Chapter 7

IN-SITU OBSERVATIONS: PLATFORMS AND TECHNIQUES

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Abstract: In-situ observations and satellite remote sensing together need to be viewed as an integrated system to provide observational data required by operational ocean modelling and forecasting. This chapter outlines the methods and platforms available to operational oceanography and how they complement remote sensing and each other.

Keywords: In-situ data, platforms, instruments, observing methods.

1. Observing needs of operational oceanography

The goal of operational oceanography is to provide routine ocean forecasts on timescales of days to seasonal, to detect and predict short-term changes in the ocean (turbulence and "ocean weather") all the way to regime shifts and climatic changes, including the associated impacts on coupled ocean-atmosphere and coupled biogeochemical systems.

Such routine modelling and forecasting requires sustained observations for initializations and validation/ground truthing, for keeping the models on the correct trajectory, and in the development phase also for model testing and calibration. This chapter addresses the options and considerations for choosing platforms and techniques to provide these data. The focus will be on complementarity between the different in-situ methods, and between in-situ and satellite observations. Not covered here is the important issue (for operational systems) of sustained routine observing system *operation*, of quality control and data dissemination. This is addressed in the companion chapter by S. Pouliquen (this volume).

Some differences need to be recognized between the data requirements of global, regional, and coastal applications, in terms of resolution, accuracy, and variables needed. Global systems do not require accurate representation of individual small-scale features but need to have the correct "bulk" properties like heat content, stratification, transports (mass and heat), mixing, and air-sea fluxes. They need to have accurate enough forcing and fluxes to run without bias for weeks and months. The biogeochemical components of global models are still uncertain enough to make data requirements less stringent – the most useful contribution of data is a good representation of the overall biogeochemical regime conditions on the large scale for a few basic variables. Coastal models usually are run only for a few days but focus on small scales, and often try to represent detailed ecosystem species, both of which require more detailed observations. These models are strongly affected by the small-scale advective processes and less sensitive to small errors in the forcing. However, mixing, which changes stratification but also affects e.g. nutrients, is equally critical as in global models. Regional applications are somewhere in the middle. They typically address conditions and changes in sub-basins (e.g. Nordic Seas) or marginal seas (e.g. the Mediterranean). Mesoscale features generally still need to be resolved and correctly represented.

1.1 Variables

The description of the physical state of the ocean requires the density and temperature (T)/salinity (S) fields (not independent of course), as well as the absolute currents. Closely coupled to this is the physical forcing at the surface (e.g. wind, radiation, heat), which is covered in the chapter by W. Large (this volume). For biogeochemical models, the basic state is described by the variables, such as nutrients, phytoplankton, zooplankton and detritus in the simplest cases. These state variables, which take values everywhere in the model domain, need to be distinguished from the quantities which are forecast – these are sometimes derived quantities or not predicted everywhere (e.g. only at the surface).

The prime variables *forecast* in current operational systems are temperature and currents, with a focus on surface fields. The rationale for this emphasis is a combination of models being primarily physical, remote sensing delivering these variables at the surface, and many applications *needing* this information at the surface. For predicting ocean circulation, however, the associated *interior* density field needs to be known. Many applications also require the vertical stratification of temperature (i.e. heat content), and density stratification (for pollutant dispersal/mixing or fisheries). Some defense applications also seek the interior sound speed distribution which is calculated from subsurface T and S. Thus a minimum data requirement for physical models is the full density field and absolute currents at some level, unless data are only used for validation (in this case, selected locations or layers may be sufficient). Conceptually also integral properties should be important for constraining and initializing models, like a water-mass or basin heat content, or transports of mass and heat in major current systems or passages. This however is not exploited in current assimilation and forecasting approaches.

