White Paper #12 – Emerging technology

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1. Introduction

Modern observing systems benefit from the flexibility to adapt as technologies inevitably advance. Since the 1980's, when the TAO array was first conceived and deployed, ocean observing technology has certainly evolved and improved. If the tropical Pacific observing system were started from scratch today with no knowledge of TAO, it seems likely that it would look quite different, with a variety of observing technologies knit together to address the scientific requirements. This paper does not specify these requirements; rather we present a menu of observing technologies plausible for large-scale deployment by 2020. We consider both traditional observing platforms that continue to become more capable, and promising emerging technologies that have yet to be deployed in large numbers in the tropics. We hope that this compendium will provide the building blocks for the future tropical observing system.

Any comprehensive discussion of ocean observing must start with that most capable platform, the ship. Whether the ship is the most modern research vessel carrying scientists and state of the art lab equipment, a commercial ship of opportunity, or a chartered fishing boat from a small island, some method of getting equipment into the ocean is needed. Research vessels are unquestionably the bedrock upon which most scientific knowledge of the ocean is built. However, research vessels are expensive to operate and costs continue to rise. Most of the technological developments discussed below would reduce the use of research vessels, often through more robust instrumentation capable of longer deployment. There are also several technologies for which less expensive ships and boats are sufficient. While we acknowledge the need for ships, we also point out the clear trend toward a reduced dependence on large, dedicated vessels.

A common theme throughout the following discussion of observing technology is the potential for expansion of measured variables. The menu of observational platforms includes an even more extensive list of sensors already deployed successfully. This potential for expansion is central to the observing system of 2020, as in situ sensors for variables previously measurable only in a lab become increasingly practical to use autonomously at sea. The current tropical array of moorings offers a great example of these sorts of expanded measurements, with observations of the carbonate system, bio-optical properties, and acoustic sensing of fish among the valuable additions. An obvious requirement for the observing system of 2020 is that it be sustainable. None of the technologies can work on their own without substantial investment in their continued health. The sustenance of a comprehensive and evolving observing system is as much an organizational problem as it is a technical challenge. We offer no prescriptions for addressing the organizational issues, but we are sure these issues must be raised, and we believe that more robust technology will help.

2. In situ observing technology

Our review of in situ observing technology is organized by platform. The discussion of each platform includes sections devoted to (1) a basic functional description of the technology, (2) an exposition of the sampling characteristics of the platform and the sensors carried, and (3) some words on typical operations. Included in the discussion of operations are comments on readiness level using the three categories of mature, pilot, and concept (Lindstrom et al., 2012).

2.1 Profiling Floats

Description

ALACE floats were developed in the 1980s as a part of WOCE, and within a decade the first CTD units were added to these instruments. The first Argo floats were deployed in 1999, and shortly after this the first CTD units from SeaBird Electronics (SBE) were tested on the floats. Argo has now been operational for well over a decade, with over 5000 floats deployed and over 3500 still active. The float technology has evolved since the early ALACE versions, and there are now at least 5 commercial versions of floats (instruments that include a buoyancy engine and a CTD) available. At present, all of these instruments still use various versions of the SBE 41 CTD that was first tested in 1999. The SBE 41 has proven to provide generally high stability and accuracy over many years in the water (Riser et al., 2008).

Argo floats typically profile from 0-2000 m and require 200-300 cm^3 of bladder inflation over this range. In recent years a newer instrument designed at Scripps and now commercially available through MRV Systems has returned to an updated variant on the rotary pump, with good results. This allows the float to be smaller and more efficient, resulting in potentially longer lifetimes after deployment. At the present time about 70% of the active floats in Argo originate from Teledyne/Webb Corporation, purchased either as fantail ready units or as components that are assembled and tested at a few research laboratories. The remaining 30% of the floats are composed of the original Scripps SOLO, the newer SIO/MRV SOLO-II, and the French Provor, with a few floats originating from other smaller vendors. All of these floats use the SBE CTD in various configurations.

Originally all floats in Argo used the Systems ARGOS for communications; beginning in 2003 the first Iridium prototype floats were deployed. In recent years the number of Iridium floats has increased greatly, and it is projected that by 2017 nearly all floats in the Argo array will communicate using Iridium. There are two types of Iridium communications used by these floats. The Teledyne/Webb floats use Iridium/RUDICS, a packet-switched version that requires floats to login to a land-based server to transmit their data. The SOLO-II floats use Iridium/SBD (Short Burst Data), a version that transmits data in a form analogous to a text message and is received as an email message. There are advantages and disadvantages to each of these methods. RUDICS requires a dedicated server and substantial processing software but allows nearly an unlimited amount of data to be transmitted during a single session. SBD is simpler (and somewhat cheaper) but is more limited in the amount of data that can reasonably be transmitted in a single session.

At present, the Teledyne/Webb floats carry sufficient batteries to collect over 300 profiles from 0-2000 m, with data transmitted at 2 m intervals using Iridium; a number of these floats have lasted well over 7 years. The SOLO-II floats are as yet only a few years old, but their higher efficiency suggests that they should be able to last as long or even longer. The readiness of these profiling floats is considered mature.

Sensors and sampling

Given the reliability of the buoyancy engine on these floats, various groups have attempted to add additional capabilities and functionality to the instruments. Several versions of dissolved oxygen sensors have been added (SBE 43, Aanderaa 3830 and 4330, SBE 63), with varying results (Riser and Johnson, 2008). These sensors have proven to be reliable over times of several years in the sense that they continue to operate and provide useful data, but there are ongoing problems with calibration and drift that are being addressed. Additionally, several versions of dissolved nitrate sensors have been used successfully, including both ISUS and SUNA (Johnson et al., 2010). To date, these sensors have been built at MBARI and have not been generally available commercially; however, it is likely that a commercial version will be available from Satlantic, Inc. within a year or two. Additionally, MBARI has developed a Durafet-based pH sensor for deep-sea use that has been successfully deployed on several floats. Given the present interest in ocean acidification, it is likely that the use of these sensors will grow in the future. Efforts are now underway to find a suitable commercial vendor. Particulate backscatter and chlorophyll sensors (FLBB sensor, commercially available from Wet Labs, Inc.) have also been successfully added to floats (Boss et al., 2008). In addition, floats have carried hydrophones that can be used for low-frequency acoustic tracking (RAFOS) and also for higher-frequency studies that attempt to estimate wind-speed and rainfall rates acoustically (Riser et al., 2008). In the near future, it appears that a version of a pCO2 sensor will be marketed by Aanderaa, and it is likely that a prototype float carrying such a sensor will be deployed shortly after the sensor becomes available.

