Jorge E. Corredor

Coastal Ocean Observing

Platforms, Sensors and Systems

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Frontispiece: Tropical Ocean Observing
Art courtesy of Mr. Mark Sabino, member of the CariCOOS Board of Directors

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To past and present members of the Caribbean Coastal Ocean Observing System (CariCOOS) whose collective knowledge I hope to here accurately reflect.

To the United States Integrated Ocean Observing System (US IOOS) and its predecessor OCEAN.US, institutions that provided funding and guidance without which CariCOOS would have been impossible.

To members of the other ten fellow US IOOS Coastal Ocean Observing Systems who generously provided support, advice, and encouragement in the establishment of CariCOOS.

Preface

This book arises from material initially compiled for a practical graduate field course on oceanographic techniques taught at the University of Puerto Rico, Mayagüez Campus (UPRM), Department of Marine Sciences at La Parguera Puerto Rico over a period of 35 years. Oceanographic techniques encompass practices developed to observe ocean properties and obtain experimental samples, practices which are in large part *remote* since instrument deployment is performed mostly from vessels at sea. The course included the operation and maintenance of oceanographic probes provided with a variety of electronic and electro-optical sensors, and of an equally wide variety of instruments deployed for remote sampling of water, sediment, and plankton. Data collection and processing from instrument casts as well as handling and preservation of samples obtained with the various collection devices were included in the curriculum. Concurrent graduate courses on theoretical and practical aspects of chemical oceanography and marine pollution provided material regarding electrochemical sensors, their design, operation, and limitations.

In 1993, support became available for the implementation of an oceanic time series observing effort off the south coast of Puerto Rico. The Caribbean Time Series (CaTS) was occupied at monthly intervals aboard various oceanographic vessels through the year 2006. Vertical profiles of physical and biogeochemical water column features were obtained using instruments here described beginning with casts to 200 m depth and eventually reaching depths of 3000 m. The CaTS effort provided a seagoing laboratory for these courses and spurred periodic updates as new instruments and techniques became available.

Support for a Caribbean Coastal Ocean Observing System (CariCOOS) for Puerto Rico and the United States Virgin Islands (PR and USVI) within a nationwide Integrated United States Ocean Observing System (US IOOS) beginning around 2004 provided unprecedented autonomous observing capabilities. Through the efforts of researchers at the University of Puerto Rico and the University of the Virgin Islands, a multicomponent coastal ocean observing system was planned, designed, and implemented and is now operational. The reward has been a wealth of data-rich sources including instrumented buoys, coastal HF radar stations, and operational autonomous glider transects yielding in turn a wealth of data products in user-friendly formats serving the coastal maritime community.

The 11 independent but coordinated Integrated Coastal Ocean Observing Systems established in US coastal waters have filled a void of information that has already proven its values in daily use as well as in several high profile events and climate-driven emergencies. Through these efforts, sustained ocean observations now allow the publication of operational data products available through a wide variety of electronic means to stakeholders and the general public. It has now become possible for the mariner to know the measured winds and waves, the temperatures and currents at several sites throughout the coastal zone with data updated within the hour through internet and cellular network connectivity. Moreover, this data, coupled to numerical models guided by assimilation of real-time instrumental data, has allowed operational implementation of hindcasts, nowcasts, and short-term forecasts of ocean conditions at a scale commensurate to the needs of the coastal ocean stakeholder.

The shift in observing strategies to prominently include autonomous land- and sea-based electronic sensing systems prompted refocusing of the coursework at UPRM to include, in addition to expeditionary oceanographic techniques, the practice of coastal ocean observing using autonomous observing platforms. Happily, these courses spanned the period over which most of the modern suite of instruments and platforms became commercially available. Many of these were put to use and indeed are still operational as part of the current observing effort.

Active involvement of the author in the establishment of the Caribbean Regional Association for Coastal Ocean Observing (today a not-for-profit entity incorporated in the state of Puerto Rico under the name of CariCOOS) provided first-hand experience in planning and implementation of observing systems. During the development of CariCOOS, opportunity arose for implementing high frequency radar as a dual-use technology to detect and track vessels at sea while simultaneously tracking ocean surface currents over a wide swath of the coastal ocean. Numerous other opportunities arose for mutually beneficial collaboration with various academic, governmental, and private-sector organizations which are discussed below in greater detail. Concurrent service of the author on the Ocean Studies Board of the US National Academies of Science, Engineering, and Medicine provided expert views on many of the topics here discussed, particularly regarding ocean observing, numerical modeling, and carbon biogeochemistry.

