Advances in the Ocean Observing System in the Gulf of Maine: Technical Capabilities and Scientific Results

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***Abstract*- The Northeastern Regional Association of Coastal Ocean Observing Systems (NERACOOS) includes the University of Maine's comprehensive solar-powered buoy array in the Gulf of Maine. The system serves a wide variety of real-time oceanographic and marine meteorological data and data products to scientists, state and federal regulators, the National Weather Service, the US 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. In addition to the hourly operational data delivery, The University of Maine provides an archive of data and model output that are significantly advancing the scientific understanding of the Gulf of Maine as a physical and ecological system. Over the nearly nine years of operation, the data have revealed marked seasonal and interannual variability of the circulation and physical properties of the Gulf of Maine. A system wide salinity anomaly event that lasted for nearly two years, as well as a potential regime shift in the inflow and outflow transports of the Gulf have been revealed in the data records.**

The Gulf of Maine observing system can be thought of as consisting of four major subsystems: the data acquisition subsystem; the data handling, processing, and archiving subsystem; the system of numerical nowcast and forecast models; and a distributed web-based data distribution/presentation subsystem. The acquisition system includes a real-time buoy array, and an array of land-based long-range Coastal Ocean Dynamics Applications Radar (CODAR) installations 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 system consists of an application of the Princeton Ocean Model (POM) for circulation and hydrographic conditions, and a high-resolution SWAN wave model

In recent years the sampling scheme of the system has increased in resolution beyond hourly for several high-value data streams. The meteorological data are collected at five minute intervals, and the water-column temperature and salinity are measured at three-minute intervals to provide records of internal wave activity. We have recently developed a serial bridge module that can provide meteorological statistics, including gusts (of specified length), min, max, and variance that are observed within the continuous five-minute samples. It has also been used to replace electronics and data loggers for the Aanderaa RCM9 current meters thus providing increased data and battery storage capacity as well as reduced power consumption. We are currently designing a new low-power, low-cost Linux-based data logger to replace the Campbell scientific data loggers which have limited our ability to handle additional sensors and data streams.

I. INTRODUCTION

The Gulf of Maine Ocean Observing System was funded in 2000 as a congressional appropriation to the US Office of Naval Research (ONR) through the National Ocean Partnership Program (NOPP). During the initial two-year funding period, approximately two-thirds of the total appropriation of approximately $6M went toward the data acquisition system, which includes the real-time buoy and HF RADAR arrays, the real-time operational circulation and wave models, regional satellite data processing and display, and a limited shipboard program of inorganic nutrient surveys. The remainder of the funding went to establishing a nonprofit organization (GoMOOS) that established a website for making the data available, in real time, to the general public. At the end of the two years of ONR funding, the system support was shifted to the US National Ocean and Atmospheric Administration (NOAA). NOAA funded the system at approximately $1M per year through 2007. In 2007 the Northeastern Regional Association of Coastal Ocean Observing Systems (NERACOOS) became the operational regional organization that absorbed the Gulf of Maine (GoM) and Long Island Sound observing systems and several emerging systems in the northeastern US. This transition had the advantage of a truly regional approach, but one unintended consequence was that the available funding had to be shared over a larger region resulting in removal of assets from the Gulf of Maine. Despite these fiscal constraints, the technical capabilities of the system have slowly increased, and the data records the Gulf of Maine system have contributed considerable new scientific understanding of the oceanographic variability of the Gulf of Maine.

II. THE GULF OF MAINE OBSERVING ARRAYS

The locations of the ocean observing assets in the Gulf of Maine (GoM) and vicinity are shown in Fig. 1. The real-time buoys have been in essentially continuous 24/7 operation since the summer of 2001, and have an unusually comprehensive suite of sensors including surface currents, Doppler current profiles, temperature, salinity, dissolved oxygen, Chlorophyll and CDOM fluorometers, radiometers, and multi-wavelength absorption and attenuation sensors.

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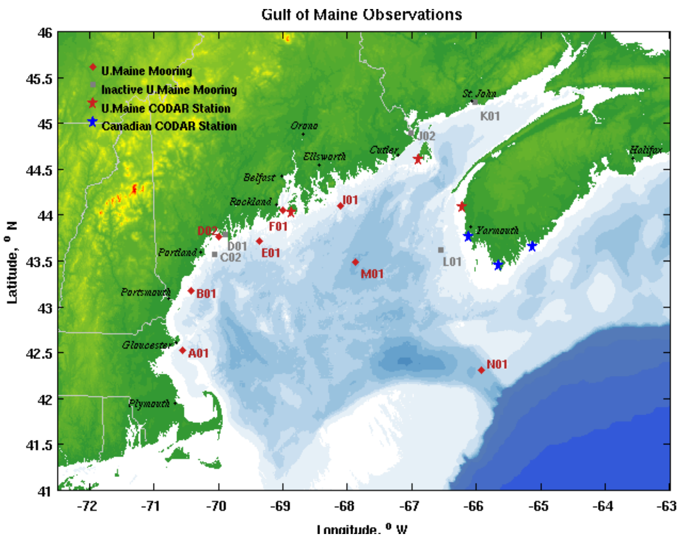

Figure 1. The NERACOOS Gulf of Maine Observing System. Red alpha-numeric symbols represent active monitoring buoys, gray alpha-numeric symbols are buoys removed for lack of funding. Red stars are UMaine CODAR stations, and blue stars are CCG CODAR stations.