Increasingly, operational systems also need to and do address ecosystem dynamics and biogeochemical cycles in the ocean. This is especially true for the regional and coastal applications. In such cases, a larger range of variables is required from an observing system. At the minimum level this includes the prime variables like oxygen, nutrients, chlorophyll or phytoplankton biomass, and zooplankton biomass (e.g. Fasham et al, 1993). In more small-scale applications, it may require the knowledge of individual species of plankton or fish, or of certain chemicals (specific nutrients, trace elements). For very specific purposes, long lists of variables can be drawn up, which however is not useful here since the goal of this presentation is the nature of typical observing systems and not the exhaustive coverage of singular cases.

1.2 Coverage and time-space sampling

The ideal observing system, both for research and for operational applications, covers the three space (x,y,z) and time (t) dimensions "completely". The word 'covering' usually denotes the extent/reach in the four dimensions. All current sampling techniques are discrete, however, in these dimensions, and 'completely' therefore must also be interpreted as having sufficient resolution to reveal the smallest scales of the variabilities of interest.

Thus, rigorously, for each application, a new system would need to be designed which can deliver the needed observations with the accuracy and the sampling specific to the needs. In general, this is not feasible. Also the envisioned 4-D sampling is not possible with current technology. There are, however, various techniques which provide different sections through this 4-D space with useful resolution in at least some of the dimensions, see Figure 1. Satellites have excellent x-y-t coverage, and sufficient x-y-t resolution for many applications. However, the sampling is provided only at or near the surface, and is restricted to few variables. The ARGO float network provides good sampling in the vertical (profiles), with global coverage and hopefully long (sustained) coverage in time, but has sparse horizontal and temporal resolution despite the large number of platforms (e.g. not eddy-resolving, unable to resolve the timescale of short events, etc). Also the number/types of variables observable with the ARGO system will remain very limited. Fixed (moored) instruments can deliver excellent (probably complete) sampling of the time domain and may have good coverage of the z-dimensions, but can only be installed in a few number of x-y locations. Therefore, a coordinated and deliberate use of several observing techniques often is required to provide the information needed.

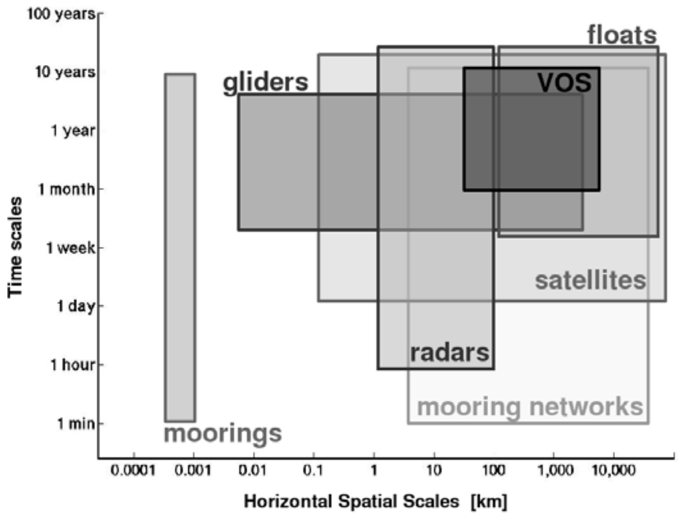

Figure 1. Spatial and temporal resolution (lower side of boxes) and coverage (upper side) of the observing methods discussed in this chapter (after T.Dickey). This representation does not include the vertical dimension, thus giving an imcomplete impression.

In all cases, aliasing in time and space should be a real concern. This results from not resolving the smallest scales of variability, and thus creating the false impression of larger/longer scale variability. A good example was provided by S.Rintoul (pers. comm.) shown in Figure 2. Also scanning satellite sensors which revisit a certain location only every 10-30 days have aliasing problems (tides, diurnal signals, etc).

