field to the model temperature by adding \( \gamma(1-\gamma)^n T_{\text{DIF}} \) at every time step, where \( T_{\text{DIF}} \) is the 3D correction field, \( n \) is the number of iteration and \( \gamma = 0.005 \). The SST field that resulted from the nowcast cycle, which serves as the initial SST for the 10 June 2002 forecast cycle, is presented (Fig. 5c).

The algorithm is steady and has produced robust sea surface temperature patterns since it was implemented. As seen (Fig. 5c), the typical summertime east–west contrast in the sea surface temperature is well-simulated, as well as the cold temperature on Georges Bank. The sensitivity of the modeled temperature field to some of the specific treatments in the assimilation algorithm, such as filling in the cloudy spots and the depth of the vertical adjustment, has been reported (Xue et al., 2004). More experiments are being carried out regarding the two parameters that describe the model error covariance (see Eq. (2)) and the speed of convergence in successive correction.

3. Assessment of the GoMOOS nowcast/forecast system

An operational system should always strive for reliability. Reliability, in part, means that the system can successfully run at designated times of the day for every day of the year; it appears that this goal is readily met. Another part of the reliability is accuracy, and that is a more challenging issue. Accuracy is often a user-dependent, problem-dependent measure. One of the questions is whether a set of metrics is needed to determine if an operational system meets the test for accuracy. If so, what are the reasonable values for the variables in the metric that can be achieved with the present technology? Before a consensus is reached, what is needed is to establish a database of error statistics of various regional systems regarding all variables under all circumstances including adverse conditions. This database can also serve as a guideline to
using the model forecasts intelligently. Moreover, it is important to understand potential sources of errors and their effects on the model forecast, which allows researchers and system developers to further improve the systems. For these reasons, the results from the GoMOOS nowcast/forecast system have been compared routinely with GoMOOS buoy observations. Results from years 2002 and 2003 are presented here. Since most of the buoys have been located near the coast with the exception of M

Fig. 6. (a) Comparisons of near surface temperature at buoys A, B, C, E, F, I, J, and M in 2002. Light (dark) curves represent the moored observations (the model predictions at the grid points closest to the buoys). They are sampled at 1 m depth. Triangular dots represent AVHRR sea surface temperature at pixels closest to the buoys. Units are in deg C. (b) Similar to (a) but for 2003.
(see Fig. 1), the error statistics represent mostly their characteristics in the coastal regions of the Gulf of Maine. With the addition of buoy L and N (in the Northeast Channel) deployed in 2004, a similar exercise in the future would yield error statistics for some of the offshore regions of the Gulf of Maine.

3.1. Temperature

Temperature is routinely measured at three depths (1, 20, and 50 m) for most GoMOOS buoys. Exceptions are the deepest temperature sensor was at 20 m on buoy C and 10 m on buoy J. Buoy M, on
the other hand, was the only mooring with temperature sensors below 50m. In 2002, buoy M had a sensor at 30m instead of 20 and 50m. Comparisons of the near-surface temperature from buoys, AVHRR and model calculations are shown in Fig. 6. It is clear that the modeled temperature matches well with the in situ temperature at most buoys, except that the modeled temperature tends to be higher at buoy I and M in the summer of 2003. This trend should be monitored carefully in 2004 to

Fig. 7. (a) Monthly averaged temperature in 2002, sampled at 20 m at buoys A, B, C, E, F, and I, but at 10 m at buoy J and 30 m at buoy M. Dark and lightly shaded columns represent the model predictions and moored observations, respectively. Markers on each column indicate corresponding standard deviations. Units are in deg C. (b) Similar to (a) but for 2003. Buoy M was sampled at the 20 m depth in 2003.
see whether it is associated with the interannual variation of the surface heat flux or with a probable long-term drift of the ocean model itself. The evidence of the former is that the net downward heat flux from Eta was 20–40 W m\(^{-2}\) higher in June–September 2003 than the same months in 2002 (not shown). The evidence for the latter is that the surface salinity in the model decreased from 2002 to 2003. Nevertheless, both the model and the moored observations indicate that the lowest SST occurred in February at most of the buoys, while the highest SST occurred in August. Secondly, SST was noticeably warmer in the western Gulf of Maine (A and B), cooler towards the east (E and I).
February and March of 2003 were colder than the same months in 2002, whereas summer SSTs in these 2 years were comparable.