Of the twelve NERACOOS-GoM buoy locations shown, only A01, B01, D02, E01, F01, I01, M01, and N01(in red) remain as active sites. Buoys C02, D01, J02, L01, and K01 (in gray) have been removed from service due to progressive funding shortfalls. As is evident from the figure, with the exception of Buoys M01 and N01 that monitor respectively the deep Jordan Basin and the Northeast Channel, the emphasis of the Gulf of Maine buoy array has been in the coastal and near-shore regions of the GoM.

In addition to the buoy array, NERACOOS has an HF RADAR array of long-range (~5 MHz) systems, manufactured by CODAR Ocean Systems Inc., that measure surface currents to a range of 120-180km with a bin size of roughly 6 km. The NERACOS CODAR units, which are shown as red stars on the map, have been integrated with three additional units owned by the Canadian Coast Guard (CCG) shown as orange stars. The combined systems provide surface current coverage of the southwestern Nova Scotia Shelf, and region offshore of the Eastern Maine Shelf. The region off Nova Scotia corresponds to the area of the highest density of Search and Rescue (SAR) in Atlantic Canada, and the CCG is integrating the current data into their SAR procedures.

University of Maine Buoy Designs

The University of Maine Data Buoy System was designed as an economical, stable, unsinkable, solar-powered platform with real-time telemetry, some onboard data processing capabilities, and the ability to operate year-round in the harsh GoM environment. Winter significant wave heights regularly exceed 4 m at all locations and occasionally approach 10 m at several locations. The design incorporates some significant improvements over the data buoys used previously in the Gulf of Maine. The improvements include more reliable data telemetry, higher wattage solar power charging systems, increased data-handling capacities in the logger/controller, increased ease of maintenance, and a greater capacity in the electronics well to accommodate additional electronics for future technological needs.

The flotation is a multi-chined two-meter discus form of closed cell foam that performs adequately with half a ton of sea ice on the buoy superstructure, and is stable enough for a technician to stand on it in calm seas in order to perform simple repairs or troubleshooting. The buoy carries dual cellular/iridium and GOES satellite telemetry systems for hourly data telemetry, reserve battery power for one month, and the flotation provides several thousand pounds of reserve buoyancy. The buoy is self righting, and designed to recover from float compression due to forced submergence. It monitors its own position, detects leaks into the electronics well, and monitors its power system. The buoys sends an alarm if it is off position, has a water in the electronics well, or its battery voltage drops below an operational level. In the later case the buoy automatically enters low-power mode in which the number of data transmissions are cut from 24 to 3 per day. Even in the low power state, all the data are retrieved each day, but the real-time data transfer is curtailed. Design details of this buoy system have been previously described [1]

Buoy Sensor Suites

The GoM is a diverse physical and ecological environment, and the sensors on the buoy array monitoring system reflect this diversity. Never-the-less, each mooring is equipped with a standard suite of instruments in addition to the site-specific sensors dictated by the variable conditions and user interests around the GoM. Standard for all buoys are a meteorological package consisting of an R.M. Young wind sensor that measures wind speed and direction, a sonic wind sensor that performs better in freezing spray conditions (no moving parts), an Aanderaa visibility sensor, a Sutra atmospheric pressure sensor, and a Campbell Scientific air temperature sensor. All buoys also measure significant wave height and period using a Summit Tri-axis accelerometer that is mounted in the instrument well.

Buoys in water depths of 100m or less are moored with a slack chain mooring system in which the scope of the mooring is provided by a pile of chain that is joins the jacketed steel mooring cable to the anchor. The length of chain is approximately 40 m greater than the distance between the bottom of the cable and the sea bed at spring high tide. At the deeper locations (M01 and N01) in the Jordan Basin and the Northeast Channel, we use elastic tethers to provide the scope rather than slack chain. The elastic tethers keep the buoy more directly over the anchors in deep water and thus help to reduce the incidence of fishermen working between the buoy and its anchor.