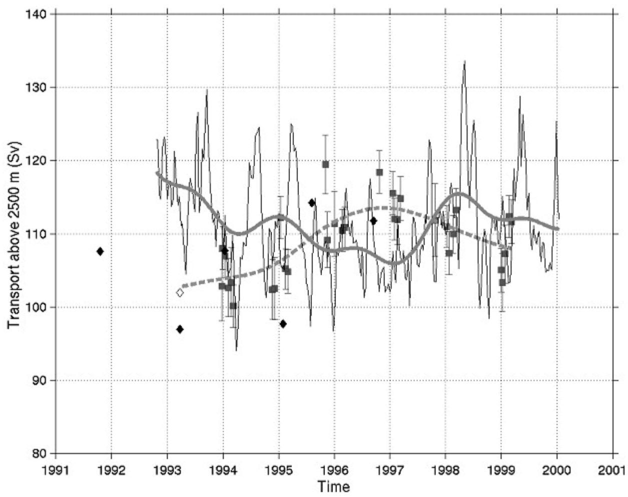

Figure 2. Interannual variability of transport south of Tasmania inferred from sporadic XBT transects (black symbols) and filtered (dashed line). The same from frequent estimates from altimetry (solid thin line) and filtered (heavy solid). The long-term trends are opposite due to aliasing. From S.Rintoul.

2. In-situ techniques and platforms

As also highlighted in the chapter by I. Robinson in this volume, a very tightly integrated approach is needed between remote sensing and in-situ observations, in order to provide the data necessary for the modelling procedures in operational ocenography and ocean forecasting. None of the two methodologies alone can acquire the ocean data required with sufficient accuracy, 4-D coverage and 4-D resolution. This section is organized on a platform basis for clarity, but the guiding principle in all cases will be the way in which in-situ data are indispensable for providing information impossible to obtain with remote sensing, or for complementing, validating and calibrating remote sensing data.

At the end of this section, Table 1 provides an overview of the platforms with their costs, strengths and weaknesses. This can help in guiding through the following sections, comparing the different methods. More importantly, however, the table is meant to emphasize the complementarity between all these elements and technologies.

2.1 Profiling floats

Description:

These are platforms that passively follow the horizontal flow in the ocean interior and periodically rise to the surface for satellite positioning and to collect profile data on the way up. Originally designed to give the current field (e.g. a deep reference flow for geoid estimation), they are presently used more for the T/S profiles they provide. The original rationale was to have a platform that is so cheap and long-lived (while requiring no other infrastructure) that it can be used in large numbers anywhere around the globe. This is still the philosophy, now implemented in the ARGO program, so most of the floats have only standard sensors. Heavy or power-hungry sensors cannot be incorporated. ARGO plans to deploy and sustain such floats on a 3°x3° grid globally, which needs a total of over 3000 instruments (see also the chapter by S. Pouliquen in this volume). The standard drift depth is 1000m in ARGO, but for profiling the floats dive down to 2000m before ascending to the surface. The cycle period is 10 days, and with a targetted capacity of 180 cycles, the floats are designed to last for 4-5 years.

Application:

Profiling floats in the ARGO approach are intended to complement satellite altimetry in two ways. From the latter, anomalies of sea surface height (SSH) can be derived which consists of the steric (dynamic height) contribution of T and S (H_{dyn}) and a reference level pressure (P_{ref}) related to a barotropic flow component. Symbolically (strictly these are different quantities which cannot be added), the contributions are

$$SSH = P_{ref} + H_{dyn} = SSH' + \langle SSH \rangle \qquad (1)$$

where <…> is the mean and SSH' are the fluctuations observed by altimetry. Altimetry has good spatial and temporal coverage but cannot determine/differentiate the

- steric and non-steric components
- mean SSH field (relative to the geoid)
- T and S contributions (spiciness)
- interior structure (vertical distribution) of H_{dyn}

The float profiles of T and S provide the H_{dyn} component globally (i.e. the steric component), as well as the spiciness and the interior structure. The trajectory data provide the absolute flow at a reference level and thus an estimate of the mean P_{ref} field. As a residual in (1) then the mean SSH field can be determined and thus the geoid.

