PAPER

The Gulf of Maine Ocean Observing System: Generic Lessons Learned in the First Seven Years of Operation (2001-2008)

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ABSTRACT

The Gulf of Maine Ocean Observing System (GoMOOS) was established in the summer of 2001 as a prototype real-time observing system that now includes eleven solar powered buoys with physical and optical sensors, four shore-based long-range HF radar systems for surface current measurement, operational circulation and wave models, satellite observations, inshore nutrient monitoring, and hourly web delivery of data. The observing system in the Gulf of Maine (GoM) is one of the most comprehensive and operational of the Integrated Ocean Observing Systems (IOOS) systems that have been established in the United States to date. It has also been a very successful system, with data returns routinely in the 85-95% range.

The Gulf of Maine is a harsh operational environment. Winter storms pose severe challenges, including high waves and the build-up of sea ice on buoy sensors, superstructure, and solar panels, and in summer its productive waters present severe biofouling problems that can affect the optical sensors. The periods of most difficult field operations often coincide with periods of greatest data value in terms of marine safety, search and rescue, and monitoring biological productivity.

The challenges of the Gulf of Maine physical environment were paired with the unexpected challenges of the funding environment that have been the hallmark of the turn of this century. Funding for the system has been chronically short and subject to the unpredictable fluctuations of the congressional appropriations process. The inadequacy and variability of funding has substantially hampered the operations of many of the Integrated Ocean Observing Systems, including GoMOOS, and has hindered technological advancements and maintenance measures. As a result, the design of the GoMOOS infrastructure is little improved from that developed almost a decade ago, and it has deteriorated with age, usage, and suboptimal replacement schedules. In the absence of an adequate and reliable funding stream, the system is fast approaching the end of its expected operational lifetime. Unless this trend is reversed, the system will no longer well serve the many citizens, organizations, and agencies that have come to rely on the data it provides.

In this article, we present lessons learned by the scientific and technical groups that have been responsible for the data acquisition of GoMOOS. We believe that these lessons are generic, rather than peculiar to the GoMOOS system, and that they have value for others who are embarking on similar endeavors. However, it is important to make clear that these lessons are from the perspective of the scientists, and that the views of others involved in complementary aspects of GoMOOS, including public outreach, fundraising, and providing data and products to the more general user community, are not represented here.

1. Introduction

The Gulf of Maine Ocean Observing System (GoMOOS) is a comprehensive prototype integrated coastal ocean observing system. It serves online an extensive array of real-time oceanographic and marine meteorological data and data products to a broad range of users including scientists, state and federal regulators, the National Weather Service, both the U.S. and Canadian Coast Guards, the National Data Buoy Center, educators, regional natural resource managers, the Gulf of Maine fishing and maritime industries, local airports and airlines, sailors, and the general public. As perhaps the first comprehensive multidisciplinary Integrated Ocean Observing System (IOOS), GoMOOS has served as a proving ground for new technologies, operational procedures, protocols, and for management structure and governance. GoMOOS has also proven to be an example of meaningful integration of interdisciplinary sensors, platforms, and predictive models.

In addition to the hourly operational data delivery, GoMOOS provides an archive of data and model output that is significantly advancing the scientific understanding of the Gulf of Maine as a physical and an ecological system. Over the first seven years of operation, the GoMOOS data have not only illustrated important aspects of seasonal and interannual variability of the circulation and physical properties of the Gulf of Maine, in some locations the array has provided the first meaningful regional baseline of physical and biological oceanographic data.

GoMOOS is an integrated ocean observing system that can be thought of as consisting of four major subsystems: the data acquisition subsystem; the data handling, processing, and archiving subsystem; the subsystem of numerical nowcast and forecast models; and a web-based data distribution/presentation subsystem. The acquisition system includes a real-time buoy array, an array of land-based long-range Coastal Ocean Dynamics Applications Radar (CODAR) installations, a satellite data receiving station, and an inshore nutrient sampling system in Casco Bay. The data handling system includes real-time QA/QC algorithms, data processing, calibration, and data archives that include sensor inventories, deployment histories and calibration records in addition to the data records themselves. The numerical modeling systems consist of an operational real-time application of the Princeton Ocean Model (POM) for circulation and hydrographic conditions (Xue et al., 2005), and a high-resolution implementation of WAVEWATCH III wave model (Padilla et al., 2007). The operational circulation model uses output from the Eta mesoscale atmospheric forecast model run by the National Center for Environmental Prediction (NCEP), whereas the wave model is driven by wind fields provided by the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) run by FNMOC (Fleet Numerical Meteorological and Oceanographic Center).

1.1 The Oceanographic Domain of the Gulf of Maine

The GoM is a complex and very productive marine ecosystem. The level of primary (phytoplankton) production, which forms the base of the marine food chain, is high relative to other continental shelf and marginal sea environments. Fisheries production in the GoM is also high. In particular, Georges Bank, which separates the interior GoM from the northwestern Atlantic Ocean, is historically one of the most productive fishing regions in the world. These high levels of production are believed to be due to a combination of nutrient delivery via the deep inflow of nutrient-rich slope waters through the Northeast Channel, which cuts between Georges Bank and Browns Bank, and strong tidal mixing that effectively mixes the nutrients up into the lighted (euphotic) zone where they are available to fuel phytoplankton blooms (Townsend et al., 2006).

Under modern climate conditions, the Gulf of Maine is a region of strong physical, chemical, and biological gradients. During summer there is a strong contrast in upper water properties from warmer, fresher, and lower nutrients in the southwest to colder, saltier, and higher nutrients in the northeast (e.g., Pettigrew et al., 2005a, www.gomoos.org). There is also a clear southwest-to-northeast increase in tidal amplitude, and thus also in the degree of vertical mixing. A surface temperature front, which trends offshore from mid-coastal Maine in the vicinity of Penobscot Bay, often develops in summer and separates the warmer surface waters of the southwestern region from the colder waters of the northeastern Gulf (Pettigrew et al., 1998).

The southwest-to-northeast gradients in physical processes and water properties in the GoM are factors in the seasonal patterns of phytoplankton blooms and the species composition. Spring blooms occur first in shallower coastal regions and later in offshore waters. The phase propagation of the blooms is southwest-to-northeast in the coastal zone and generally northeast-to-southwest farther from shore. Summer patterns are a strong reflection of stratification and nutrient limitation over the deeper basins and tidal mixing and vertical nutrient flux over shallow and northeastern regions (Thomas et al., 2003). By autumn, cooling and overturn stimulate strong blooms, starting in the northeast and propagating to the southeast.

