Physical Oceanography from Deep Ocean Submarine Cable Observatories

Douglas S. LUTHER

Department of Oceanography, University of Hawaii

KEYWORDS: Physical Oceanography, Observatories, Instrumentation

ABSTRACT

Seafloor cabled observatories have an obvious role as part of the sustained infrastructure needed to observe climate variability. To highlight this point a couple of important discoveries of the physical climate of the ocean that have been based on data acquired at open ocean "observatories" are reviewed. Perhaps the more important role for observatories in physical oceanography may be the provision of an infrastructure that will permit long duration studies of the smaller scale processes in the ocean (e.g., vorticity waves, mesoscale eddies, sub-mesoscale vorticies, internal tides/waves, turbulence), enabling the direct study of the low-frequency variability of these phenomena as well as their interaction with other phenomena. Instrumentation developed in the last two decades, such as moored velocity and water property profilers, that can enhance the scientific return on investments in cabled observatories are noted. Some technological enhancements that are feasible and would be desirable for observatory-based instrumentation for physical oceanography are listed.

1. INTRODUCTION

During most of the last half of the 20th century, the study of physical oceanography (PO) was advanced primarily by analytical theory and expeditionary, usually exploratory, field work. With some notable exceptions, the long time series of oceanic properties that are now so earnestly sought for climate studies were acquired at "observatories" established for other purposes, such as the U.S. Ocean Weather Ship program. Despite the prodigious multi-national World Ocean Circulation Experiment (WOCE) [1] of the 1980's and 1990's, there are vast areas of the oceans that have never been plumbed by conductivity-temperature-depth (CTD) sensors or been visited by a sub-surface drifter. It cannot be seriously stated that even the important structures of the ocean's circulation have all been observed, to say nothing of their variability. Significant characteristics of even the most well studied currents such as the Gulf Stream continue to be revealed [2].

What has produced the greatest advance in observational PO in the last two decades is the satellite altimeter, which is in essence a global sea surface height observatory. The altimeters now flying, or to be flown, represent an infusion of large sums of money into the study of physical oceanography that dwarfs the annual oceanographic R&D budgets of U.S. Federal agencies. Only with the application of such large amounts of money can rapid progress be achieved. Unfortunately, the interior of the ocean cannot be accurately deduced with just observations of its surface, even with the aid of complex numerical models. This situation has led to the recent development of such programs as ARGO [3] which will eventually deploy thousands of sub-surface drifters to measure water properties beneath the ocean's surface.

In physical oceanographic field work there has always been a conflict among the variables space, time and money. To acquire data with adequate temporal resolution and duration at sufficient spatial locations to produce definitive information about any oceanographic phenomenon requires large sums of money. This conflict has produced solutions for climate research such as ARGO that will provide information on just the largest time and space scales of variability, because it is simply too expensive to permanently deploy and maintain thousands of deep ocean weather ship style stations.

Yet, the need for unambiguous discrimination of temporal and spatial variability is acute. Herein lies one of the great benefits of the ocean observatory concept. That is, that ocean observatories will be a significant component of a sustained infrastructure, complementing satellite missions and drifters, etc., that is required for the acquisition of full-water-column properties for long periods of time. At each of the suite of globally distributed observatory sites there will be the capability of continuously monitoring the ocean within a neighborhood of the observatory. This point is obvious for cabled observatories such as NEPTUNE [4] with its distributed nodes, but even for mooring observatories [5] it must be emphasized that an observatory site does not imply the acquisition of data at just a single geographic location. Time series from a number of locations within the neighborhood of the mooring can be expected to be acquired in order to address the impact of spatial gradients on temporal changes.

But observing climate changes may not be the greatest advantage of ocean observatories to physical oceanography. Ocean observatories, by establishing a permanent infrastructure providing power and communications, present the opportunity for the next great leap in data acquisition to study the dynamics of shorter period phenomena (vorticity waves, mesoscale eddies, sub-mesoscale vortices, internal tides/waves, and turbulence, to name just a few) in a large variety of environments (e.g., different stratifications, topographies, ambient mean currents) with as much temporal and spatial resolution as existing instruments can acquire. Multi-year experiment durations (almost unheard of in the study of smaller scale variability) promise to yield datasets to address longstanding questions about the low-frequency variability of these higher frequency phenomena, and about the interactions among the various time scales. These shorter period phenomena control much of the energy flow through the oceans, with expected significant impacts on horizontal stirring and vertical mixing of water properties that determine the ocean's climate state.

