Chapter 13

Conclusions

Chapter Outline

Ocean-current measurements are important for a wide spectrum of applications extending from the domain of scientific research to the domain of a multitude of operational applications. Observations and experiments have been crucial to untangling the mysteries of fluid processes in the ocean. Quite often, observations guide the progress of our science. There are only very few instances in oceanography in which theory preceded observation; one such example was the prediction of southward flow under the Gulf Stream by the Stommel-Arons theory of abyssal circulation (Stommel and Arons, 1960a, b). Even in such instances, confirmation of the theory requires direct measurement.

13.1. PROGRESS IN OCEAN CURRENT MEASUREMENT TECHNOLOGIES

Over the past few decades, various methods of current measurement, through a variety of instrumentation ranging from the conceptually simple time-series position measurement of drift bottles, poles, and parachute drogues to the sophistication of current meter (CM) moorings, HF Doppler radar systems, satellite imagery, satellite altimetry, acoustic tomography, satellite-tracked surface/subsurface drifters, and remote profiling using a variety of free-falling/rising devices and acoustic Doppler techniques, have been employed. Such measurements have revealed that the ocean is populated by several small to medium-scale circulation trajectories and patterns analogous to the weather systems in the atmosphere, and not often, some strange features and complex motions in the interior of the ocean, which are not found in the atmosphere, have been identified.

13.2. MOORED CURRENT METERS AND THEIR LIMITATIONS

Eulerian-style current measurements continue to be widely used to support offshore construction in the continental shelf and environmental projects. In such applications, regimes of interest range from the surface to several hundred meters and from concentrated, short-term measurements to sparse, long-term measurements of up to three years or more. The timeliness, reliability, and availability of the data are frequently more important to the operational user than absolute data accuracy. A detailed study in 1975 by the Current Meter Review Panel within the NOAA Office of Marine Technology (OMT) established the urgent need for measurement of currents in the mixed layers of the ocean and on the continental shelf to support marine surveying and offshore construction projects. Major obstacles to satisfying this need were the inability of available current measurement systems to operate reliably and to deliver accurate measurements under the influence of the dynamic ocean environment within these regions. The Working Conference on Current

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Meters held at the University of Delaware in January 1978 also confirmed these observations and noted that neither the need for ocean-current data nor the number of associated problems has diminished.

General knowledge of oceanic motions increased considerably during the past few decades, primarily due to the successful use of moored current meters. The technology of mooring and maintaining chains of CMs in the deep ocean steadily improved and moorings became maintainable for over a year or more, yielding time-series measurements long enough to cover the greater part of the spectrum of oceanic motions. Fortunately, as a result of decades of design and development efforts by oceanographic technologists, laboratory-scale experimentation, flow flume experiments, and field intercomparison studies, a number of promising state-of-the-art current sensors were developed and incorporated into CMs for judicious selection by the user communities to suit their specific application needs. In some instances, modifications and adaptations of current sensors have been made to facilitate at-sea testing on subsurface arrays designed to decouple the sensors from the effect of surface waves. Some modern CMs have been designed with remote capability to allow controlling and monitoring of the status of current-measurement subsystems from the surface during short-term, at-sea testing as well as near-real-time data transmission capability. Schmitz et al. (1988) combined CMs and floats to describe mean and eddy flow in the eastern North Atlantic and found remarkable agreement of Eulerian and Lagrangian mean flows and eddy statistics.

Ocean currents, both on the surface and at mid-depth, have been measured and analyzed since the early 1900s. Several time-series records of horizontal currents and temperatures exist from fixed instruments on taut-wire moorings in the deep ocean and on continental shelf and slope locations. These measurements have shown that the energy in horizontal currents is contained mainly in low-frequency motions. Quasi-geostrophic, tidal and inertial motions account for the great bulk of the energy. Because low-frequency, energetic motions are of great interest for several studies, the temporal sampling rate is often reduced.

Unfortunately, data from fixed instruments tell a rather complicated story about vertical spatial structure. Records from adjacent instruments on an array in the vertical plane show low coherence at all but the lowest temporal frequencies (quasi-geostrophic). Webster (1968) describes the character of inertial oscillations as coherent horizontally over much greater scales (more than 3 km) than they are coherent vertically (less than 80 m). Based on examination of the extensive data bank at the Woods Hole Oceanographic Institution, it was inferred that some of the most energetic temporal frequencies are badly sampled in the vertical by typical fixed instrument spacing. Considering further what is already known about temperature and salinity distributions, it is considered that vertical profiles of scalar or vector quantities of interest cannot be obtained with an economical number of fixed instruments. The often-observed extremely low correlation between motions at different depth levels (Webster, 1968, 1969, 1972), together with the great expense of CM chains, indicated the necessity for additional tools (say, a vertically moving sensor package providing high-resolution profiles) to effectively measure ocean currents over a variety of space and time scales. Thus, although in the past the moored CMs were useful, their limitation of poor spatial coverage is rather obvious.

Furthermore, although Eulerian-style CMs deployed from moorings have been able to measure the mean currents fairly accurately, measurements of very slow currents (such as vertical currents that are usually less than 0.001 cm/s) remain an unfulfilled dream of physical oceanographers. In the absence of suitable instrumentation for direct measurements, these small currents were computed from wind stresses or from horizontal velocity fields using the equation of continuity. Flow determination by computation only is less complete unless supported by actual measurements, at least for cross-checking. The growing emphasis is, therefore, to achieve still lower threshold, greater accuracy, and resolution so that very slow motions such as upwelling currents, which have significant biological importance, may actually be measured instead of depending entirely on mathematical calculations. Each sensor type has its own merits and limitations as regards differing range limits, thresholds, accuracy, resolution, and the like. The type of sensor to be employed in a particular situation depends on the nature of the intended study.

Although steady currents can be measured comparatively easily with sufficient reliability and accuracy, accurate measurements of mean current in the presence of complex, mixed steady, and unsteady currents containing a myriad of temporal and spatial scales pose a real challenge. The problem becomes further complicated by the lack of fixed reference points arising from the motion of the platform or the mooring that supports the CM. In estuaries and coastal environments, the current regime of which is often required to be known, the steady current will generally be disturbed by wind and wave activity. The current flow regime of the upper ocean consists of high-frequency, wave-induced spurious surface currents superimposed on long-period mean current. A surface-following float or the floating platform suspending the CM (e.g., the boat from which the CM is suspended) inevitably moves in many directions, and the CMs beneath sense such motions as well because of the physical coupling between the CM and the surface platform through the interconnecting cable. However, this limitation is absent in the case of the CMs mounted on fixed offshore platforms.

It has been reported (e.g., Gould and Sambuco, 1975) that on a mooring with a surface-following buoy, the vertical motion of the buoy in the wave field is communicated to great depths. Any CM on such a mooring is exposed to vertical motions many times stronger than the mean horizontal current. Field experiments have shown (Halpern and Pillsbury, 1976) that high-frequency surface wave motion is transmitted via mooring cable to instruments suspended at depths. It was also inferred that the CM on a mooring line would receive a good percent of the vibrations transmitted along the cable and contributes to errors in the data records. Observations have shown (Chhabra, 1977; Hogg, 1986; Hendry, 1988) that subsurface moorings could undergo considerable horizontal and hundreds of meters of vertical excursions in response to the associated horizontal drag forces, resulting in complex motions of the instrument and causing contamination of measurements. Vertical excursions associated with these horizontal movements are more problematic because horizontal currents can vary significantly with depth on the scales of the expected vertical displacements, with the result that the instrument measures a mixture of temporal and spatial variability (Hendry, 1988).

To some extent, the CMs' motion can be reduced by the use of subsurface moorings. The effect on the current measurements depends, therefore, on the kind of mooring, the kind of CM, and the environmental conditions of winds, waves, swells, and currents. Though some types of CM sensors are found to be more sensitive to current speed measurement errors due to mooring motion, contamination of current measurements by mooring-line motion is common to all types of sensors incorporated in Eulerian CMs.

Von Zweck and Saunders (1981) mathematically treated the effects of mooring motion on current spectra, independent of instruments' inherent performance characteristics, by taking into account the displacement of CMs within the oceanic current field. They found that mooring motions contaminate current measurements by redistribution of energy in frequency, wave-number-dependent attenuation and linear superposition of mooring motion. The type of contamination arising from redistribution of spectral energy to higher and lower frequencies, as well as wave-number-dependent attenuation (which is a function of the ratio of meter displacement to wavelength), are difficult to remove. This poses a serious problem in determining the true energy spectrum from the data obtained from CMs deployed on a wave-influenced mooring line.

Another source of error in measurements from moored CMs is the tilting of the CM sensor during high horizontal currents. A major difficulty involved in Eulerian measurements is that deployment and retrieval methods for such systems are both time-consuming and costly, besides the peril of losing the CM (and data) in rough seas or to shipping traffic or fishing activity in the area. Because the effects of mooring and wave motions vary with environmental conditions and are difficult to quantify, the data may lose its desired credibility for specialized applications. However, for a detailed study of a particular region on a long-term basis, ocean-current measurement in a Eulerian fashion is a necessity. Nevertheless, long-term, time-series ocean-current measurements from moorings have been essential to much of the understanding gained about ocean currents. In fact, most of the quantitative knowledge of deep currents has been gained from moored current measurements. The CM mooring with subsurface floatation has now become a standard tool for exploring the ocean and gathering statistical information on mean currents, eddy energies, and fluxes of momentum and heat. It is worth mentioning that acoustic release systems have facilitated moorings with subsurface flotation.

13.3. LAGRANGIAN MEASUREMENTS OF SURFACE CURRENTS

In oceanography, lack of systematic synoptic current observations in the Lagrangian style has been a major hindering factor in the development of synoptic current charts for the analysis and prediction of surface currents for various operational activities. Sea surface drifters of various kinds have traditionally been used to yield an estimate of sea surface currents and their trajectories. There had been several problems associated with drifter buoys (Vachon, 1977), the typical one being slippage. The effect of wind on the buoys can be reduced by keeping the amount of buoy volume above the water as small as possible, but true windage effects are not yet known. Typical results show that slippage can be as high as 1 percent of the wind speed when wave effects are included. Measurements are needed to show how well buoys with and without drogues drift relative to the water under different conditions. Another problem is the quantitative interpretation of Lagrangian measurements. In strong currents the interpretation is easier than in the mid-ocean, where mean flow may be weaker than the time-dependent flow. For statistical interpretations, large samples are required. In spite of these difficulties, the potential of the sea surface drifter techniques is large, and the entire fields of drifter technology and interpretation are very much active.