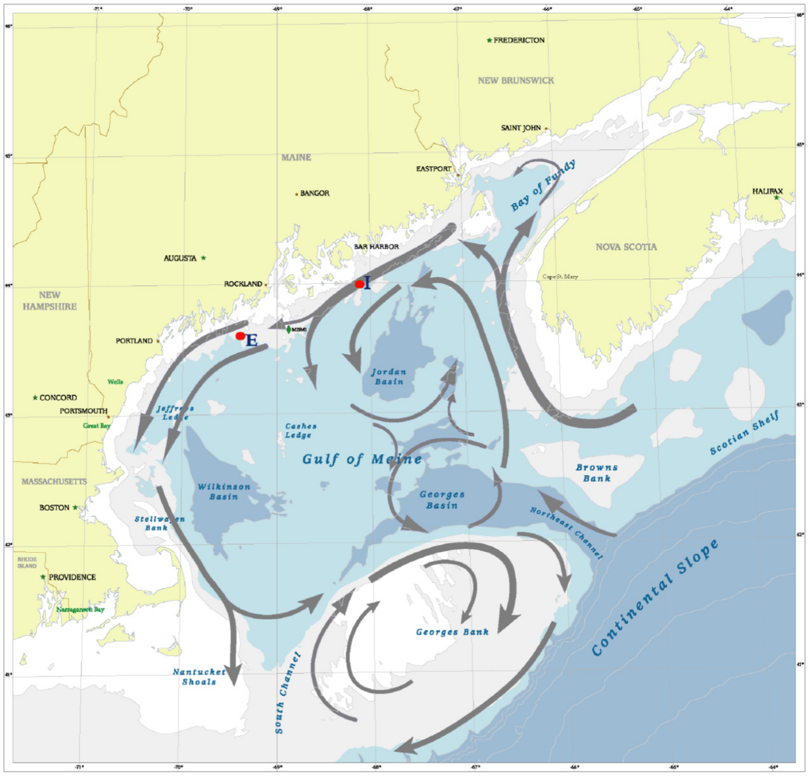
The base of the ecosystem is highly sensitive to the patterns and intensity of thermally and salinity-driven stratification, which in the Gulf of Maine are impacted significantly by patterns of precipitation, run off, wind, and heat exchange, and thus very sensitive to climate change. Under present climatic conditions, the Gulf of Maine is the northern coastal geographical limit of several temperate species as well as the southern coastal limit of several boreal species (Sinclair et al., 1991). These circumstances make the GoM an area that is biologically sensitive to the climate change signals since modest changes in temperature can result in large swings of the species composition (ranging from phytoplankton species to commercial fish species) within the Gulf. Thus the GoM can be expected to exhibit early ecological effects of climate change.

The GoM circulation is generally cyclonic (Bigelow, 1927; Brooks, 1985), and its shelf regions have a complex, variable, and interconnected coastal-current system that is best developed in the summer season (Brooks, 1985; Pettigrew et al., 2005a). A schematic diagram of the near-surface summer circulation is shown in Figure 1, which depicts a pair of cyclonic (anti-clockwise) gyres over the basins in the eastern Gulf, and a partial separation of the coastal current from the shelf at a mid-coast location in the vicinity of Penobscot Bay. Even this somewhat complex pattern is highly simplified in both time and space.

Recent moored current measurements and hydrographic surveys from the Ecology and Oceanography of Harmful Algal Blooms (ECOHAB) experiment in the Gulf of Maine showed marked interannual variability in the degree of separation versus through-flow that occurs along the coast (Pettigrew et al., 2005a). This seasonal and interannual variability in the connectivity of the eastern (EMCC) and western (WMCC) branches of the GoM coastal current system is expected to have far-reaching consequences with regard to the transport of nutrients, planktonic larvae, harmful algal blooms, and coastal pollution (cf. Luerssen et al., 2005). All of these fluxes are important factors in determining both short- and long-term variations in the state of the GoM ecosystem. GoMOOS moorings I and E, which are, respectively, in the EMCC and WMCC (see Figure 1), have revealed a strong seasonal component to this connectivity. The two branches generally merge each fall

FIGURE 1

Schematic diagram of the summer surface circulation of the Gulf of Maine (Pettigrew et al., 2005a).



and separate each spring (Pettigrew et al., 2005a). The lack of long-term direct current measurements made within the Gulf of Maine Coastal Current system, and at key inflow and outflow locations near the open boundary, has significantly hindered our understanding of both the physical and biological oceanography of the GoM. The first seven years of operation of the GoMOOS array have begun to relieve the paucity of flow data.

The surface inflow into the GoM of relatively fresh Scotian Shelf water (SSW) from the Atlantic seaboard of Nova Scotia, and the deep inflow through the Northeast Channel of relatively warm, salty, nutrient-rich slope waters (SLW) are the two most important inflows into the GoM. The large buoyancy input of the SSW accounts for more of the annual freshwater budget of the GoM than the combined inflow of all the rivers that drain into its confines. The density contrast between these relatively fresh surface and intermediate waters with the deep salty slope waters survives the vigorous tidal mixing and winter convection in the eastern GoM. The geostrophic adjustment processes in response to these persistent density contrasts engender the cyclonic general circulation pattern of the GoM. The monitoring of these inflows has long been recognized as requisite to a Regional Coastal Ocean Observing System (RCOOS) in the GoM, as well as to the understanding of the large interannual and decadal variability that characterize the hydrographic structure and the fisheries yields of the region.