Other capabilities

Originally floats were deployed from research vessels while on station. By the 2002, it was possible to deploy floats from rapidly moving container ships, allowing important expansion in the geographical extent of the Argo array. Additionally, several hundred floats have been air-deployed by US Navy C130 aircraft, with good success. At this present time, this capability is not available to non-navy researchers (it was used by civilian scientists during the years 2003-2006), but there is hope that civilian air deployments might resume in the future. To allow the array to expand to higher latitudes, the capability of using floats under sea-ice has been developed and used extensively in the Antarctic (Wong and Riser, 2011). Using the present generation of floats in the Arctic, where the buoyancy requirements are more severe, is more problematic, but such deployments will be attempted in the near future.

Deep floats

There is considerable scientific interest in sampling the global ocean at much greater depth than is possible with present Argo-style profiling floats. To this end, several new prototype floats have been produced. In Japan, a 4000 m version of the Ninja float has been deployed, and in the US both Scripps and Teledyne/Webb have produced and tested versions of 6000 m floats. These testing efforts are ongoing, with the goal of having tested and reliable floats available by 2015. The Argo Steering Team has set a goal of eventually having such deep floats comprise as much as 1/3 of the Argo array, in order to examine the heat content of abyssal waters and the changes in properties of these waters over time.

Such deep floats will not be inexpensive, owing to their increased complexity in order to withstand extreme pressure cycling over many years. Additionally, increased CTD accuracy and precision will be required for such floats, given the considerably smaller temperature and salinity signals in abyssal waters. Issues such as a suitable sampling strategy for these deep floats, and additional sensors that might be carried, await the continued successful testing of these prototypes. The deep-floats have a readiness of pilot at this time.

2.2 Underwater gliders

Description

Autonomous underwater gliders developed over the last several years, and now operated routinely, offer the possibility of sustained fine resolution observations (Rudnick et al., 2004). In typical use gliders profile from the surface to 500-1000 m, taking 3-6 h to complete a cycle from the surface to depth and back. During the cycle the gliders travel 3-6 km in the horizontal for a speed of about 1 km/h. Deployments of 3-6 months are routine, during which time the gliders survey track extends well over 2000 km. During a few minutes on the surface, gliders obtain location by GPS and communicate through the Iridium satellite phone system. Gliders may be deployed and recovered from a wide range of platforms, including small boats and chartered fishing vessels.

Underwater gliders profile by changing buoyancy, and move horizontally through lift generated by wings. Missions of long durations are possible because gliders move slowly to limit the loss of energy to drag. Propeller-driven autonomous underwater vehicles (AUVs) might also be used to achieve similarly long missions if they were driven comparably slowly. Such long-range AUVs have been conceived and deployed, including hybrid vehicles that use both buoyancy and propeller. But it is fair to say that most propeller-driven AUVs are used for short-duration, high-speed missions, and do not have the record of sustained operations as do underwater gliders.

Sensors and sampling

Underwater gliders are profile generating machines, much like profiling floats, with the added capability of control over horizontal position. Sensors on gliders measure such physical variables as pressure, temperature, salinity, and velocity, biological variables relevant to the abundance of phytoplankton and zooplankton, and ecologically important chemical variables such as dissolved oxygen and nitrate. In sustained operation gliders are most often used to repeat a survey pattern, the simplest being a single repeated line. For example, three approximately 500-km lines off California have been continuously occupied starting in 2006, constituting the longest running sustained glider network to date (Davis et al., 2008; Todd et al., 2011a; Todd et al., 2011b). In the first attempt at a sustained equatorial glider deployments two gliders were recently deployed from the Galapagos Islands, with the goal of making repeated sections along 93°W, between 2°N-2°S (Figure 2.1). One glider takes about 20 days to complete this line, so the two gliders provide a realization of this section on a roughly 10-day interval. To summarize, in an equatorial application, underwater gliders would provide 10-day resolution of a section between ±2°, with 150 profiles per section when profiling to 500 m.

