A GLOBAL BOUNDARY CURRENT CIRCULATION OBSERVING NETWORK

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ABSTRACT

Western and eastern boundary currents are key regions for understanding and monitoring the ocean's influence on and response to climate change processes. Yet the present global ocean observing is poorly suited for capturing the small scales, intense currents, often large vertical extent, the eddy-rich conditions, and (for eastern boundary currents) the biogeochemical and ecosystem variables needed. This paper reviews available technologies and methods, none of which can satisfy all requirements for the needed observing system. Therefore, merged hybrid approaches are proposed, which need to be evaluated in each case since conditions vary strongly. A global network is presented as a vision, of which 50% has at least partial implementations already.

1. INTRODUCTION

The global system of oceanic boundary currents is a critical element of the ocean’s role in climate, yet the current sustained observing infrastructure is poorly suited for capturing the relevant processes and variability. Broadly speaking, western boundary currents (WBCs) represent a key climate *mechanism* while eastern boundary currents (EBCs) are strategic locations for societally relevant *impacts* of climate processes.

Mid-latitude WBCs in the upper ocean, by balancing the entire interior circulation of the oceans in a narrow, swift, warm current, play a dominant role in the poleward heat transport by the oceans, which is comparable to heat transport by the atmosphere at the tropical/subtropical boundary (*Bryan, 1982; Roemmich et al., 2001; Kwon et al., 2010*). Low-latitude equatorward WBCs in the Pacific are thought to contribute much of the meridional mass flux variability associated with the El Nino-Southern Oscillation (ENSO) (*Meinen et al. 2001; Kug et al., 2003*), and subpolar WBCs are critical due to their buoyancy transport in latitudes with low water column stability (e.g. *Katsman et al., 2004; Talley, 2008*). Deep boundary currents are the main subsurface conduit for the thermohaline circulation and thus control much of the abyssal transport, distribution, and residence time of properties. Beyond their direct transport of heat, mass and buoyancy, theory suggests that western boundary currents play a still poorly-understood role in the redistribution of potential vorticity (PV) that has been created by the basin-scale winds (*Katsman et al., 2001; Edwards and Pedlosky, 1998*). In particular, equatorward WBCs in the tropics must accomplish the PV modification that permits flow to and across the equator, as is required in all the tropical oceans.

EBCs are relevant as they carry the local effects of climate variability and are of vital economic and ecological importance for a variety of reasons (e.g., *Snyder, 2003; Wilkinson and Rounds, 1998; Roemmich and McGowan, 1995; Bakun, 1990*). Some of the world’s most important fisheries are along eastern boundaries, because they are sites of active upwelling, and strong eddy activity, but the ecosystems are often under stress and subject to important management activities. Also, variability in sea surface conditions along the eastern boundary affects atmospheric conditions along the western side of continents (e.g., *Haack et al., 2008; Bakun and Nelson, 1991*). Finally, the eastern boundary is tied robustly to the equator through coastally trapped waves, so that equatorial anomalies (as due to an El Niño) propagate poleward, causing fundamental changes in circulation and water properties (*Rouault et al., 2007; Merrifield, 1992; Enfield and Allen, 1983*). The mechanisms are still poorly understood by which the effects of equatorial disturbances reach poleward. The relative roles of atmospheric teleconnections, coastally trapped waves, and direct advection must be elucidated. Observations are also required of the pathways by which water reaches the upwelling zone, and how water properties get modified along this path. Such data are essential for a better understanding of ecosystems, the carbon cycle, ocean acidification, and for management of fisheries (e.g., *Chavez and Messie, 2009 and therein; Feely et al., 2008 and therein*). A challenge for an observing system is the role of eddies in the transport of physical and biological properties, and in the regulation of primary productivity. Eddies are strong relative to the mean flow along eastern boundaries, so their quantification is important.

A number of boundary current properties should be observed in a sustained fashion in order to complete a global ocean observing system. Foremost, the transport of mass, heat, and fresh water by these currents must be monitored to complement broad-scale globally-distributed observations and thus define basin-wide transports. The combination of these can provide time series of both the integral of transports through trans-basin sections and the structure of temperature, salinity and velocity fields which are needed to:

(1) establish the mean and seasonal cycles of mass, heat, and freshwater transports in order to explain the global circulation, heat engine, and water cycle and to validate the representation of these processes in dynamical models used to simulate global climate and its long-term variations;

(2) define interannual climate variability in order to (a) identify the key processes linking the ocean and atmosphere and connecting different regions, (b) characterize the physical environment affecting ecosystem management, and (c) define the temporal sequences of change to validate models used to forecast climate variability; and

(3) describe, in real-time, the structure of non-seasonal variability to assist, through data assimilation, initialization of models used to forecast weather and climate for operational purposes.

The program’s objectives also serve to define the user community for the observations. Boundary current and basin-wide transports and fluxes are essential for basic oceanographic/climate/ecosystem research and for societally-mandated documentation, attribution, and forecasting of climate variability, change, and impacts. As ocean and coupled modelling skill levels grow, applications grow in ocean data assimilation modeling and seasonal-to-decadal prediction. Indeed, the *global* ocean observing system, for all of its users, is seriously incomplete without boundary current observations.

Beyond mass, heat, and freshwater transports important to climate, a number of internal boundary-current properties need to be observed. These include the impact of the strong eddy activity, changes in potential vorticity, air-sea interaction, ecosystem dynamics, and biogeochemistry.