Given the limited space for this exposition, only a few points will be made here to motivate the opinions above. In Section 2, some notable discoveries made with data collected from spatially-fixed ocean "observatories" are described in order to argue, among other things, that even time series of low-frequency variability require relatively rapid sampling in order to avoid aliasing. Here, the term "observatory" is used in the broadest sense most familiar to oceanographers, that is, the acquisition of data from repeated collection of information at a single location, which collection need not have high temporal resolution, e.g., occupation of the HOT [6] and BATS [7] sites, quite well-described now as "observatories" occurs generally only for a few days every month (although there are installations of moored instrumentation, e.g., the Bermuda Test-Bed Mooring [8], which observe more frequently a subset of the variables that are acquired during the monthly occupations by research vessels). Except in Section 2, the term “observatory” will mean a permanent installation of components (buoy, cables, nodes, etc.) that provide power and real-time communications to the deployed instruments, as well as the means for regular maintenance and augmentation of the instrumentation (by research vessel, ROV, etc.).

In addition to the obvious utility of observatories to contribute to sustained climate observations, Section 3 provides a description of some advantages of the observatory infrastructure for the exploration of shorter scale (in time and space) ocean physics. In Section 4 is presented a classification system, with examples, for the kinds of physical oceanographic work enabled by the classes of planned observatories. Section 5 describes some less familiar, but extant, instrumentation that can be deployed (perhaps with some modification) on ocean observatories to acquire the data needed for studying the phenomena listed in Section 4. As well, Section 5 describes a few minor technological advancements which would greatly enhance the value of existing instrumentation that can be deployed at an ocean observatory.

This note deals generally with “deep water” physical oceanographic issues. It therefore suffers from a lack of discussion of coastal [9], air-sea interaction [10] and multi-disciplinary [11] science.

2. SOME IMPORTANT CLIMATE VARIABILITY DISCOVERIES MADE WITH PHYSICAL OCEANOGRAPHIC DATA FROM NON-COASTAL “OBSERVATORIES”

Well-sampled and long time series of variables such as current, temperature and salinity from the interior of the deep ocean are rare, but what they have revealed about the ocean is striking. Many of these observations came from the now-discontinued Ocean Weather Ships, which were only serendipitously located in places that were subsequently understood to be important oceanographically. For example, using OWS Bravo and nearby hydrographic data from the Labrador Sea, the formation of Labrador Sea Water (LSW) - an important component of the thermohaline circulation - has been found to undergo dramatic changes in properties, transport and depth of penetration over time scales of decades (e.g., Fig. 1). These LSW changes have an obvious value in tracing out the rates and pathways by which this mode water spreads, but their more important value arises from their role as part of a complex ocean-atmosphere coupling on decadal time scales (as opposed to ocean anomalies that are just the passive responses to atmospheric variability) [12].

In the North Atlantic, at Bermuda Station S, Joyce and Robbins [13] found a strong trend (nearly 0.5 deg C/century) in abyssal (1.5-2.5 km) temperatures from 1955 to 1995 (Fig.2). This time series, in addition to providing a remarkable peak at the possible large magnitudes of deep ocean climate variability, demonstrates an important advantage of “observatory” data. That is, with sufficiently rapid sampling, the context of occasional expeditionary datasets can be properly understood. For instance, the temperature differences that can be calculated between widely spaced (in time) hydrographic sections would otherwise be difficult to interpret; given Fig. 2, hydrographic data taken decades apart (for instance, 1955 vs. 1970) might not reveal any temperature increase in the abyssal waters. This incorrect conclusion would occur as the result of aliasing of the substantial inter-annual variability that is only revealed with the long and relatively well-sampled Station S time series.