Figure 2 shows a schematic diagram of elastic-tether basin mooring (M01) that is deployed in approximately 290 m of water. The buoy N01 mooring is the same except that the total water depth is at 190 m and we use two anchors connected by chain. The very strong current and high waves (up to 1.5 m/s and 10m) that are occasionally observed in the Northeast Channel region combine high drag with periodic unweighting of the deadweight connected to the elastic tethers since the float is large enough to suspend the

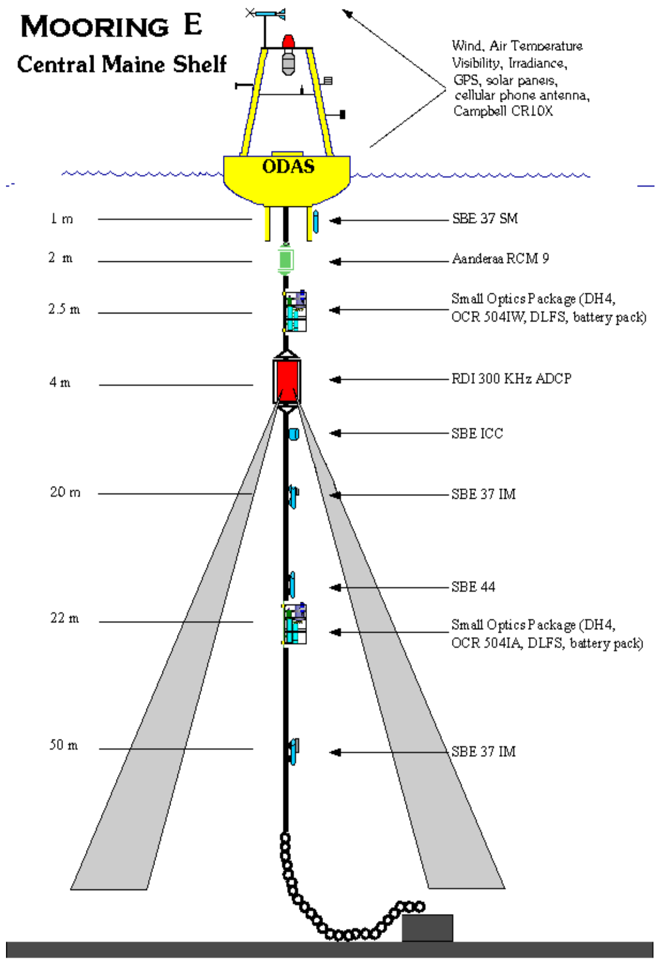

Figure 2. Schematic drawing of a University of Maine real-time coastal observing buoy. The buoy is solar powered, has dual data telemetry systems, and has an inductive modem system for sending subsurface sensor data up the mooring wire.

anchor and the tethers strong enough to support it. As a result, a single anchor can occasionally "hop" to a new position when simultaneously subjected to high waves and strong currents. The compound anchor design eliminates this tendency to wander down current since the second (trailing) anchor is never unweighted by the tethers.

The in-water sensor payload is what really distinguishes the NERACOOS GoM buoy array from their NDBC predecessors. The sensors include a Seabird microcat measuring temperature and conductivity mounted on the base of the buoy at a depth of 1 m, an Aanderaa RCM-9 MKII current meter measuring current velocity at 2 m, a downward-facing acoustic Doppler Current Profiler (RDI workhorse) at 4 m measuring current profiles throughout the water, and additional Searbird microcats and/or seacats that measure temperature and conductivity at various depths.

Most of the buoys presently in service include optical sensors. The optical packages generally consist of WET Labs digital chlorophyll fluorometers (DFLS) and Satlantic 4-channel downwelling irradiance sensors (OCR504I, a WET Labs ac9 and attenuation meter, a WET Labs ECOvsf, three-wavelength, 3-angle back-scattering sensor, and a Satlantic OCR507R 7-channel upwelling radiance sensor.

The most obvious problem with deploying optical sensors for extended periods in the ocean is biofouling. To cope with this problem the sensors 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 shutter operation, and copper tubing on the flow-through instruments. The copper dissolves in seawater, creating a toxic layer of water over the sensors while they are in sleep mode; once the sensors turn on, the shutters rotate away from the sensing head, or in the case of the flow through instrumentation, the water is flushed away by a pump prior to data collection. We have found these strategies to be effective in most cases. For a more thorough discussion of the sensors and systems see [2].

UMAINE BUOY TELEMETRY SYSTEMS

The telemetry system of the UMaine buoy has three functions: to send data from submerged instruments to the buoy; to send data from the buoy to the University of Maine server for quality control and processing; to allow direct remote communications with deployed sensors in order to trouble shoot operational problems.

The transmission of data from the submerged sensors to the buoy is usually handled by an inductive modem (IM) system. The system uses the jacketed steel mooring cable, rather than dedicated electrical cables, for communications. Use of this system makes possible 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 IM system manufactured by Sea Bird Electronics has been a very reliable component of the buoy system. The failures that do occasionally occur are generally due to either failure of the electrical cable that couples the system to the buoy, or due to fishing activity, which sometimes damages the jacket on the mooring cable. In these cases the data are retrieved from 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.