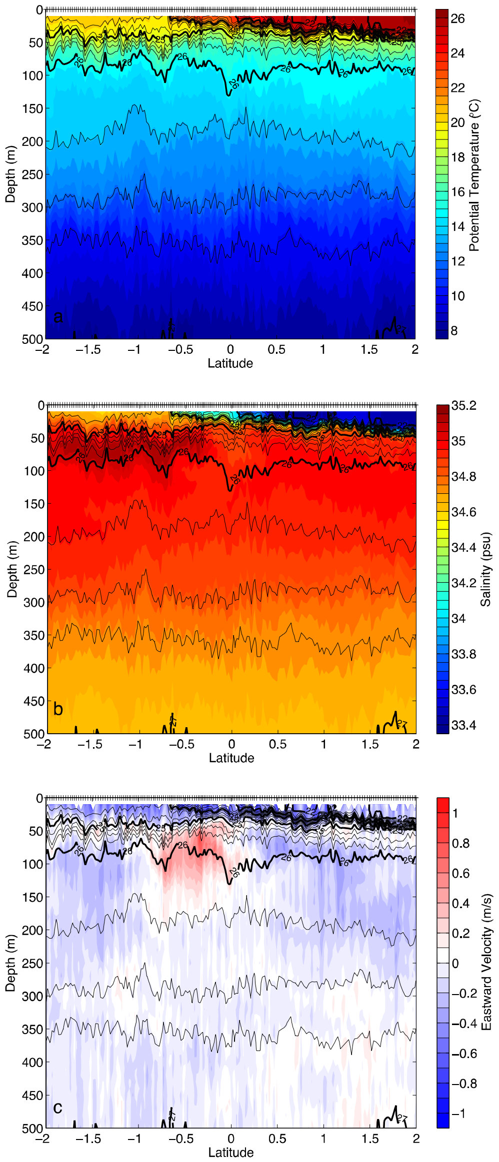


Figure 2.1 - Sections of (a) potential temperature, (b) salinity, and (c) eastward velocity at 93°W measured by two Spray underwater gliders equipped with CTDs and Doppler current profilers. Values for each variable are indicated by color shading, and potential density is contoured using black lines. Tick marks on upper axes of each panel indicate the locations of 170 profiles for an average spacing of 2.6 km. The section was occupied during 24 October – 6 November 2013. Note the equatorial front at the surface near 0.7°S, salty water from the south penetrating to 0.3°S between 25-26 kg m^{-3}, and the equatorial undercurrent near 80 m depth and 0.3°S.

Operations

Underwater glider operations involve a series of considerations with substantial effect on operations. Glider operations include refurbishment, shipping, deployment and recovery, piloting, communication, and data acquisition, archiving and quality control. Glider operators in the US

(Rudnick et al., 2012) are now doing routine sustained missions, with 3-4 glider deployments per year. Thus the readiness level of gliders can be considered mature. This sort of operation is practical from land exclusively using small boats for deployments and recoveries. A number of efficiencies may be achievable with a fully realized network of gliders. If glider missions can be lengthened the annual operating costs could be lowered. While it is fairly simple to add batteries to gliders, the ultimate limiting factor is likely biofouling. Capital costs could be dramatically lowered if the market for gliders were bigger, as is the market for profiling floats. In any case, with current operational constraints and costs it is practical to begin an equatorial glider network. Because gliders have not yet been used routinely in the equatorial Pacific, this particular appplication has a readiness level of pilot.

2.3 Emerging Surface Moorings

Description

Emerging surface mooring technology shows promise of integrating Surface Ocean and atmospheric measurements along with sub-surface profiles in real-time (Figure 2.2). The smaller, easier to deploy technology is not necessarily intended to replace all conventional moorings, such as those used as reference stations with heavy and redundant instrument loads. However, the low cost, ease of deployment high frequency sampling, long endurance, and potential for some vandal resistance will complement some observing needs and completely enable other fixed time series measurements. Significant size and weight reduction can be realized with an integrated, easy to deploy mooring. Up to 10 complete deep-ocean moorings can fit in a single 40 ft container. This type of mooring is commercially available for tsunami observations (Lawson et al., 2012) and the design has been proven in limited production quantities (<12) in high and low latitudes and in depths up to 5000 m. Small climate type buoys are now in the advanced R&D stage and have collected data in limited tropical deployments, see Figure 2.3.

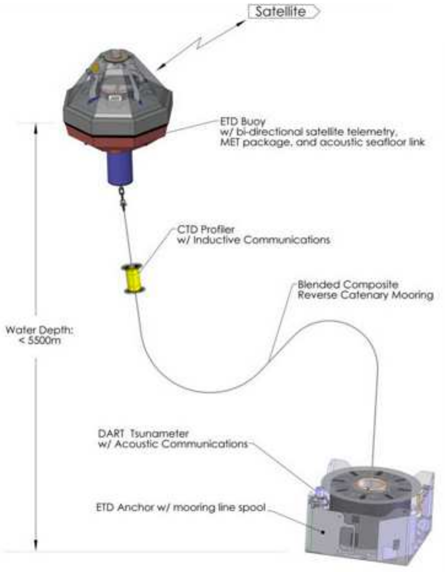
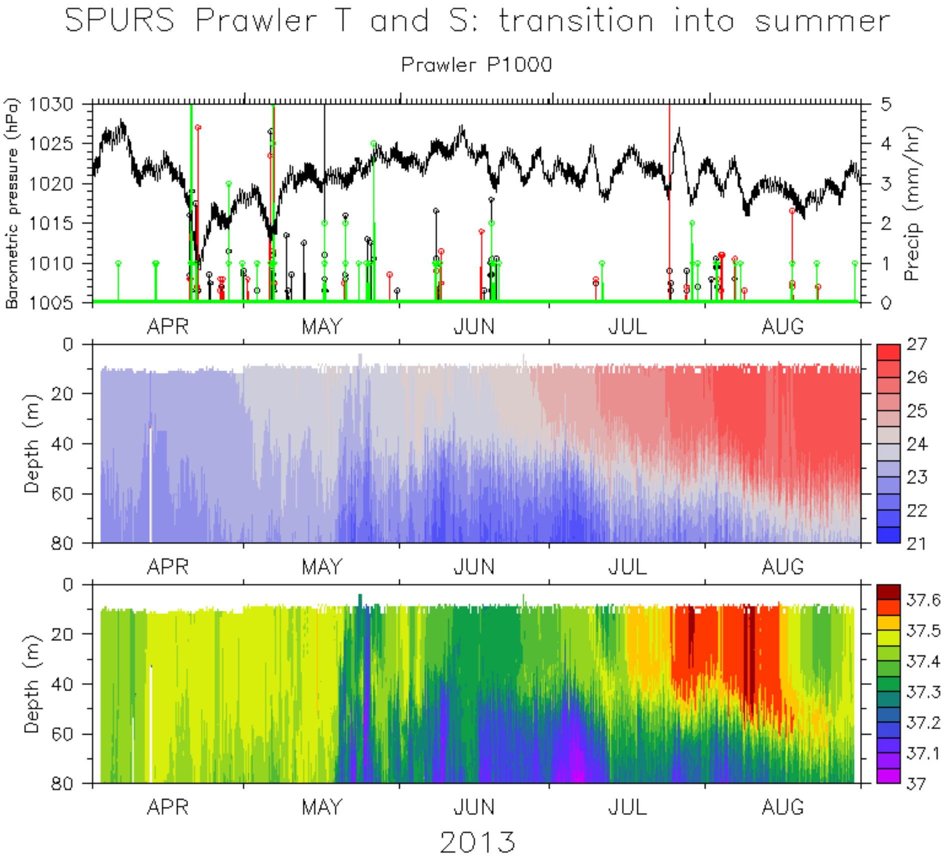