2. The Ocean Observing System

2.1 GoMOOS Real-Time Buoy Designs

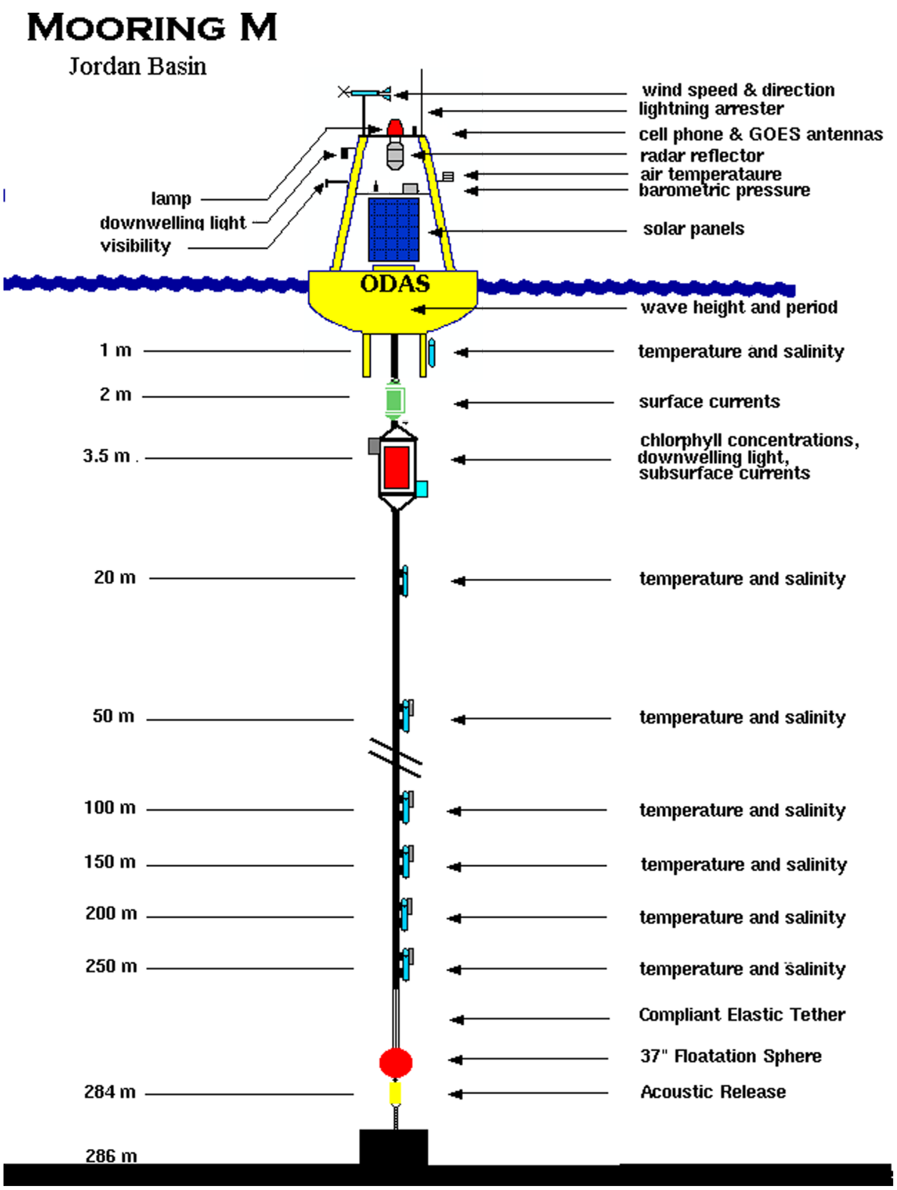
The concept of the GoMOOS Data Buoy System design was an economical, moderate sized, stable, solar-powered platform with real-time telemetry and some onboard data processing capabilities. The GoMOOS design incorporates many significant departures from the buoy designs used previously in the Gulf of Maine by the National Data Buoy Center (NDBC). Funding constraints dictated that the buoys be much cheaper to produce, cheaper to maintain, and small enough to be deployed from a relatively small ship. While required to be smaller, cheaper, and lighter than the NDBC buoys, the GoMOOS buoys had to be capable of interfacing with many more sensors, handling an order of magnitude greater data volume, and still withstanding the rigors of the Gulf of Maine winters. The starting point of the GoMOOS design was the buoy described by Irish (1997) that he and others used successfully on Georges Bank.

The GoMOOS buoy is a multi-chinned two-meter discus buoy with flotation made of closed-cell Surlyn foam. There is a central water-tight instrument well, made of aluminum, which houses the buoy electronics including the voltage regulation system, solar storage batteries, and the data-logger/controller. The buoy is designed to survive knockdown and compression due to forced submergence, it monitors its own position, and sends an alarm if it detects it is off position or has a leak in the electronics well. The buoy is solar powered, has dual cellular/iridium and GOES satellite telemetry systems for hourly data telemetry, and has room for expansion in both its power and electronic systems. Some of the design details of the GoMOOS buoy system have been previously described by Wallinga et al. (2003) and Pettigrew and Roesler (2005).

The basic GoMOOS buoy platform is moored in two different configurations: a compliant tether mooring for the offshore basin and channel buoys, and a slack chain mooring for the shelf moorings for water depths of 100 m or less. Both mooring styles have been very successful, although neither has been immune to dragging and damage associated with the fishing and marine transportation industries. A schematic diagram of the GoMOOS offshore elastic-tether mooring system is shown in Figure 2. The advantage of the elastic mooring system is a reduced watch circle, which reduces the chances of draggers working between the buoy and its anchor, and the spar-like motion reduction of the surface float. The disadvantages include the expense and short (~2 year) lifetime of the elastic members, and the requirement of using an expensive acoustic release system that leaves the anchors on the bottom (an expense to the observing system, and a potential hazard to the draggers). All buoys are mechanically identical and carry a surface sensor payload of dual sonic and mechanical anemometers (for wind speed and direction), air temperature, atmospheric pressure, and visibility (fog), and a wave accelerometer. Spectral solar insolation is included on about half the buoys.

FIGURE 2

Schematic diagram of a GoMOOS Basin Buoy. The buoy scope is provided by an elastic tether near the bottom that reduces the watch circle of the mooring. Subsurface sensors send data up the mooring wire using inductive modem technology.



2.2 Telemetry System

The telemetry system of the GoMOOS buoy has three functions: to send data from submerged instruments to the buoy; to send data from the buoy to the server at the University of Maine for processing; and to allow direct remote communications with deployed sensors for trouble-shooting operations. The transmission of data from the submerged sensors to the buoy is handled by a Sea-Bird Electronics inductive modem (IM) system. The system uses the jacketed steel mooring cable, rather than dedicated electrical cables, for communications. Use of this system enables the deployment of up to 100 sensor packages that are inductively coupled to the mooring cable. Because the IM system does not require sensors to be plugged into an electrical cable, shallow sensors can be replaced in water by divers, and changes in deployment depth can be made by sliding the sensor up or down the cable. The Sea-Bird IM system has been very reliable. Failures do occasionally occur (generally caused either by failure of the electrical cable that couples the system to the buoy or by fishing activity damaging the jacket on the mooring cable) however the data are retrieved from internal instrument data loggers after buoy recovery. This redundancy maintains the quality of the data archive; however, failure or intermittency of the IM system causes a sometimes significant reduction of the real-time functionality of the buoy system.

The transmission of data from the buoy to the University of Maine is achieved via one of two telemetry systems. The principal system is digital cellular/iridium (the cheaper cellular is chosen in regions of adequate coverage near shore) and the secondary system is a Geostationary Operational Environmental Satellite (GOES) transmitter. The use of two different telemetry systems helps insure that real-time data transmissions are successful even when one or the other is not functioning properly as a result of either environmental conditions or technical difficulties originating with the service provider.