In several cases we have used acoustic modem systems to couple bottom-mounted sensors to the buoy system for storage and relayed transmission to the laboratory. Although this procedure is not a standard feature of the buoy system it has been tested on for future incorporation.

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 Satellite server (GOES) transmitter. The use of two different

Figure 3. University of Maine oceanographers deploying a real-time data buoy from the RV Cape Hatteras.

telemetry systems helps to ensure that real-time data transmissions are successful even when one or the other is not functioning properly due to either environmental conditions or technical difficulties originating with the service provider. It has been a very rare occurrence when both systems failed and these instances were generally quickly resolved.

The 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 due to 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.

III. The HF Radar Array

The University of Maine (UMaine) currently uses three long-range CODAR units to map surface currents over the eastern GoM. The long-range CODAR array is a potentially exciting element of the observing system able to provide remote wide-area surface-current measurements from a limited number of shore-based radio-wave transceivers. The nominal range of 180 km is almost never realized in the GoM region (especially at night), and three-to-four additional units are needed to provide 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 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 analyzed to give a consistent picture of the general circulation patterns over substantial regions.

A recent partnership with the Canadian Coast Guard has raised the possibility of better coverage in the eastern GoM. As shown in Figure 1, there are now six long range CODAR units in various stages of operation/installation in Nova Scotia, New Brunswick, and Maine. When all six of these units are fully operational we anticipate continuous two-dimensional vector coverage out to a range of order 100km. This capability will be of tremendous utility to SAR activities of this high marine traffic area, as well as providing our first spatially-extensive time-series observations of the surface velocities of the Southwest Scotia current, the Eastern Maine Coastal Current, and the connections between them.

IV. The Gulf of Maine Ocean Observing System in Retrospect

The ocean observing data acquisition system in the Gulf of Maine has been remarkably successful. In many ways it was the first comprehensive operational ocean observing system in the US. The buoy program, in particular, set high standards in terms of the diversity of sensors deployed and in the reliability of the system. Many other IOOS systems over the years only rarely had all their listed platforms in the water, and often those that were deployed had only meteorological sensors and a sparse array of hydrographic sensors in the water column. In contrast, the GoM observing system has consistently produced research quality data in real-time on a 24/7 schedule, has always included current measurements throughout the water column, and worked to incorporate a wide array of optical measurements including dissolved oxygen (optode), chlorophyll fluorescence, ocean color radiometers, and light scattering and attenuation.

The design of the UMaine buoy system was innovative in the year 2000. It represented significant advances in the sea worthiness and reliability of the platform, and in the dual data telemetry systems. The ten-buoy array exceeded performance expectations [3] and worked reliably in a region in which real-time year-round operations had not previously been achieved. The buoy array also soon found a large group of dedicated users among the fisherman, mariners, scientists, educators, and general public of the region. In short, in nearly all aspects the buoy array hit all the marks set out in the proposal and in the myriad US national IOOS planning documents.

Despite the good start, the years of inadequate funding have resulted in some decreases in both the coverage of the system and the rate of data return. Budgets have been inadequate to allow unscheduled servicing when problems arise, and the problems arise more frequently as the sensors and systems age. Despite these economic difficulties the system has maintained an observing infrastructure in the GoM that continues to serve a wide range of scientific, commercial, and recreational users on a daily basis. The web sites that serve the data consistently record several million page views per year.

V. RECENT TECHNICAL DEVELOPMENTS IN THE GULF OF MAINE OBSERVING SYSTEM

Within the last several years, improvements in Internet access and wireless communications, have made realistic the long-term desires of oceanographers to have more extensive interactions with deployed (often submerged) instruments. In the past, a chief frustration of moored-instrument field investigations has been the difficulty and expense of detecting and rectifying sensor and system malfunctions. Bad weather, remote locations, and the great expense of operations at sea have all curtailed attempts to do something as simple as reprogramming an instrument, resetting a clock, or cycling power to a deployed system. In many case crucial data have been lost by an inability to remotely initiate simple trouble-shooting procedures.

Modern workstations offer a stable environment and effective command and control of instruments attached directly to them. Through the Internet one can control a remote workstation as if it were local, and thus control its sensors and instruments. This infrastructure is so stable that we no longer think it remarkable. These capabilities make feasible the extensive virtual control of remotely-deployed sensors. One can load new firmware, re-synchronize clocks, reprogram sensors, cycle power, and change data calibrations, sampling schemes, and onboard data processing. In effect, engineers and technicians can do virtually anything they can do with the instrument on the bench short of disassembly or other physical manipulations.

A solution to the need to command and control of sensors remotely deployed on ocean buoy is the installation of a low-power Linux-based "work station" within the buoy. Until very recently, the cost and power budgets of such systems were both prohibitive.