The book is biased to the practice of ocean observing in the balmy tropics. Due apologies are extended to colleagues working in more rigorous climes and to the reader for the comparative void of information in this regard. Likewise, international readers outside the USA will find the book necessarily biased to the author's experience within this jurisdiction to which PR and USVI are subject.

Professor Aurelio Mercado offered invaluable assistance in clarifying and correcting concepts regarding numerical modeling. Drs. Roy Armstrong and Miguel Canals were extremely helpful in the graphic documentation of oceanographic instruments and platforms in current operational use. Most of the equipment here depicted is composed of working units. The challenges of the environment where they are deployed are readily apparent.

Mayagüez, Puerto Rico Jorge E. Corredor

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Chapter 1
Introduction to Coastal Ocean Observing

One major development of the past decade was the advancement of operational oceanography and, specifically, the implementation of ocean observing systems that encompass observations, models, and analysis to yield societally relevant oceanographic information in near real time.

Edwards et al. (2015)

Abstract Technology developments in the fields of electronic sensing, signal amplification, communications, and autonomous navigation have led to the design, manufacture and deployment of autonomous environmental sensors in distributed networks allowing monitoring of a number of environmental variables in near real time at multiple locations. Autonomous instrument-laden platforms plumb the ocean depths at unprecedented data rates, and active and passive electromagnetic sensing instruments aboard satellites in terrestrial orbit provide wide ranging synoptic views of ocean surface and subsurface features. Advances in autonomous remote sensing are contrasted to the historical practice of ocean observing aboard manned vessels. The nature and priorities of operational coastal observing systems are set forth emphasizing the timely release of data and data products tailored to provide *societally relevant* oceanographic information.

Keywords Electronic sensing · Distribute networks · Autonomous platforms · Data products

Modern electronic environmental sensors using recently developed materials can quantify states and process rates for numerous physical and biogeochemical variables. Parallel advances in integrated electronic circuitry allow the ability to collect data at unprecedented rate, accuracy, and precision. Data processing, integration

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and telemetry, battery storage capacity, and electronic 3-D navigation have equally improved. Availability of novel primary transducers together with these advances has led to the development of robust, miniaturized, field deployable instruments. The advent of electro-optical devices has revolutionized the capability for detecting and measuring a wide range of chemical and biological variables and processes.

These advances have now reached the point of allowing sustained, widely distributed collection of environmental data by compact, autonomous instrument systems. Wide band dual communications allow remote operation of these networks with ever-increasing capabilities. Hart and Martinez (2006) define such integrated systems as *environmental sensor networks* where these capabilities are integrated into systems providing multilayered, data-dense views of spatial and temporal variability of environmental conditions.

In the field of ocean science, expeditionary oceanographic research aboard manned vessels provided an important testbed for the design and development of such instrument systems. Today, instruments recording temperature and salinity and other variables routinely operate at data sampling rates up to 24 Hz. Vertically operated profiling instruments known as CTDs (for conductivity (C), temperature (T) and depth (D)), descending at rates up to 60 $m.min^{-1}$ thus achieve sampling densities up to 24 data points per meter or 120,000 data points for a full ocean depth cast to 5000 m.

Instrumental Data: Then and Now

Fifty years ago a vertical hydrographic wire cast from a ship sampling to full ocean depth would have sampled 24 data points using reversing mercury thermometers for temperature measurement mounted on bottle samplers for subsequent laboratory salinity and oxygen analyses making a total of 86 data records including depth, derived from temperature anomalies of protected versus non-protected thermometer pairs. Bottles were affixed sequentially to a weighted wire rope and then tripped by means of bronze *messengers* (weights sequentially traveling down the wire rope) to invert the thermometers and simultaneously trip the bottle to capture a water sample. Paired thermometers were read at sea (through a handheld magnifying glass) upon retrieval of the array and salinity was determined with bench salinometers in the laboratory. Dissolved oxygen and a few other variables were measured in the laboratory using wet chemical techniques. The same cast today, performed with sensor-based electronic instrumentation, obtains 5000 times more coupled depth, temperature, salinity and oxygen data points with real-time graphical representation, electronic readout, and digital data recording. Data density may be increased severalfold by addition of various optical, bio-optical, and opto-chemical sensor devices to the instrument package.

CTD and shipboard flow-through systems have evolved into multiparameter data acquisition systems incorporating a variety of optical, chemical, and biophysical sensors. Many current profiling instrument packages accommodate modular sensors interchangeable in the field as may be required in addition to the traditional pressure, temperature, and conductivity sensors. Many versions of these instruments, first developed for cable deployment, are now employed in shipboard or shore-based infrastructure using pumped flow-through sensor systems. Flow-through sensors, vertical profiling and sampling systems, and towed vehicle-mounted instruments have vastly multiplied the data-gathering capability of research vessels.