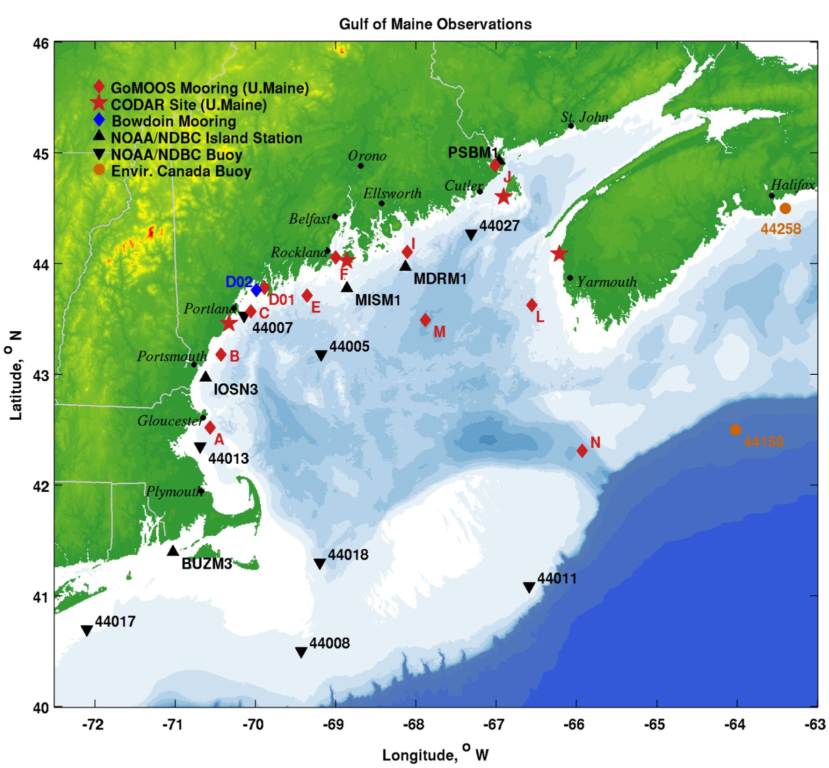
The two-way cellular/iridium link has proven to be a vital component of the overall operations of the array. There are numerous occasions when instruments fail to send data because of clock drifts, spontaneous resets of the sampling scheme, or more rarely, problems with the data logger. The ability to call the data logger and "talk through" to the sensor to reinitialize, set clocks, or "reboot" has saved substantial time, effort, and funds by enabling remote "fiddling" rather than having to rely on personnel and ships going to sea to toggle switches and reprogram sensors and data loggers.

2.3 The GoMOOS Buoy Array

The GoMOOS buoy array is shown in Figure 3. The diamonds with alphanumeric labeling show the locations of the twelve GoMOOS buoy locations within the GoM. Reference to Figure 1 shows that many of the buoys (B, C, E, I, L) are located within the Gulf of Maine Coastal Current System (GMCC) (see Pettigrew et al., 2005a), which had never been effectively monitored "year round" prior to the IOOS. These buoys collectively represent the first buoys that have gathered long time-series data at multiple sites within the GMCC, and have been in nearly continuous operation since July of 2001. The nearshore buoys A, C, F and J monitor the mouths of four GoM major estuarine embayments and buoys D (D01 and D02) are inshore buoys that are deployed in two small estuaries within Casco Bay (buoy D02 was funded under a grant from NSF to Bowdoin College, its operational costs are not covered by NOAA IOOS, and it is not officially part of GoMOOS). Buoys L and N monitor, respectively, the inflows into the Gulf of Maine from the Scotian Shelf and the North East Channel that were discussed earlier. Buoy M, located in the Jordan Basin, monitors the seasonal inventory of the nutrient-rich SLW in the interior of the GoM, which contributes to the high productivity of this important fisheries region. Bio-optical sensor packages are deployed on buoys A, B, D01, D02, E, F, I, M, and N.

FIGURE 3

Ocean Observing assets in the Gulf of Maine. Red diamonds indicate GOMOOS buoys, the blue diamond represents a buoy funded by NSF that has been integrated with GoMOOS, black inverted triangles are NDBC buoys, upright triangles are NOAA island meteorological stations, and the orange diamonds are Environment Canada buoys. GoMOOS CODAR stations are shown as red stars. (Color versions of figures available online at: http://www.mtsociety.org/publications/?fa=online).



2.4 Buoy Operations

Associated with the eleven active GoMOOS buoy sites are twenty two buoys and twenty two complete sets of instrumentation. At approximately six-month intervals (Spring and Fall) the entire array of buoys and instruments are exchanged for a set that has been refurbished, tested, repaired and calibrated in the interim since their previous deployment. Mooring cable is replaced yearly. This rotation of sensors and buoys, and early replacement of mooring components is probably the principal factor that has made the GoMOOS data streams among the most reliable of the IOOS buoy arrays.

The data quality assurance program, performed by the Physical Oceanography Group at the University of Maine, is a process of continual quasi-real-time evaluation and validation. Detailed histories are kept of sensor performance, repair, and calibration. Signatures of failure modes for the various sensors and systems have been identified over the years of operation since 2001, and real-time performance is continually evaluated and compared with these failure modes in order to flag suspect data in near real time. With each passing deployment year the QA/QC procedures become more skillful and further automated; however, they still require a great deal of attention and judgment by seasoned oceanographic personnel.

2.5 The GoMOOS Optics Program

Of all the components of GoMOOS that could not be considered to have operational capabilities in 2001, the optics program stands out as perhaps the biggest leap of faith. The most obvious problem with deploying optical sensors for extended periods in the ocean is biofouling. In addition, many of the optical sensors were still in a beta configuration with electronic and mechanical problems that had to be worked out as we went along. Despite early problems with sensor electronics and system integration, the bio-optical data streams are unparalleled in their temporal and spatial coverage and the comprehensiveness of the derived biologically-relevant data products. Because of the high data rates and high data volume of the optical sensors, on-board processing and raw data storage were necessary, with telemetry only of statistical properties. Thus the bulk of raw data processing, data product computations, and archiving are performed on the internally-logged raw data post-recovery. This blend of real-time and post-processed products has allowed significant progress not only in algorithm development but also in instrument development and sensor characterization.