LINUX-BASED DATA LOGGER/CONTROLLERS

The data logger presently used in the NERACOOS GoM buoys is a Campbell Scientific CR10XD, which is a reliable industry standard data logger. By modern standards it has limited capabilities for communication and control. While some two-way communication is possible, it has limited compute power, a non-standard programming interface, and limited ability to address serial and analog interfaces. At the present time, the NERACOOS buoy work load has outgrown the CR10 capabilities. Each new data stream added may cause problems with the handling and storage of extant data streams.

The new buoy data logger/controller is being developed using a Linux-based computer module. The Linux operating system affords stability and capable infrastructure support for all current networks, and devices with little development required. While our conceptual design is not bound to a particular manufacturer or architecture, we have chosen the Gumstix Verdex Pro. The Gumstix product offers a 600 MHz processor with a wide range of functions including OMAP, PXA, microSD slot, Bluetooth, a 802.11g wireless interface, USB, Ethernet, and RS232 in a very small form factor package (about the size of a stick of gum).

Communications paths for the new buoy system will be varied. When it is in the lab, on the deck of a ship, or immediately after deployment a wireless point-to-point connection allows communications without constantly plugging and unplugging cables. For systems deployed within ~15 miles of shore, a cellular wireless connection has proven to be capable and reliable. For some high data volume installations, a point-to-point 900 MHz wireless back-haul connection is planned. For offshore applications Iridium or BGAN options are used with a backup system of either GOES or SBD iridium. The Linux system allows integration of all these feeds with little effort. Support for these systems will be included in the base design.

The bulk of the design work is in the instrument interfaces, power distribution, and file structures. There are advantages to using a distributed approach to data collection. The Linux control module will be tasked primarily with communications, control, and data archiving. Collection of data from the sensors will be done by the instruments themselves or interface circuitry specifically designed to accommodate them (see Serial Bridge, MetBuffer, Digital Wave Module, etc., below). This approach offers several significant advantages. It allows the use of low-power electronics to do simultaneous routine data gathering, and the modularity of the system allows the addition of tasks and sensors while placing few demands on the core operating environment.

Instruments that have their own processors, and communicate via serial lines, will connect directly to the control module via serial interface modules (described below). The power distribution is handled by a power control module.

Serial Interface Module

Each Serial Interface module allows connection of up to four serial instruments, with multiple protocols offered for each stream (RS232, RS422, RS485, and CanBuss). The module will act as a switch, buffering the incoming serial data, signaling data available to host, and transmitting to host. Control of the ports will allow enable/disable and power down. Provision is made to switch power for each port when it is enabled. CMOS1.5 amp load switches are used to switch power.

Power Control Module

The Power module monitors power generation via four solar panels of 40-50 watts each, and a wind generator that produces 240 watts of peak power. Limited power regulation and UPS support is supplied to the control monitor. Most power is distributed as unregulated battery voltage, Information about voltage levels, charging rate, etc., is transmitted to the main control unit.

Hydrogen Sensing Module

The NERACOOS GoM buoys use sealed Absorbed Glass Mat (AGM) lead acid batteries. These batteries have a pressure release valve that is closed under normal operating conditions, but that opens to vent gases into the buoy electronics well if excessive pressure builds up. Generation of potentially explosive hydrogen gas is a normal by product of lead acid battery charging. In order to avoid this dangerous situation, we have developed a hydrogen monitor based on a FCM6812 hydrogen-gas sensing module from Figaro Engineering. The sensor is capable of detecting minute gas concentrations that are far below the explosive limit and thus serves as an early warning system for hydrogen gas buildup within the sealed buoy electronics well. During laboratory testing of the charging system under maximum charging scenarios, low concentrations of hydrogen gas were detected indicating that the rate of gas generation exceeded the rate of dissipation. As a precaution during servicing, buoys with detected hydrogen gas are disconnected from chargers and not serviced until the gas dissipates to a negligible concentration.

Serial Bridge

The serial bridge is best described as a controller for multiple instruments. It serves as a bridge between the multiple sensors and instruments and the principal data logger/communications system of the buoy system. The host software is written in C with support routines that allows rapid addition of new instrument drivers to its repertoire. The board has been in service for 2+ years and is being used on several instrument packages both as an element of the buoy system, and also as a submerged data logger with inductive modem capabilities. The module acts as a switch, buffering the incoming serial data, signaling data available to host, transmitting to host, switching power, and enabling/disabling ports.

The serial bridge uses the Persistor CF2 processor, with a 2 gigabyte solid state flash drive, and an RS232 console port with 3 Serial RS232 Ports (with switched power, 1.5 amps unregulated), 2 ports Regulated Power, 1 amp, selectable voltage, 5 channels 16 bit A-to-D converter. There is a thermistor temperature interface, a pressure/ vacuum sensor, and an interface for the Seabird Inductive Modem Module.