Strengths and weaknesses:

The strength of these platforms is the broad (basin-scale or global) spatial coverage achievable, as in the ARGO program, and the vertical information provided. While at first sight they tend to spread randomly with time, there are regions (divergences, passages) that are impossible to sample. Some sampling biases can exist, like convergences towards regions with larger velocities (giving too high mean flows), Stokes drift in oscillating flows with

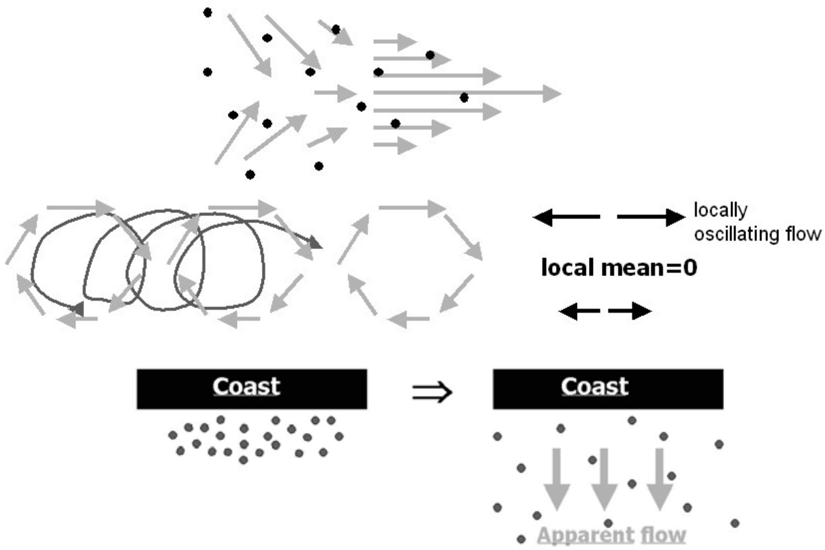

Figure 3. Three types of biases that can occur with lagrangian platforms (floats). Top: convergences accumulating floats in regions of larger flow. Middle: Stokes drift in oscillating flows with spatial gradients. Bottom: Diffusion bias due to spreading in a preferred direction.

spatial gradients, and diffusion bias if high float concentrations spread preferentially in one direction (e.g. near a coast), see Figure 3. The spatial and temporal resolution, as implemented in ARGO, is coarse. Floats are expendable so can not be post-calibrated, thus a sensor drift is difficult to detect or correct.

Further readings: Davis (1991), Davis et al (2001), ARGO website.

2.2 Surface drifters

Description:
Surface drifters are cheap and light-weight platforms that passively follow the horizontal flow at the surface via a drogue/sail at usually 15m depth. The drogue is connected to a small surface float which carries the satellite transmitter and other electronics. All of them measure SST and many also air pressure.

Application:
While profiling float data have the strongest synergy with satellite *altimetry* measurements, sea surface *temperature* (SST) observations from space are best complemented by surface drifters. The chapter by I. Robinson in this volume explains in detail the difficulty in defining and observing the different types of SST. Surface drifters are an important resource for collecting such data.

A ten year long data set now also seems to allow an estimate of the mean geostrophic surface circulation, after subtracting the Ekman component, which can also serve to determine absolute SSH and thus the geoid. There is a global operational drifter program under way, which maintains on the order of 1000 drifters in the ocean.

Strengths and weaknesses:
The strengths and weaknesses of drifters are similar to the ones of floats (section 2.1), but are restricted to the surface. In addition they normally do not measure salinity, yet.

Further readings: Niiler et al (1995), Niiler et al (2003), Global drifter center website.

2.3 Ship sections

Where better horizontal resolution is desired than achievable with floats or drifters, especially on regular transects across ocean basins or across boundary currents, ship sections are currently the best way to obtain this.