Having relatively small scales, boundary currents usually cannot be adequately sampled with the principal broad-scale networks that we rely on in the interior, i.e. Argo floats and satellite altimetry. The inherent properties of boundary currents pose particular observational challenges. The scales must be resolved to measure heat and freshwater transport even where geostrophy allows volume transport to be computed without such resolution. Boundary currents produce turbulence on multiple scales in response to coastline, bathymetric irregularities, and flow instabilities. The speed of WBC flows means they are inherently nonlinear, producing internally-generated variability that can be the dominant term in the momentum and vorticity balances, and which demands sustained sampling. High flow speeds through thick layers can make operation of various platforms untenable in some regions. WBCs often have large vertical extent, which can require full-depth profiling and cause assumptions about reference levels to be especially unrealistic. Finally intense fishing activity close to coasts poses problems of vandalism, while the need to work within EEZs (exclusive economic zones) can lead to political complications.

These diverse challenges will not be met by any particular tool, and a global boundary current strategy will demand multiple observational techniques tuned to the particular conditions of each current system. This document summarizes the challenges and technologies, existing and newly-emerging, that are proposed to meet them.

2. MOORING ARRAYS

Arguably, bottom-anchored moorings supporting instruments that span the water column are the “gold standard” for observing the time-varying ocean currents and water properties over sustained periods of a year or longer. The state of the art for mooring deployment duration is around 1 year for surface moorings and 2-2.5 years for subsurface systems, with 4-5-year subsurface installations undergoing proof-of-concept demonstrations now. Sensor durations however lag behind. While discrete conductivity-temperature-pressure sensors and some other devices can easily accommodate a 15-minute sample rate for 2+ years, many of the other instruments now available exceed their battery or memory capacities after about a year at this sample rate. The extended durations cited above require sampling at reduced frequency, risking aliasing error. Remarkably, some 30 years after the invention of the Vector Averaging Current Meter (VACM), there is no modern current meter presently available that is able to acquire “true” vector-averaged velocity data (or the practical equivalent) from the deep ocean at ½ hour interval for 2.5 years (the effective limit of the VACM). The sample-rate/endurance issue is even more problematic for the upper ocean where the buoyancy period is just a few 10s of minutes or shorter.

While often deployed in 2-dimensional arrays to explore flow dynamics, moorings have also been widely used to estimate transport by arranging them in a “picket-fence” configuration across a current. Perhaps the most widely-cited open-ocean transport value derived from a mooring line is the International Southern Ocean Study (ISOS) Drake Passage estimate for the Antarctic Circumpolar Current (ACC) at 134 +/- 13 Sv (*Whitworth, 1983; Whitworth and Peterson, 1985*). As the ISOS program discovered, a key design requirement for a transport array is that the mooring spacing be less than the decorrelation distance of the flow variations. Some ISOS mooring losses seriously degraded the array resolution in places, leaving open the possibility that at times, the Drake Passage array missed some of the ACC transport. Complementary horizontally-averaged velocity estimates derived from bottom pressure and dynamic height difference estimates spanning these gaps and the geostrophic relation were helpful in quantifying such errors. Another design requirement is that a transport array fully span the current being studied. Apart from those regions where a current is confined bathymetrically and it is feasible for the array to extend that full distance, the point where a particular current ends can be quite nebulous. This can make difficult transport estimate intercomparisons between arrays at different locations along a flow or between observations and model results. One aid to the former is the ability to partition transport estimates by density since bounds on the diapycnal velocity can be estimated. Such partitioning requires knowledge of the ocean temperature, salinity and velocity profiles.

These array design considerations, endurance limits and the costs associated with building, deploying and recovering oceanographic moorings dictate that the community can afford to instrument only a limited number of sites with transport-resolving arrays. Less-costly alternative approaches are detailed in adjoining paragraphs, but there is no capability presently able to return high temporal- and spatial-resolution volume and water-property transport estimates with accuracy comparable to those from a dense oceanographic moored array.

2.1 Example: Labrador Current

Downstream of the Greenland – Scotland overflows and the subsequent entrainment of ambient water, and also downstream of the main subpolar convection sites (the Labrador and Irminger Seas), North Atlantic Deep Water (NADW) is first combined in the Deep Western Boundary Current (DWBC) at the exit of the Labrador Sea. From there, all constituents of NADW are exported to both, the basin-wide subpolar recirculations and the deep limb of the meridional overturning circulation (MOC) (e.g. *Bower et al. 2009*). A moored ‘Labrador Sea Export Array’ was installed at this location to monitor the strength and variability of the DWBC on time scales from intraseasonal to decadal. The initial array, deployed from 6/1997 to 6/1999, consisted of 5 full ocean depth moorings with 21 current meters and ADCPs (acoustic Doppler current profilers) covering all deep water levels from upper LSW (Labrador Sea Water) down to the DSOW (Denmark Strait Overflow Water). In subsequent deployment periods, the array was reduced to 1 to 3 moorings, but the most recent 1-year installment (5/2009) has now 5 moorings across the core of the outflow.

The current meter data, supplemented by shipboard lowered ADCP and profiling floats, are used to establish a ‘reference’ state and corresponding transports of the Deep Labrador Current (DLC) (*Fischer et al., 2004*; Fig 1; lhs). It is also used for additional comparisons (*Dengler et al., 2006*) and monitoring of possible long term changes. A pronounced, about 100 km wide boundary current – the DLC – hugs the continental slope off the Labrador shelf break. The flow is baroclinic at the shelf edge, and also further offshore where the DSOW is focused in a bottom-intensified current core. The intermediate layers – mainly LSW - show only weak vertical shears.