Monthly means of the modeled and observed temperature at 20 and 50 m are compared (Fig. 7 and 8, respectively). Note that the temperature was taken at 10 m at buoy J and 30 m at buoy M in 2002. From January to March, the monthly mean temperature increased slightly from 1 m (though not shown, can be deduced from Fig. 6) to 20 m at buoys A, B, C and F and further increased to 50 m at buoys A, B and F, while the upper 50 m of the water column appeared to be relatively well mixed at buoys E, I and J. The water column began to warm up in April. For most of the buoys in both years, the highest monthly mean temperature occurred in September at 20 m and October at 50 m. The exceptions were, at 20 m, the observed temperature at buoy A and B in 2002 as well as buoys A and E in 2003, where the highest monthly mean temperature appeared in October; at 50 m, the monthly mean of the observed temperature was highest in November at buoy A but in September at buoy F (from both the observations and the predictions).

Temperature decreased from the surface downward between April and November. The vertical gradient in temperature was maximum in August, with the temperature decrease as much as 6–8°C from 1 to 20 m at the more stratified locations such as buoys A, B, C, E and M, about 3 and 2°C at F and I. The temperature was almost the same from 0 to 10 m at buoy J. The maximum temperature gradient between 20 and 50 m occurred mostly in September, ranging from about 3°C at A and M to a few tenths of a degree at I. The temperature

![Graphs showing temperature data for different buoys over months](image)

Fig. 8. (a) Similar to Fig. 7a but for 50 m. In 2002, observations were made at buoys A, B, E, F, and I. There were no conductivity–temperature–depth (CTD) sensors at 50 m on buoy M, and no data were returned from the CTD at 80 m. (b) Similar to (a) but for 2003. A CTD was mounted at 50 m on buoy M beginning in July 2003.
gradient became slightly negative (cooler water on the top) again in December. These spatial and temporal variations in temperature were consistently reproduced in the model. The predicted temperature, however, was generally lower than the observed temperature both at 20 and 50 m except for buoys A and B with RMS of 1.00 and 1.16 °C at 20 and 50 m, respectively. The largest differences were at buoy F.

3.2. Velocity

The GoMOOS buoy array uses acoustic Doppler technology to obtain current measurements. Important advantages of the Doppler technology include immunity to bio-fouling and self-wake problems that affect most other types of current measurement devices. GoMOOS uses the Aanderaa RCM 9 MKII acoustic Doppler current meter for making current measurements 2 m from the surface. The 2 MHz current meter is operated in burst mode once per hour and collects measurements that have a statistical precision of ~0.005 m s^{-1} in speed and ~5° in direction. For deeper currents the GoMOOS array uses RD Instruments 300 kHz Acoustic Doppler Profilers (ADCPs) that are also operated in burst mode once per hour. The ADCPs are set to sample for approximately 8 min with a vertical resolution of 4 m, and speed and direction uncertainties equivalent to those given above for the RCM 9 MKIIs.

Harmonic analysis is applied to the velocity time series to separate the tidal current from the residual flows. The quality of predicted tidal current varies.
from buoy to buoy. In general, the model performs better at buoys in relatively open water. Magnitudes of the tidal current along the major and minor axes are calculated from the predicted and observed velocities. These values for the semi-diurnal lunar tide ($M_2$) are examined (Fig. 9). Overall the spatial variation is consistent from buoy to buoy. RMS error is about 1.9 cm s$^{-1}$ (15%) for the major axis, 1.2 cm s$^{-1}$ (52%) for the minor axis, and 11.5° for the orientation of the major axis. Buoys C, F and J are excluded from this comparison since the now-

cast/forecast system at the present resolution (see Fig. 2) cannot properly resolve the tidal regime in the bays.

The predicted tidal residual surface velocities on the shelf, namely, at buoys A, B, E and I appear to match with the observed velocity in terms of magnitude and variance (Fig. 10). Furthermore, the prediction detects the timing of seasonal transition and some of the interannual variations of the coastal current. There are also visual correlations for events in the weather band, especially in winter. To help quantify the similarities and differences between the predicted and the observed velocity, both the monthly correlation coefficients and monthly means are presented. Note that some of these monthly statistics are strongly distorted due to missing a large portion of observations in particular months.

The squared correlation coefficients for the eastward velocity at 2 m of buoys A, B, E, and I (left-hand panels of Fig. 10a and b) are examined in monthly bins (Fig. 11). It appears rather consistent in 2 years that the correlations are higher in winter than in summer. The exception at buoy A in January 2002 is due to missing a large portion of observations in that month (Fig. 10a). On the average, there are about 240 data points for the months without missing data. Assume the decorrelation time scale of 24 h, the degree of freedom is estimated at about 30 and the corresponding 95% significant value for $R^2$ is 0.12. Some of the correlation coefficients are smaller than the significant value, especially during summer months. To put these numbers in perspective, the squared correlation coefficients between the Eta predicted and the observed westerly wind at the same buoys are also examined in the right-hand panels of Fig. 11. These correlations also decrease in summer months for reasons that winds in summer are more variable in direction and that atmospheric forecasts are less satisfactory in summer months since a large percentage of the weather systems that affect the Gulf of Maine come from south and scarce observations above the water provide only limited information to the Eta model. In addition to the errors in the wind forcing, the intrinsic errors of the ocean model itself also contribute to the differences between the predicted and observed velocity. It appears that the GoMOOS nowcast/forecast system is better at predicting predominantly wind-driven events in winter than the processes affected more by stratification in summer, e.g., internal tides. On the