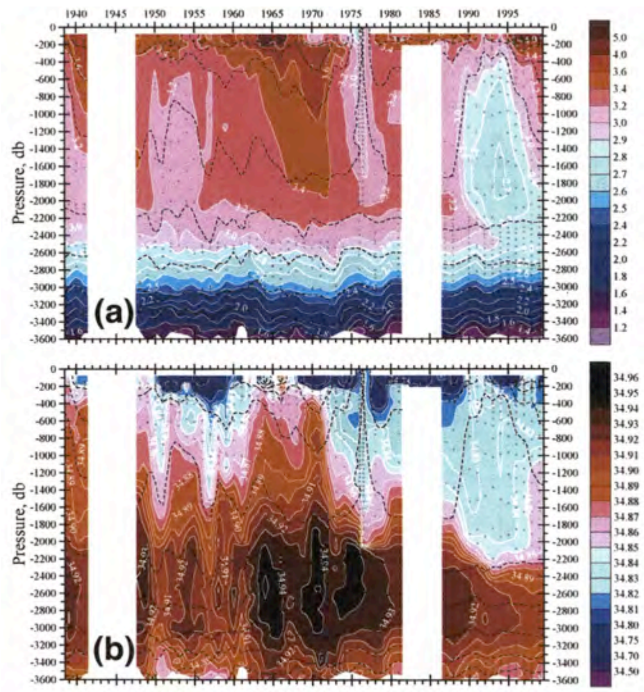

FIGURE 1: Changes in the potential temperature (top; deg. C) and salinity (psu) of the water column to a depth of 3600 dbars in the Central Labrador Sea from 1938 to 1999 [12]. Labrador Sea water is a major water mass in the North Atlantic between 1000 dbars and 2000 dbars.

Of course, these kinds of decadal variations in ocean properties can be derived over large domains from the infrequent hydrographic cruises and ship-of-opportunity datasets [14] but then temporal and spatial resolution are sacrificed and temporal and spatial variability are intertwined. As such, the potential for gaining insight into the physical mechanisms causing the variability is reduced. Only permanent observatories will provide the resolution in time (and distinction in space) needed to fully understand the inter-decadal variability of ocean water properties and circulation.

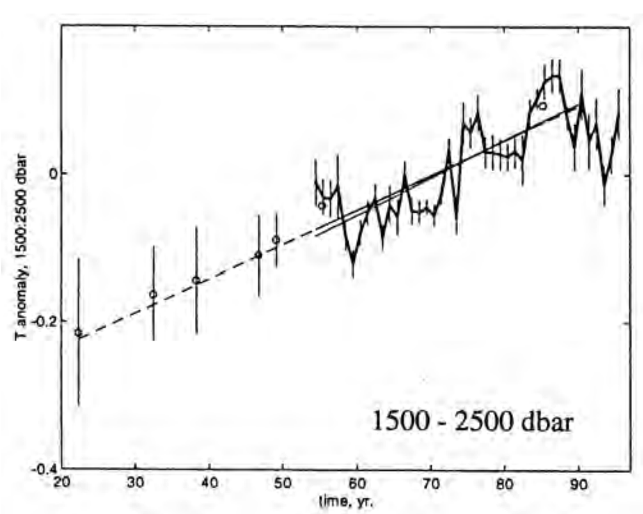

FIGURE 2: Temperature averaged for the 1500-2500 dbar layer, using hydrographic data taken at Station S near Bermuda, with additional hydrographic expedition data indicated by open circles. The trend line for the Station S data from 1955 to 1995 has a slope of 0.50 deg C/century (solid line). [13]

A unique "observatory" in the Florida Straits has yielded a remarkable oceanographic time series by measuring the motionally-induced voltage changes across the Straits as a proxy for Florida Current transport [15]. The inter-decadal variability of the transport, although weak, has been shown to be well-correlated (with opposite phase) [16] with a large-scale atmospheric mode of inter-decadal climate variability called the North Atlantic Oscillation (Fig. 3). I believe this is the first direct evidence of the impact of (non-ENSO) inter-decadal atmospheric variability on a directly measured component of the oceanic circulation (as opposed to transport inferred geostrophically).

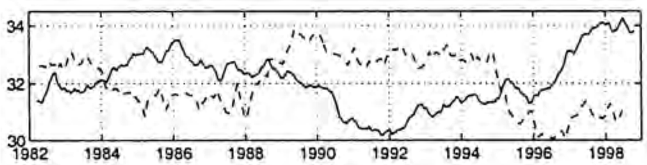

FIGURE 3: Two-year running mean (solid line) of daily Florida Current transports (in units of Sverdrups equal to 10^6 m^3 s^{-1}) inferred from submarine cable voltages spanning the Florida Straits from nominally Jupiter Inlet, Florida, to Settlement Point, Bahamas. The monthly mean North Atlantic Oscillation index (dashed line) was re-scaled for plotting to have the same mean and variance as the cable transport (unitless). [16]

3. WHAT IS THE VALUE OF CABLED OBSERVATORIES FOR PHYSICAL OCEANOGRAPHY?

The discoveries above and others that have revealed the long-term internal oceanic variability provide the classic motivation for acquiring long-duration physical oceanographic measurements at fixed locations in the deep ocean. Observatories, with their provision of continuous power and real-time communication, can provide exceptional temporal (and limited spatial) information on oceanic water properties at a non-trivial number of locations that will complement other methodologies (e.g., satellite altimetry, ARGO drifters) that provide water properties at more irregular space-time intervals.