During the last decade, weak convection activity (*Avsic et al., 2006*) and the lateral advection of heat by eddies led to substantial warming of the upper 2000 m of the Labrador Sea. This warming exists in the central Labrador Sea at a rate of 0.05 °C/y and is also present at the corresponding depth range in the DWBC along its path from the exit of the Labrador Sea to the Tail of the Grand Banks.

In contrast, the intensity of the DLC does not show any long term variations during that period, although interannual transport / flow variability of 10 – 20% has been observed.

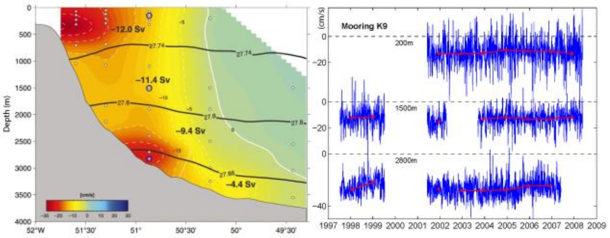

Figure 1. Two-year mean alongshore flow of the Deep Labrador Current (DLC) at the exit of the Labrador Sea (Fischer et al., 2004), with transports in water mass classes defined by isopycnals; rhs: a decade of current meter records from the centre of the DLC (blue circles) for upper, LSW, and DSOW levels; annual means in red.

3. SHIPS OF OPPORTUNITY (SOOP)

The unique advantages of SOOP (*Goni et al., 2010*) sampling in the boundary currents are both logistical and scientific, including (i) regular and low-cost access along repeating transects and (ii) the ability to integrate boundary currents with interior circulations or into basin-wide transports. The core SOOP measurement is eXpendable BathyThermograph (XBT) profiling to 800 m depth, with the High Resolution mode of XBT sampling (HRX) providing profiles at spatial intervals 10 to 50 km in boundary current and interior regions respectively (e.g. *Roemmich et al., 2001*). Additional SOOP measurements may consist of expendable conductivity-temperature-depth (XCTD) profiling, acoustic Doppler current profiling (ADCP, *Rossby et al., 2005*), marine meteorological observations, and surface water properties.

Regular SOOP/HRX sampling is being carried out in all five mid-latitude western boundary currents, with multiple crossings of the Kuroshio, the Gulf Stream, and the East Australian Current/East Auckland Current system. HRX boundary current sampling began as early as 1986 (East Auckland Current) and most of the time-series are longer than 15 years. Combinations of HRX and satellite altimetry (Fig. 1, *Ridgway et al., 2008*) have demonstrated the ability to estimate boundary current transport variability accurately on interannual and decadal timescales. In all oceans except the South Pacific, the SOOP transects span the full ocean basin at mid-latitude, including the western boundary current, the interior circulation, and the eastern boundary current, allowing basin-wide integrals of mass, heat, and freshwater transport (e.g. *Douglass et al., 2010, Uehara et al., 2008, Garzoli and Baringer, 2007*).

Limitations of SOOP sampling are: (i) it is possible only where there are stable commercial shipping routes, and (ii) measurements are limited to the upper ocean. ADCP measurements also require a substantial effort for installation, but the direct observations of boundary current velocity (*Rossby et al., 2005*) are uniquely valuable. A more complete description of SOOP sampling, objectives and results is provided in the OceanObs White Paper by *Goni et al. (2010)*.

3.1 Example: The Oleander Project – 16 years of Gulf Stream observations

The Gulf Stream has been studied extensively over the years. But with few exceptions, these studies and the concomitant estimates of its transport have been based on the dynamic method, an indirect method, which although accurate in its own way, can only obtain the velocity relative to some assumed (usually zero) reference velocity at depth. Further, given the very large scatter in these observations, it has proven difficult to accurately estimate the mean transport, let alone how it varies seasonally or from year to year. In late summer 1992 operation of an ADCP began with the installation of a narrow-band RD Instruments 150 kHz ADCP on the MV Oleander operating between Port Elizabeth, New Jersey and Bermuda. This instrument can reach to typically 250-300m depth depending upon location and sea state. In 2004 a 75 kHz Ocean Surveyor ADCP was installed and the project is in its 16th year of operation. This instrument reaches much deeper, typically in excess of 600 m in the Sargasso Sea in good weather. Figure 2 shows the meandering and mean velocity vectors between the continental shelf break and Bermuda for the period 1992 (fall) through 2008. Close to 800 transits to or from Bermuda contribute to this figure. It also shows the time variability of the flows in the three principal domains covered by the Oleander route: the Slope Sea, the Gulf Stream and the Sargasso Sea to Bermuda. One can thus examine the sections as a function of time to study the temporal and spatial variability of the current and neighbouring waters. Of the three regimes the Sargasso Sea is clearly the most variable with factor 2 variations in upper ocean transport.

4. UNDERWATER GLIDERS

Gliders (*Davis et al., 2002; Testor et al, 2010*) can provide, at a moderate cost, valuable augmentation of the present sustained observing systems used in boundary currents. These vehicles are optimized for relatively long duration compared with ship cruises or conventional AUV (autonomous underwater vehicle) operations, so they now operate at slow speeds of O(25 km/day) for ranges (distance travelled through the water, not carried by the currents) of 3000-4000 km. Following a saw-tooth pattern of diving and ascent while moving forward, many gliders can sample to 1000-m depth, or deeper, while others are limited to the upper 100-200 m but can operate into waters as shallow as 10 m. Glider operations are flexible because they communicate and are located by satellite while briefly at the surface and, therefore, do not require installation of acoustic tracking networks. Typically, gliders successively surface at distances of 5 to 6 times the maximum dive depth, thereby providing high spatial resolution (the mid-depth positions of 1000 m profiles are only 2-3 km apart).