Application of Lagrangian measurements to monitor sea surface circulation greatly expanded in the 1980s and 1990s through effective utilization of the progress made in satellite technologies and global positioning systems (GPS). The global World Ocean Circulation Experiment (WOCE) took advantage of such progress and adopted the WOCE Lagrangian drifter for studies of the circulation of the surface layer of the global ocean. The WOCE-type drifters were designed for open-ocean applications. In an attempt to minimize wind-driven drag, the drogue of the drifter was sufficiently long that the current measurements represented a vertically averaged current of the 12.5- to 17.5-m water layer. Thus, the drifter was designed to record the current at ~15 m depth and could be easily deployed because it was preprogrammed and its drogue was self-extendable. Furthermore, the WOCE drifter utilized satellite communication, which has several advantages and some disadvantages. The most obvious and highly significant advantage is global coverage. Among the disadvantages are the relatively high cost and the indirect, one-way communication with the drifter, which make the instrument expendable. In the framework of the WOCE project, over 4,000 such drifters were deployed and tracked by satellites from 1990 to 2002. Subsequently, the WOCE drifters began to be used worldwide for open-ocean Lagrangian measurement of surface circulation. Undoubtedly, these surface drifter networks have improved the description of surface circulation.

Space-based observation of offshore currents would provide added information to support coastal current observations. These measures would fulfill the currently existing need for a minimum safety level, which is being challenged through climate change. Disaster risk reduction is an essential element of climate-change adaptation.

In the recent past, the trajectory data of satellite-tracked drifters became available and made great progress with increasing long-term ocean-observing systems in response to the growing demand for climate study and global operational predictions. The World Ocean Circulation Experiment—Tropical Ocean Global Atmosphere (WOCE-TOGA) program has established the Surface Velocity Program (SVP) for monitoring ocean currents; this program arranges global deployment of Lagrangian drifters.

At the surface of the ocean, measurements are difficult for other reasons as well, primarily because sea surface lies in the wave zone. Wind waves and swell have periods of a few seconds. A 6-s-period wave will subject a surface platform to almost 1 million flexure cycles every month. It is not surprising that reliability and longevity are prime problems. Surface drifters play a continuing role in ocean research.

Note that "ARGOS" is the short form of the French satellite system known as *Advanced Research and Global Observation Satellite,* which, since 1978, offers capabilities for satellite-based position fixing of radio buoys. In the oceanographic context the platform transmit terminal (PTT) onboard a radio buoy (known as *ARGOS float*), which floats on the sea surface and freely drifts with the local sea surface current, allows periodic tracking of the radio buoy; thus allowing determination of both the trajectory of sea surface current and the current-velocity at various points along the trajectory. In contrast, "Argo" is the short form of an international program, known as "*Array for Real-time Geostrophic Oceanography*". An *Argo float* is a robotic float (used under the *Argo* program), which autonomously ascends from a parking depth (1,000 m) to sea surface, synchronously measuring the temperature and salinity in environmental water mass, and then drifts for 10−12 h on the sea surface before it descends to its parking depth, and then freely drifts at this depth with the water motion at that depth. Subsequently it resurfaces from the parking depth to continue another cycle. This cycle repeats until the battery power depletes. Thus, whereas *Argo float* is a profiling float that is primarily used for determining subsurface current, *ARGOS float* is a freely drifting surface-float. Interestingly, the ARGOS float that is always floating on the sea surface and the Argo float that floats on the sea surface only during its 10−12 h surface-parking interval in its profiling cycle are both tracked by the ARGOS satellite system. The tracking data collected during the Argo float's 10−12 h surface-parking interval in its profiling cycle are used for determination of surface current (both trajectory and current-velocity).

Tracked by Argos satellite or relaying GPS positions by cellular phone, drifters benefit from high-tech systems already in place. Since the work of Johnson et al. (2003) and Schmidt et al. (2003), availability of low-cost handheld GPS units gave rise to the development of several surf-zone drifters at reduced expense. This enabled an increase in the number of drifters that can be deployed simultaneously, thereby further increasing the statistical confidence of surf-zone water-velocity estimates. In addition, small, inexpensive, off-the-shelf waterproof cases rated to a submersible depth of 30 m became available for most handheld GPS units, thereby reducing engineering and production time. Owing to their small size, handheld GPS units can be mounted to the exterior of a surf-zone drifter rather than in the interior, allowing variation in drifter design while reducing costs and production time. Taking into account the hazardous nature of the surf zone, inexpensive drifters relax the logistical costs and pressures of drifter recovery.

Despite the apparent difficulties of using drifters in the surf zone, their design and deployment have been surprisingly successful. Small, simple drifters have proven very robust and easy to deploy. The quality of surf-zone water-motion data (both trajectory and velocity) obtained through the GPS drifters was found to be good in terms of positioning accuracy and coverage. Both modeling and field validations have suggested that the drifter closely measures the depth-averaged and wave-averaged Eulerian current in low- to moderate-energy surf zones if drogued in an appropriate manner. Purpose-built drifters have been found to possess very significant potential as a valuable tool for surf-zone investigations and have already been used successfully by several researchers to study transient rip currents. Drifters have also been used to monitor pollution dispersion from recreational areas and study of tidal fronts. Small GPS drifters have been found to be valuable instruments in studies of circulation and dispersion in a whole range of aquatic environments in which Lagrangian measurements are scarce. These environments include the near-shore zone, small and medium-sized lakes, rivers, and estuaries. In these applications, the full capabilities of more sophisticated drifters that currently exist may not be required, and very simple, low-cost devices may be more appropriate.

13.4. GLOBAL OBSERVATION OF SEA SURFACE CURRENTS AND THEIR SIGNATURES THROUGH IMAGERY

Sea surface imagery is another useful product to examine the surface expressions of various kinds of motions in the upper ocean. For example, the ocean is rich in short- and long-lived mesoscale dynamic features. Examples include meandering currents and eddies with distinct sea surface temperature fronts, the sporadic occurrence of filaments and jets, and wind-driven coastal upwelling and downwelling. It has been found that imageries of large areas over the ocean surface can be used effectively in studies of frontal features and their impact on the mesoscale variability of large-scale ocean-current systems (e.g., the Gulf Stream and coastal boundary currents).

Upper-ocean fronts and eddies are dynamic features that importantly contribute to mesoscale variability, coupled physical-biochemical processes, and rapid changes in air-sea interaction. Such features are usually manifested by the sea surface temperature pattern and chlorophyll-*a* concentration, in thermal infrared and visible-wavelength satellite remote sensing images, respectively. In synthetic aperture radar (SAR) images they are manifested by virtue of sea surface roughness changes. Among the different components of the surface current gradient tensor, the dominant contribution is mostly related to the effects of convergence and divergence. Indeed, variations in the mean-square slope and wave breaking as well as Bragg wave modulations (via the intermediate-scale wave-breaking mechanism) are all strongly affected by such current gradients. Consequently, enhancement and suppression of surface roughness occur in the zones of convergence and divergence, respectively. Interestingly, surfactants also tend to accumulate in the zones of the current convergence to dampen short wind-driven waves. The effects of pure wave-current interaction and surfactant damping may then lead to opposite SAR signatures for current convergence areas. It is reasonable to anticipate that the resulting net effect depends on the wind conditions, the magnitude of the current convergence, and the properties of any surfactant material that is present. Satellite observational techniques, which surpass all previous methods of synoptic surface current measurements from the open sea, promise to obtain a near-simultaneous picture of ocean surface current features.

Most of the dynamic features contribute to the complication of surface roughness modulation patterns, which are often manifested in visible-wavelength photographs and microwave images. The track of sea surface roughness contrast can be imaged in the visible-wavelength photography because the sea surface roughness variability alters the sun-glint pattern. The efficiency of visible-wavelength photography is, however, hampered during periods when clouds are present or visibility is poor. The problem is of particularly serious proportion in the cloud-belt regions within 15° of the equator and near the poles. Because visible-wavelength aerial photography is practicable only during daytime with a clear atmosphere, this method is generally unsuited for long-term systematic remote sensing studies of ocean surface circulation. Furthermore, the method of aerial photography is largely restricted to coastal waters. The advent of microwave imaging radar systems has removed these restrictions, thereby permitting efficient scheduling of flight operations, regardless of weather and visibility conditions. These radar systems permit obtaining round-the-clock imagery of the sea surface roughness contrasts under most weather conditions. Furthermore, radar imaging systems provide larger aerial coverage. However, as a result of relatively poor resolution arising from comparatively larger wavelength of the radar (relative to that of light used in photography), the quality of imagery obtained from radar systems does not generally match that obtained from visible-wavelength photography.

Images obtained from aircraft-borne side-looking microwave radar systems have been of great value for coastal surveillance during nights and cloudy days. However, use of aircraft for routine generation of images from large oceanic areas is impractical (costly and time-consuming). Fortunately, the fundamental equations for SAR imaging of surface current features have gradually become better known and can now be applied to simulate SAR image expressions. The spatial resolution of space-borne SARs typically ranges between a few meters and more than 100 meters, depending on the product type (that is, continuous or burst mode). Accordingly, the spatial coverage varies between approximately 100 × 100 km (standard image mode) to 500 × 500 km (wide swath or ScanSAR mode). Today three spaceborne SARs—the ERS-2, Envisat, and Radarsat-1—are available. The reasonably good resolution properties of space-borne SAR systems, as well as their independence of light and cloud conditions, together make SAR imagery a crucial source of information for a number of marine and coastal applications. SAR observations have also demonstrated their ability to routinely monitor different ocean-surface parameters, such as swell direction and amplitude (Beal et al., 1983; Hasselmann and Hasselmann, 1991). Hydrodynamic modulation of the surface roughness resulting from wave-current interaction makes possible the observation of oceanic features such as current fronts, eddies, and internal waves. Recent research activities have led to progress in more emerging SAR applications, such as Doppler-based surface current measurements and oceanic and atmospheric feature identification, which offers new insights for observing and modeling mesoscale meteo-oceanic processes.