Figure 2.2 - Slack line PICO-PRAWLER mooring

Moored profilers that use wave energy from surface moorings to sample the water column are emerging and have made thousands of high resolution CTD profiles. Systems such as the Wirewalker (Pinkel et al., 2011), Brooke Ocean Technology Seahorse (Fowler et al., 1997) and the NOAA-PMEL PICO-PRAWLER (Milburn and Kessler, in prep) are potential candidates to fill a high-frequency/long endurance sampling niche. For example, a PMEL PRAWLER (Meinig, in prep.) has averaged ~25 profiles per day (over 6 months and up to 500 m depths) for a recent experiment at 20°N 38°W. The PRAWLER, Wirewalker and Seahorse use wave energy for locomotion and batteries control and inductive communications, and can accommodate a limited number of low-power sensors.

Sensors and sampling

Small surface buoys cannot host as many sensors as large traditional Ocean Climate Station type buoys. However, many small buoys are hosting meteorological and biogeochemical sensor payloads with sufficient power and real time communications. Profilers on surface moorings require a continuous length of wire to climb and make profiles. Although the surface wave action provides motive power, batteries are still required for sensor, processor and inductive communication.



SPURS Prawler T and S: transition into summer

Prawler P1000

Figure 2.3 - The top panel includes rain rate from two SPURs PRAWLER moorings (black and red), and the WHOI mooring (green). Temperature and salinity shown from PRAWLER in bottom panel.

Operations

The comparison chart outlines the advantages and tradeoffs using small surface moorings.

Comparison Chart:

	Emerging Moorings	Conventional Moorings (CM)
Size	20 pre-packaged PICO units can fit into a single 40 ft. shipping container.	1-2 CMs fit into a 40 ft. container in ~15 pieces each (anchors, buoy, bridle, tower, wire rope, nylon line, barrels of chain, hardware, and tools).
Sea Transport	Can be sent aboard smaller vessels of opportunity, i.e. a fishing craft on its regular route. Able to deploy in higher sea states than CM.	Large research ships with specialized personnel and equipment.
Building & Assembly	Pre-built, factory assembled, and deployment-ready when shipped.	Deployments are sea state limited. Shipped in many parts and assembled on ship deck with skilled technicians in the field.
Manpower	Can be deployed by 1-3 people with basic seagoing skills. Buoy/mooring experience is unnecessary.	Requires 6-12 specialized crew and technicians.
Operational Life	Estimated 2-3 years.	1 year.
Vulnerability to Vandalism	Smaller surface expression that is harder to see and has less radar return. Nothing to climb on and no hardware to steal.	Vandalism is a major cause of failure for CMs.

A specialized organization and facilities are required to support sustained ocean climate observations. The stringent requirements on sensor accuracy and real-time quality control require constant vigilance. Functions include: specification, procurement, integration, calibrations, packaging, engineering, testing, quality control, advocacy and leadership for TPOS etc. Technology obsolescence, software development, sensor firmware upgrades and software maintenance need constant attention. These relatively new surface moorings have a readiness level of pilot.

2.4 Conventional Moorings: TRITON and m-TRITON system

TRITON

Description

The basic technology was developed in 1990’s based on the ATLAS buoy taut-line mooring system. The biggest difference between ATLAS and TRITON is the concept for safety operation. The surface buoy was designed to persist under higher vandalized area with strong towing cases. The surface float is 2.4 tons in air, and has 7 tons of buoyancy. The wire cable is 18 mm diameter down to 750 m, and Nylon is 24 mm diameter down to the sea bottom. The scope is 0.9, which is similar to ATLAS. The TRITON is equipped with mid-depth buoyancy to aid recovery sensors in case the surface buoy is lost.

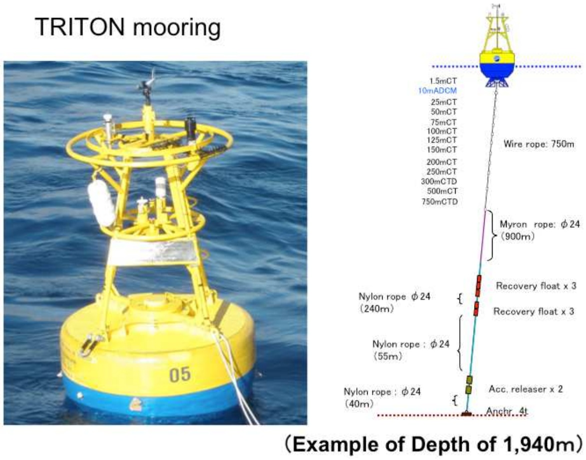


Figure 2.4 - A TRITON mooring.

Sensor and sampling

The ocean sensors are SBE37IM for underwater temperature and salinity measurements, and Teledyne current meter for 10 m velocity. In addition to the commercial CTD sensors, a JAMSTEC original CTD sensor has been developed and tested, including a calibration system adhering to Japanese national standards (Ando et al., 2005). The meteorological sensors are packages of JAMSTEC original signal processing system with commercial sensors from R.M. Young and other manufacturers. The sampling strategies are the same as ATLAS and the depth of ocean sensors are the same as TAO in the western Pacific.

Argos-2 is used for the data telemetry system, which collects the 1 hour data in near real time. The data return rate in real time and delayed modes are continuously higher than 80% in the last 13 years, except for the sites near the coasts of New Guinea and Sumatra.