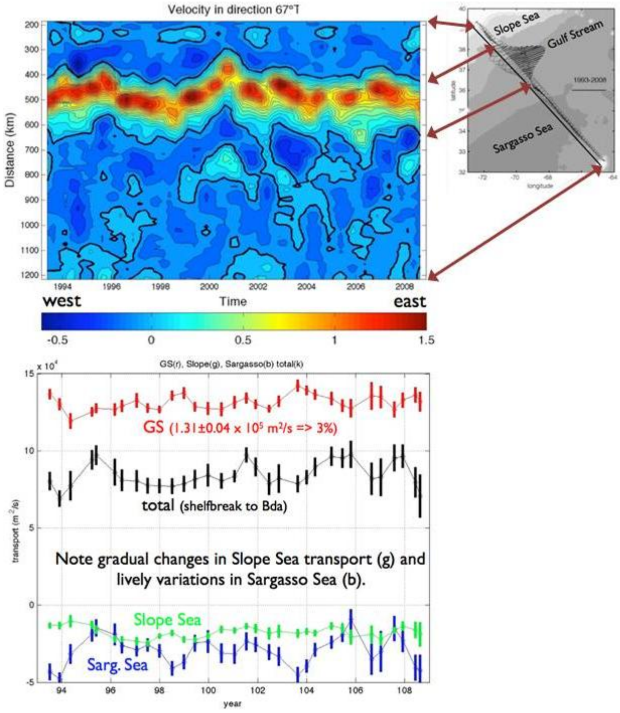

Figure 2. Top: Hovmöller diagram of velocity (m/s) in 67°T from shelf break to Bermuda (left) and mean velocity vectors and associated variance ellipse (right) for the period 1993 through 2008. Bottom: 55 m transports (1 m layer) with standard errors. Three principal domains covered by the Oleander route: the Slope Sea, the Gulf Stream and the Sargasso Sea to Bermuda.

Many small, low-power sensors are available to complement the depth-average velocity inferred from glider dead-reckoning and successive surface positions. CTDs provide density from which geostrophic shear can be calculated and referenced to the depth-average flow to obtain absolute geostrophic velocity; T and S are valuable tracers of water type and source and needed for heat and freshwater fluxes. High-frequency (600-1000 kHz) ADCPs measure current shear with depth which can, with care, be integrated and referenced to provide directly measured absolute velocity with which ageostrophic transports can be observed. A large number of water properties can also be mapped, including chlorophyll fluorescence as an indicator of phytoplankton abundance; acoustic backscatter strength as an indicator of zooplankton and/or fish abundance; optical backscatter and CDOM (coloured dissolved organic matter) as a measure of water source and plankton type; and oxygen, which serves as a tracer of water source and also describes changes in the geographical and depth ranges where low oxygen concentrations dramatically affect the ecosystem. More sensors are becoming available for gliders but sensor suites will always be limited by available energy; adding an ADCP to a glider decreases its range 20-25%.

Gliders complement other boundary-current observing systems in several ways:

(1) Relatively low operating costs and vehicle loss rates of about 3% per operation provide time series of mass, heat, and freshwater transports at moderate costs. Spatially dense glider sampling (station spacing of less than 3 km is typical) resolves the small cross-stream scales of boundary currents.

(2) The combination of accurate dead reckoning and navigation provides a reference for geostrophic shear calculations.

(3) Glider subsurface measurements complement satellite measurements of sea surface temperature, ocean colour, and sea surface height, although at only at a few points. Gliders can sample close to shore where satellite SSH measurements are confused by bathymetry and topography. In addition, gliders can sample across the continental slope and into shallow inshore water better than e.g. moorings.

Sampling strong boundary currents with ocean gliders is made difficult by their slow speed compared to the ocean velocity; for example, the ratio of glider speed and depth-averaged currents are 1:5 in the core of the Gulf Stream. Gliders can be operated in a mode similar to a swimmer crossing a river: the glider swims perpendicular to the current while being swept downstream. When cast in a stream-wise coordinate system gliders can provide a cross-section of the boundary currents when along-stream variations are small. Comparison of glider-measured water properties and geostrophic currents referenced by depth-average velocity and ship-borne sections across the Gulf Stream showed little differences, even though geostrophic velocities are compared to ADCP measurements. With repeated transects, gliders can monitor integral properties, such as transports of mass, heat, and freshwater, within boundary currents and also provide estimates of the structure of the boundary currents in stream-wise coordinates.

For boundary currents that are not in the vicinity of research institutions or convenient ports, either significant fractions of the mission must be used for transit or significant ship-time will be needed to service the gliders. The economic advantage of gliders is greatest when operations can be done near shore from small boats.

Since existing gliders can only operate to 1000m, they sample only the upper portion of boundary currents, which can omit a significant fraction of the current. The ability to use the absolute vertically-averaged velocity from dead reckoning and navigation data to reference the upper geostrophic shear is crucial in this situation, but the complete vertical structure of boundary currents can still be missed.

4.1 Example: glider observations of a low-latitude western boundary current

The equatorial Pacific, where cold water normally upwells from the Equatorial Undercurrent, is the site where air-sea interaction modulation impacts global climate. The New Guinea Coastal Undercurrent (NGCUC) connects the South Equatorial Current to the western equatorial zone where it feeds the Undercurrent. It has been hypothesized that variations of the properties (*Gu and Philander, 1997*) or the volume transport (*McPhaden and Zhang, 2002*) of this transport path can change the oceanic heat source for equatorial air-sea interaction, thereby affecting climate variability. In order to understand the variations of the NGCUC a US – New Caledonian consortium has been monitoring it with gliders since August 2007.