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Fig. 9. Comparison of (a) the major axis, (b) the minor axis, and (c) orientation of the major axis of the $M_2$ tidal ellipses derived from the predicted (dark) and the observed (light) velocity. Units are in cm s$^{-1}$ in (a) and (b) and degree in (c).
other hand, some of the low correlations between
the predicted and the observed surface velocities are
more obviously linked to the low correlations
between the Eta predicted and the observed winds,
for example, May 2003 at buoy A.

Another way to measure the system performance
in a statistical sense is by the monthly means
and standard deviations. They are compared
(Fig. 12–14) for depths at 2, 18 and 50 m,
respectively. At 2 m, on the monthly average, the
v-component (north–south) of velocity is greater at
buoys A and B, the u-component (east–west) is
greater at buoy E, while u- and v-components are of
similar magnitude at buoy I. The model is able to
reproduce the change of directions associated with
the monthly mean currents at these four buoys.
There appears to be a trend of slowing or even
reversing direction of the coastal current during
winter months both in the observations and in the
predictions. Although the correlations are lower in
summer (Fig. 11), the predictions produce monthly
mean velocities that are in a better agreement with
observations in summer. The predictions tend to
under-predict the north–south velocity at buoy A in
2002, but over-predict the north–south velocity at
buoy B in 2003. The large difference between the
predicted and the observed monthly mean velocities
at buoy B in January 2003 is partly an artifact of
missing observations in the later half of the month.
Standard deviations, as measures of the variability
in the velocity field, are rather consistent between
the predictions and the observations, both in terms
of changes from buoy to buoy and from month to
month.

Overall variations of the monthly mean velocities
from buoy to buoy and season-to-season at 18 and
50 m (Figs. 13 and 14, respectively) are similar to
those at 2 m (Fig. 12). The predictions, however,

Fig. 10. (a) Tidal residual velocities at 2 m of buoys A, B, E, and I in 2002. Dark and light curves represent predicted and observed,
respectively. (b) Similar to (a) but for 2003.
tend to over-estimate the monthly mean velocity at depths and under-estimate the associated standard deviation except for the north–south velocity at buoy A in 2002.

3.3. Salinity

Subsurface velocities are of course influenced more by the water-column stratification, which is determined by both the temperature and the salinity, than by the wind forcing at the surface. Though the present nowcast/forecast system is able to produce reasonable spatial and temporal variations of the temperature, there is a time-and-space-dependent bias in the predicted salinity field ranging from about 0.5 ppt in winter to as much as 2.5 ppt in spring early summer (Fig. 15). The salinity predicted by the ROFS, which is used as the open boundary condition for the GoMOOS nowcast/forecast system, is higher than the monthly climatological salinity in the Gulf of Maine and higher by as much as 3 ppt on the Scotian Shelf when the maximum inflow occurs in January/February (Xue et al., 2000). It is noteworthy that the maximum bias at buoy I occurs before the spring freshet from the St. John River arrives at buoy I in June and that the bias increases from the surface down, both facts suggest that a large portion of the salinity error detected at buoy I is probably not because of the local rivers in the Gulf of Maine, namely the St. John River, but due to the inherited error from the ROFS. The bias does not change much from I to E, suggesting that the predictions estimate correctly the effect of the Penobscot River on coastal salinity. On the other hand, the considerable increase in the 1 m-bias from buoy E to buoys B and A is likely due to the model errors in resolving the estuarine processes associated with the Kennebec, Androscoggin, and Merrimack Rivers.
4. Summary

With the real-time atmospheric forcing and river discharge, as well as the ROFS predicted open ocean boundary conditions, the GoMOOS nowcast/forecast system is able to produce real-time, three-dimensional distributions of the circulation and water properties for the Gulf of...
Fig. 12. (a) Monthly mean tidal residual currents at 2 m in 2002. Dark and lightly shaded columns represent the model results and moored observations, respectively. Markers on each column are the standard deviation corresponding to the monthly mean. Units are in cm s\(^{-1}\). (b) Similar to (a), but for 2003.
Maine, Bay of Fundy and the adjoining Georges Bank region. By assimilating the satellite-derived SST, the system corrects the errors in the temperature field caused by the errors in the Eta surface heat flux and generates robust SST distributions. Analyses of the predicted temperature in 2002 and 2003 indicate that the system produces realistic seasonal variations of temperature in the
top 50 m. In addition, in the synoptic frequency band, the correlation coefficients between the predicted temperature and the in situ temperature are higher in the western Gulf of Maine than in the eastern Gulf of Maine, and higher on the shelf than in the bays (Xue et al., 2004).