But the opportunities for PO provided by cabled observatories go far beyond simply acquiring long time series of climate-relevant variables. Observatories, especially cabled observatories, promise to provide technological advantages which open up new dimensions for observing the ocean, such as long duration observations of small-scale features over broad spatial domains (e.g., 10 m shear from the bottom to the surface). As noted in the Introduction, physical processes working at small scales are expected to have a profound impact on how energy flows through the ocean and how water properties are dispersed (e.g., [17]).

In brief, there are, at least, three important advantages that observatories promise to provide to enable new paradigms in physical oceanographic field work. These are the same advantages provided to other disciplines, and are as follows:

- **continuous power** for:
  - high sampling rates (in space and time);
  - long duration (to observe the low-frequency variability of high-frequency processes and to observe the interaction of low- and high-frequency processes);
  - long duration (to capture intermittent events);
- **real-time communication** for:
  - evaluation of observational strategies of expected phenomena;
  - adaptive sampling of expected phenomena;
  - responsive event sampling of un-expected phenomena;
- **facilitation of instrument deployment and retrieval** for
  - repair, upgrades and experiment modification.

Considering the issue of continuous power, some examples will make the point. During the recent Near-Field component of the Hawaii Ocean Mixing Experiment (HOME [18]), Mark Merrifield and I deployed an RDI 75 kHz acoustic Doppler current profiler (ADCP) for 7 months. The deployed ADCP (Fig. 4) incorporated the maximum battery capacity available, because one of the goals of the experiment is to observe the longer-period (weeks to months) variability of the small-scale (8 m) vertical shear of horizontal currents, which can be related to turbulence energy levels. Yet, even with the extra battery capacity, in order to ensure the duration of the data collection for just 7 months we had to (i) reduce the number of individual 1-sec Doppler measurements averaged per stored sample to 18, thus increasing the expected noise per sample to a rather high rms of 1.7 cm/s, and (ii) lengthen the sampling interval to a non-optimum interval of 10 minutes (which meant the Nyquist frequency was less than the buoyancy frequency at some depths, where the buoyancy frequency is the highest frequency for the free internal gravity waves that are expected to produce the oceanic turbulence). There are so many time-dependent factors that can impact the nature and level of oceanic turbulence (e.g., "mean" current amplitude, direction and vertical shear, tidal amplitudes, inertial wave amplitudes) that a 7-month-long experiment is really quite inadequate to observe all the variability and interactions. Yet, to mount even this experiment required non-optimum sampling trade-offs due to the limited available power.

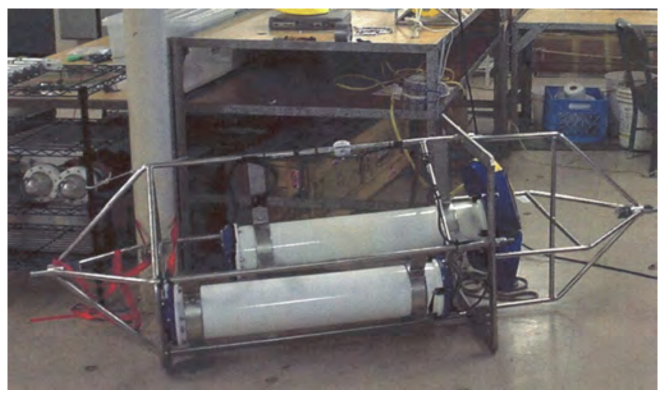

FIGURE 4: RDI 75 kHz ADCP just after recovery from a seven month deployment in HOME. The ADCP's transducers are at the right and face upward when the cage is attached to the mooring line. The second white cylinder in the foreground is an external battery case.

In some areas of the deep ocean it has been discovered that even lower frequency variability, such as mesoscale eddies, has a substantial intermittency (e.g., Fig. 5). Thus, infrequent events can dominate the transport of water properties, kinetic energy levels and the magnitudes of dissipation. Lukas and Santiago-Mandujano [20] describe a long-lived eddy observed at the HOT site in January, 2001, that drifted 3000 km from its origin off Central America, bringing with it radically different water properties than normally present around Hawaii. The implications of this observation for basin-wide property transport are still being investigated. A major difficulty is the lack of spatial information: how many eddies reach Hawaiian longitudes, but at latitudes (or times) not sampled by HOT? While the HOT program is a classical "observatory," observations are not made continuously but for only a few days each month. Therefore, while Lukas and Santiago-Madujano [20] found only one event in 13 years, they occupied the site for only about 15% of the time.