The main cause of reduced data return is vandalism. Various countermeasures have been used over the years, but it is impossible to protect from vandalism perfectly. Even in such severe conditions, the countermeasures worked to some degree, and the data return rate from TRITON buoy system was higher than m-TRITON and ATLAS. Following is a list of vandalism countermeasures for the TRITON buoy system.

- Pentagon type bolts and nuts
- Stainless steel tower

- Hidden satellite transmitter to send position for backup
- Flat type transmitter to send data
- Double steeled wire rope down to 750 meters
- Underwater sensor protectors from long-line
- Iron-mask met tower for the heavily vandalized region
- Meteorological sensor and tower painted to look old and vandalized

Operations

TRITON moorings are a highly mature technology. A goal is to lengthen mooring deployments from the current 1 year to 1.5 year, to at least 2 years in future. The main challenges are vandalism and biofouling to sensors. For vandalism, towing by fishing boats is the main issue, so we are testing double steeled wire rope. Biofouling problems are not well solved yet, and it is just confirming stage about the quality of data from 1.5 year mooring.

m-TRITON

Description

Unlike the TRITON buoy system, m-TRITON is designed to be deployed by smaller vessel of 2000 tons. The system is not taut line but slack line type (Ueki et al., 2010). By using slack line, the weight of the surface buoy is 1/3 as much as TRITON. Below the surface buoy, buoyant line is used below nylon line to keep the mooring S-shaped below sea surface.

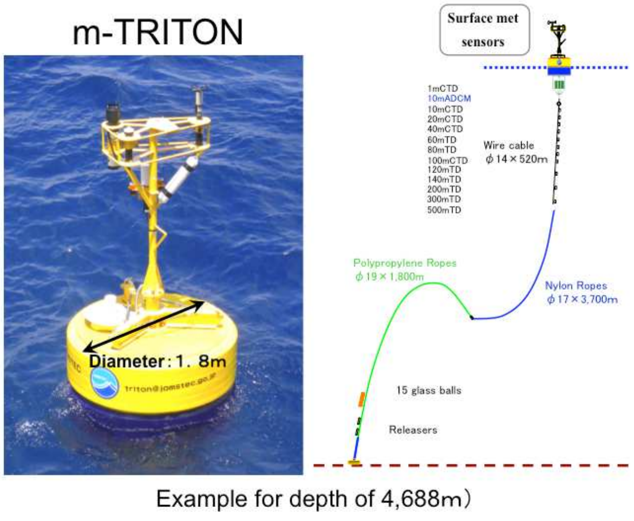


Figure 2.5 - An m-TRITON mooring.

Sensors and sampling

The sensors for m-TRITON are the same as for TRITON. The data telemetry system for m-TRITON is Argos-3, which allows two-way communication with higher data transmission, as often as every 10 minutes. The data return rate is lower than TRITON as the mooring system is small. Again vandalism is the main cause of reduced data return. The prevention of vandalism is particularly important in the eastern Indian Ocean, where vandalism occurs more often than in the western Pacific Ocean. Countermeasures are almost same as TRITON.

Operations

m-TRITON moorings are a mature technology. A goal is the same as that of TRITON, but it would be more difficult to lengthen mooring deployments from the current 1 year to 1.5 year, to at least 2 years in future. The main challenges are vandalism and biofouling to sensors. For vandalism, towing by fishing boats is the main issue, so we are also testing double armored wire rope. Biofouling problems are not well solved yet.

2.5 Subsurface moorings with acoustic links

Description

Subsurface moorings with acoustic telemetry links are candidates for adding capability to the sustained tropical observing system. They are fully submerged and thus not subject to vandalism, and also exhibit reduced impact of biofouling compared to platforms permanently or frequently at the surface. Experience has shown that they can be deployed such that the uppermost sensors are within about 30 m of the surface (Send et al., 2011), providing good vertical coverage except right at the surface. Deployment durations of 2-3 years are routine, and the design and cost is relatively cheap since the subsurface environment is not very demanding. In addition to telemetering data acoustically, other methods to recover data from subsurface moorings exist, including data capsules that get released to the surface at fixed intervals, and loose small tethered telemetry floats with very low profiles at the surface.

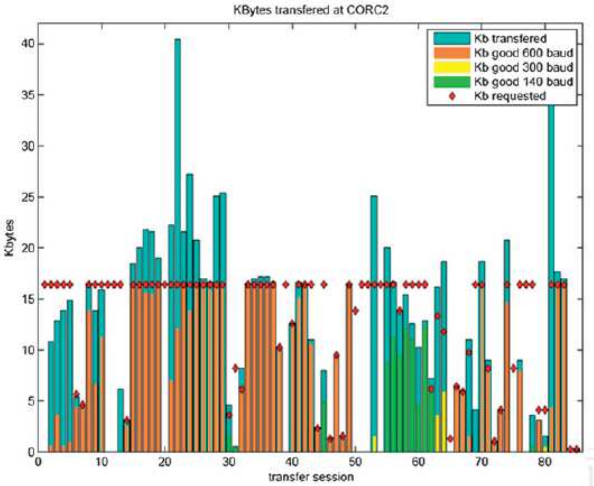


Figure 2.6 - Diagram summarizing the data transfer success from a 160-day Spray glider mission, for the CORC2 mooring in the California Current; each bar represents one dive. The red diamonds show the number of kbytes requested/sought during the dive. The overall height of the bar shows the number of kbytes received, and green/yellow/brown show the amount of good data received (color coded by baud rate).

Technical developments from the NOAA CORC project have resulted in the now routine capability to use commercially available acoustic modems, and inductive communication *within* the mooring, to telemeter all sensor data to gliders or ships which pass by the mooring (Send et al., 2013a). This works well over horizontal ranges of 2-5 km, with the modem in the mooring at a depth between 1500 m and 4000 m. A typical data transfer session by a glider requests 16 kB of data, and a typical data transfer success rate is 75% (Figure 2.6). A standard modem has sufficient battery power to transmit 2-3 Mb of data during a deployment, which is sufficient for most discrete sensors and ADCP current profilers using standard sampling/ensemble intervals of 30 minutes to 2 hours. Projects where this is being used routinely at present are the California Current NOAA CORC (Figure 2.7) and the NSF OOI (http://oceanobservatories.org/infra- structure/ooi-station-map/station-papa/).