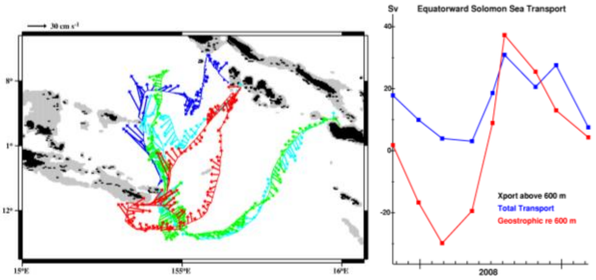

Figure 3. Left: Color-coded tracks and 0-600 m average current velocity (vectors) from four Spray cruises measuring the flow through the Solomon Sea. The land mass at the left (water depths of 0-200 m are shaded) is the reef southeast of New Guinea; the islands on the upper right are the Solomon Islands. The blue track spans July-October 2007; light blue is November 2007 - February 2008; green is February-July 2008; and red is July-November 2008. Right: Time series of integrated equatorward 0-600 m transport for each trans-basin section. Blue is the absolute transport from referenced geostrophic shear. Red is the transport above 600 m of geostrophic shear relative to 600 m. Early 2008 was a La Nina period in the tropical Pacific; the fraction of the low-transport anomaly associated with this remains to be seen when the seasonal cycle has been determined.

Because rapid flow in the boundary current was expected to make it impossible to repeat a prescribed sampling track, gliders measure the transport through the Solomon Sea between the southeastern tip of New Guinea and the Solomon Islands. The region and the tracks of the first four cruises are shown in Fig 3a along with vectors showing the 0-600 m depth average current velocity. The tracks do not coincide primarily because several begin and end positions were used and detours were taken to explore the region but at times the current field prevented maintaining the desired track.

Strong seasonal and/or interannual variability of the flow through the Solomon Sea is shown in the transport time series in Figure 3b. This shows the integrals of both the measured flow above 600 m and the geostrophic shear relative to 600 m.

5. END-POINT MOORINGS AND PIES

Complete horizontal integrals of the geostrophic mass transport through a section can be obtained from knowledge of the vertical pressure distribution at the end points (if the Coriolis parameter f is approximately constant), which in turn may be calculated from the density profiles to within an unknown offset. This is the classical method to estimate geostrophic flows from ship-board hydrographic data, but in recent years it has become possible to carry out such observations continuously from moorings (*Kanzow et al 2008*). Extremely careful calibration of moored temperature, conductivity, pressure measurements allows to achieve accuracies in dynamic height of *0.15-0.2cm* from vertical integration of density over a water column of 4000m depth (*Kanzow et al 2006*). This allows transports to be estimated with e.g. an accuracy of 0.3Sv per 1000m depth at 30°N. The unknown integration constant is equivalent to the absolute horizontal pressure gradient (along an equipotential surface) at some depth or the absolute horizontally integrated flow at some level. Without that, only the flow relative to some reference level can be determined.

Bottom pressure measurements have reached an equivalent accuracy, at least over time scales of months. Thus the fluctuations of horizontally integrated geostrophic flow at the bottom can be determined from pairs of bottom pressure sensors, and the transport of the water column above can be calculated from the density measurements above the pressure sensors. This allows quantification of the complete transport fluctuations from end-point moorings with density profile measurements and bottom pressure.

In some cases, vertical traveltime (IES, inverted echo-sounder) between the bottom and the surface is highly correlated with dynamic height of the surface. This is usually true only in a regime with a 1½-layer dynamics, i.e. a single degree of freedom where the variability of a surface layer over an inactive deep layer leads to a mirror image between the surface height and pycnocline depth (with opposite sign). Adding bottom pressure (PIES) allows determination of a second degree of freedom, e.g. surface and interface depth moving independently such as in clear 2-layer systems (e.g. Denmark Strait overflow, Strait of Gibraltar). These are still flows/transport estimates relative to some reference level, and sometimes an absolute current measurement at the bottom using a current meter (C-PIES) is used to provide this. Since that is not a horizontally integrated measurement however, it does not help in determining horizontal flow integrals (transports) over large distances without resolving the flow structure (which is just the strength of end-point techniques).

While end-point techniques are powerful in capturing horizontal mass transports over large distances, they do not resolve any internal structure and thus also not the horizontal correlation of T and S with the flow (i.e. heat and freshwater transports).

5.1 Example: Deep western boundary current

An end-point array has been maintained for 9½ years at 16N in the west Atlantic, between the Antilles islands (Guadeloupe) and the Mid-Atlantic Ridge, an approximately 1000km long section (CLIVAR/AMOC project "MOVE"). The goal is to study the southward transport of the North Atlantic Deep Water (NADW), assuming it is balanced by northward flow above it and thus providing an overturning transport estimate. The section includes most of the boundary current flow of the NADW, and the integration far into the interior removes the need to define where the "end" of the boundary current is. The small component of the flow shoreward of the deep end-point mooring section is captured by a simple single current meter mooring (found to be sufficient after starting with more intensive current meter moorings on the continental slope). The 9½ -year long timeseries of internal (density-derived, referenced to a "level of no motion") and continental slope transport show large intra-seasonal fluctuations (which are not reduced if the bottom-pressure component is added) and a long-term weakening trend.