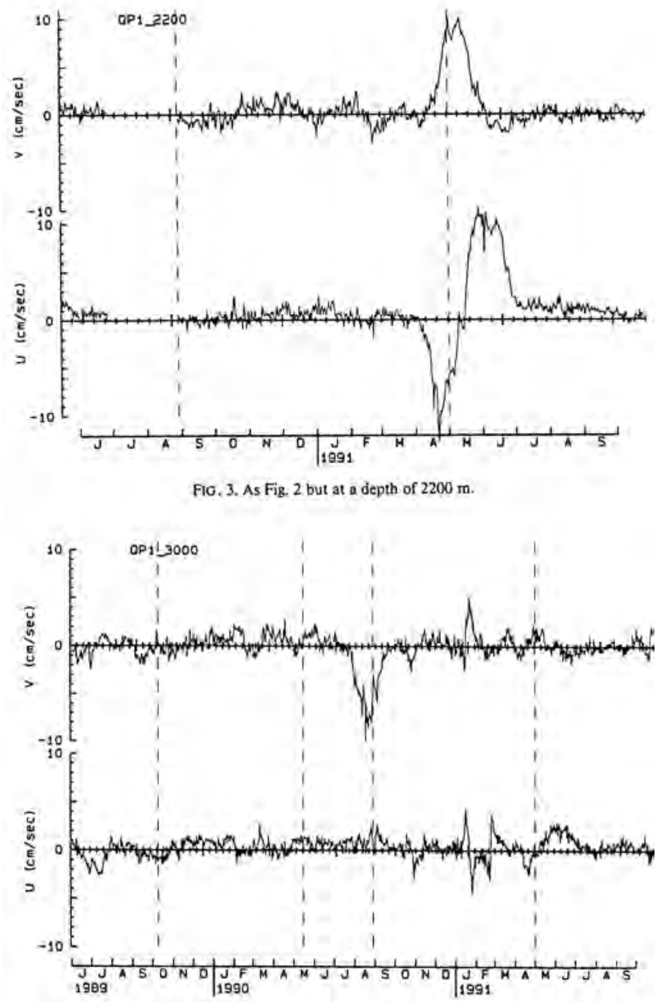

FIGURE 5 Zonal (U, positive east) and meridional (V, positive north) velocity measured at 49° 33' N, 138° 38' W at depths of 2200 m (top frames) and 3000 m for up to 28 months. The vertical dashed lines indicate the times of mooring recovery and servicing operations. Note the remarkable intermittency of the variability. [19)]

4. WHAT PHYSICAL OCEANOGRAPHIC SCIENCE IS ENABLED BY CABLED OBSERVATORIES?

4-1. A Hypothetical Study of Small-Scale Processes

One way to imagine the potential for new paradigms of investigation enabled by cabled observatories is to present a possible scenario for how physical oceanographic experiments would be established, maintained, modified and augmented over a few years. Consider an observatory that provides communication and power over a region encompassing multiple significant environments (that is, varieties of mean flows and variability, an assortment of differing topographies, and so on; NEPTUNE [4)] is an appropriate example). A team of oceanographers prioritizes the phenomena that can be studied. It is decided that the first experiment to be established will study the reflection of internal waves from a sloping boundary, the continental slope, where it's expected that there will be enhanced vertical shear (with enhanced diapycnal mixing [21)]) within 500m of the bottom, possibly accompanied by rectified flow [22)], and with low frequency variability along the slope providing the mechanical stirring of the mixed products into the interior of the ocean [17)].

A standard ship survey with profiling instruments [23)] identifies an energetic diapycnal mixing spot near a node of the observatory. A set of three 1000 m tall moorings in a triangular array is deployed on the slope at 1500 m depth and is connected to the node by cables. On each mooring are near-bottom 75 kHz ADCPs, as well as profiling CTDs [24)] with their docking stations that recharge their batteries and download data. Given the plentiful power available from the observatory, the ADCPs sample every second, providing currents every 12 m out to 700 m, thus observing the boundary layer and the domain of strongest amplification of internal wave energy produced by bottom interaction. The mooring spacing is set at 1 km.

During the first few months of the experiment the characteristics of reflected internal waves at the critical frequency are explored. Shear, strain, horizontal structure, rectified flow, etc., are studied. The choice of mooring spacing is found to be good, but the temporal sampling of the CTD as it profiles up and down the wire is found to be too infrequent. The CTD profiling scheme is re-programmed to provide more frequent samples over the near-bottom 300m.