The assimilation scheme continues to be examined, as are the predicted subsurface temperature
and stratification. For example, the subsurface temperature in the western Gulf of Maine, particularly at buoys A and B, tends to be too warm in summer months. The winter convection is stronger in the western Gulf of Maine, and the deep convection in winter could have lingering effects on the subsurface temperature in summer. On the other hand, mooring M was the only mooring with conductivity and temperature sensors at greater depths (130, 180 and 240 m in 2002; 100, 150, 200
and 250 m in 2003), and in both years the instruments were not functioning in the first half of the year, which makes it impossible to depict the entire seasonal cycle. Nevertheless, the predictions appear to have larger seasonal variations at depths and the temperature at depths below 200 m is too cold, at least at mooring M. With the addition of buoy N in the Northeast Channel, which has CTDs mounted at 100, 150 and 180 m, predicted results will also be compared with moored observations at

![Fig. 14. (a) Similar to Fig. 12a, but for 50 m. (b) Similar to Fig. 12b, but for 50 m.](image-url)
M and N in future years as well as the NMFS hydrographic data (Taylor et al., 2003). A spatially and temporally varying adjustment depth might be needed and a viable approach may be the feature-oriented model of Gangopadhyay et al. (2003).

A more pressing issue is, however, to correct the salinity field in the model. It appears that a significant portion of the error is inherited from the ROFS through the open boundary. New operational products are anticipated from NCEP...
future coastal ocean forecast system (Rao, 2004) or from the Global Ocean Data Assimilation Experiment (GODAE) with possibly much improved salinity field on the continental shelf. Meanwhile, we plan to incorporate the climatological hydrography and the real-time hydrography of the Scotian Shelf into the GoMOOS nowcast/forecast system.

Velocity comparisons are conducted in different frequency bands, including the tidal, synoptic, and seasonal. Predictions so far have depicted a seasonal trend in the coastal current with the southwestward Gulf of Maine Coastal Current being slower or even reversing its direction in winter. Similar seasonal variation in the climatological circulation was found in an earlier study, which was attributed to the seasonal evolution of the density field in the basin (Xue et al., 2000). More in-depth investigation of the dynamics associated with the seasonal variation is the focus of an ongoing effort between the GoMOOS buoy group and the GoMOOS modeling group.

These comparisons also help to identify the sources of errors and their attributions to the errors associated with the open boundary condition, surface wind forcing, and the predicted hydrographic structure and mixing processes. For example, monthly correlations suggest that the predictions do a good job in estimating wind-driven events during winter. However, the decrease in correlation during summer points to the weakness of the system in estimating baroclinic processes related to both the lateral and vertical gradients of density. In addition to the continuing effort to improve the water column stratification, finer resolution is also needed to better resolve some of the near shore processes (e.g., plume dynamics on the shelf). Continuation of these comparisons is expected to lead to new insights in terms of predictability of the model and guide the assimilation of the sea surface velocity observed by CODARs.

CODARs are the high-frequency radar units that can be used to map ocean surface currents. To assimilate the CODAR data into numerical ocean models, a shear stress approach was adopted by Lewis et al. (1998) such that the predicted velocity was nudged towards the CODAR observed velocity by imposing an additional shear stress. It was noted that errors in the CODAR data could cause unrealistic horizontal divergence and sea surface height in the model. The unrealistic divergence, however, could be limited by first filtering the CODAR velocity field (Lipphardt et al., 2000). A
data assimilation scheme similar to that of Oke et al. (2002) has been developed for the GoMOOS nowcast/forecast system and is now under extensive tests. It is a simplified Kalman filter data assimilation system that assimilates low-pass filtered CODAR velocity. The non-homogeneous and non-isotropic forecast error covariance is derived empirically from an ensemble of typical model simulations.

Coastal ocean forecasting is one of the major challenges that the oceanography community faces. Using data to constrain models has been recognized as a potentially key element for accurate forecasts. On the other hand, benchmarks for accurate predictions need to be established, although they may vary from region-to-region as limited by the available open boundary conditions from larger-scale models and by the atmospheric forecasts of different resolutions and quality. It is hoped that the overall quality of coastal ocean forecasts will be improved as GODAE products become available and more standardized and as experience with coastal ocean forecasting is accumulated.

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References


pressure observations. Journal of Physical Oceanography 9, 768–784.