The serial bridge module is used as the basic building block for many of the specialized modules that we use on the buoy and in the water column. Below is a representative list of applications:

Metbuffer

The Met buffer is a specialized version of the serial bridge that was designed to reduce the processing burden of the main buoy data logger by collecting continuous meteorological data and calculating statisitics. The buffer can communicate to the host via a serial console port and/or archive the data internally. In its present configuration, the Metbuffer handles data collection and processing for an RM Young Wind Sensor, a sonic Gill Wind Sensor, an Aanderaa MIRA visibility sensor, a Setra atmospheric pressure sensor, an air temperature sensor, and a three-axis magnetometer (compass).

Aanderra PDP4/SR10 converter

The NERACOOS GoM buoy array has used Aanderaa RCM9 Doppler current meters since 2001. While the current meters have performed admirably, they have consistently drawn more power than their specs suggest, and we had early incidents of power failures. Our first remedy was to build external battery packs in order to extend the instruments through the typical 6-month deployments. As the instruments aged, the RCM9s began to exhibit more troublesome electrical problems with severe power drains that caused premature failure of both battery packs. Thus we have started to replace the electronics with a version of the serial bridge. The electrical interface to the Aanderra RCM9 instruments is unusual in large part because it has a negative supply voltage. This difficulty is easily overcome using the serial bridge with the added bonus of coupling with the Seabird inductive modem interface. Recently Aanderaa has developed a Z-pulse Doppler sensor that uses multiple frequencies to significantly reduce measurement noise without resorting to extra pings that draw more power. This sensor has been interfaced with the low power serial bridge electronics. We have had one unit in the field for 2 years with excellent performance and no more power failures.

Directional Digital Wave Module

The Digital Wave Module uses the serial bridge and a Microstrain 3DM-GX2 sensors that include a 3 axis accelerometer, a 3-axis magnetometer, and a 3-axis gyro to provide wave directional spectra, significant wave height, wave direction, and period. The wave parameter, wave spectra, and raw data may be logged to the Flash Drive and/or transmitted to a host computer. This module is currently being lab tested at the University of Maine, and will shortly be field tested in the buoys.

Figure 4. The serial bridge as the electronics and data logger of an Aanderaa z-pulse current meter sensor, as a data logger and inductive modem for the Aanderaa Optode, and as part of a directional wave sensor to be mounted within the buoy electronics well.

VI. Recent Scientific Advances Arising from the GoM Observing System

The operation of the NERACOOS GoM buoy array has resulted in a two order of magnitude increase in the existing time series oceanographic data than existed for the GoM. In many locations, these data represent the first meaningful baseline data.

Much of the hydrographic and nutrient structure of the GoM is controlled by deep transport of slope water through the Northeast Channel, which is the only avenue of communication with the North Atlantic (see Buoy N01 in Fig. 1). This transport is believed to be the source of much of the new nitrogen that fuels the high productivity of the GoM. There have been several previous studies in this area that consistently showed strong inflow into the GoM throughout the year [4], [5]. The results of the monitoring by Doppler profiler at buoy N01 associated with the NERACOOS GoM observing system have shown flow conditions that are in stark contrast with the finding of the earlier studies.

Two contour diagrams of northward (into the GoM) transport are shown in Fig.5. The comparison of these two records leads us to conclude that there may have been a regime shift in the transport dynamics that occurred between sometime between 1997 (the end of the most recent previous study) and the NERACOOS deployment in the summer of 2004. Where as all previous studies showed inflow throughout the year, the new results show dramatic outflows during the autumn-spring periods that are concentrated near bottom, but that sometimes to the surface. The Northeast Channel inflows now seem to occur primarily in the upper and mid water column during the summer season.

This startling finding has apparently had an impact on the on the hydrographic and nutrient structure of the inner GoM [6]. Fig. 5 shows an example of the salinity from buoy I01 on the eastern Maine shelf. These data suggest strongly that the interruption of the deep inflows of salty water may have resulted in a large order 1 salinity decrease in the interior of the GoM at all depths in 2005. While the size of the both flow and salinity anomalies have decreased since that time, they are still evident, and may represent a regime shift in the hydrographic, nutrient and transport dynamics of the Gulf of Maine. The implications of these changes may include changes in the productivity of the GoM, the prevalence of harmful algal blooms, and species composition.