It has been found that large-scale oceanographic features can produce corresponding signatures in SAR imagery. For example, many researchers have examined the SAR signature of the large-scale oceanic fronts such as the Gulf Stream North Wall (GSNW). The GSNW is made evident in SAR imagery by the buoyancy and air-sea momentum flux discontinuity that often accompanies it. Field observations, including hydrographic measurements, microwave imaging radar measurements, and HF radar measurements, have revealed the evolution of complicated frontal interactions between various water masses. In some instances, the water masses were found to have been separated by intersecting frontal lines configured in a manner analogous to occluded atmospheric fronts. As a result of the occlusion, the water mass with intermediate density subducts and intrudes under the most buoyant water, carrying with it strong horizontal and vertical shears and a frontal band of diverging currents, is created in the densest water mass. Model studies have suggested that in the ocean there will be an increase in hydrographic and velocity fine structure downstream of the frontal occlusion point.

SAR instruments have been used not only for imaging oceanic circulation features but also for imaging meteorological features such as cold and warm fronts of various kinds. SAR has been found to be useful in studying the evolution of convective storms from their footprints on the sea and in studying the signatures of spatially evolving atmospheric convection over the oceans. Patterns in SAR backscatter from the ocean result from corresponding modulations of the centimeter-scale, wind-induced wave state by both oceanic and atmospheric phenomena. Given the high resolution of typical SARs and their order 100−1,000 km swath widths, they are ideal devices for sensing the sea surface signatures of those phenomena over a wide range of scales. Examples of signatures of oceanic phenomena imaged by SAR include swells, internal waves, surface currents, and sea surface slicks. The signatures of atmospheric phenomena commonly imaged by SAR include convective cells, roll vortices, gravity waves, mesoscale cyclones, and synoptic-scale weather systems.

Space-borne SAR measurements have effectively been used to forecast polar mesoscale cyclones in the Bering Sea (Friedman et al., 2001). Footprints of the atmosphere can be derived from SAR images of the ocean surface. Space-borne SAR imagery of the sea surface has effectively been used in detecting the presence and structure of the convective marine atmospheric boundary layer (Sikora et al., 1995, 1997). Analysis of several thousand RADARSAT-1 SAR images from the Gulf of Alaska and from off the east coast of North America revealed the presence of, and the mesoscale and microscale substructures associated with, synoptic-scale cold fronts, warm fronts, stationary fronts, occluded fronts, and secluded fronts. It is expected that in the near future related experimental products such as SAR-derived wind-speed datasets will have the potential to further the field of SAR meteorology.

The high-resolution properties of space-borne SAR systems, as well as their independence of light and cloud conditions, make SAR imagery a crucial source of information for a number of marine and coastal applications. Recent research activities have led to progress in more emerging SAR applications such as Doppler-based surface current measurements and oceanic and atmospheric features identification, which offers new insights for the observation and modeling of mesoscale meteo-oceanic processes. Very small gradients and low-value currents, which are inferred from sea surface heights estimated from satellite altimetry, are already routinely used in the global circulation models.

Sequences of sea surface temperatures and ocean-color data can be used either in the maximum cross-correlation method or the optical-flow method to derive absolute measurements of current vectors (Vigan et al., 2000; Yang and Parvin, 2000). However, they do not achieve the spatial resolution of SAR-based methods and they are limited by the solar-illumination and cloud-cover conditions.

13.5. REAL-TIME TWO-DIMENSIONAL MAPPING OF SEA SURFACE CURRENT VECTORS

Routine monitoring of sea surface currents and waves in the offshore and near-shore regions is of great interest to both coastal and scientific communities. Crombie's meticulously careful observation of the backscattered high-frequency (HF) radio waveband echoes from the sea (the Bragg scattering principle) led to the discovery of the unique backscattering phenomenon behind the development of radio-wave Doppler radar systems (with frequencies of 3−30 MHz and wavelengths of ∼10−100 m). Bragg-resonant backscattering, which is a coherent backscattering of radio-wave energy by ocean surface waves with half the electromagnetic radar wavelength, just like X-rays are scattered in crystals, allows near-surface currents, along with wave heights and wind direction, to be measured and mapped at distances up to 200 km, depending on the transmitted frequency. Some of the transmitted HF energy is guided by the sea surface; this phenomenon allows measurements to be made beyond the normal radar horizon.

Remote sensing of near-surface currents with HF radar was demonstrated in the early 1970s by Stewart and Joy (1974). Subsequent theoretical investigations by Hasselmann (1971) and Barrick et al. (1977) strengthened Crombie's findings. Bragg waves in the HF band happen to be "short" surface gravity waves, which can be assumed to be traveling as deep-water waves, except in very shallow depths of a few meters or less. This is important because it allows information contained in the Doppler shift of Bragg peaks to be used to estimate ocean currents and other parameters. Because the ocean is generally covered by waves of many different wavelengths and directions (continuous spectrum), there are always trains of waves propagating toward and away from the radar. The current measurement by HF Doppler radars is close to a "true" surface current measurement. Because radar pulses scatter off ocean waves, the derived currents represent an integral over a depth that is proportional to the radar wavelength. Stewart and Joy (1974) show this depth (d) to be approximately $d = \lambda/(8\pi)$. Because wavelength of the resonant sea surface wave depends on the radar frequency, it is feasible to use multifrequency HF radar systems to estimate vertical shear in the top 2 m of the ocean.

At NOAA in the United States in the early 1970s, Donald Barrick, B. J. Lipa, and co-researchers played a big role in demonstrating the ability of coastal HF Doppler radar systems to map ocean surface currents. Since that time, there has been a push to develop this technology into a useful and affordable tool that would fill a big gap. Before the 1970s there was nothing else available that could map surface currents continuously over space and time. Successive advancements in technology led to the development of different kinds of devices for remote mapping sea surface current fields, sea surface waves, and winds. These include the coastal ocean dynamics applications radar (CODAR) system, SeaSonde, the ocean surface current radar (OSCR), and the Wellen radar (WERA), all of which hold a prime position in coastal-observing systems in many parts of the world. Other, more recent developments include the coastal ocean surface radar (COSRAD), Courants de Surface MEsures par Radar (COSMER), PISCES, high-frequency surface wave radar (HF-SWR), high-frequency ocean surface radar (HFOSR), multifrequency coastal radar (MCR), Ocean States Measuring and Analyzing Radar (OSMAR2000), and PortMap.

Different designs of these HF/VHF Doppler radar systems have taken full advantage of improved electronics and computer technologies and incorporated different methods to perform spatial resolution both in range and azimuth. Range resolution could be achieved by means of short pulses, frequency-modulated chirps known as frequency-modulated continuous waves (FMCW), or frequency-modulated interrupted continuous waves (FMICW). Azimuth resolution could be obtained by means of beam forming or direction finding (phase comparison).

HF/VHF Doppler radar systems provide the unique capability to continuously monitor the coastal environment far beyond the range of conventional microwave radars. The working range of Doppler radar systems depends on the attenuation of the electromagnetic wave between the transmitter and the target. Attenuation is strongly affected by the condition of the sea state (sea too rough or too calm). The attenuation also increases with decreasing seawater conductivity, increasing transmission frequency, increasing distance between the transmitter and the target, and increasing atmospheric noise and/or radio-wave interference. A compromise should be found between working range and range resolution, which decreases with decreasing frequency, because of interference from long-range radio sources (transmissions from all over the world reflected by the ionosphere).

HF Doppler radar systems based on ground-wave propagation proved highly beneficial for remotely sensing ocean surface currents and gravity waves. Coastally located HF Doppler radar networks permit synoptic time-series mapping of coastal surface current circulation over a wide area in real time, under all weather conditions, for a variety of oceanographic research purposes and operational utilities and can also provide timely and valuable information to improve safety in coastal waters. Shore-based HF and very high-frequency (VHF) radar (typically in the range 3–50 MHz) proved very useful tools for analyzing and understanding coastal sea surface water currents. Pairs of HF/VHF radar devices operate mostly from shore (except in the case of offshore platform-mounted systems) and provide a convenient way to measure surface currents over a large area.

The reason for the great importance attached to the HF/VHF Doppler radar technology is that it has the ability to map ocean surface currents in real time over large areas, revealing evolving current structures that are difficult to monitor using any other instrument. HF radar systems have now become a popular technology for studying coastal circulation processes. The high spatial and temporal resolutions make HF radar technology suitable for aiding search and rescue operations, studying pollutant and larval dispersal, and analyzing the physical forcing of coastal flows. Because HF Doppler radar systems have the advantage of being real-time and noninvasive, several countries have begun to consider shore-based systems that are capable of mapping ocean surface currents from shore to far-off distances as their national coastal ocean surface current mapping systems.

Cochin et al. (2006) demonstrated the operational feasibility of VHF Doppler radar systems in a region dominated by strong tidal currents. They also showed that extraction of tidal components can be accomplished within a large area by the same process as for *in situ* instruments. Tidal-current ellipses are particularly useful for calibrating numerical models. Doppler radar measurements are also used to increase the precision of coastal hydrodynamic models by means of data assimilation. These measurements also have an important role in terms of operational surveillance, because of their high temporal resolution (every 30 min, down to 10 min) and large-scale domain, which offer good opportunity for control and operational surveys.

The spatial coverage provided by HF/VHF Doppler radar network and its superb capability for remotely measuring ocean surface currents as far out as 200 km offshore, generating hourly maps indicating the speed and direction of the currents at a number of spatially dense locations, are ideal features for meeting the requirements of port authorities and search-and-rescue operations. Port authorities have the responsibility to mariners to provide accurate and up-to-date information to allow for the safest passage possible. Knowledge of sea surface currents and winds over a reasonably large area offshore of the ports has been recognized as an important factor in meeting this responsibility. Such data are also important for many major industries, whether it is to predict the course of an oil spill, to calculate the best path for the installation of a pipeline, or to aid in search and rescue operations. The surface current maps generated at close spatial and temporal intervals are also immensely valuable for addressing several research problems.

Today remote sensing using satellite-borne sensors as well as fixed-platform-based HF/VHF Doppler radar systems permits collection of near-real-time "snapshot pictures" of oceanic surface circulation over large areas. In terms of monitoring the ever-increasing menace of oil spills from oil tankers and oil-drilling platforms as well as conducting successful rescue operations, the capability of these devices for all-weather, near-real-time mapping of oceanic surface circulation is of immense practical utility. The land-based multiple-site HF Doppler radar system is indeed a major development that enables round-the-clock remote time-series mapping of sea surface circulation features over large areas.