Most of the optical sensors used in GoMOOS are configured with combinations of copper shutters that lie over optical faces until the instrument turns on, copper tape on surfaces surrounding the optical heads to prevent macrofaunal growth that might impede the sensor head (or worse, prevent the shutters from opening), and copper tubing on the flow-through instruments. We have found these strategies to diminish fouling, even during a 6-month deployment during the most productive portion of the year; particularly for the algal growth on chlorophyll fluorometers (Figure 4) and other flat-faced sensors such as colored dissolved organic matter (CDOM) fluorometers and backscattering sensors. We do find some bacterial growth on the optical windows, particularly on the absorption-attenuation meter. For this reason, it is particularly important that we are able to identify when this fouling occurs in real time and perform cleaning using divers when possible as well as look to redundant data products for real-time analysis. One of the important strengths of the bio-optical program is the development of sensor-independent data products. For example, on buoys D02, E and I, we have the capability of independently estimating phytoplankton biomass from four separate sensors. Thus when the temporal pattern of one sensor stops being coherent with the others we can examine, in real time, whether the problem is a biofouling or sensor malfunction. The protocols for real-time and post-recovery calibration have been described elsewhere (Pettigrew and Roesler, 2005; Roesler and Boss, 2008).

FIGURE 4

Underwater photograph of WET Labs fluorometer, after 5 months in the water. Antibiofouling copper tape has kept algal growth from affecting the optical window even though the sensor was deployed without a shutter. Photo credit: Steve Karpiak

The GoMOOS optics program uses two moored optics packages: the "phytoplankton biomass and production" packages and the larger "Ocean Color" packages. Each phytoplankton package consists of a chlorophyll fluorometer and a 4-channel downwelling irradiance sensor (used to estimate phytoplankton biomass and spectral photosynthetically available radiation). The combination of phytoplankton biomass and light measurements are sufficient for calculating primary production to first order (Siegel et al., 2001). The ocean color packages have all the instruments of the smaller package, plus an AC9 nine-wavelength absorption and attenuation meter, a backscattering sensor, a CDOM fluorometer, and a 7-channel upwelling radiance sensor. The details of the moored optics program, and its goals have been discussed more fully elsewhere (Pettigrew and Roesler, 2005; Pettigrew et al., 2008).

2.6 The HF Radar Array

GoMOOS uses four long-range CODAR units to map surface currents over the GoM. The GoMOOS long-range CODAR array is a potentially exciting element of the observing system capable of widespread, remote surface-current measurements from a limited number of shore-based radio wave transceivers. The nominal daytime range of 180 km is almost never realized in the GoM region (especially at night), and four units are not capable of providing consistent full coverage of the GoM.

Because of the highly variable CODAR radial overlap and vector coverage in the GoM, and the very strong tidal variability, it has been challenging to produce useful surface current fields. The inability to consistently receive data throughout the tidal cycle often reduces the data to a gappy series of realizations that can not be properly averaged to give a consistent picture of the general circulation patterns. Because of these limitations, we have begun to apply Artificial Neural Networks in order to fill in missing data values to provide tidally-averaged surface current maps, and to work toward the goal of short-term, wide area predictions of the GoM surface current fields.

2.7 Applications of Neural Network Models to Sensor Array Data

Artificial Neural Networks (ANNs) are parallel arrangements of simple processing units that are loosely analogous in structure and function to a biological central neuron. ANNs are comprised of a large number of these neurons in multiple layers. These neurons connect input and output through a collection of weights and transfer functions designed to minimize the differences between predictions and realizations (data). By adjusting the weights, the ANN can be "trained" to make very accurate predictions. ANNs that adjust their weights automatically can "learn" to make predictions. We have been quite successful with the nowcast and forecast of near-surface currents at the buoy locations (Pettigrew et al., 2005b; Pettigrew and Neville, 2008; Pettigrew et al., 2008).

Predictions of CODAR data fields are more problematic than predicting direct surface current measurements from the GoMOOS buoy array. The CODAR data have a lower signal-to-noise ratio, and the available inputs for the model fluctuate in time and space. Because the data availability was spotty, we were unable to provide tidal predictions, average currents for the previous tidal cycle, or even previous values at each location as inputs. In fact, we were limited to wind forcing and a varying collection of current vector values from "nearest neighbors" in the CODAR field, and the radial values in regions where vectors were not available because of the absence of overlapping signals from adjacent CODAR units. In order to cope with the variable inputs, we developed a weighting system that produces a spatially-weighted value for the nearest neighbors so that unique ANNs need not be developed for each of the myriad possible input configurations (Pettigrew et al., 2008). Under favorable conditions, when some neighboring values are available, the vector correlation values between nowcast and observed values vary from 0.8-0.9. An example of the ANN nowcast to fill in missing values on a CODAR surface current map is shown in Figure 5. Panel A shows the vectors from the CODAR vector data. Spatial gaps in the data are caused by reduced range so that radials do not overlap. The map in Panel B shows considerable improvement in coverage using winds, nearest neighbors, and radials as inputs to the ANN model. Although this example shows tremendous improvement, it represents relatively favorable conditions with regard to the extent of data gaps. These conditions are not always met, and further improvements in the model are required for an operational product that produces significant improvements over a broader range of conditions.

2.8 Satellite Data

The infrastructure for research-based acquisition and processing of NOAA AVHRR and SeaWIFS ocean color satellite data at the Satellite Oceanography Laboratory at the University of Maine was already in place prior to GoMOOS. Infrastructure for acquisition and processing of the MODIS telemetry streams was added after the establishment of GoMOOS through research funding of the Satellite Oceanography Data Laboratory, while GoMOOS provided the motivation and funding to place data acquisition, processing and delivery into an operational mode. Thus the process of incorporating satellite data into the IOOS framework was essentially a transition from episodic research funds and ad hoc data processing and posting for specific research projects, to partial IOOS funding and a daily operational mode. GoMOOS funds were also used to modify some of the extant products and to add scatterometer wind data. The GoMOOS website links directly to the web pages of the University of Maine Satellite Oceanography Data Laboratory rather than taking the data and reposting them on the GoMOOS site as is done with the Buoy and CODAR data.

2.9 Numerical Circulation Model

The operational GoMOOS circulation model (Xue et al., 2005) is based on the three-dimensional Princeton Ocean Model (Mellor, 2003) in a curvilinear grid with a variable resolution of 3 to 5 km in the horizontal and 22 sigma levels in the vertical. It is initialized and forced at the open boundaries with 6 major tidal constituents and daily nowcasts of velocity, surface elevation, temperature, and salinity from the National Center for Environmental Prediction (NCEP)'s Regional Ocean Forecast System (ROFS - http://polar.wwb.noaa.gov/cofs/Welcome.html). Surface forcing, including heat, moisture and momentum fluxes, is obtained from the NCEP's North America Mesoscale (NAM) forecast on 221 AWIPS Grid (http://www.nco.ncep.noaa.gov/pmb/products/nam/). Also specified at the coastal boundaries are daily freshwater discharges from the St. John, Penobscot, Kennebec, Androscoggin, Saco, and Merrimack Rivers based on U.S. Geological Survey gauge observations. Satellite derived sea surface temperature is assimilated using a simple optimal interpolation algorithm (Xue et al., 2005).