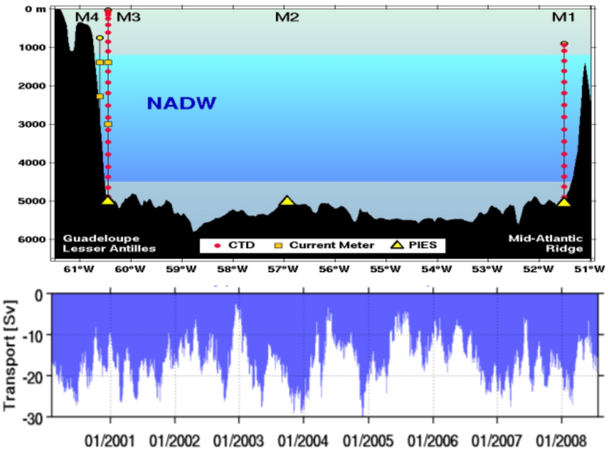

Figure 4. Top – MOVE section with endpoint moorings and PIES. Bottom - Absolute internal plus continental slope transport of NADW through the MOVE section from end-point moorings with density sensors. The long-term mean is -14.9Sv (southward).

6. ELECTROMAGNETIC OCEAN TRANSPORT OBSERVATIONS

Basic physics electromagnetic theory requires that when charged particles, such as salt ions in seawater, move through a magnetic field, such as that produced by the Earth, an electric field perpendicular to the motion of the ions is created. Because seawater is electrically conductive, the electric fields created at different depths essentially 'short' together to produce a single electric field that represents the vertical integral of the horizontal transport. *Stommel (1948; 1957)* pioneered the first applications of this basic physics principle to the ocean, attempting to collect estimates of the volume transport of the Gulf Stream/Florida Current between Key West and Havana by measuring the voltage induced on a submarine telephone cable. Analysis of this early electromagnetic-derived data proved difficult, however, and subsequent research identified one challenge to this technique. Because ocean sediments are also electrically conductive, and because that conductivity varies based on sediment type, in regions where ocean currents can meander over significantly different types of sediment the transport-induced electric field can 'short' by varying amounts into the sediments, resulting in measured voltage changes that are unrelated to transport fluctuations (*Schmitz and Richardson, 1968; Wunsch et al., 1969; Larsen, 1992*). In regions where ocean currents cannot meander widely, such as the Gulf Stream/Florida Current in the northern Straits of Florida, this is not an issue, and the first successful applications of the electromagnetic technique were made with a telephone cable spanning the Straits between the east coast of Florida and Grand Bahama Island between 1969 and 1975 (*Sanford, 1982*). A long-term NOAA program restarted those measurements in 1982 and has continued them nearly continuously to the present (e.g. *Larsen and Sanford, 1985; Baringer and Larsen, 2001*). This technique is powerful in that it provides a true vertical and horizontal integration of the transport instantaneously – low pass filtering of the data, required to eliminate variability associated with the magnetic field of the Earth, results in daily averages of transport. It should be noted that the voltages involved in these measurements are small, and to monitor for cable breaks, wiring problems, and volt-meter offsets it is necessary to make regular calibration checks on the cable using in situ transport observations, such as using dropsonde observations from a ship. Nevertheless, in regions where cables exist spanning tightly confined ocean currents, this technique is extremely cost effective and produces reasonably accurate near-real-time data (correlations better than r=0.8 since 2004 between dropsonde observations of transport from ships and concurrent cable estimates).

A parallel use of electromagnetic theory has resulted in the development of free-standing, bottom moored, instruments that measure the induced voltage at essentially a single point; with filtering to reduce geomagnetic noise the result is daily estimates of the vertically averaged horizontal velocity at a single location once the instrument is recovered (e.g. *Chave and Luther, 1990; Luther et al., 1991*). These instruments, referred to as Horizontal Electric Field Recorders, or electrometers, have been used to measure major ocean currents such as the Antarctic Circumpolar Current (e.g. *Meinen et al., 2002; 2003*) and efforts are presently underway at the Univ. of Washington to merge the electrometer with the PIES (Tom Sanford and Doug Luther, personal communication, 2009). Where the submarine cable technique requires regular in situ ship sections for calibration checks, an electrometer array can be ground-truthed using a single tall current meter mooring, which can reduce costs in some circumstances (*Chave et al., 2004*). Both techniques, cable and electrometer, represent innovative and cost effective ways to measure boundary currents now and into the future.

7. SATELLITE ALTIMETERY

Satellite altimetry data have been utilized intensively in monitoring the flow field of various boundary currents. For example, transport of the Kuroshio south of Japan has been estimated since 1992, during missions of the TOPEX/Poseidon altimeter and its successors (Jason-1 and Jason-2) measuring the sea-surface height repeatedly every ten days; assuming geostrophy, the total transport of the Kuroshio was found to be proportional to the sea-surface dynamic height difference across the Kuroshio along a sub-satellite track (*Imawaki et al., 2001*). The horizontal resolution along a track (less than ten kilometers) is satisfactorily fine, although the distance between tracks (200 to 300 km) is rather large. Those joint NASA-CNES altimetry missions will be succeeded by the joint CNES-EUMETSAT-NOAA mission of Jason-3 to be launched in 2013–2014. The altimetry missions should be continued on the same satellite tracks, in order to obtain the continued long-term sea-surface height data. Horizontally two-dimensional surface flow fields of boundary currents have also been studied. For example, variation of the Kuroshio axis position has been monitored using the surface flow field estimated from combining the satellite altimetry data with satellite-tracked surface-drifting buoy data (*Ambe et al., 2004*); the weekly gridded data used were composed from a few altimeters' data by AVISO. Those gridded data are inevitably contaminated by temporal variability measured at different times during the week. The planned altimeter SWOT (Surface Water and Ocean Topography), which is designed to measure the sea-surface height in the swath along sub-satellite tracks, will provide the horizontally two-dimensional height field with much finer resolution. Recent gravity satellite missions including GRACE (Gravity Recovery And Climate Experiment) are providing a geoid model much more accurate than precedents, which could be used as the reference to estimate the absolute sea-surface dynamic height. The horizontal resolution, however, is not fine enough to be used for narrow western boundary currents.