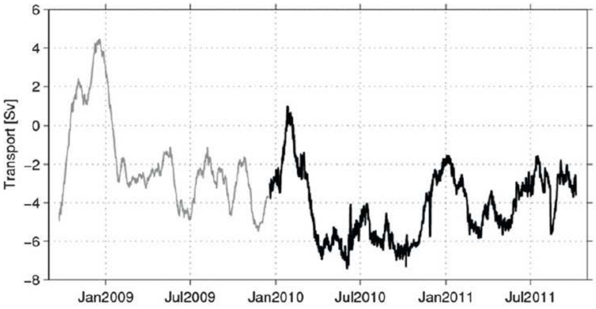


Figure 2.7 - Geostrophic transport (relative to 3500 dbar) of the California Current component over deep water, derived from microCat data on two CORC moorings. The black line shows transports entirely derived from data downloaded acoustically with gliders.

Two brands of gliders are now available with this capability, the SIO Spray glider and the Teledyne Webb Slocum glider (Rudnick et al., 2004). While the transducer takes up some payload space and weight in the glider, the additional task of retrieving mooring data does not seriously impact the power budget since the glider modem mainly listens which consumes less energy than the mooring modem requires. As such, in a tropical array, gliders traversing a meridional section as suggested in the glider description above, could pass by subsurface moorings on each transect and retrieve/telemeter the mooring data. In those areas which are too remote for glider deployments from land/islands and where gliders need to be deployed/recovered with ships, glider endurance can be enhanced by profiling less often, loitering at depth for periods of one or several days. The longest mission achieved in this way is 375 days.

Sensors and sampling

A minimum suite of physical sensors for the subsurface moorings probably is a set of high-precision temperature/conductivity instruments, clamped onto the wire and communicating inductively, in order to observe stratification changes and to calculate dynamic height relative to e.g. 1500 m depth (for zonal pressure gradients). This usually requires 10-15 instruments from the top of the mooring down to 1500 m (Kanzow et al., 2006). In addition, an upward-looking ADCP can cover the layer from near the surface to depths of 150m or 500m, depending on resolution and proximity of bins near the surface required.

Subsurface moorings are able to carry virtually any set of biogeochemical autonomous sensors, including large, heavy, or power-hungry instruments. These can be incorporated into the uppermost floatation if measurements near the surface are of interest, or they can be distributed along the mooring wire, either clamped-on or integrated into larger load-cages (Ohman et al., 2013). Typical sensors on such moorings would measure dissolved oxygen, pH, nutrients, chlorophyll fluorescence, optical backscatter/absorption, or down welling irradiance (measuring this at several levels allows determination of column-integrated chlorophyll). Passive and active acoustic instruments for sensing of marine organisms or mammals can also be accommodated, as well as water samplers, wet-chemistry analyzers, or genomic instruments. Most of these data can be telemetered inductively and acoustically.

Operations

For estimating manpower effort and ship time needs, two sample cases are considered – one where a total of 3 moorings are operated by an agency or institution, and one where 10 moorings are operated, both with a 2-year service interval.

Purchasing, assembly, maintenance, and testing of mooring components in the lab requires approximately 9 person-months of technical staff (shared between one engineer and one mooring technician), for approximately 3 moorings, or 12 person-months for 10 moorings. The work related to cruise preparation, shipping, execution, demobilization, is estimated to require the same person-months again. This means that a team of 2 FTEs can service and deploy 10 subsurface moorings each year (1.5 FTE for 3 moorings). If data retrieval, processing, dealing with telemetry issues, basic quality-control, and dissemination is added, that requires another FTE for 10 moorings continuously (or 0.75 FTE for 3 moorings continuously). Since the moorings only need to be deployed every 2 years, the average FTE effort would be 2 FTE for 10 moorings, or 1.5 FTE for 3 moorings (in terms of expertise, 3 people are desirable, but they can do other things 1/3 to 1/2 of the year). A medium-size research vessel is required for deployment and recovery of these moorings, the requirements of the ship are modest since no single component is very large or heavy (with the exception of maybe the anchors, which can be slid/tipped into the water without need of lifting them). Two cruise participants are needed who are trained in the handling of this type of equipment, while another 2-3 people are required to assist in handling gear and lines on deck.

For ship time needs, we could make the most conservative assumption that a cruise is executed every 2 years for nothing other than servicing 3 or 10 subsurface moorings. For this scenario, we estimate 3 weeks of transit and 1.5 days station time per mooring, every 2 years. Then the ship days (including transit) needed are 4.25 days/mooring/yr for 3 moorings, and 1.8 days/mooring/yr for 10 moorings. Since in general the ship time will be shared, the assumption can be made that half the ship costs are assigned to the subsurface mooring work. In that case the annual ship time need per mooring is 1.5-2 days, depending on the number of subsurface moorings operated. The technologies employed for this approach are mature, and are being routinely used in a number on ongoing ocean observing programs.

2.6 Moored profilers

Description

Moorings can carry vehicles that profile vertically with a diverse sensor suite. Currently existing types of moored profilers are wire-crawlers, wire-ratcheting systems, and underwater winches.

Wire crawlers are the most widely used moored profiler, with the MMP sold commercially by McLane Research Labs. It is only deployed on subsurface moorings (a surface buoy causes too much vertical wire excursion), and uses a motor/wheel mechanism to roll up and down the mooring wire. It can cover the entire water column, but experience has shown that failure risk increases when the top of the mooring and profiling range is closer than about 150m from the surface. The total profiling distance with full batteries is about 800,000 meters. Versions are now available which can communicate inductively through the mooring wire, so the data could be assembled in a deep mooring controller and telemetered acoustically from there. The advantage is that no surface mooring is needed (no vandalism, less fouling, longer endurance), but the method does not provide observations near the surface.