The daily operation includes three consecutive jobs: pre-processing, model integration, and post-processing. Preprocessing downloads the river discharge, AVHRR sea surface temperature data from the University of Maine Satellite Data Laboratory, NAM and ROFS forecasts, which are then interpolated to the Gulf of Maine model grid to prepare the boundary conditions. Then the automated daily procedure calls for the model integration session. A 24-hour nowcast cycle assimilates the satellite SST and updates the initial condition for the next 48-hour forecast. Post-processing includes archiving the model results and updating the graphical output on the web.

The operational GoMOOS circulation model has been updated since January

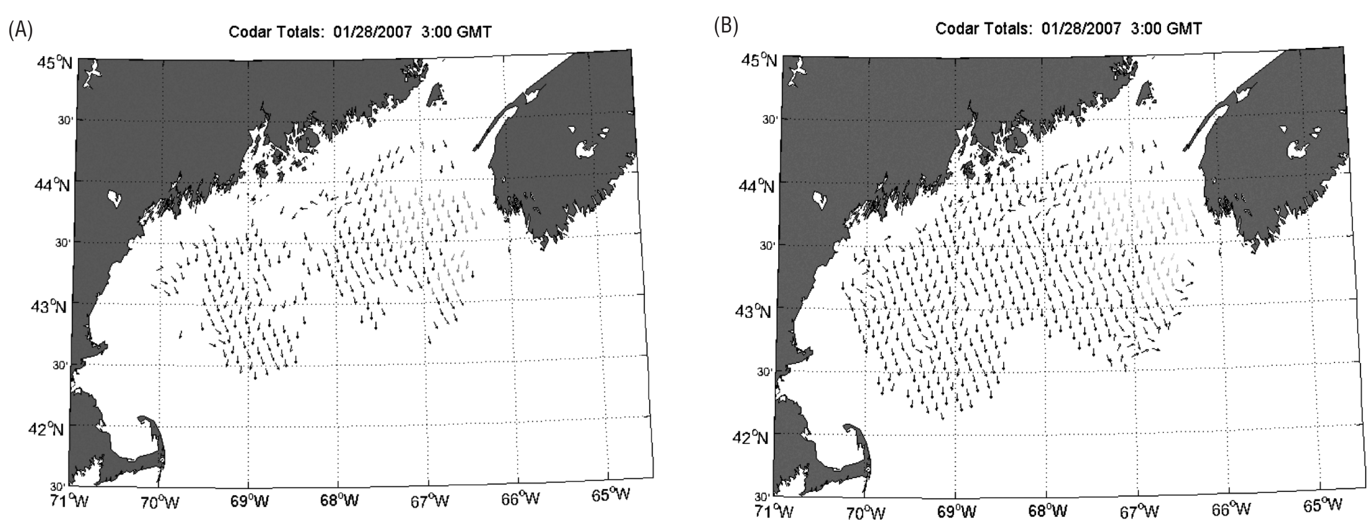


FIGURE 5 A, B

Left plot (A) shows surface current vectors observed by CODAR. Right plot (B) shows the observed data together with the ANN nowcast of the missing vectors. The inputs to the model are: available radial data, weighted-averages of neighboring vector values, and winds (Pettigrew et al., 2008).

2007. It now uses the NAM forecast on 218 AWIPS Grid for meteorological forcing at the surface, and the forecast from the NCEP's Real-Time Ocean Forecast System (http://polar.ncep.noaa.gov/ofs/), which is the NCEP's current operational forecast system, for the subtidal open boundary forcing. At the same time, the daily forecast has been extended from 48 hours to 60 hours. Model output of every 3 hours has been archived since 1 January 2001, from which monthly averages have been generated that are accessible through the web portal Live Access Server (LAS). In addition, daily restart files have been saved incrementally for hindcasts of specific events.

2.10 Numerical Wave Model

The GoMOOS wave forecast includes wave height, direction, duration and period; as well as a comparison to buoy observations for validating the forecast predictions. The forecast covers a 48 hour period and is presented in 3 hour increments. The wave forecast, based on the WAVEWATCH III model and driven by wind fields provided by the COAMPS atmospheric model run by FNMOC, is provided by the Bedford Institute of Oceanography (BIO) in Dartmouth, Nova Scotia. WAVEWATCH III is implemented on a system of three nested grids. The spatial resolution increases from 1.0o in the coarse grid to 0.2o in the intermediate grid to 0.1o in the fine resolution grid. Details of the grid dimensions and resolutions are given by Padilla et al. (2007).

2.11 Casco Bay Nutrient Sampling

Since 2001, water samples collected in Casco Bay by The Friends of Casco Bay, a nongovernmental organization, have been analyzed for NO2+NO3, NH4, Si(OH)4, and PO4 at the University of Maine. Home to Maine's population centers and its largest city (Portland), Casco Bay is prone to the effects of anthropogenic nutrient additions, and yet at the same time, it reflects the influxes of nutrients from the deeper offshore waters. Sampling stations are located throughout the Bay, and are sampled approximately weekly, from the surface and various depths to the bottom. In addition, surface water samples are collected approximately daily from a dock at the southwest entrance point to Casco Bay.

2.12 Shipboard Observations

Due to funding constraints, there has never been a functional shipboard observing program as part of GoMOOS. Although the buoy program uses approximately 24 ship days in a typical operational year, there has never been a budget to add a few days for hydrographic surveys. From the scientific point of view, this practice would certainly seem to be "penny wise and pound foolish." For an additional 10-20% in ship time the buoy cruises could have been augmented to collect important (although not comprehensive) biannual hydrographic surveys at stations along the tracks between the buoy locations and at a few other key locations. The decision to not fund shipboard observations is a consequence of the overall scarcity of funding as well as the priorities of a GoMOOS administration that strongly favored products easily presented to the general public in real time. Thus, the limited funds were directed more toward the user interface at the expense of the historical content of the data archives. It is hard to argue convincingly, pro or con, about the wisdom of this policy, since it pits the scientific content of the archives against the real-time impact of the system. In any case, this issue is illustrative of the tradeoffs that must be made when funds for operating a multiuse system are severely limited.

3. Lessons Learned

In operational oceanography, as in most human endeavor, we learn from successes and failures, from hardship and ease, and from discord and harmony. From these outcomes, individuals and working groups develop "best practices" aimed at optimizing success, ease, and harmony. In essence, if something works we try to keep doing it, and if something fails we try something else. Through this process, a collection of procedures, methods, and opinions arise that are consistent with the working philosophy of the group, and which generally reinforce positive outcomes while sequentially eliminating practices that lead to negative outcomes or interactions.