While appreciating the merits of the HF/VHF Doppler radar systems, it is important to keep in mind their limitations as revealed by several intercomparison studies. Perhaps the most important among them is due to their spatial resolution, where measurements are smooth and do not provide local strong currents. Another limitation is due to the presence of spurious peaks in the Doppler spectrum. Those peaks represent energy that is stronger from the Bragg waves in the direction of the side lobes in the antenna pattern than those from the principal radar beam. This happens in some cases of wind and current conditions. Time-frequency analysis on the whole duration of the signal or unmixed processing could be applied to eliminate spurious peaks. Attenuation of the HF ground wave is strongly dependent on radio frequency and sea-water conductivity. Experimental data have confirmed the predicted decrease of propagation range with decreasing conductivity. High salinity allows optimum performance; strong attenuation prevents HF radar being used for remote sensing in freshwater lakes and over ice-covered areas. Radio interference or high sea states can limit the actual range at times. Wet and moist sandy soils enhance the ground-wave propagation, whereas dry and rocky ground reduces signal strengths.

There is a "baseline problem" that occurs where both radar sites measure the same (or nearly the same) radial component of velocity, such as along the baseline between the sites or at great distances from both sites. Generally, two radials must have an angle $>30^\circ$ and $<150^\circ$ to resolve the current vector. Typical azimuthal resolutions are $\sim 5^\circ$. Near the coast, this gives a measurement width of ~ 0.5 km; the width is ~ 10 km at range cells 100 km offshore. Fortunately, radar backscatter use is increasing and there are several different systems in the marketplace at a range of frequencies. These have extended uses. The use of HF radar has already become commonplace; as a result, a new level of understanding of the coastal ocean is emerging.

It may be added that there is no single oceanic current measuring system "for all seasons," but HF/VHF Doppler ocean surface current radar systems are among the few that go a long way in approaching that ideal. HF/VHF Doppler radar systems offer a very interesting opportunity to retrieve the full vector of sea surface currents with a temporal sampling of a few minutes. However, the coverage area is substantially more limited than that offered by space-borne systems. Furthermore, the deployment and maintenance of such systems often induce additional costs and administrative difficulties. Nevertheless, such a system may be well suited for local measurements and validation purposes. It is quite clear that two-dimensional maps of surface currents from HF radar networks represent a useful and unique resource for the improvement of coastal ocean circulation models, particularly in the critical depth range encompassing the euphotic zone.

After a long gestation period consisting of validation studies and analyses by several groups, the operational era has arrived. Until 2010, over 13 countries had established real-time networks, defined as four or more radar systems (Barrick, 2010). In the United States, real-time data are posted to two national Websites and several individual regional ones for public use. In search-and-rescue operations, the U.S. Coast Guard incorporates these real-time maps into a short-term predictive system that narrows their search regions. NOAA and the Coast Guard use the maps for oil-spill and floating-pollutant impact studies and cleanup mitigation. Oil companies make decisions regarding safety of platform operations based on the radar outputs. Based on these data, the local coastal municipalities decide whether to close beaches due to pollution. Several groups have demonstrated how HF surface maps significantly improve numerical model forecasts, not just of surface flow but of subsurface circulation, temperature, salinity, and transport. According to Barrick (2010), one New York forecast model assimilates data in real time. Ocean research scientists now routinely accept and incorporate these data among other sensor outputs into understanding oceanic processes and their impacts on climate and biology. In recent years the evolving capability to use shore-based HF radar systems to continuously monitor vast stretches of coastal ocean surface currents has presented a new possibility for improving our understanding and monitoring capabilities in these marine environments (Paduan and Graber, 1997).

Present system and coverage capabilities of HF Doppler radar systems are quite impressive. Measurements can be made in range as short as 1 km and as long as 200 km from the shore at a resolution of ~0.3–3 km along a radial beam. Among other technologies, HF Doppler radar is now considered a new technology for tsunami early-warning systems. This is a welcome addition. In case of an approaching tsunami, a strong ocean surface current signature can be observed by the radar when the tsunami waves enter the shelf edge. HF Doppler radar measurements from offshore platforms are very useful for offshore drilling and oil prospecting applications.

But despite the availability of appropriate technology, approaches, and options for replication of good practices, there is still an unacceptable delay in implementing schemes that enable rescue of coastal population from hazards involving coastal currents. HF Doppler radar systems for routine monitoring of currents along coastal regions and around islands would also be useful for detecting the climate-induced variability in these currents. Real-time reporting of currents via the Internet would be a practical means of awareness-raising and climate-change adaptation. This approach would result in a substantial reduction of disaster losses in terms of lives and in the social, economic, and environmental assets of coastal communities.

In recent years, the utility of HF radar-derived surface velocity fields as input to data-assimilating numerical circulation models has been the focus of several studies. Pandian et al. (2010) reported an overview of recent technologies on current and wave measurement in coastal and marine applications. The potential benefits of HF radar data are large, particularly in light of the dearth of real-time observations from the marine environment. These data are also potentially important because they can cover significant portions of coastal ocean model domains. They make it possible, for the first time, to track the location and movement of mesoscale oceanic features in a fashion analogous to the superior capabilities provided by data inputs to numerical weather forecast models (Paduan and Shulman, 2004). The unique advantage of the HF radar is the ability to map the horizontal variability of currents, which is needed for several applications. Eddy dynamics, such as propagation and decay, can be studied, as can the spatial variability of tidal currents. This is a further step in research on current-wave interaction.

Finally, HF radar offers a very interesting opportunity to retrieve the full vector of sea surface currents with a temporal sampling of a few minutes. However, the coverage area is more limited than the space-borne SAR coverage. Many questions still exist, however, about the details and effectiveness of HF radar-derived surface currents as sources for data assimilation. Despite several tasks, it is clear that two-dimensional maps of surface currents from HF radar networks represent a useful and unique resource for the improvement of coastal ocean circulation models, particularly in the critical depth range encompassing the euphotic zone (Paduan and Shulman, 2004). Despite the several merits associated with HF Doppler radar systems, their application is generally restricted to coastal waters.

13.6. GLOBAL OBSERVATION OF SURFACE GEOSTROPHIC CURRENTS AND MESOSCALE CIRCULATION FEATURES

Satellite-tracked surface drifters certainly play a major role in global observation systems, providing surface measurements for calibration of satellite data, giving a direct measurement of surface currents for use with hydrographic data, and providing an interpolation between moorings. A second satellite technique is the measurement of surface topography. Because radar altimeters can measure the distance from the satellite to the sea surface with great accuracy (to better than 10 cm), one need only combine such a measurement with accurate knowledge of the geoid in order to get the surface pressure field. Accuracy in three elements—the satellite orbit, the altimeter measurement, and the geoid itself—is required. Aspects of these problems are discussed in the National Academy report *Requirements for a Dedicated Gravitational Satellite* (Committee on Geodesy, 1979). The uncertainties in the three areas are rapidly decreasing, and thus this technique may be one of the most promising for a synoptic view of surface circulation.

Measuring sea surface height anomaly provides a means for determining global surface geostrophic currents and mesoscale circulation features such as cold-core eddies, warm-core eddies, meanders, and so on. In the past, little sea-level data were available from the vast offshore regions. To circumvent this problem it was necessary to have a spatially dense set of observations made over the entire globe once every few days. Satellite altimetry provides a technique for collecting just such a dataset. A satellite altimeter is a "sea-level gauge in space" and is considered to be a key device for measuring offshore sea-level variability and deducting the just-mentioned oceanic currents and their mesoscale features through measurement of sea-level variability. To accomplish this effectively, further advances will be required in the gravity field modeling and orbit determination. Accurate computation of mesoscale variability from altimeter data, however, requires elimination of the effect of errors in the height of the satellite. Fortunately, mesoscale variability can be detected with pairs of altimeter passes that have the same track. The very long wavelength relative error between two or more repeated (collinear) passes can be effectively removed as a linear trend. The technique of collinear differences had been used effectively by several investigators to derive the global mesoscale variability from altimeter data. The dominant contributor to the random error of an altimetric satellite system used to be the long wavelength uncertainty in the orbital radius. However, calibration by a comparatively modest sea-level gauge system can drastically reduce the overall error in global estimates of large-scale oceanic variability.

Seasat was the first satellite dedicated to establishing the utility of microwave sensors for remote sensing of oceans. Satellite technology could provide the mechanism for monitoring the world ocean on a scale appropriate to oceanographers' requirement. The brief 100-day mission of Seasat in 1978 revealed for the first time how satellites carrying radar altimeters and scatterometers could provide quantitative global-scale information relevant to ocean circulation and the wind fields that force it.

Using the voluminous altimeter-derived sea-level dataset covering vast offshore regions, it has been possible to document large-scale meridional water transport in the equatorial Pacific. Similar studies of interannual variability have been conducted for the tropical Atlantic and Indian oceans as well. Subsequent to the demise of Geosat in late 1989, a few other improved versions of satellite altimeters were launched, and the large datasets derived from them have been used successfully for the study of several hitherto poorly understood oceanic phenomena, such as the warm (El Niño) and the cold (La Niña) phases of the ENSO cycle, massive quantities of surface water transport along the equator in the form of equatorial Kelvin waves, and so forth.

Very small gradients and low-value currents, which are inferred from sea surface heights estimated from satellite altimetry, are already routinely used in global circulation models. Satellite altimetry provides all-weather coverage of large-scale ocean circulation features such as gyres/eddies, western boundary currents, and the like as well as global surface geostrophic currents using surface height anomaly measurements. However, this method is unable to capture the nongeostrophic components of the surface currents, which are dominant in the tropic oceans.

13.7. CURRENT PROFILE MEASUREMENTS USING FREELY-MOVING SENSOR PACKAGES AND ADPs

The difference in horizontal velocity of neighboring depth layers in the ocean gives rise to what is known as *vertical shear of horizontal current velocity* (defined as the derivative of current with respect to depth). Although current shears are most frequently found in the upper layers of the water column, primarily because different time responses by water layers at different depths to a fluctuating wind regime induce high lateral shear, they are also found within the main thermocline and within 500 m of the seafloor.

Moored CMs can give us only a time series at a few points (depths or horizontal positions), and the moorings are not yet adequate for strong currents; features such as narrow jets may not be seen. Thus for a long time there has been interest in techniques to measure currents as a function of depth or horizontal position.