A different technology uses the vertical excursion of the wire underneath a surface buoy in the presence of surface wave activity, in order to ratchet a buoyant platform down the mooring wire. Once it reaches a pre-determined lower profile depth, it stops, and then can rise up the wire using its buoyancy. This uses no battery power for the profiling itself. Available models are the Seahorse profiler and the WireWalker. They also communicate inductively, here with the surface buoy, which allows telemetry to shore. These systems require a surface buoy, which may be perceived as a drawback given problems with vandalism and endurance of some tropical surface moorings.

Moored winched profilers use mechanical winching of a wire in order to profile from the upper end of the static subsurface mooring to typically the surface. When the platform breaks the surface, it can establish communication to shore. At first sight this is an elegant approach, since the mooring itself avoids the surface, making it more robust and long-endurance, reducing fouling and vandalism, and reducing the fish-attracting “reef effect”. However, building and operating a reliable underwater cable spooling mechanism is demanding. In the model by WET Labs (AMP/”Thetis”) the winch and the sensors are both located inside the profiling body, which raises itself to the surface and then winches itself down again against its buoyancy. It has a maximum working depth of 100 m, can carry out 180 profiles (to 100 m). The Ocean Profiler by NiGK has the winch stationary at depths up to 250 m, and the sensor float is raised to the surface/pulled down again. The maximum profiling depth is 250 m and it can perform 250 profiles to 100 m. The buoyancy and sensor payload of both models is limited, which may pose problems when operating in stronger currents.

Another winched approach is the “SeaCycler” developed by BIO/Halifax and being commercialized by Rolls Royce Canada (Send et al., 2013b). In this system, the winch remains at depth, and in fact winches itself down as the sensor platform is raised to the surface. The buoyancies of the two bodies are balanced such that potential energy is exactly conserved during profiling, meaning that (other than friction and motor inefficiencies) no energy is required for the profiling itself. This allows large buoyancy for the sensor platform (over 75 kg), enabling operation also in larger currents. Typical lower parking depth is 150-250 m (depending on expected currents), number of profiles is 400 or 800 depending on battery (alkaline or lithium) . A drawback is a much larger size (and cost) of the system, which in its current version is designed to withstand pressures up to 1000 dbar (which can result from mooring blow-over by strong currents).

Sensors and sampling

All profilers usually carry a diverse suite of sensors in their current applications, measuring for example temperature/salinity, currents, oxygen, chlorophyll fluorescence, and other optical quantities. The SeaCycler is designed for larger, heavier, or more power-hungry sensors, which can include CO_2, nutrients, acoustic backscatter systems, or wet-chemistry systems.

Operations

The most common type of wire crawler must be considered mature due its wide-spread use, but many users report that highly specialized expertise and great care is required to make them function reliably, so maybe it is less than “operational” or “sustained”. The wire-ratcheting profilers are in an advanced pilot phase, possibly bordering on mature. All winched profilers are still in the early demonstration or pilot phases, and extensive field experience with long deployments in diverse environmental conditions is still lacking. The overall less-than-mature development stages of the moored profilers also imply that more specialized staff and more effort is needed to successfully operate these systems in a sustained mode. By 2020 however, some of these system should be operational.

2.7 Unmanned surface vehicle (USV)

Description

Unmanned surface vehicles are rapidly evolving and offer the possibility of sustained fine resolution surface and subsurface observations. Only USVs with the potential of long ranges and high endurances will be discussed. USVs such as the Liquid Robotics Wave Glider (Hine et al., 2009), that use wave power for propulsion and solar power for electrical power, have crossed the entire Pacific and the first generation SV2 fleet has logged over 400,000 NM. A limiting factor for MET measurements is the small mast and low height to the water. A larger SV3 vehicle with significantly larger payload, slightly higher mast and additional power is now commercially available as well.

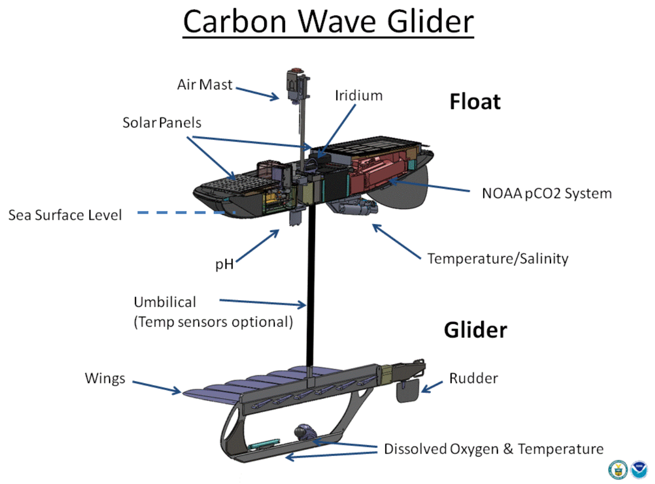


Figure 2.8 - Schematic of a NOAA Carbon Wave Glider.

Speed is wave and current dependent, but has averaged around 1 kt in several missions over 30 days in duration (Meinig et al., 2012). Numerous scientific, military and national security missions with a broad array of sensors (including carbon, see Figure 2.8) have been completed in high and low latitudes.

Wind powered USVs (Sailbuoy, Saildrone, Ocean Aero, Harbor Wing, Robotboat) are also rapidly developing, but less mature and have only been deployed with limited sensors. This class of USVs is typically 2-4 m long with a 4-5 m mast. Speed is wind and current dependent, on a recent deployment of the Saildrone from San Francisco-Hawaii-Palmyra, the vessel averaged 3-4 kts over >100 days (Saildrone.com). Deployments of 3-6 months are now possible with very limited proven scientific payloads.

Figure 2.9 - Wind Powered Saildrone.

Sensors and sampling

The unique advantage of USVs is that they have persistent surface presence and use wave, wind and currents for propulsion and can navigate thru waypoints in high and low latitudes. Solar cells and batteries provide payload power and the space available is larger than profiling floats and underwater gliders, but smaller than surface moorings.