Despite such advances, sustained coastal ocean observing programs involving periodic occupation of established stations and/or transect lines remain rare due to the expense of operating manned vessels at sea which can range well into the tens of thousands of dollars per day. Fisheries surveys and fishery-related data gathering remain the exception although some such observing mission are now being performed by autonomous surface and underwater vessels equipped with acoustic fish sensing instrumentation. Remarkable among such sustained, manned vessel-based efforts is the CALCOFI Survey, arising from the preceding California Cooperative Sardine Research Program dating to 1949. CALCOFI arose in response to the collapse of the California sardine fishery. Today, the survey incorporates 60 core stations along 11 transect lines normal to the California coast. While a large part of the effort is devoted to fish stock assessment through various means, hydrographic profiles including physical, chemical, and biological variables are secured at all stations. CTD/rosette casts provide instrumental profiles plus bottle samples. Variables that require calibration samples, or those for which electronic transducers do not exist, are measured from bottle samples. Process rates such as primary biological production (photosynthetic rate) are also measured.

Oceanic in character and research-driven in practice the Bermuda Atlantic Time Series (BATS) and the Hawaii Ocean Time Series (HOT) also deserve mention. Large, research ships equipped with sophisticated sampling systems and shipboard laboratories are dedicated to long-term documentation of biogeochemical ocean properties and processes and their response to climate forcing. Together, these efforts, occupying single stations at monthly intervals have provided irrefutable evidence for a long-term ocean warming trend and have demonstrated strong covariance of ocean pH decrease with the increasing atmospheric CO_2 load (Dore et al. 2009).

Today, expeditionary oceanography is increasingly being supplemented, and replaced in some cases, by instrumental observations using a variety of autonomous stationary and mobile platforms equipped with dedicated suits of advanced sensors coupled to electronic navigational, computational, and telemetric packages. Coastal ocean observing systems, in particular, have burgeoned in recent years spurred by these advances and responding to the growing needs of a wide range of stakeholders operating in this domain.

Ocean observatories, of great value to oceanographic research and in some ways akin to the astronomical observatories, are primarily concerned with the advancement of science. Ocean observing systems, on the other hand, while invariably useful to science, are primarily dedicated to serving stakeholder needs. Stakeholders in the commercial, conservation, recreational, regulatory, security, and scientific fields increasingly rely on observing system data products, nowcasts, and forecasts for operational planning and execution. Such packaged data products are now supplied by government-supported integrated coastal ocean observing systems (such as those forming part of the United States *Integrated Ocean Observing System* IOOS) as well as by commercial enterprises. These developments have brought us to the dawn of an era of truly operational autonomous ocean observing.

This book is focused on the practice of operational coastal ocean observing providing data and data products useful to the stakeholder. The book describes the wide available range of electromechanical, electrochemical, electro-optical, and electroacoustic sensor systems at the heart of current field-deployable ocean observing instruments. Their principles of operation, precision, and accuracy are discussed in detail as well as their power requirements and associated electronics. Observing platforms bearing these instruments cover a diverse spatial range from satellites in orbit, to surface vessels or buoys afloat, to submerged vehicles, and to subsurface and ocean bottom emplacements. Autonomous profiling buoys are now capable of characterizing water column properties from the surface to great depths. Shore-based platforms also provide meteorological data and the novel capability of HF radar surface current mapping for coastal ocean observing. Active and passive electromagnetic sensing instruments aboard satellites in terrestrial orbit provide wide ranging synoptic views of ocean surface and subsurface features. Observing platforms ranging from the traditional to the most recently developed are described as are the challenges of integrating instrument suits to individual platforms.

Operating and maintaining a coastal ocean observing network is subject to the challenges posed to operating electronic instruments and platforms in remote environments where electrical power is unavailable and equipment is subject to harsh conditions. The book describes currently available provisions for reliable power supplies and for protection from seawater pressure, corrosion, and biofouling, provisions which are essential to operational ocean observing.

Large volumes of data are generated by distributed networks of observing platforms constituting an observing system. Depending on the platform, observations from one to several instruments, together with metadata such as time stamps, geolocation, and depth must be integrated into a standardized data packet for transmission to one or more data assembly centers. Electronic data is digitized, filtered, and processed into discrete data packages prior to transmission. Data are then either made available in a few currently accepted data formats or integrated into value-added data visualization products. The book describes the processes involved in data conditioning, quality assurance, and quality control procedures as well as accepted data formats and representative data products.

Data from remote observing sites must be transmitted to the operator. Data telemetry can make use of cables to shore. Data from subsurface emplacements must be transmitted to the sea surface via acoustic means due to the opacity of