The often-observed, extremely low correlation between motions at different depth levels (Webster, 1968, 1969), together with the great expense of CM chains, indicated the necessity for additional tools (say, vertically moving sensor packages providing high-resolution profiles or appropriate remote sensing devices) to measure effectively ocean currents over a variety of space and time scales. Obviously, it would be interesting to explore how these horizontal motions on different time scales couple in the vertical. This calls for fine-resolution measurements of horizontal motions over both small and large vertical separations. Besides being suitable for directly verifying coupled thermal and circulation models in the ocean and large lakes, the dataset obtained from vertical profilers possessing fine spatial and temporal resolution should provide an insight into a number of geophysical phenomena and processes, such as the evolution of the surface mixed layer; the generation and decay of internal waves and seiches; and the turbulent transport and mixing of heat, momentum, and water masses.

Various methods have been used to determine the vertical profile of horizontal current $V(z)$. The profiler methods emphasize the vertical rather than the temporal dependence of ocean currents. In the initial years of vertical profile measurements of horizontal currents, direct-reading and -recording CMs lowered from ships had been employed. Further improvisation resulted in the use of CMs slowly lowered from a tracked buoy and freely falling CMs measuring relative velocities (e.g., CMs falling along a taut wire). Motionally induced EMF values surrounding a freely falling probe were also used to estimate velocity profiles. Subsequently, freely moving sensor packages (e.g., buoyancy-driven sensors on unattended moorings and free-falling probes horizontally advected by currents and tracked acoustically using seabed transponders) became available for high-resolution profile measurements.

The simplest profiler, in principle, is the analog of the meteorological balloon: the sinking float. The float is tracked acoustically as it sinks, and its path is differentiated to yield velocity as a function of depth. A subset of this class is the transport float, the position of which before and after a trip to the bottom is shown by dye patches at the surface. The second class is the free-fall device that has a current sensor on it, including the electromagnetic and the airfoil lift probes. We also have the class of instruments known as the cyclesonde, which consists of a CM that goes up and down a line attached to a ship, mooring, or drifting buoy. Acoustic Doppler current profilers (ADPs) outshine all the previous current profilers.

In contrast to a moored instrument, a freely sinking/rising probe has been found to possess certain advantages in that an entire profile is obtained from a single record and the measurements are not contaminated by mooring-line motions. Most profilers had ingeniously incorporated a combination of discoveries made in the fields of electronics, hydraulics, electromechanical engineering, and underwater acoustics. Ocean-current velocity profile observations have revealed considerable complexity to the vertical structure or distribution of currents in the deep sea. Until the arrival of ADPs, vertical profile measurements could not replace moored instrumentation, which was deployable for several months. The advantages of the profilers are that they can be used effectively as mobile, real-time survey tools or when detailed vertical structure measurements are required.

Examples of appropriate applications include studies of (1) the vertical or modal structure of low-frequency currents and internal waves; (2) zones of strong but spatially intermittent shear; (3) geostrophic structure and dynamic stability (e.g., Richardson numbers) based on combined density and shear measurements; (4) the velocity field in which real-time results are needed to guide further work; and (5) intense currents, such as the Gulf Stream, where moorings are difficult to deploy and maintain. No single instrument has the mobility, accuracy, and vertical resolution of all the existing profilers. There was, however, a need for a mobile, rapid, absolute velocity profiler accurate to within 1 cm/s with a vertical resolution of 10 to 50 m that yields nearly real-time results and is easy to operate at sea.

Measurement of vertical profiles of horizontal currents in the ocean was a daunting task for several years. It was only with great difficulty and good fortune that the just-mentioned profilers could be operated for more than several weeks at one site. The idea of tracking a sinking float for velocity profiles came out of World War II acoustic developments.

Successful development of ADP took several decades. In this process, a Doppler sonar system for measurement of upper ocean-current velocity was developed in the late 1970s. This sonar transmitted a narrow beam that scattered off drifting plankton and other organisms in the upper ocean. From the Doppler shift of the backscattered sound, the component of water velocity parallel to the beam could be determined to a range of 1,400 m from the transmitter with a precision of 1 cm/s. The instrument was used successfully from a floating instrument platform (FLIP). The ADP, initially used as a profiler on ships, is now used routinely in moorings. For bottom-mounted deployments, ADPs are caged to protect them from uprooting by trawling vessels.

Emergence of ADPs was a great relief to a wide spectrum of oceanographic communities who are interested in the measurement of ocean currents. The unique feature of ADPs is their capability to remotely sense the undisturbed flow velocity at multiple sections in the water column. Unlike the freely sinking current profiler probes, the ADPs can be made to “look” in any direction and their deployments may be on fixed or moving platforms or on surface, bottom, or mid-depth moorings. Furthermore, the acoustic Doppler technique permits continuous, unattended, fast profiling of currents. Remote sensing with Doppler sonar, therefore, provides an attractive alternative to all previous methods of current profile measurements.

Apart from this, in situations in which only short-term current measurements are needed, the capability of hull-mountable, downward-looking remote profilers to make measurements from moving vessels is a remarkable feature that permits large spatial coverage and virtually eliminates the tedious and time-consuming logistics in deployment and retrieval, if conventional moorings were to be used. While mounted beneath a moving vessel, the ability of shallow-water ADPs to measure the speed of the ship with respect to the bottom allows current profile measurements to be made without the motion of the ship significantly affecting the current measurements. ADPs can map the horizontal (restricted to its field of view) as well as vertical distribution of the current field and its temporal variations, yielding three-dimensional current distribution patterns. Current profiling over vertical ranges of hundreds of meters in the deep ocean was achieved by acoustic profilers mounted on top of subsurface moorings. Special precautions must be taken, however, to obtain reliable data from near the surface.

Probably ADP’s most important characteristic is its ability to provide a substantial increase in the vertical density of current data obtainable from a single instrument.

Because the majority of measurements are made remotely, only a small part of the current field—immediately surrounding the instrument—is perturbed. Therefore, current measurements are made in a theoretically ideal way. An added advantage, not obtainable with older-generation current profilers, is that the acoustic system can also create profiles of acoustic backscattering strength. This information provides an additional window into the environment by which researchers can synoptically study the vertical distribution of biological scatterers such as plankton. The backscattered signal can also be useful to fisheries scientists and fishermen alike, assisting them in estimating fish population. Thus, backscattering-strength information obtained from the ADP is a valuable bonus that throws immense light on the biomass, suspended sediments, and so on. The different time responses by water layers at different depths to a fluctuating wind regime induces high lateral shear. Oceanic water-current velocity shear has great importance in turbulent mixing and dispersal effects. An interesting application of ADP in oceanography is in the study of fine structures and velocity shear in the water column.

ADP's remote sensing capability permits monitoring of current fields in logistically difficult environments such as ports and estuaries where high flow regimes, ship traffic, or fishing activity make impractical the deployment and maintenance of conventional moorings. Furthermore, bottom-mounted, moored, and ship-borne ADPs provide time-series information on the subsurface and deep-sea features of ocean currents from different horizontal layers of the ocean. In addition, use of acoustic Doppler current profilers mounted on subsurface floats can considerably reduce the number of Eulerian CMs that would have been required otherwise and provide better spatial resolution than normally achievable by conventional "single-point" Eulerian CM arrays.

Apart from the use of ADPs for studies of academic interest, offshore industry began to draw a great deal of benefit from these devices. For instance, leakage from multiphase underwater pipelines carrying oil, gas, and water in any combination produced from one or more oil wells is not uncommon in the offshore oil and gas exploration industry. The 2010 Macondo incident off the coast of Louisiana, one of the largest submarine oil spills in history, boosted the worldwide need for detection and quantification methods for leakages from offshore oil and gas installations. Large discrepancies still exist in the calculated amount of discharged oil and gas, the vertical and lateral plume dimensions and transport, and biogeochemical degradation. Whereas geochemical methods (including chemical sensors) are mainly used to identify the variable gas/fluid sources, plume distribution, and secondary degradation processes, quantification of gas fluxes and transport in the water column requires measurement using hydroacoustic devices such as ADPs. Combining measurement with modern tools such as ADPs and pipe trackers will allow for a more complete picture of the leakage.

Standard techniques for measuring sea surface gravity waves use arrays of sensors, surface-following devices, and single-point subsurface devices. These traditional methods have complementary advantages and disadvantages, and generally the sacrifice for improving data quality is more complex logistics. However, ADP changed this picture by providing the power of an array, the quality of a surface-tracking device, and the simplicity of a single-point instrument. The ADP provides the powerful method of a beam-forming array for directional wave analysis. The array can be visualized by viewing from above the ADP's multiple beams and depth cells along each beam. In the analysis, the wave orbital current fluctuations observed in successive depth cells are transformed to the surface via linear wave theory. Together with the beam data at the surface, they emulate a grid of independent sensors recording the incident wave field.

Current meter development is a vigorous field, with the number of ADPs on the market doubling every few years. Acoustic Doppler sensors have been through many evolutions. With their digital signal processors, high-performance acoustic transducers and amplifiers, and large data rates, they are truly beneficiaries of advances in high-tech fields such as digital speech processing and laptop computers, but they also have pushed certain technologies themselves. Broadband techniques have broken the sample frequency-speed, resolution-range product limit of the earlier incoherent ADPs and permitted their application in some configurations to turbulence measurements, which require rapid sampling and high resolution of speed to resolve turbulent spectra. Broadband ADPs provide finer vertical resolution and shorter averaging times for accurate velocities but require greater sophistication in their use.

ADPs are available in more frequencies, more sizes, and from more manufacturers, and they are filling specialized niches. The price is even dropping, which is the sign of a maturing technology. One of ADPs' greatest impacts has been the reduction in mooring costs for bottom-mounted instruments. Particularly in shallow water, a profile of the entire water column is possible, except for a 15-percent ambiguous region at the top where side lobe reflection from the surface interferes. But fishing activities put these bottom-mounted instruments at risk, and this danger inspired a cottage industry of trawler-proof ADP mounts. Designed to direct trawl nets over the top yet be recoverable on acoustic command, at least three designs have been developed; several have been presented at Oceans conferences (Williams, 1997).

Because the ADPs combine the required functionality to measure both waves and currents in a single compact package, there has been considerable interest in exploring their efficacy as a wave sensor. A bottom-mounted, upward-looking ADP provides a robust means of determining wave height and direction in coastal and deep waters. When equipped with a pressure sensor, the ADP yields three independent estimates of the nondirectional wave-height spectrum and hence provides an internal consistency check on the performance of the instrument. Directional spectra obtained from the ADP tend to be sharper than those from point measurements, such as pressure velocity (PUV) triplets or directional wave buoys, and because of the greater number of degrees of freedom in the measurement, the ADP can resolve complex multidirectional wave distributions.