2.3.1 Research Vessels

Description:

Research vessels are still the backbone for much of ocean research. Ships are usually needed to deploy heavy or big instrumentation (geophysical equipment, moorings, nets) or to collect samples for chemical and biological analyses. These are very important applications, but the vessels are not suited for routine, frequently repeated, operational observations – they are very expensive and e.g. the one-time survey of the oceans with hydrographic sections under the WOCE program took 10 years! An exception is the use of research vessels as "ships of opportunity", where they are used to collect underway samples as they go to remote and ill-sampled areas for other work. The instrumentation used then are XBTs (expendable, free-falling temperature probes), thermosalinographs analyzing water pumped into the ship from near the surface, and Acoustic Doppler Current Profilers (ADCP) built into the hull of the vessels.

Application:

When using research vessels for operational underway measurements, continuous surface temperature/salinity measurements are usually obtained with the thermosalinograph. These data have value in adding to the in-situ reference data base for surface temperatures, but it is important for operational use that the data are transmitted to shore at least daily. An increasing number of vessels also deploys XBT probes now routinely when steaming on long sections or in transit. This provides more valuable temperature *profiles*. Depending on need, funding, and watch schedule of the crew, the probes are launched 2-4 times per day, and exceptionally every few hours. For ships steaming at 10 knots, this gives a horizontal spacing of 50-200km.

Strengths and weaknesses:

Research vessels are extremely expensive, and most cruises have a length of 2-4 weeks. Thus it is not realistic to use such ships purely for operational routine measurements. When a ship is on the way for another purpose, however, measurements that *do not require stops or extra labour* can be collected nearly for free.

The advantage of these vessels is that they often go to remote areas where no other in-situ observations are available. A drawback is the lack of regularity, since most research ships do not routinely go along the same sections (an exception are Antarctic supply ships).

Further readings: Routine research vessel website.

2.3.2 Volunteer observing ships

Description:

Volunteer observing ships (VOS) are merchant vessels which are willing to collect underway sampling (or deploy instruments) for free as they transit along their most economical paths (which are not always the same, and they do not stop or slow down for measurements). Thus they are useful for performing repeat section measurements on trans-basin paths, with a repeat interval of usually 2-4 weeks. Most measurements are only at the surface of the ocean (sampling water from the engine intake), but this is done for an increasing number of variables. For example complete CO_2 analyzers are now installed on various ships. Depth profiles are limited to temperature, for which the expendable XBT probes are used (normal profile depth is 800m), employing automatic launching system. XCTDs to measure also conductivity are used more rarely because of their high cost.

Application:

The so-called low-density sampling of the GOOS XBT program is carried out on 70 VOS on 26 transects in the three ocean basins at a density of usually 4 profiles per day (note that commercial vessel are usually twice as fast as research ships). These data are used operationally for weather/climate forecasting (e.g. by NCEP) and for climate research. Further VOS sampling is organized by the Ship of Opportunity Program (SOOP). These include high-resolution XBT lines, which sample every 50km in the open ocean and every 10-30km in boundary currents, some ADCP measurements, and pumped surface observations of temperature, salinity, $p\mathrm{CO}_2$, and chlorophyll.

Strengths and weaknesses:

This is a cost-effective methods for collecting data with high resolution along repeated trans-oceanic tracks. For the surface layer, a wide range of variables can be measured now. However, the initial installation of equipment may be difficult, and then there is no guarantee that a ship operator will not change ship routes or destinations. Spatial coverage is limited to commercial ship routes, and subsurface sampling (profiles) is restricted to temperature and usually not deeper than 800m.

Further readings: Smith at al (2001), Upper ocean thermal center website, SOOP website.

2.4 Moorings and fixed platforms

Description:

In many applications, temporal resolution much higher than with satellites, floats, and repeat ship sections is needed, as well as measurement of a wider range of variables. This requires timeseries observations in fixed locations, and for operational purposes a sustained mode of sampling is a prerequisite. This leads to the useage of moored sensors or bottom-mounted systems. The more generic modern expression is “ocean observatories”. Sampling is possible, depending on sensors, from minutes to years, and from the surface to the ocean bottom. There are “subsurface” and “surface” moorings, depending on where the top buoy is located.