8. EXPLOITING THE SYNERGIES: HYBRID APPROACHES

The above discussions and examples clearly document that no single technique exists which can observe all required aspects of boundary currents in various settings, while several individual technologies have matured and proven themselves in recent years. The obvious step then would be to combine several approaches and merge their respective strengths, in order to obtain more complete and accurate observations of the essential boundary current properties.

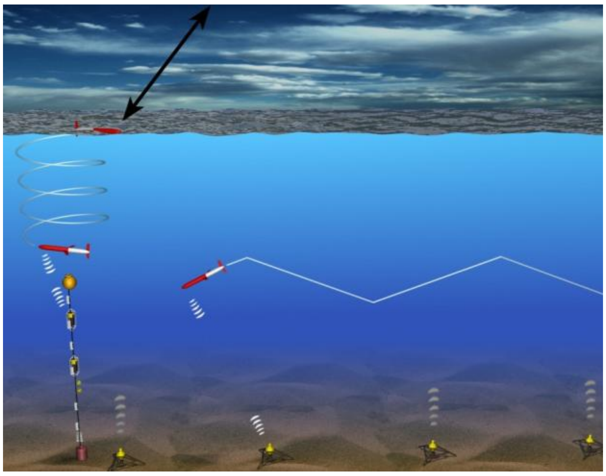

Figure 5. Example of hybrid approaches merging upper-ocean glider sampling, horizontal integration using moorings, and vertical integration using PIES. In the figure here the gliders also act as data shuttles for subsurface instruments.

The "right" mix of technologies depends on many aspects like the time scales of interest, the depth range that needs to be covered, the complexity of the vertical structure, the strength of the currents, the size of the signals and accuracy sought, the accessibility, availability of vessels, and the range of variables wanted. Also, in many cases a more intensive network may be desirable initially to learn about the degrees of the freedom of the system, in order to then design a sparser and cost-effective observing scheme. Finally, it must be kept in mind that there is no "end" of a boundary current but that it merges smoothly with the ocean interior, thus a connection with the interior-basin observing system is important. In order to fully exploit the synergy between various approaches and their different space-time sampling/averaging, data assimilation may be best suited to fully exploit the complimentary information. Here we can only give a few conceptual examples of hybrid approaches.

- *Deep or deep-reaching boundary currents:* The above end-point mooring example from MOVE is a cost-effective starting point for obtaining timeseries of deep mass transport. Satellites, XBT's, gliders, ship ADCPs, or PIES currently cannot deliver this. However, if additional information like heat transport is sought, supplementary data are necessary. Gliders can provide this in the upper 1000m or so, and a set of PIES along the section could fill in the heat content below that and the deep flow with some horizontal resolution.
- *Shallow slow boundary currents:* Eastern boundary currents probably can be well observed mainly with gliders, which can also provide some of the vital ecosystem information in those regimes. If high time resolution of some components is needed to capture events or guard against aliasing, end-point moorings or gliders in virtual mooring mode can be added, or altimetry may provide surface components (consider co-locating section with altimeter tracks). XBT sections provide an ideal connection to the basin interior.
- *Single-mode currents:* The Gulf Stream and the Kuroshio can to first order be treated like a 1½ layer geostrophic current, with a single degree of freedom. Altimetry or end-point PIES work well in this case. If water mass changes are expected/possible, or if the lower layer is also active, end-point moorings bracketing the strong flow regime would provide additional constraints.

9. A PROPOSED GLOBAL NETWORK

Ideally, a global network of boundary current monitoring arrays will be optimized within the greater ocean observing system, i.e. the arrays would connect to end points of high density repeat XBT lines, lie on repeat satellite altimetry tracks or cross-over points, or overlap with long-range coastal radar installations. They can also be connected to dedicated basin-wide arrays, such as the UK/US program RAPID/RAPID-WATCH, which is merging cross-basin section transport observations with moored boundary current observations by the US MOCHA program and with Florida Strait transports using cable measurements (*Cunningham et al, 2007; Johns et al, 2008*).

By embedding in the broad-scale observing system, the boundary current information can be more easily given a larger context, as well as providing intercalibration opportunities between sensor and platform types which is crucial for establishing a bias-free climate record.

There is a clear requirement to monitor the heat, freshwater, and volume fluxes carried by the intense boundary currents of the subtropical gyres – notional locations are indicated by blue bars in Figure 6. The subpolar gyres are areas of low stability and deep ventilation which is sensitive to freshwater transports – these can and need to be observed at locations exemplified by the orange transport arrays. We further envisage the need to quantify the connection between the equatorial current systems and the subtropical gyres as they feed and possibly modulate each other, with conceptual sites shown by the black arrays. In the eastern boundary regimes, fast coastal Kelvin waves largely ensure a coherent along-shore low-frequency response, and thus the minimum global requirement would be for one array along these boundaries (pink in Figure 6). The global network should also include arrays or systems monitoring the major interbasin exchanges (*Gordon et al, 2010*), which may use similar technologies (green in Fig. 6).