As the experiment proceeds into the winter months, it's discovered that intermittent inertial waves generated by passing storms greatly affect the near-bottom shear magnitudes and scales even though the inertial wave periods are far from the local critical frequency. The ADCP is re-programmed to acquire currents every 8m. The CTD is again re-programmed to acquire data further up in the water column in order to observe the inertial waves before they begin to interact with the bottom. But it is also found that the 1 km spacing is too large during these events; horizontal coherence falls off in less than a kilometer. During the next maintenance run the moorings are moved closer together, or, preferably, two additional moorings are deployed within the original mooring array.

Even after a year at this site, the moorings are not removed. Much data is needed to study the variability of the slope processes on long time scales, especially as the local low frequency flows vary. But other phenomena need to be studied, such as the conversion of barotropic tidal energy into internal tides and local turbulence. So a second site (on the Juan de Fuca Ridge, for instance, if NEPTUNE is the hypothetical observatory) is chosen for establishment of an experiment to study this phenomenon. Instruments are again deployed in an array near an observatory node.

The revolutionary paradigm is the establishment of a series of experiments over a number of years, each of which is focused perhaps on a single physical process or the interaction of two processes, and all of which have no constraints on sampling due to lack of power, have instruments that can be re-programmed to alter sampling schemes as needed, are maintained for years, and are periodically upgraded and augmented as conditions and analyses dictate. Furthermore, all of the data is immediately available to any researcher, whether part of the observatory team or not. Not only does this paradigm supersede what would take numerous expeditions to accomplish otherwise, it achieves what is rare and difficult to achieve by expeditionary study of small-scale processes with self-contained instruments, that is, the study of the low-frequency variability of these phenomena and their interactions with lower frequency phenomena.

4-2. Classifying Opportunities for Physical Oceanography

The types of observatories - cabled, moored, coastal - result in a broad range of PO that can be addressed. In general, for each type of observatory, the applications for PO measurements can be classified as follows:

(1) Exploration.

Some topics are principally descriptive and exploratory in nature. While most science has an exploratory component, many investigations are based on substantial prior knowledge that permits the construction of reasonable hypotheses about what to expect. However, there still exist time and space scales of variability, as well as the modulation of known phenomena on long time and space scales, about which there is so little data that only crude hypotheses are possible. Studies of variability of this sort are what I call "exploratory." In this case, the scientific questions can usually be simplified to "What is out there?" E.g., what are the time scales and magnitudes of variability of oceanic variables in regions of the ocean where few measurements exist, let alone time series? What are the dynamics of the variability on time and space scales that have never been observed? Some specific subjects for "exploratory" investigation at NEPTUNE include the following: circulation driven by the discharge of hot water through deep seafloor vents; statistics of low-frequency flows in the deep ocean (recall Fig. 5 above); seasonal and inter-annual variations of the structure and statistics of mesoscale and sub-mesoscale eddies, and their interaction with the boundary, ridge, and general circulation; heat flux variability; the "climate" of topographic waves; linkages between coastal and ridge variability; etc.

(2) Baseline variability for climate change studies.

If there are no observations of the state of the ocean, "climate" changes in the ocean can't be deduced. This is a specific subset of "exploratory" science that deserves special attention due to its importance. As Wunsch [25] plainly stated "The history of oceanography, and the wider field of fluid dynamics, suggests that no amount of theory or modeling can compensate for missing observations."

Time series of oceanic variables in poorly-observed regions of the world's oceans are needed. And, temporal sampling needs to be sufficiently frequent to visualize not only the low frequency variability of ocean variables but also the low-frequency modulation of high-frequency phenomena. NEPTUNE, for instance, could address this issue with monitoring of regional barotropic and baroclinic mass transports, water column heat content, and temperature and property fluxes, while supporting long-duration studies of smaller-scale phenomena as outlined in Section 4a above.

(3) Ocean physics.

For many phenomena, the state of the art is sufficiently advanced to permit the construction of credible hypotheses that can be tested at ocean observatories. Some examples relevant to NEPTUNE include the following: baroclinic flow dynamics; eddy-mean flow interactions; direct atmospheric forcing of mesoscale variability in the presence of a boundary and acute topography (theories of the ocean's baroclinic response have not been well tested due to the long time scales involved); dynamics of ridge-trapped waves that are potentially important for dispersal and mixing of ridge crest effluents and biota; barotropic tide energy flux; generation of internal tides by distinct topographic features; reflection/transmission/scattering of internal tides; bottom boundary layer dynamics in distinct topographic environments in the presence of vorticity and internal waves, mesoscale eddies, and "mean" currents; infragravity wave sources; and, tsunami model validation.