Moorings can carry heavy sensors and thus observe, in case an autonomous instrument exists, nearly everything. Apart from physical sensors for T, S, currents, there now are optical sensors (for radiation measurements, chlorophyll fluorescence, oxygen), optical plankton counting and video instruments, chemical sensors (analyzers with wet reagants, or samplers), acoustic instruments for zooplankton backscatter or long-range tomography transmissions, and more.

Mooring networks are a special case and provide high time resolution at a set of fixed locations covering an ocean region. For dense networks like the tropical TAO/TRITON array in the Pacific, spatial gradients are sought, while more widely spaced systems sometimes only intend to contrast differences between areas or to occupy different parts of an ocean region.

Application:

Since moorings can only be installed and maintained in a discrete number of selected locations, the rationale normally is to use them in locations with critical ocean processes or in places that are expected to be representative of larger areas of an ocean basin. Examples are water mass formation regions, where the location of the deep mixing process is well known, and where a single mooring with sensors for water mass properties (T, S, etc) and possibly vertical currents (ADCP sensor) is sufficient. Similarly, flows and transports through important straits and passages, like Denmark Strait, the Indonesian Passages, or the Strait of Gibraltar, could be monitored by fixed observatories. Observing the uptake of CO_2 on the global scale is also a crucial type of information, which can be provided by a network of moorings with CO_2 sensors in the major regions of uptake or release by the ocean. The concept of ecological ocean provinces (Longhurst 1995) helps to identify locations which may be representative of larger areas in terms of chlorophyll and nutrient concentrations/distributions, mixed-layer depth, and other aspects. Maintaining observatories in each of these global provinces might enable the detection of variability or regime shifts in the different ecosystems.

In obtaining in-situ chlorophyll data, moorings will become an important complement to satellite chlorophyll estimates, which are very difficult to determine and have an accuracy of 30% in the best of cases. In addition, moorings are already able to provide other biogeochemical variables, like nutrients and O_2 which are critical for biogeochemical models (see chapter by A. Oschlies in this volume) but are not available from remote sensing.

Strengths and weaknesses:

Moorings are expensive to build and maintain, need a lot of technical effort, and require regular visits by research vessels. Therefore, only a limited number of distinct locations can be monitored by moorings. They have no x-y coverage or resolution, thus normally should be complemented with other techniques. On the other hand, they are ideal for sampling in the time domain, covering many multidisciplinary variables, and measuring in difficult fixed locations (straits, boundary currents). Moored instruments can be re-calibrated so may serve as in-situ reference stations both for satellite data and other types of sensors like floats and drifters.

Further readings: Tupper et al (2000), Dickey et al (2001), Dickey (2003), OceanSITES website.

2.5 Gliders and AUVs

Description:

A new class of platforms are autonomous gliding or self-propelled vehicles. These navigate under water and can be programmed (or “steered”) to sample along specific mission tracks. AUVs have propellers, usually not a very long range or endurance (order of days) and need support ships. Gliders on the other hand propel themselves by buoyancy changes and wings, thus they undulate up/down through the ocean. They are still in the prototype stage. Current versions have a limited speed of 20-25cm/s, a depth range of 1000m, and endurance of 6-12 months. Like floats they are very restricted in terms of additional payload mass and energy consumption, but usually carry more sensors than floats. Therefore they have the potential to provide biogeochemical data like fluorescence (for chlorophyll) and other optical measurements in a spatial mode and thus to greatly complement timeseries data from moorings.

Application:

Gliders can be used for repeat transects in remote areas or to complement VOS lines, either on orthogonal tracks or by providing additional variables. Every 2 weeks a glider could cover the equivalent of a 300 km XBT section (though not synoptic, i.e. not a snapshot, but for assimilation into models this makes little difference). Useage under the ice is also imaginable. Apart from running along repeat sections, holding position like a “virtual mooring” is also possible, and even entering a float mode may be feasible soon.