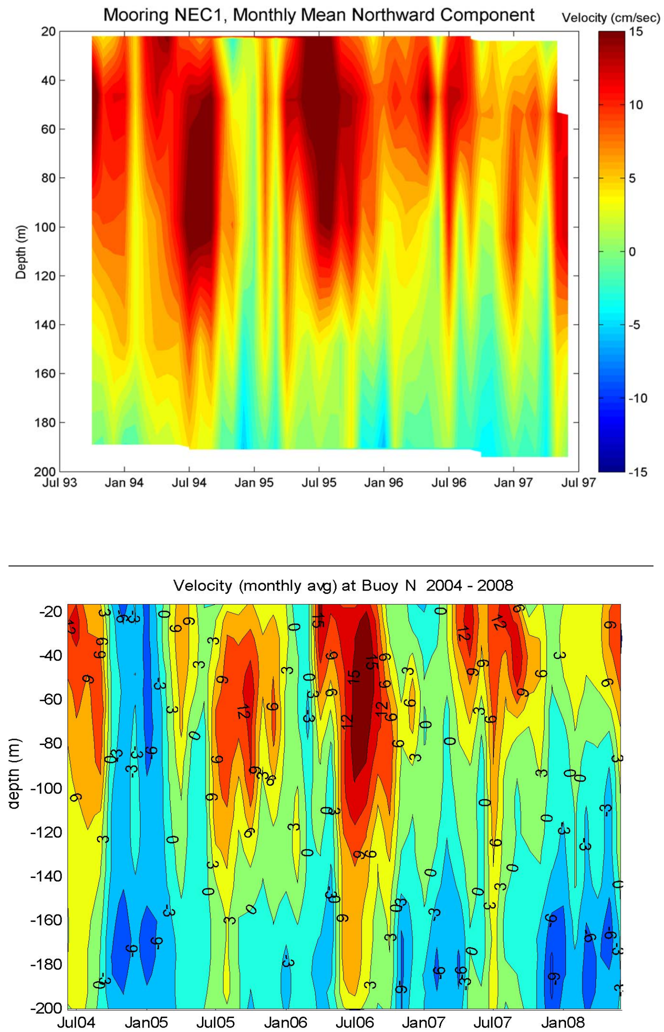

Figure 5. Time series contours of vertical profiles of flow through the Northeast Channel GoM. The upper panel shows currents from the GLOBEC GoM experiment from 1993-1997, and conform to the results of earlier work. The lower panel shows data from the 2004-2008 Buoy N01 deployment. Color schemes are consistent for the two panels with red depicting flow into the GoM and Blue depicting outflow. Comparison shows a possible regime shift in the latter experiment in which strong deep inflows occur in the fall-spring periods and sometimes extend to the surface.

VII. Future Directions: Beyond Buoys

It seems unlikely that funding levels for the NOAA IOOS program will, within the next several years, increase to levels that can adequately support the existing operational systems in the US let alone expand the scope, power, and utility of the systems. Never-the-less, although the immediate prospects for NERACOOS are not very favorable, the long-term prospects are excellent. The NERACOOS system has built up an extensive user group over its first seven years of operation who have become accustomed to accessing the data that the system provides. In effect, the concept of a real-time ocean data service has been proven sound, and the data provided have been proven useful. Since the demand will shortly greatly exceed the supply of GoM data streams, we are hopeful that funding will be restored to the systems sooner rather than later.

Ocean observing technologies are in a period of rapid development. The operational systems (such as NERACOOS) now in the water were not feasible 20 years ago, and substantial improvements in communications, microprocessor technology, battery technology, sensor

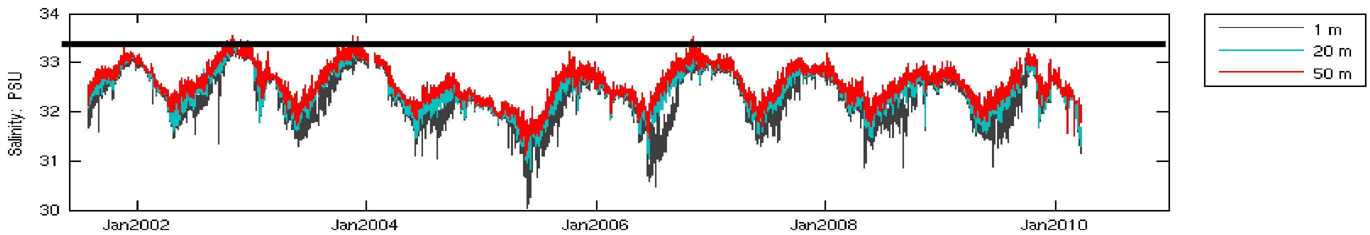

Figure 6. Salinity records at a shelf location in the eastern GoM that shows the large negative salinity anomaly at all depths that occurred in starting fall 2004 through spring 2005. Lessor salinity anomalies are indicated in the winters of 2008-2010 and may be associated with a regime shift in the transport patterns shown in fig. 5.

technology, information technology, and data visualization techniques are all in the offing. Assuming reasonable funding levels, we can expect that application of these improvements to operational systems will be forthcoming.

At the present time ocean sensor technologies capable of long-term moored deployments are largely limited to measuring physical and optical parameters. However, practical new chemical and biochemical sensors are appearing that are capable of measuring inorganic nutrients, dissolved gases, toxic metals, hydrocarbons, and harmful algae. As these sensors achieve longer deployment durations they will revolutionize ocean observing systems and water quality monitoring.

Sensor platforms are also undergoing revolutionary changes. Towable buoys are in the planning stages and buoys that deploy themselves in the coastal zone will become a practical reality within the decade. Packages that vertically profile on surface moorings by adjusting their buoyancy (a profiling float on the string) are at the conceptual design phase and when funding becomes available they will fundamentally change the vertical resolution with which we are able observe the coastal ocean in real-time.