13.8. EVOLUTION OF ACOUSTIC TOMOGRAPHY: MONITORING WATER FLOW STRUCTURE FROM OPEN OCEAN, COASTAL WATERS, AND RIVERS

Despite great success achieved in ocean-current measurement technologies, it became clear that maintaining enough moorings to monitor large-scale ocean circulation is too expensive for both equipment and logistics. One must look to other, more sophisticated methods, together with a modest number of moorings and hydrographic observations. Taking this necessity into account, Munk and Wunsch, (1979) proposed an acoustic technique of great promise. Called *ocean acoustic tomography* (OAT), after the medical procedure of producing a two-dimensional display of interior structure from exterior X-rays, the technique monitors acoustic travel time with a number of moorings. Because the number of pieces of information is the product of the number of sources, receivers, and resolvable multipath arrivals, the economics of the system is enhanced over the usual spot measurements.

The necessary precision did not appear difficult to achieve, and the main limitation at high acoustic frequencies was imposed by the effects of variable ocean fine structure (limiting horizontal scales to 1,000 km). Using geophysical inverse techniques, Munk and Wunsch showed that it should be possible to invert the system for interior changes in sound speed and, by inference, changes in geostrophic velocity associated with density variations. They concluded that such a system is achievable and that it has potential for cost-effective, large-scale monitoring of the ocean.

The acoustic tomography method, which allows remote sampling from many directions, promises a detailed study of the interior features of the large-scale oceanic circulation. OAT was found to be an important remote sensing method for making "CAT scans" of the internal temperature and current structure of large volumes of the oceans. Testing the performance of "pure" one-way acoustic tomography was realized in 1981. The method produced useful spatially averaged profiles of sound velocity, even with the limited acoustic bandwidth then available. Although the array configuration was adequate for producing maps of mesoscale features, the poor travel-time resolution (due to the limited bandwidth) meant that large error bars prevented going much beyond pattern recognition. Initial tomographic experiments in the early 1980s demonstrated the capability of mapping the mesoscale sound velocity with an accuracy of about 1.5−2 m/s (about 0.3−0.4°C) at 700 m, which is the most energetic level. Performance worsened near the surface, and at greater depths both the error limits and the signal energies decreased. Since 1979 this technique has steadily grown from the sea-trials stage to a routine measurement tool in the oceanographer's toolbox.

Measurement of ocean currents by reciprocal sound transmission was successively carried out on scales of 10−1,000 km by Worcester (1977). Vorticity fields in the central North Pacific Ocean and in the adjacent areas of the Gulf Stream in the North Atlantic Ocean were measured with triangular and pentagonal arrays of acoustic transceivers in which reciprocal transmission was possible between a pair of stations. A reciprocal transmission system using a triangular array of the inverted echo sounder (IES) moored near the bottom was also developed for measuring depth-averaged velocities of the Kuroshio Current south of Japan. Thanks to consistent efforts expended by several oceanographers and technocrats, OAT became a well-developed technique for monitoring the mesoscale fluctuations of temperature and current fields in the open ocean.

Acoustic tomography is a subject that saw the need for intense interdisciplinary and interlaboratory collaboration. One way to speed the research efforts was the introduction of outside groups into the project. For example, in the initial phase of OAT research at Scripps and Woods Hole institutes of oceanography in the United States, the other groups helping the researchers included the Massachusetts Institute of Technology, where Wunsch and others concentrated on the data taken from the at-sea tests and performed the inversions relating to the science. Likewise, the University of Michigan provided expertise in both signal processing and underwater signal propagation; NOAA provided ship support and independent hydrographic surveys of the test areas. The private sector also showed interest, with three companies (Hydroacoustics, Inc.; Webb Research Corp.; and Gould Inc.) assisting Scripps, either as potential suppliers or through studies of prototypes. In addition, support was provided from the Underwater Sound Attachment of the Naval Research Laboratory in Orlando, Florida.

Although one could imagine that the project might become saddled with all the diverse groups, according to Wunsch one of the strengths of the project was the ability of people with diverse backgrounds to work together. The many different kinds of expertise included in the project were people who were experts in acoustic sources and receivers, getting moorings in, and knowing how to make independent quality measurements at sea.

The OAT program also was the genesis of several interesting spin-offs. For example, tomographic techniques were used to probe the subseafloor structure. They were also used to estimate sea surface roughness and internal properties of sea ice in the Arctic.

A number of studies were made to adapt deep-ocean acoustic tomography methods to coastal environments, in which shallow-water propagation and high environmental variability make the inversion significantly more difficult. Although coastal tomography remained a topic of active research, parallel developments in wireless communication technology, combined with significant advancements in computing power, opened the way to acoustically focused oceanographic sampling (AFOS). AFOS consists of a network of acoustic arrays connected to a fleet of autonomous underwater vehicles (AUV) and to a shore station using wireless local area network technology.

In contrast to the frequent use of reciprocal transmission techniques in the open ocean, no reciprocal transmission experiments were performed in the coastal ocean in OAT's initial decades. The reason was that most of the acoustic oceanographers had focused their major interest on the open ocean. Coastal acoustic tomography (CAT) was proposed as an application of OAT to the coastal sea, aiming at continuous monitoring of tidal currents in ports, bays, and semi-enclosed and inland seas without disturbing shipping traffic or fishing and marine aquaculture activities. The CAT system was developed by Hiroshima University in Japan and since 1995 has been successfully applied to measurement of current structure in coastal seas around Japan. Range-averaged water-current velocities, estimated from travel-time data obtained reciprocally, were in good agreement with the results of ADP measurement obtained along the sound transmission line. It was thus suggested that reciprocal sound transmission is applicable to velocity measurement in the inland sea having complications associated with heavy ship traffic and fishing activities.

Surprisingly, no serious CAT application experiments were carried out outside Japan. This void was filled by the CAT experiment attempted for the first time in China in 2009, with seven acoustic stations for mapping the tidal currents in the Zhitouyang Bay near the Zhoushan Island. The experiment identified the generation of a clockwise tidal vortex of diameter $\sim$5 km in the eastern part of the bay in the transition phase from ebb to flood. It was suggested that the CAT is a powerful device for continuously mapping the horizontal tidal current structures in coastal regions in China.

Success of the CAT system led to its further enhancement and modification through technology additions to river acoustic tomography (RAT) systems with capability for river discharge measurements. The RAT technology for current measurement was successfully carried out during April through December 2009 in the upstream region of the Qiantang River in China, about 90 km from the mouth of Hangzhou Bay. Range-averaged water-current velocities, determined from the travel-time differences along the transmission line, were in good agreement with those from an ADP, producing a root-mean-square difference of 0.03 m/s. The variations of river discharge caused by tidal bores were well captured. Based on these encouraging results, it has been suggested that the RAT is a powerful instrument and that the RAT method provides a prosperous method of continuous, long-term monitoring of river discharges, even in large tidal bore-infested rivers with quite heavy shipping traffic.

Coming back to the history of open ocean-current measurements, much of classical physical oceanography was devoted to the study of the general circulation of the world oceans. Most of our early ideas about ocean circulation were based on the indirect evidence of the temperature and salinity fields and the assumption of geostrophy. The principal observational tools used in such studies were the dynamic method and water mass analysis. The latter was useful in establishing pathways, the former for determining fluxes. In deep and abyssal waters, the dynamic method, which gives only differential velocities (shear), becomes useless in the absence of reliable reference velocity information. Box models and inverse methods were developed to provide closure to the circulation in an integral sense. Clearly, it became necessary to make direct measurement of deep and abyssal flows.

13.9. LAGRANGIAN MEASUREMENTS OF SUBSURFACE CURRENTS

Considerable efforts were expended over the years in the design of subsurface drifters suitable for subsurface and abyssal current measurements. The factors that influenced the performance of a drifter as a Lagrangian current follower were wind-induced slippage and wave drag on the surface float, drag on the tether for large depths, and drag due to the finite size of the drogue.

John Swallow's (1955) pioneering development of neutrally buoyant subsurface floats provided an important new method for observing ocean subsurface current velocities, particularly low-frequency, large-scale currents in a Lagrangian perspective. With the advent of direct velocity measurements by deep floats and CMs during the 1960s and early 1970s, the necessary data for a consistent picture of ocean circulation, at least in limited areas, began to come in. Worthington's attempt to put together for the first time such a picture of circulation in the North Atlantic was based on the new direct data.

Neutrally buoyant floats were a vital tool in the exploration of the global ocean circulation and now provide a central element of the *in situ* ocean-observing system through the Argo project. The original Swallow floats were relatively thin-walled aluminum cylinders that became neutrally buoyant at a certain depth, primarily because they were less compressible than seawater. They carried acoustic sources that were tracked at relatively short range from an attending ship. The Swallow float-tracking technique proved itself to be robust and capable of application to a range of depths and geographical locations. The Western Boundary Undercurrent work really marked the transition of float use from exploration to hypothesis testing—although much more exploratory work would follow. By mid-1958, Swallow and Hamon made a further attempt in the Northeast Atlantic to use floats systematically, to extend their lives, and to compare the direct measurements with geostrophy. Rather than allowing the floats to signal continuously (their life in this mode was limited to two weeks), an internal mechanical clock programmed the transmissions for 4 h per day and thus extended the float life to 12 weeks.

The results provided several examples of closely spaced floats with very different velocities and showed no "level-of-no-motion" but rather a sheared unidirectional flow at depths between 1,500 and 4,300 m. These measurements provided a clear indication that the ocean was not behaving as theory or classical hydrography suggested it should and that the previously held notion of "level-of-no-motion" is baseless.

Apart from these deployments, floats were used by the NIO (UK) scientists in the Labrador Sea in 1962 (Swallow and Worthington, 1969), in the Norwegian Sea outflow in 1963 (Crease, 1965), and in the Somali Basin during the International Indian Ocean Expedition (Swallow and Bruce, 1966).

Until the advent of World War II, oceanography proceeded at a rather leisurely pace. The anti-submarine-warfare program during World War II forced the rapid development of underwater acoustics. Measurement of deep motions by the use of *in situ* moving floats requires some method of tracking. The great strides made in acoustics during World War II yielded the necessary technology for acoustic tracking of instruments in the ocean.

Discovery of the SOFAR channel, an acoustic waveguide in the ocean, led to great success of tracking subsurface floats over long distances. The SOFAR channel is produced in many parts of the ocean by the combination of pressure and temperature effects on the speed of sound, which decreases with depth from the surface to about 1,000 to 1,500 m, owing to the decrease of temperature, and increases with depth below this level, owing to the increase of pressure. In the SOFAR channel a few watts of sound can be heard about 2,000 km away.