(4) Synergisms.

PO observations can be used to support and enhance research in other disciplines [11], and to test the efficacy of new PO observational methodologies.

(5) Support of non-observatory science and technology development.

For example, observatory data can be used to provide ground truth for satellite missions or long-range acoustic tomography [26].

(6) Operational uses.

For example, observatory data can be input to real-time warning systems, such as PMEL's DART tsunami warning system [27], and will constrain numerical models for both research and operational uses.

While the examples provided above were primarily motivated by the concept of a regional cabled observatory such as NEPTUNE, there are plenty of examples for observatories based on the autonomous mooring concept [5] that will be distributed over the globe. In addition, globally distributed observatories enable truly global science in another way, by providing sound sources for sub-surface drifters and tomography between moorings, and power for AUVs, etc., which enable measurements far afield from the actual observatory location (especially, potentially, into very remote and harsh environments, like under ice or in near-polar seas), thus enhancing the infrastructure available for long-term observations of oceanic properties and circulation needed to establish "Baseline" climate variability. Thus, the "Seafloor Observatory" becomes much more than a single observation point of a suite of variables, but the tool that enables a set of basin-wide measurements.

5. INSTRUMENTATION TO ENHANCE THE VALUE OF CABLED OBSERVATORIES FOR PO

Perhaps the most important instrumental issue is how to achieve the horizontal and vertical spatial resolution of measurements of water column variables, given a (relatively small) set of observatory nodes. The most valuable existing sensors or techniques are those that extend the geographic impact of each cabled observatory node, i.e., the three-dimensional imaging capability. Some examples are as follows:

- Acoustic Doppler Current Profilers at 300 kHz, 150 kHz, and even 38 kHz (see Section 5.1 below), for high-resolution profiling in the bottom boundary layer, and coarser resolution current profiling up to 1000 m off the bottom;
- transducers for inverted echo sounding to acquire heat content time series [28] at nodes and baroclinic current structure between nodes [29];
- horizontal electric field recorders for measuring the total vector water transport; [30] [31]
- transducers for RAFOS float navigation;
- transducers for communication with outlying autonomous seafloor instruments;
- moored profilers, such as the McLane Moored Profiler (MMP) [24], to obtain water column profiles of temperature, salinity, O_2 and currents.

5.1 Short List of Desirable Technological Developments

Additional technological enhancements that would be highly desirable for observatory-based PO instrumentation are those that further extend the spatial and temporal imaging capabilities at each node and/or provide measurement capabilities that heretofore have not been possible on long-duration deployments in the ocean. Some examples are as follows:

- MMP docking station to download data and re-charge batteries;
- robust sensor design (or active cleaning capabilities) for MMP sensors to minimize the impact of bio-fouling;
- microstructure sensors for the MMP;
- low-frequency (e.g., 38-50 kHz) seafloor-mounted ADCPs for extended vertical range of direct measurement of currents, focusing on their small-vertical-scale shear;
- docking station & navigation protocols for autonomous vehicles (AUVs).

6. FINAL COMMENTS

Lest this presentation appears too optimistic, let me embrace a phrase from the SCOTS [11] report: "... the cabled observatory approach is clearly not the most practical or economical approach for every important scientific problem and cannot supplant observations from satellites, moorings, drifters, AUVs & gliders." This acknowledgment, however, does not diminish the prospect that deep ocean observatories may provide another paradigm shift in how the physics of the ocean is studied.

Physical oceanographers should not miss this opportunity, and observatory designers should keep in mind the value added by incorporating physical oceanographic instrumentation.

ACKNOWLEDGMENT

Some ideas in this note grew from discussions with Alan Chave, Bruce Howe and Tom Sanford.