Although moored buoys will always be an important element of observing systems, other sensor platforms are rapidly growing in capability and importance in monitoring efforts. Gliders can hold station and act as a virtual mooring for several months, and perform wide-area repeated marine environmental surveys that are an important element of ocean observing and monitoring. However, because of the high expense of ship-board synoptic surveys, they are rarely done with adequate temporal or spatial resolution, and are sometimes neglected entirely. Forgoing or curtailing survey work can be a false economy that severely limits the outcomes of marine research and monitoring activities and leaves them with insufficient spatial context and temporal resolution.

The development of energy efficient autonomous survey vehicles (AUVs), including both propeller-driven mini-submarines and buoyancy-driven gliders can be an economical alternative to the shipboard surveys that supply the 3-dimensional spatial structure to complement the vertical/temporal structure from the buoy observations. There is increasing recognition of the role of subsurface events such as mixing and nutrient injections from inflows in driving episodic productivity and bloom collapse in the GoM that represent rapid carbon drawdown events. These events cannot be sensed, or properly quantified, without regular sampling independent of clouds, which confound satellite remote sensing, and ship schedules that are set months or years in advance. These observational constraints can be largely overcome by gliders and other AUVs at greatly reduced costs compared with shipboard surveys.

We envision an increasingly prominent role for both gliders and propeller driven AUVs in the future operations of the Gulf of Maine observing system. Gliders typically are very energy efficient since, after adjusting their buoyancy, gravity and the wings provide the forces that propel them along their path. Thus, they are the high endurance vehicles of the current autonomous fleet and in the Gulf of Maine they can sustain profiling missions in shallow waters on the order of a month or two in duration while traveling with a horizontal velocity component of approximately 0.25 ms^{-1} (~12 nautical miles per day). Doppler current profiling capabilities are being added to gliders, and that capability will be important for monitoring the GoM Coastal Current system (GMCC) and the important inflow and outflow regions of the outer Gulf [4]. Gliders generally include CTD (conductivity, temperature, Depth) sensors, an oxygen optode, and a chlorophyll *a* fluorometer/optical backscattering sensor, and an altimeter. In GoM surveys we often include a glider-mounted CDOM fluorometer and a down/upwelling spectral (7λ) radiometer.

Propeller-driven AUVs are highly maneuverable, operate at speeds up to several ms^{-1}, and can typically achieve survey missions of ~ 50 km depending on speed and sensor payload. They typically carry CTD a sensor payload similar to the glider, and in addition often carry a side-scan sonar. There is a rapidly developing Doppler current profiling capacity and a nascent multi-beam bottom profiling capability. These capabilities make the AUV well-suited to obtaining transport and hydrographic transects from shore out to the coastal GoM buoy locations while providing detailed characterization of the bottom topography and substrate. These measurements would provide important new abilities for environmental surveys in the coastal envriroment. They also provide context for the buoy measurement program that is unable to sense meandering of the currents or seasonal changes in current width [6]. The AUV, being a true rapid response vehicle, is especially well-suited to transport studies during important episodic events including Harmful Algal Bloom (HAB) outbreaks, northeast storms, and oil spills in the GoM.

Although only in the early stages of development at this point, small autonomous surface vessels (ASVs) hold great promise for long survey missions (on the order of a year). If a profiling capability is added, these vehicles could truly revolutionize our sampling of the coastal at a small fraction of the operational cost of other vehicles. Given the relative economy of autonomous vehicles, the consistent need for survey information in IOOS, and the prospects of steadily rising fuel and ship costs, we anticipate that a fleet of autonomous vehicles including AUVs, gliders, ASVs, and aerial drones will routinely patrol the waters of the world's coastal ocean by the end of the next decade.

VIII. SUMMARY

The observing system in Gulf of Maine has been very successful since its deployment in the summer of 2001. Although low funding has slowed the development of new capabilities, the long-term prospects for IOOS activities in the GoM are good. The first nine years of operations have resulted in an energized and enthusiastic scientific and technical community involved in operational ocean observing activities, and a large user group who have come to depend upon the real-time data streams that the system provides.

Ocean sensors, ocean platform technologies, and modeling and visualization techniques are in a period of rapid technical development. If stable funding can be achieved, the capabilities of operational ocean observing systems will increase dramatically over the next decade. Autonomous vehicles could become the fast response survey fleet of the IOOS, as well as taking on routine, sustained, marine survey functions that are prohibitively expensive at present. Practical autonomous vehicles will likely expand beyond gliders and propeller-driven AUVs to include surface vessels. The combination of time series measurements from profiling packages on buoy arrays with the repeatedly spatial surveys of the autonomous fleets will provide a new look at our coastal oceans that could transform coastal ocean science and management.

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