Lagrangian-style subsurface current measurement programs involving subsurface floats tracked by moored hydrophones in the SOFAR channel unfolded into two well-defined efforts; one of these was to put the sound in the water, and the other was to get the sound out. The development of the SOFAR float, based on a relatively high-power 250-Hz sound source, made possible long-range unattended tracking and operational float lifetimes of several years. The first big SOFAR floats were placed out in a triangle of listening stations at Eleuthera, Puerto Rico, and Bermuda. The range of listening was about 700 km, and the floats were successfully tracked (Rossby and Webb, 1971). This success generated enough interest that a large program could be funded as part of the MODE-1 experiment. Underlying the design of the MODE-1 experiment was the need to test the hypothesis that eddies do play an important role in the general circulation.

The weak absorption of low-frequency sound by seawater made SOFAR float tracking possible at ranges of a few thousand kilometers in those oceanic regions with an intermediate-depth sound-speed minimum (sound channel). Although developing the receiving instrumentation and the program for the data analysis were relatively straightforward, the technology involved in the development of these floats was much more demanding. Economy of power, batteries with high energy density per unit weight, and a low-frequency acoustic projector with low weight and high efficiency were all requirements where little compromise was tolerable. In particular, the projector required considerable engineering time. The requirement to efficiently project low-frequency sound made SOFAR floats large (8 m in length and 430 kg in mass) and, consequently, costly and operationally difficult. Nevertheless, Owens (1991) mapped mean flow and eddy variability over much of the western North Atlantic using a collection of SOFAR data from various regional experiments.

The isopycnal-following (i.e., following the same density surface) float was found to be an ideal tool for the investigation of a number of upper-ocean processes in frontal regions. Using clusters of these instruments along with hydrographic surveys, studies of the topographic effects (e.g., the Gulf Stream departure from the Blake Plateau south of Cape Hatteras) as well as entrainment and subduction processes in the ocean could be carried out. In addition to providing three-dimensional flow-path information, additional sensors such as oxygen, pressure, and vertical velocity could be incorporated into the isopycnal-following float. Multiple float arrays on the same density surface, together with hydrographic sampling, were expected to permit studies of relative vorticity and its variation in response to topography and curvature along the float trajectory.

Since Swallow and Worthington's (1961) measurements of absolute velocity under the Gulf Stream and Swallow's (1971) landmark discovery of what is now known as mesoscale variability, much of our understanding of ocean circulation came from floats. Early studies tended to concentrate on regions that could be relatively well sampled by tens of floats positioned by a few acoustic stations. Important contributions based on such float arrays were the pioneering study of eddy statistics by Freeland et al. (1975), the mesoscale mapping by McWilliams (1976), the discovery of small long-lived coherent eddies called *Meddies* by McDowell and Rossby (1978), and the intensive study of Gulf Stream kinematics by Bower and Rossby (1989). As more floats were deployed and more trajectories accumulated, investigators began to map large-scale, low-frequency seawater motion velocities and eddy statistics over modest areas. Rossby and Dorson (1983) estimated Eulerian mean flow in a region using floats as moving CMs (averaging together all velocity observations in specified areas) and estimated the lateral single-particle diffusivity. Combining average absolute float velocities with geostrophic shear from hydrographic sections, Richardson developed a detailed velocity section of mean flow in the Gulf Stream as it crosses 55°W, accomplishing what the pioneering study that Swallow and Worthington (1961) began. It is heartening to note that since the mid-1950s, neutrally buoyant floats have been used in various forms to explore and to discover many aspects of ocean circulation. The successful collaboration in the study of western boundary undercurrent and the exploratory work over the Iberian abyssal plain led to what is probably the best-known early use of floats: the 1960 so-called *Aries* experiment led by John Swallow. (*Aries* was a 93-foot vessel that had been donated to WHOI in 1959.) The SOFAR floats, considering their relatively short development and trial phase, were remarkably successful. The Mini-MODE system developed by Swallow and co-researchers in the early 1970s allowed up to 18 floats to be tracked simultaneously (each identified by its own frequency in the range 5.0−6.5 kHz).

The SOFAR float restriction to the western north Atlantic was removed by the ingenious development by Al Bradley and Jim Valdes of Autonomous Listening Stations (ALS). These were moored hydrophones with data loggers that recorded the signal arrival times from floats within acoustic range and were deployed on moorings with the hydrophones near the SOFAR channel axis. The use of subsurface moorings to reduce mooring cost, risk of damage, and acoustic noise meant that data were not available in real time. ALS deployments of six months to one year were typical.

Along with extending coverage in the western north Atlantic to include the Gulf Stream, the ALSs allowed SOFAR floats to be used in the eastern Atlantic. In this case, floats were deployed as a contribution to US efforts to study Meddies and to support US research in the US/Soviet Polygon Mid-Ocean Dynamics Experiment (POLYMODE; Schmitz et al., 1988). Acoustically tracked floats were ideal for this purpose, and the presence of the Mediterranean water core at around 1,000 m resulted in a double sound channel, with the deeper channel allowing tracking of floats at depths as great as 3,000 m at ranges of 1,000 km. Autonomous floats were also used to study a number of physical processes such as deep convection in the Labrador sea, diapycnal mixing in the North Atlantic Tracer Release Experiment, and subduction.

SOFAR floats were bulky, heavy, and cumbersome, and their lifetime was limited by their need to carry large battery packs while still remaining neutrally buoyant. The SOFAR floats' impediment to use in large numbers was alleviated by the development of the RAFOS acoustic tracking system in which floats listened to moored sound sources. The RAFOS float enabled greater power output and longer life. These smaller, cheaper RAFOS floats developed by Tom Rossby and his group at the University of Rhode Island recorded the signal arrivals from an array of moored sources. Acoustic receptions were processed in the RAFOS float, and at the end of a mission the float surfaced and transmitted the log of acoustic-signal arrival times through the Argos satellite system. The floats were used extensively as both traditional isobaric floats and, by the addition of a compressible element, isopycnal rather than isobaric floats. Such floats were small enough to allow successive releases from a moored near-bottom "float park" (Zenk et al., 2000).

The scientific applications of floats of various types during the 1970s, '80s, and '90s were numerous and significantly improved our understanding of the oceanic eddy fields and, to a lesser extent, the basin-scale mean circulation. The topics explored included but were not restricted to (Gould, 2005):

- The origins, dynamics, history, and distribution of discrete intense eddies
- The statistics of mesoscale eddy variability on the scale of ocean basins
- The Gulf Stream and its dynamics
- Local oceanographic phenomena, including flow interactions with topography and abyssal circulations
- Pathways of cross-equatorial flow
- Internal wave dynamics
- The processes of winter convection, subduction, and mixing

An important application of neutrally buoyant floats was to study internal waves. Several of the floats in MODE were instrumented to record pressure, temperature, and vertical water motion. As well as being applied to studies of internal waves, the technique for measuring vertical velocities was particularly applicable to the study of deep-winter convection and was used in the western Mediterranean in 1970 (Webb et al., 1970; Gascard, 1973) and subsequently in the Greenland and Labrador seas (Lherminier and Gascard, 1998).

Neutrally buoyant floats had operated only on the scale of ocean basins, and the provision of a global acoustic float-tracking network would have required far too great a level of commitment. A novel system was required to allow floats to be tracked globally. Thus, during the 1980s, Russ Davis and co-researchers jointly developed the Autonomous Lagrangian Circulation Explorer (ALACE), which was a float that would have a multiyear life and could provide useful subsurface water-motion velocity information throughout the ice-free ocean. Observing mid-depth oceanic currents is rather a challenge, especially for large-scale and near-real-time operations in the global ocean. Davis et al. (1992) discussed the mid-depth currents based on measurements by ALACE floats and successfully applied these measurements to analyze the currents in tropical and South Pacific afterward. These studies showed that the small, cheap autonomous instruments in large numbers can play a vital role in ocean observations.

If acoustic tracking was impossible globally, the only alternative was to have the floats surface periodically and be tracked by satellite. Both SOFAR and RAFOS floats had the capability of surfacing at the end of their mission by dropping a ballast weight, either on a timer or by acoustic command. What was required additionally for the ALACE was a capability to surface and then return to the parking depth repeatedly. The solution to this problem was found to be in pumping fluid from within the pressure case into an external bladder to reduce the float's density and hence drive it to the surface. Deflating the bladder would return the float to the desired depth.

In total, 1,110 ALACE-type floats were deployed in WOCE. In large measure they achieved their objectives. Although not all achieved their target five-year life, many exceeded it, and the longest-lived floats continued to operate exceeding eight years after deployment. The data were used to construct velocity fields across the entire ocean basins (e.g., Davis, 1998) and to constrain inverse calculations (e.g., Wijffels et al., 2001).

Mainly between 1991 and 1995, some 306 autonomous floats, mostly of the ALACE type, were deployed in the equatorial region and South Pacific, including the Pacific sector of the Southern Ocean. All but 23 of those floats had expired by July 2003. Between 1994 and 1996, another 228 ALACE floats were deployed in the Indian Ocean, including its Southern Ocean sector. Only 90 of those floats were still operating at the end of 2003. Based on available data the mean circulation, seasonal changes, and eddy variability in intermediate-depth flow in the Indian and South Pacific Oceans seen by these floats could be studied. Integration of float measurements with hydrographic data yielded a three-dimensional coverage of the circulation and provided some insight into the nature of regional circulations. Because ocean *variability* is generally more energetic than *mean flow*, extracting accurate mean from observations requires substantial averaging. Thus, multiyear records are necessary to achieve useful accuracy, and for floats this requires spatial averaging or filtering. It is impossible to directly measure mean transport without observations at many depths. Combining float-measured velocity at one level with hydrography holds the promise of deducing such transport.

It may be recalled that neutrally buoyant floats had been used in various forms to explore and discover many aspects of the oceanic subsurface circulation. The demonstrated capability of P-ALACE (profiling ALACE) and similar floats for estimation of *drift current* at the parking depth and for collection of high-quality CTD data above and into the permanent thermocline, as well as the success of the numerous deployments of ALACE and P-ALACE floats in the World Ocean Circulation Experiment (WOCE), pointed the way toward their use as a tool for prolonged global-scale ocean monitoring that would complement and greatly enhance other elements such as altimetry, hydrography, XBTs, and the like. ALACE, P-ALACE, and SOLO floats are drifting instruments that measure ocean temperature and salinity. SOLO floats are very similar to P-ALACE floats but have better satellite communication and acoustic tracking capabilities. Because the floats are only about 6 feet long and 80 lbs in weight (body plus antenna), they could be deployed from any ship by one or two people without special equipment. Typically, the instruments are simply lowered over the side of the ship with a rope. In high seas, the floats can be deployed in biodegradable boxes that protect the instrumentation from rough landings. Once a float is deployed, neither ships nor people are required to obtain the measurements.