In a complex enterprise like IOOS (with a mix of funding agencies, political bureaucracies, administrators, scientists, and technicians) no one group has the power to effect all the changes that they believe are needed to improve the system. As a result, convergence toward best practices is noticeably slower than the pace to which scientists and technicians are accustomed in classical R&D projects. The frustration that this situation engenders is undoubtedly similarly experienced by administrators, funding agents, and politicians. Each group can wind up feeling that their vision, and their efforts, are being hampered by others in control of others aspects of the IOOS process. Below we discuss briefly some of the lessons learned by the scientists, engineers, programmers, and technicians who are responsible for operating the observing system in the Gulf of Maine. We hope that these lessons will be of use (or at least comfort) to groups involved in similar endeavors. We acknowledge that our perspective may in some cases be decidedly different from that of other groups that have different roles in the enterprise of ocean observing.

We have structured the list of lessons learned into those that evolved into as "best practices" from successful operations (Type I), and those that still need to be implemented to improve the function and efficiency of the observing system in the GoM (Type II). Finally, we list some general suggestions about organizational structures, funding processes, and regional decision making that we believe are important considerations as we look toward the future of coastal ocean observing.

Type I Lessons

- Academic institutions and academic research groups are capable of efficiently and economically operating ocean observing systems. This lesson was not one that needed to be learned by the academic community, but it was a point of serious discussion amongst commercial and governmental entities involved in the IOOS movement. Colleges and universities, in part because of their insular nature, must perform numerous operational functions including operating power plants, fire and police services, radio stations, communication networks, and health services as part of their everyday operations. The ability of academic institutions to add the more "academic" function of operating an observing system focused on environmental science and engineering would seem obvious. In each year of its operation, GoMOOS's initial goal of 80% data return has been exceeded.

- Basing IOOS at academic research institutions is an effective hedge against instability and funding shortfalls. IOOS, across the country and in the Gulf of Maine region in particular, has been heavily subsidized by academic institutions. Without the financial support of the academic institutions, the observing systems would have failed years ago as a result of the lack of sufficient funding to carry on operations. In the case of land grant and sea grant colleges and universities, this providing of service to the citizens of their states and the generation of new knowledge, together with their primary pursuit of education, form the three components of their tripartite mission. In turn, the academic institutions benefit from the research and educational opportunities that accompany IOOS operations, and from increased visibility that comes with success in new and highly visible endeavors. Universities are large and diverse entities that have the ability to take a long view of the benefits of programs that are, in the short view, a financial burden.
- Duplicate buoys and a six-month servicing schedule keep the system at a high level of performance. The decision was made at the onset of GoMOOS to build two buoys with two sets of instrumentation for each buoy monitoring location. This practice allowed us to replace each buoy with a newly-prepared buoy every six months. Although this schedule seemed excessive from the point of view of many of the physical measurements, it was minimal from the point of view of the optical sensors that are very sensitive to biofouling. In hindsight, we believe this protocol to be a primary reason for the unprecedented success of the GoMOOS buoy array, which has operated in a very harsh environment, and yet has consistently been an IOOS leader in data return rates, the number and variety of sensors deployed, and the percentage of buoys in continuous operation.
- Wide band-width Internet connecons, parallel software systems, and collaborative operations between two satellite receiving stations with overlapping station masks allow both systems to have backup capability in the event of episodic hardware failure. The high cost of satellite data receiving stations generally precludes redundant, or backup, systems within an individual observing system. However, station masks are geographically large. By partnering with another station that has similar goals and operations (in our case Rutgers University), as well as similar software, both systems have backup and can maintain daily operations and a consistent, continuous data stream.
- Regional forecast models can take advantage of a higher level of coordination; not only between modelers and observers, but also between modelers running models of different scales. When we were informed in 2006 about NCEP's decision to switch its operational ocean forecast model from ROFS to RTOFS, which provides open boundary conditions for the operational GoMOOS circulation model, we had sufficient time to respond and update the operational GoMOOS model to make the transition as seamlessly as possible. Moreover, we were able to reach an agreement with the ocean forecasting group at NCEP to maintain their previous operational system (ROFS) for about a year so that an overlap was established to allow us identify the advantages and disadvantages between the new and the old systems.
- Direct communication between operational system developers and users can lead to benefits for both groups. Dialogue and feedback between the system developers and users can accelerate the development of analysis tools, advance scientific understanding, and improve the system overall. For example, the collaboration between the operational GoMOOS modeling group and the Massachusetts Water Resources Authority (MWRA) led to a closer examination of the modeled Gulf of Maine Coastal Current (GMCC) in response to Northeast storms during the spring. It also led to the development of a map-based interactive particle tracking module using the GoMOOS forecast and the General NOAA Operational Modeling Environment, which is a useful research, management, and educational tool (http://rocky.uemcoe.maine.edu/GoMPOM/cdfs/gnome/web).
- Dual telemetry systems increase the success of real-time data systems. The real-time mission of IOOS dictates that the telemetry functionality must be among the most reliable components of the observing system. GoMOOS uses two independent data telemetry systems (cellular/iridium and a GOES satellite system) to increase substantially the successful transmission of real-time data.
- Diverse sensors and multiple approaches to deriving data products is a powerful methodology for maintaining high-quality bio-optical observations and products. Our

primary bio-optical data product is phytoplankton biomass. We have between two and four methods for assessing this product on any of the bio-optical buoys (e.g. chlorophyll fluorescence, chlorophyll absorption, chlorophyll-specific light attenuation, solar-stimulated chlorophyll fluorescence). Because of this approach, we can lose 75% of our sensing capabilities onboard and still maintain the time series observations. In addition, this sensor diversity provides the data necessary to identify and correct for biofouling and sensor drift.

- Two-way communications with the buoy data logger and sensors is an indispensable element of the successful observing system. We routinely call the buoys to retrieve missed data transmissions, and can often reset sensors that have stopped sampling and/or communicating.
- Wind sensors are a potentially lifesaving element of the OOS. Dual sensors with different operating principals helps assure that these potentially lifesaving data are reliably at hand. On GoMOOS buoys we use both traditional mechanical propeller and vane sensors (susceptible to interruption in freezing-spray conditions) and sonic anemometers (susceptible to noise during heavy rain).
- Automatic alarms for exceeding the watch circle or leaks in the electronics well are simple to implement and provide an early warning of impending trouble. The GoMOOS buoys send a message to the University of Maine Physical Oceanography Group (PhOG) server if the buoy exceeds its normal watch circle, or if moisture is detected in the electronics/battery well.
- Although the fishing and piloting communities in the GoM were initially skeptical of the value of the buoys, initially complained about the deployment locations, and in a few cases dragged or attempted to drag buoys out of their way, they have since become ardent supporters of the buoy system. As these communities have come to rely upon the data provided, the system operators have come to rely on fishermen and pilots to keep them informed about the condition of the buoys. The maritime and fishing industries are among the most enthusiastic users of the buoy data and often take the initiative to report problems that they observe (broken light, broken solar panels, etc.).