Strengths and weaknesses:

A main limitation of gliders is the maximum current they can stem due to their low speed. While the range is already a few 1000km, this still limits the ability to reach a mission area from shore, to carry out survey work, and return to a base. A very strong point is the flexible useage, both in terms of sampling and sensors, of being able to choose tracks that are defined by science not by merchant ships, of mission type, and the ability to steer the glider from shore.

Further readings: Davis et al (2002), Seaglider website, Spray website.

2.6 Integrating techniques

Description:

A few methods exist which inherently provide spatially integrated information, rather than data at the location of the platform. One is acoustic tomography, which samples the ocean horizontally with sound over large distances. This is usually done between pairs of moorings, which are fixed, but the information extracted from the traveltime of the sound (temperature, current along the path) represents an average over the entire section between the moorings. This technique has been used successfully in a number of experiments.

The other approach exploits the geostrophic relation and the principle that the average (or integrated) geostrophic current can be determined alone from the pressure distribution (as a function of depth) at the endpoints of a section. This is usually calculated from density profiles, traditionally collected with shipboard CTD's, but can now be done with self-recording sensors on a mooring. One thus obtains timeseries of mass transport, integrated over the section between the moorings again. As in the traditional geostrophic method, there is still a reference level problem, since the pressure field determined from the density measurements is relative to a pressure level whose depth and inclination is not known. For this, high-precision bottom pressure measurements are now possible to within a few millimeters of equivalent sea surface elevation, which at least give the *fluctuations* of the pressure gradient at a reference level.

Application:

Tomography is not much used in the "imaging" sense anymore, i.e. trying to extract horizontal mapping resolution from the integrals along the transmission paths. Instead, it is most useful where heat content or currents along a section are of interest (water mass formation regions, straits). Over long ranges it is also sometimes called "thermometry" and can then provide basin-scale temperature changes.

The geostrophic transport monitoring is suitable for timeseries of transports over entire sections. These maybe confined currents (passages), wide boundary currents, or meridional flows across entire ocean basins. In a German CLIVAR application (MOVE project), this was carried out successfully over a 1000km long section.

Strengths and weaknesses:
Acoustic tomography is an expensive technique requiring highly specialized teams and equipment. The niche in providing large-scale integrals has become smaller with the advent of ARGO, but the strengths remain full depth coverage and occupation of specific sections of interest. Both tomography and geostrophic integral techniques require specific geometry and bathymetry, thus cannot be used anywhere. However, they are remote sensing approaches, providing integral information about ocean regions without the need to deploy instruments everywhere.

Further readings: Kanzow et al (2005), Dushaw et al (2001).

2.7 Coastal radars

Description:
Radar installations with typically 50-150km range are able to sense the surface currents in the vicinity of coasts, by analyzing the doppler shift from surface waves which Bragg-scatter the radar signal. Each piece of ocean surface to be sensed needs to be covered by two separate radars. The variables that can be extracted are the very near-surface current vectors, and as a second-order quantity, the wave height. The spatial resolution is 2-3km, and the time resolution typically 1 hour. Shorter-range systems also exist.

Application:
For operational applications like ship routing, prediction of pollutant transport, harmful algal blooms, etc, this is is a method of increasing interest. To date, most installations are only in select locations of specific interest. However, some countries are starting to set up radar networks along entire coastlines. These would contribute to monitoring systems of coastal or near-shore ocean processes.

Strengths and weaknesses:
An advantage of radars is that they are entirely land-based and have useful spatial and temporal resolution. However, they coverage is limited to near-coast, they require elevated terrain for the installations, and can only sense currents at the surface.

Further readings: Essen et al (2000), EuroROSE website.