Some types of floats (e.g., SOLO) apply an offset to the pressure data on board the float and, therefore, the transmitted data need to be corrected. This has limitations when it comes to data manipulation. Therefore, as an improvement, the APEX float only transmits raw data but also notes the offset that it thinks should be given to the data. This way the user can decide how the data are manipulated. The EM-APEX float is an improvement on the APEX float that is designed to make long-duration measurements in inhospitable conditions (e.g., hurricane regions). After the floats are deployed, they move with the ambient currents and can therefore travel long distances on their own without the need of a ship or a person to handle them. Floats are programmed to come to the sea surface at regular intervals to transmit their data and geographical position to orbiting satellites. Afterward, they continue measuring ocean conditions, with at-sea missions lasting four to five years. This provides oceanographers with a wealth of near-real-time data, often from remote regions of the world's oceans. A deep, neutrally buoyant float that periodically pops up or reports in some acoustic mode to the surface and to a satellite would yield a kind of global coverage, as would acoustic tomography.

The international Array for Real-time Geostrophic Oceanography (Argo) program aimed at building a global array of 3,000 free-drifting profiling floats. In the upper 2,000-m ocean, an Argo float autonomously ascends from a parking depth to sea surface synchronously measuring the temperature and salinity in environmental water mass, drifts for 10–12 h on the sea surface before it descends to its parking depth, and then freely drifts at this depth. Subsequently it resurfaces from the parking depth to continue another cycle. While a float drifts on the sea surface, only its thin antenna (~2 cm) is outside of seawater and its 1-m-long cylindrical hull with ~17 cm diameter always submerges. For low wind speed, it is designed to follow water parcels well while both drifting on the surface and parking on mid-depth. With more than 5,000 floats deployed in the global oceans since the initiation of the Argo program, there has been a unique opportunity to simultaneously measure surface and mid-depth currents in the global scale in near real time.

Since 2000, the international Argo project has provided real-time monitoring of thermohaline (temperature and salinity) profiles for the global upper ocean and drift measurements at a known depth level (approximately 1,000 m) to enable estimation of thermohaline circulation at different depth levels. By late 2004, over 1,500 neutrally buoyant floats were drifting at depth throughout the global ocean. They were approximately 50 percent of the targeted final global Argo array, scheduled for completion by 2007. As of March 2007, more than 2,800 Argo-type profiling floats (Argo floats) were active in the world ocean.

Argo forms the core of the *in situ* ocean component of the Global Climate Observing System, essential for quantifying the oceans' response to climate change and to improving our understanding of, and making improved predictions about, shorter-lived climate events. The technology used for the production and operation of neutrally buoyant robotic floats such as Argo has improved greatly over recent years, thereby allowing the floats to collect more data more efficiently and reliably.

It seems that neutrally buoyant floats will remain a key element of ocean exploration and monitoring, both in the global Argo program and when used regionally to explore particular phenomena. Floats will carry a growing range of sensors. The potential for floats to act as monitors of ocean mixing through microstructure measurements has already been demonstrated. Surprisingly, floats have survived under Antarctic sea ice to download their profile data when spring arrives.

Undoubtedly, the surface current estimates from Argo trajectories provide a new means to describe the surface circulation in the global ocean in real time. Although the number of Argo float arrays is more than that of the surface drifter array (3,000 vs. 1,250) of the Surface Velocity Program (SVP), the number of surface velocity estimates from Argo float arrays is still less than that of SVP surface drifter arrays because Argo floats spend more than 90 percent of their time in the subsurface, whereas SVP surface drifters always remain at the surface. The combination of all surface trajectories can give more detailed description for global ocean circulation. Meanwhile, the preliminary results of mid-depth currents in the Pacific Ocean indicate that the trajectories of Argo floats would become one of the important sources to acquire knowledge on the specific mid-depth circulation.

Advantages of the Argo floats are ease of deployment, ability to conduct long-lived missions, and capacity to acquire and communicate data to researchers throughout the world without the direct involvement of ships or people. The Argo floats are, however, not free from limitations. For example, the datasets recorded by these floats can contain small gaps. The reasons are that ALACE floats do not acquire data when they are descending or ascending, and this scheme results in a data gap, especially when strong currents push the float a significant distance during ascent or descent. Similarly, P-ALACE and SOLO floats do not acquire data when they are descending or floating at depth, so a similar gap in data can result.

Despite these limitations, Argo marks a radical broadening of the use of floats. Seventeen countries have provided floats for the Argo array. The commitments ranged from the United States (contributing half the floats) to fewer than five floats contributed by countries such as Mauritius, Denmark, Ireland, Netherlands, New Zealand, and the Russian Federation. Many other countries assisted with float deployments and access to their Exclusive Economic Zones. Use of float data broadened, too. Operational centers are still using data from Argo in the production of ocean and climate analyses and forecasts (Gould and the Argo Science Team, 2004). So, the concept originated by John Swallow and further developed by other researchers for global application in the 1980s and 1990s grew from a rather exclusive research tool into a central element of the ocean-observing system that addresses issues of global socioeconomic significance (anthropogenic climate change, sea-level rise). According to Gould, we have arrived at our present exciting position thanks to a small number of far-sighted individuals and to a close and very productive interaction between ocean scientists and engineers. With that in mind, we can optimistically look forward to a very exciting era that was surely not envisaged by John Swallow when he scavenged the storerooms of the NIO to build the first Swallow float.

Oceanography has not yet reached meteorology's operational level because progress in numerical modeling still has to be made and because routine data assimilation is still to be developed. For assisting offshore operations, surveying companies rely on *in situ* real-time current measurements. Although providing valuable information, this approach remains costly (human and ship costs for at-sea operations, instrument deployment, etc.), time-consuming (moorings often have to be deployed for lengthy periods to gather enough data for reliable statistics to be established), and somewhat incomplete (for budget considerations, only scattered point measurements can be made). Forecasts cannot be established with *in situ* data alone.

To predict local circulation, even at relatively short time scales, a large area must be monitored synoptically with a high spatial and temporal coverage. At present, commercial companies (e.g., SAT-OCEAN) provide cost-effective solutions based on satellite imagery, allowing a reasonably accurate diagnosis and forecast of oceanic upper-layer currents over a large part of the world's oceans. This approach presents a huge potential for offshore surveying and for statistical studies of unknown oceanic provinces, as demonstrated during an assistance mission offshore South Africa (see Vigan, 2002).

Availability of a wide variety of technologies has begun to enable generation of accurate ocean environmental forecasting, which is necessary for a variety of offshore engineering operations. For example, some commercial companies (e.g., Horizon Marine Inc.) produce loop-current eddy (LCE) forecasts to prevent disruption of deep-water operations. The eddy-watch service utilizes data from oceanographic buoys, current profiles at rig locations, and all publicly available satellite observations to provide comprehensive operational monitoring and analysis of ocean currents and eddies based on numerical ocean models. It is of interest to single out the subject of satellite-tracked drifting buoys for special attention, however, because of the potential of this technique for large-scale measurements. Lagrangian floats play an important role in mixing studies as well, and several investigators are vigorously developing novel floats to study deep convection, internal wave shear, and boundary layer deepening.

13.10. COMPREHENSIVE STUDY OF OCEANIC CIRCULATION

Although it was not until much later that the successors to Seasat were launched (for example, Geosat in 1985; ERS-1 in 1991; TOPEX-Poseidon in 1992; Jason in 2001), these satellites and the development of floats, moored CMs, high-quality CTD, and tracer measurements opened up the possibility of a comprehensive study of the ocean circulation on a global scale. Several passive radiometry images revealed visual indications of the most salient features of eddies, and the congruence between the physical and biological structure of eddies and rings was often found to be remarkable. It is conceivable that a global monitoring system for the ocean circulation could consist of a combination of several of the elements discussed: (1) satellite observations of the surface temperature and surface pressure fields; (2) direct measurements of the surface current and temperature by drifters and a modest number of moorings; and (3) deep-ocean monitoring by a combination of acoustic tomography, ship-borne hydrography, and moorings. All the elements are present now or are being tested.

Ocean-current measurement is a first-order task in ocean process research, environmental monitoring, climate studies, ship traffic control, and offshore work. Vector measurements are always harder than scalar measurements, both to make and to interpret.

Since 1965 there has been a flood of new instruments and new ideas, thanks to a few good and determined engineers and physicists. As a result, our view of the ocean has changed markedly, especially on the smaller scales, where the old instruments and techniques were essentially blind. In this endeavor, the information gained in actual field tests was crucial to the development of reliable instruments. The development of technologies in a number of areas in the 1950s and 1960s laid the foundation for rapid improvement in observing techniques, starting in the mid-1960s.

I do not want to leave the reader with the impression that the technologies for measurement of ocean currents have reached a plateau. Perhaps still better technologies will evolve in the future, with further advancements in science, technology, and sensor design. Nevertheless, the present technologies provide the opportunity to have a long-term presence in any part of the oceans, to collect continuous streams of data, and to observe processes and transmit data about them in real time. Though various elements of these real-time observations have been functional for some time, the comprehensive array and potentially integrated nature of sensor networks have only recently become possible. The datastreams from sensors within and at the junctures of atmosphere, ocean, and solid-earth realms provide the potential for the development of a quantitative understanding of ocean processes across otherwise unattainable space and time scales. This potential has fundamentally important consequences for different groups, namely, scientific researchers, commercial interests, government regulators and policy makers, teachers, the military, and the public. The solution to the problems that still remain in understanding oceanographic processes depend in great measure on the continuation of close interaction between ocean scientists and engineers.

Several techniques are developing in parallel, and each offers special advantages in certain tasks. Some technologies, specifically acoustic Doppler and radar backscatter, have expanded rapidly. We still need testing, intercomparison, and most significantly, interpreted datasets from measurements made with these techniques to gain an understanding of where they can be trusted and where not. There is no saturation of the current measurement field. Although there is maturing in specific technologies, new technologies or reinventions of older technologies spawn new cycles of development.

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