Operations

USV operations involve a series of considerations with substantial effect on piloting and costs. Wave gliders require a small boat to recover and deploy from the near shore. Some present USVs have been successfully deployed and recovered from a dock, requiring only a small harbor tender. USV operations include refurbishment, shipping, deployment and recovery, piloting, communication, and data acquisition. This sort of operation is practical from land using exclusively small boats for deployments and recoveries for several classes of vehicles. A number of efficiencies may be achievable with a fully realized network of USVs, underwater gliders and buoys since the personnel and physical infrastructure to deploy and maintain them is similar. In any case, given the large distances that USVs have already proven themselves, the technology should be strongly considered for inclusion into the R&D portfolio for tropical measurements with a readiness level of pilot.

2.8 Dual-Use Subsea Telecommunication Cables

Description

For the first time, serious considerations are being given to add sensors to commercial subsea telecommunications cables. Over the past three years, the International Telecommunication Union (ITU), the Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization (UNESCO/IOC), and the World Meteorological Organization (WMO) have organized three workshops to bring the science, engineering, business and law communities together. Focus has been on disaster mitigation (tsunami, sea level rise, earthquakes) and moving towards a demonstration project. Three publications are available (http://www.itu.int/en/ITU-T/climatechange/task-force-sc/Pages/default.aspx)

Sensors and sampling

The initial sensors being explored for inclusion on future cables include 1) high resolution pressure, 2) seafloor temperature and 3) seismic instrumentation. Subsea cables have a proven life of > 20 years and provide wide bandwidth and power to seafloor sensors.

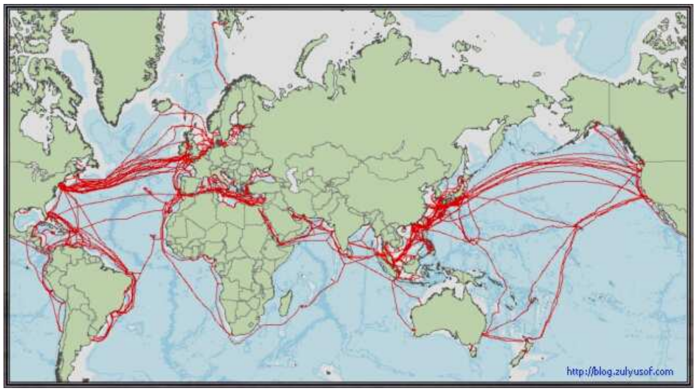


Figure 2.10 – Overview of subsea cables.

Operations

A large trans-Pacific cable is a substantial undertaking with significant unknowns. As such, the readiness level is considered concept.

2.9 Surface drifters

Description

Floating objects were likely used to make the earliest observations of ocean currents, hundreds of years ago. Over the last few decades, the Global Drifter Programme (GDP) has pioneered the global observation of surface current, with an average of 1250 drifters in the water over the last ten years (Maximenko et al., 2013). A GDP drifter uses a holey-sock drogue at 15-m depth tethered to a surface float that communicates via satellite. Most current GDP drifters use the Argos satellite system, but a growing number are moving to Iridium communication and GPS navigation. The GDP is a firmly established component of the global ocean observing system, and the combination of drifter velocities with satellite sea surface height has produced definitive maps of global mean geostrophic surface currents.

Sensors and sampling

The standard sensor suite on a GDP drifter includes temperature and atmospheric pressure in addition to the estimates of velocity from displacement. With standard Argos communication, these observations are transferred to shore several times per day. A large variety of sensors have been deployed on drifting platforms, including acoustic Doppler profilers, conductivity sensors, meteorological instrumentation, and wave sensors. The surface waves themselves provide the energy for drifting profilers, such as the Wirewalker (Pinkel et al., 2011).

Operations

GDP drifters are deployed from ships of opportunity, from research to commercial container vessels. The drifters are relatively easy to deploy by minimally trained personnel. Operational costs include the price of the drifters, shipping, and communication. More capable drifting profiling platforms may require a dedicated research ship for deployment and recovery. The GDP drifters are very mature observing platforms.

3. Discussion

The tropical Pacific observing system of 2020 will be some combination of the technologies discussed above. Deciding on the balance between these different approaches is a challenging problem that depends intimately on the scientific requirements. Until these scientific requirements are determined, presumably as an outcome of the TPOS planning process, any attempt at scoping out an observing system is probably a futile task. However, as an exercise of the tradeoffs involved, we think it is worthwhile to discuss how the technologies might be combined to achieve resolution in space and time, and to realize operational efficiencies.

One conception of a tropical observing system would start with enhanced Argo float density in a band around the equator. With standard Argo float density of one float every 3° square, there are about 50 floats in the equatorial band ±1.5°. Doubling this density would require an additional 50 floats, which might be deployed from either volunteer ships or a relatively inexpensive dedicated vessel. An open question is how long the increased observational density would last considering dispersion of floats off the equator. Finer resolution in space and time, atmospheric reference observations, and more intensive chemical/biological sampling can be achieved using moorings, underwater gliders, and USVs, perhaps a few of each deployed at a finite set of different longitudes. While such an array would require dedicated ship time because of the distances to be covered, the servicing of several platforms of different types is an operational efficiency. Savings might also be realized to the extent that some of the mobile platforms can be deployed near land or from less expensive vessels. The implementation of the observing system requires careful analysis far beyond this brief discussion, but the creative process of going through the possibilities will be valuable in and of itself.

Transitioning an observing system to new technology is a challenging task. An aspect of this challenge is to preserve the integrity of long time series during the transition. The guidelines provided by the 10 GCOS monitoring principles are helpful. For example, running new and established technology in parallel for some time is essential. In the end, it takes a certain measure of daring to move on from methods that are tried and true. As long as this boldness is tempered by the resolve needed to sustain observations, the emerging technologies summarized above will likely lead to an improved tropical Pacific observing system.

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