3. Conclusions

An overview of the most widely used or most promising in-situ observing techniques for operational applications has been provided. The main intention was to emphasize the differences in terms of sampling and capabilities, in order to give appreciation of the complementarity of the approaches. No one method can usually fulfil the observational needs of any operational (or science) application. Table 1 is meant to summarize the main characteristics of the platforms discussed, and to help in guiding to the most appropriate choice of observing means for specific observational requirements. More importantly, however, it is meant to emphasize the complementarity between all these elements and technologies which exist.

It is clear that many observing techniques had to be omitted here. Acoustically tracked floats, electromagnetic methods to sense currents, or inverted echosounders are some of them. They are not, however, used operationally and there seems to be no plan at present to include them in operational systems.

To highlight the sampling and complementarity in space and time, Figure 1 at the beginning of this chapter summarized the spatial and temporal resolution and coverage of the observing methods discussed. While the figure does not do justice to various methods by omitting the depth dimension (where satellites would just provide a single horizontal layer/slice), it is helpful to think in terms of this horizontal and temporal sampling. There seems to be a gap on scales of 10 m - 1 km and on short timescales, but most processes of interest to operational oceanography can be observed with suitable combinations of existing methods.

One aspect that was not addressed above is that of data delivery. Operational systems require in-situ data with minimal delay, usually within one day. Some approaches inherently have a built-in data telemetry capability, like drifters, floats, and gliders. Coastal radars and vessels just need to be equipped with the required transmission systems, which is no problem in principle. For moored or bottom-mounted instruments, and even more so under the ice, data telemetry is not easy. Either seafloor cables need to be available, or surface buoys are required, or telemetry packages that occasionally come to the surface need to be attached to moorings. All these exist or are under development.

The challenge in collecting data for operational applications is to combine the available methods in the most efficient way, in order to provide the observing system – together with remote sensing – that really samples all four dimensions and the variables of interest such that models can make maximum use of them.

Platform/cost	Strengths	Weaknesses
Research vessels ($25,000/day)	- taking samples - deployment of heavy equipment - reach remote areas (VOS-like)	- sparse sampling (operational) - too expensive for operational obs (but needed for servicing of operational installations)
VOS (free)	- high resolution along repeat tracks - many variables (for surface measurements)	- not always where wanted - tracks may change, they don't stop - subsurface only for T (800m)
Surface drifters ($3,000)	- global coverage - rapid sampling in time - low-cost, robust technology	- sparse spatial sampling - only surface observations - limited variables (T, air-p, S)
Floats ($15,000)	- global coverage - vertical profiling to mid depth - large numbers since "cheap"	- coarse x,y,t resolution - limited weight/power (sensors) - avoid/quickly leave passages, divergences, places of interest
Moorings ($250,000)	- high time resolution, surface to bottom - many variables possible - difficult locations possible - re-calibrations, referencing	- no x,y resolution - expensive, including the need for ships - large technical effort
Gliders ($70,000)	- good sampling along tracks - free choice of track, can be steered/controlled - small sensor suite feasible	- very slow (20-25cm/s) - limited depth range and variables
Integrals	- integrate over long distances - good time resolution	- expensive - limited variables and places possible
Coastal radars	- good x,y,t resolution - land based	- limited coverage - only currents, waves (surface)

Table 1. Typical costs and tradeoffs of the observing methods discussed in this chapter.

4. Study and discussion questions

The following example applications are meant to motivate discussion and critical evaluation of the observing methods, including remote sensing, for achieving the operational goals. Therefore consider the following needs:

1) Monitoring of water mass formation in specific regions
2) Detection of coastal eddies and their impact on the ecosystem
3) Observation of the outflow through the Strait of Gibraltar
4) Collection of routine observations under the ice in the Arctic and Southern Ocean.

Even though at first sight some of these may appear obvious, it is helpful to consider each approach in the earlier table and diagram, and also remote sensing, and discuss why a certain method may not be suitable or less so than another. In many cases, the requirement of real-time data transmission poses a particular challenge. The problems do not have a unique answer, and the solutions will evolve with the implementation of new technologies.

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