REFFERENCES

1) Gould, J.: WOCE and the ocean observation revolution, *Sea Technol.*, 43 (10), 7-7 Oct, 2002.
2) Rossby, T and H.M. Zhang: The near-surface velocity and potential vorticity structure of the Gulf Stream, *J. Mar. Res.*, 59 (6), 949-975 (2001).
3) Wilson, S.: Launching the ARGO armada, *Oceanus*, 42 (1), 17-19 (2000).
4) Delaney, J.R. and A.D. Chave: NEPTUNE: A fiberoptic 'telescope' to inner space, *Oceanus*, 42 (1), 10-11 (2000).
5) 1999 DEOS Global Buoy Working Group Project, at http://www.coreocean.org/Dev2Go.web?id=208887.
6) Karl, D.M. and R. Lukas: The Hawaiian Ocean Time-series (HOT) program: Background, rationale and field implementation, *Deep-Sea Res., Pt. II*, 43 (2-3), 129-156 (1996).
7) Bermuda Atlantic Time-series Study, at http://www.bbsr.edu/ cintoo/bats/bats.html.
8) Dickey, T. et al.: Initial results from the Bermuda Testbed Mooring program, *Deep-Sea Res., Pt. I*, 45 (4-5), 771-794 (1998).
9) Coastal Ocean Processes Report, at http://www.coreocean.org/Dev2Go.web?id=208887.
10) Global Eulerian Observatories (GEO), at http://www.coreocean.org/Dev2Go.web?id=208891.
11) Scientific Cabled Observatories for Time Series (SCOTS), at http://www.coreocean.org/Dev2Go.web?id=208887.
12) Dickson, B. et al.: The world during WOCE, In: Ocean Circulation and Climate: Observing and Modeling the Global Ocean, G. Siedler, J. Church and J. Gould, Eds., Academic Press, San Diego, 557-583 (2001).
13) Joyce, T.M. and P. Robbins: The long-term hydrographic record at Bermuda, *J. Climate*, 9, 3121-3131 (1996).
14) Levitus, S. et al.: Warming of the world ocean, *Science*, 287, 2225-2229 (2000).
15) Larsen, J.C.: Transport and heat-flux of the Florida Current at 27 degrees N derived from cross-stream voltages and profiling data – Theory and observations, *Phil. T. Roy. Soc.*, A 338 (1650), 169-236 (1992).
16) Baringer, M.O. and J.C. Larsen: Sixteen years of Florida Current transport at 27 degrees N, *Geophys. Res. Lett.*, 28 (16), 3179-3182 (2001).
17) Munk, W. and C. Wunsch: Abyssal recipes II: energetics of tidal and wind mixing, *Deep-Sea Res.*, Pt. I, 45, 1977-2010 (1998).
18) Pinkel, R. et al.: Ocean mixing studied near the Hawaiian Ridge, *EOS*, 81 (46), 545 & 553 (2000).
19) Freeland, H.J.: Intense currents in the deep Northeast Pacific Ocean, J. Phys. Oceanogr., 23 (8), 1872-1876 (1993).
20) Lukas, R. and F. Santiago-Mandujano: Extreme water mass anomaly observed in the Hawaii Ocean Time-series, *Geophys. Res. Lett.*, 28 (15), 2931-2934 (2001).
21) Eriksen, C.C.: Internal wave reflection and mixing at Fieberling Guyot, *J. Geophys. Res.-Oceans*, 103 (C2), 2977-2994 (1998).
22) Zikanov, O. and D.N. Slinn: Along-slope current generation by obliquely incident internal waves, *J. Fluid Mech.*, 445, 235-261 (2001).
23) Lien, R.C. and M.C. Gregg: Observations of turbulence in a tidal beam and across a coastal ridge, *J. Geophys. Res.-Oceans*, 106 (C3), 4575-4591 (2001).
24) McLane Moored Profiler, at http://www.mclanelabs.com/mmp.html.
25) Wunsch, C.: Physical oceanographic and climate applications of fixed observatories, American Geophysical Union General Assembly, San Francisco, Calif., December, 1998, paper U32B-04.
26) Worcester, P.F. et al.: A test of basin-scale acoustic thermometry using a large-aperture vertical array at 3250-km range in the eastern North Pacific Ocean, *J. Acoust. Soc. Am.*, 105 (6), 3185-3201 (1999).
27) Bernard, E.N. and H.B. Milburn: Improved satellite-based emergency alerting system, J. Atmos. Ocean Tech., 8 (6), 879-883 (1991).
28) Watts, D.R. and H.T. Rossby: Measuring dynamic heights with inverted echo sounders: Results from MODE, *J. Phys. Oceanogr.*, 7, 345-358 (1977).
29) Meinen, C.S. and D.R. Watts: Vertical structure and transport on a transect across the North Atlantic Current near 42° N: Time series and mean, *J. Geophys. Res.*, 105, 21,869-21,801 (2000).
30) Sanford, T.B.: Motionally-induced electric and magnetic fields in the sea, *J. Geophys. Res.*, 76, 3476-3492 (1971).
31) Meinen et al.: Combining inverted echo sounder and horizontal electric field recorder measurements to obtain absolute velocity profiles, *J. Atmos Oceanic Tech.*, 19, 1653-1664.