Type II Lessons

- Observing systems can not operate at optimal efficiency when funding is year-to-year, late in arriving, and subject to significant and unpredictable fluctuations. Year-to-year operating budgets for GoMOOS have fluctuated by a factor of two–four. Under these chaotic conditions, effective planning, scheduled infrastructure maintenance, and staff continuity are extraordinarily difficult to achieve.
- Scientists responsible for the collection and QA/QC of data and must have authority over data released to users. There can be only one authoritative data archive, and it must be controlled by the scientists who are responsible for the data collection, calibration, and quality control. In the case of the Gulf of Maine, a separate nonprofit organization (GoMOOS, Inc.) controls the release of data to the public and to NDBC. At various times over the first seven years of operation, the data being released by GoMOOS, Inc. were not the highest quality data available, and in some cases were corrupted in the transfer process. Although the correct data were available at the University of Maine website, the majority of users downloaded data either from the GoMOOS site, or from NDBC.
- A fraction of an RCOOS budget (~15%) should be set aside to fund research and development, replacement of aging sensors and platforms, and the incorporation of additional observing assets into the system. The GoMOOS buoy array was designed in 2000. At that time it represented a significant advance over the buoy systems that had previously been used for real-time observing in the region. Because of a shortage of funding, no major improvements in the design have been made since operations started. Today the technology exists to produce a much more able system than the one that is presently deployed in the GoM. The CODAR array has similarly suffered from that lack of ongoing investment. Initial estimates of the range of the CODAR system in the GoM were optimistic, and the performance has deteriorated with age. The result is that the overlap of the units is rarely adequate, and the system has not achieved operational status.
- Test platforms for new technologies are a vital element of an evolving IOOS program. New advances are not made in operational oceanography without missteps, equipment failure, and lost data. Since the real-time nature of IOOS is a very important aspect of the overall mission, new technologies need to be tested in a way that does not detract from the existing service. Once an innovation has been tested and proven on a test mooring, it can be implemented throughout the array.

Suggestions for Future IOOS

- The IOOS funding process needs to be much more stable and predictable. To date, it has not been well matched to operations, continuity, and technical advancement of the observing systems. Until recently, IOOS has been funded primarily through the political process of congressional earmarks. As a direct result of this process, IOOS funding went preferentially to states with representatives who were powerful in the appropriations process. This flawed arrangement has resulted in bizarre funding decisions where some states without established ocean observing capabilities or existing OOS infrastructure were given several million dollars per year, while other states with extant and successful operational systems went virtually unfunded because the representatives of their states lacked sufficient political power to compete for funds. We believe that this unfair and ineffective funding process has significantly hampered IOOS, and has resulted in far less data per dollar being served to system users.

- The competitive process for future IOOS funding needs to be fully implemented without political influence remaining as a major factor in funding decisions. Although there has been improvement in the funding decisions by having a formal proposal process, it seems that "regional" factors are still weighted heavily in the funding decisions. We believe that proposal merit, scientific justification, efficiency, past performance, and technical capability should be the overriding factors that determine funding decisions. Otherwise the limited IOOS funds will continue to be used sub-optimally.
- Decision making by Regional Associations, as the conduits for the NOAA competitive IOOS funds, can be negatively influenced by those who continue to view the funds as a regional entitlement to be divided among the participating states and institutions. We favor starting by establishing the highest priority regional outcomes, and then determining those technical groups best able to produce those outcomes economically and reliably. There is a tendency for the process to be derailed by an effort to find something that could be done by each of the regional partners. We hope that the NOAA IOOS office will provide high-level guidance on allocations; especially in situations where the award is less than the requested budget.
- Although it is often said that data acquisition, data management, and modeling are the three pillars of IOOS, the funding of modeling activities has been limited. There is sometimes the lack of enthusiasm to support operational models, especially when the funding becomes tight, because the models are often perceived as inaccurate and inaccessible to users. It is thus important for the community to establish standards for operational models and to heighten public awareness about the usage and limitation of ocean forecasts. Continuous investments are needed in maintaining operational models to meet standards as well as in research and development that will allow achievement of improved standards.
- The management structure of the RCOOS systems should be careful not to put the scientists and engineers in the position of having the major responsibility for making the RCOOS function, without having commensurate authority over the setting of technical and budgetary priorities. The highest priority of the RCOOS should be the reliable measurement and delivery of research quality data to all users. In times of funding shortages, these core functions need to be preserved even at the expense of higher-level product development, improved user interfaces, and public relations.
- RCOOS systems should resist the temptation to favor larger numbers of "qualitative" data streams over research-quality data streams. In some cases managers and administrators favor data quantity over data quality since many real-time users are satisfied with approximate readings. While this may offer short-term public relations advantages, the long-term benefits of the scientific archive continue to accrue indefinitely.

4. Summary and Conclusions

For the scientists who have made the GoMOOS data acquisition and modeling programs notable successes, the experience has been simultaneously exhilarating and disheartening. It has been very gratifying to have had the opportunity to implement plans, which had long existed, to instrument the GoM in a comprehensive and sustained manner. The scientific impact of this system on GoM research is enormous and its impact will continue for years even if the system does not. It was also a rare treat for many of the scientists to be involved in a project that was so highly regarded by the general public, generated so much interest, and engendered a devoted group of GoMOOS data users. We owe this opportunity, and the public interest, largely to those who served on the administrative and organizational side of GoMOOS.

At the same time, the experience has been unusually frustrating and disheartening. Funding levels seemed unrelated to excellence and to the successful execution of the project. In addition, the scientists had an ever decreasing role in the funding process and the setting of priorities. In a good funding climate, the structure of GoMOOS would have been less problematic, since the proposal process affords direct input from the scientists and a contractual obligation to honor the priorities, plans, and budgets set forth in the proposal. However, the proposals were almost never fully funded, and detailed guidance for structuring the cuts were not (to our knowledge) provided by NOAA. The end result was that the administration and board of directors restructured the budget and, as the funding levels dwindled, the scientists felt powerless to protect the observing infrastructure.

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