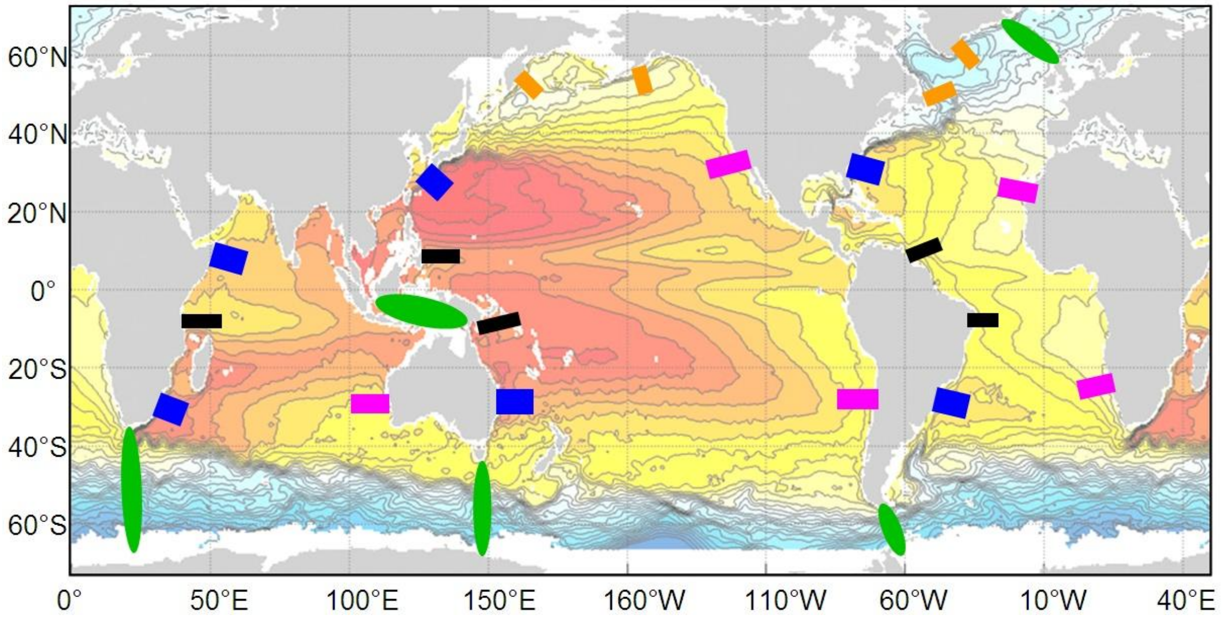

Figure 6. Conceptual locations for a global network of boundary current arrays. Subpolar boundary current arrays are shown in orange, poleward subtropical western boundary systems in blue, equatorward low-latitude boundary systems in black, major eastern boundary systems in pink. Green shows the possible locations of arrays to monitor key interbasin exchanges. The background field is surface dynamic height from Maximenko et al. (2009). The locations are notional and not meant to represent specific existing or planned programs.

10. INITIAL IMPLEMENTATION STEPS

Just as a global observing system for the ocean interior was not practical prior to the development of profiling floats, an observing system for the world's boundary currents has been similarly limited by a lack of enabling technology. Recent developments including autonomous gliders and cost effective moorings create opportunities that are now being tested in prototype observing systems. Prototype systems such as those in the California Current, the Solomon Sea, and elsewhere are the next step toward implementing global sustained observations.

However, the ideal boundary current observing system is still not practical, that is, one providing high resolution observations in space and time along the full length of the ocean's boundary currents. Progress can be made by initiating or supplementing sustained observations at key locations for each boundary current. The along-current dimension may not yet be fully accessible, but the "key locations" strategy can provide essential global constraints on the ocean's time-varying mass, heat, and freshwater budgets.

An analogous sampling strategy was adopted during WOCE, where a trans-oceanic hydrographic section was linked to a western boundary current moored array in all subtropical oceans near 30N or S. The challenge now is to exploit technology-based efficiencies to implement sustained measurements rather than the 1-2 year "snapshots" of WOCE, and to do this at more key locations. Clearly there is no universal prescription for a boundary current observing system. Sites must be selected and designed individually, based on regional knowledge and requirements, and prioritized globally. General principles to be used in the process of selection, design, and prioritization, are:

1. Select sites that allow boundary currents to be tied to basin-scale observations (e.g. repeat hydrography, Argo, High Resolution XBT transects).
2. Exploit and supplement existing or historical measurements and sites wherever possible.
3. Design cost-effective sustainable long-term observations, but with more intensive short-term measurements as needed for validation and interpretation. Previous examples include cable measurement of Florida Straits transport with occasional in situ validation observations, or satellite altimetry in combination with moored arrays, XBT, or repeat hydrographic transects.
4. Develop collaborations between technology experts and regional groups having capacity for logistical and technical support. This could take the form of identified "facilities" for moorings, gliders, hydrography etc. and a collaborative international

mechanism for joining their capabilities with regional support providers.

5. Adopt a “global” perspective from the outset by selecting initial sites according to their contribution to the global observing system. Avoid a northern hemisphere bias by pressing national agencies to agree that global coverage is essential.

The global system in the map above is feasible, possibly with the exception of the western Indian Ocean sites. Arrays near many of the notional locations are already being operated or planned (see also *Gordon et al., 2010*), which would give a presence and at least partial implementations at approximately 50% of the sites. Completion should be a community goal.

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