

Oceanic Boundary Currents

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ABSTRACT – Measurements of oceanic boundary currents for integral quantities such as heat and freshwater transports are very important for studying their long-term impacts on the global climate. There are a variety of boundary currents, including surface, intermediate and deep boundary currents on both the western and eastern sides of ocean basins. The dynamics and physics of these boundary currents are different, as are the ways of monitoring them. Here, we choose to explore the strategies adopted for observing four representative boundary current systems which have been the subject of detailed studies in recent years: the Kuroshio; the East Australian Current; the Indonesian Throughflow; and the low-latitude boundary current system of the Atlantic.

The transport of the Kuroshio south of Japan has been monitored using satellite altimeter data in conjunction with an empirical relation between the transport and sea surface height difference across the stream. Monitoring the transport of the East Australian Current has been achieved by repeated high-resolution expendable bathythermograph (XBT) and/or conductivity-temperature-depth profiler transects maintained at several locations, supplemented with satellite altimeter data. Repeated XBT transects have also been used to monitor transport of the Indonesian Throughflow, in association with current meter and other instrumental estimations of transport through a few major throughflow straits. Finally, the complicated flow field of the low-latitude boundary current system of the Atlantic has been revealed using neutrally buoyant floats, moored current meters and hydrographic observations. The survey will be continued using further advanced observation technologies.

Introduction

The ocean circulation comprises a broad spectrum of currents ranging in character from the basin-scale gyres down to micro-scale motions associated with mixing and turbulence. In contrast to the atmosphere, the large-scale ocean circulation is essentially bounded, not only by the continental land masses but also by the submarine relief. The amplitude of the relief is of the same order as the depth of the ocean circulation, unlike the atmosphere where orography only directly influences the lower atmosphere. This boundedness has many profound consequences, one of which is the tendency for the formation of distinctive flow regimes adjacent to the boundaries, both at the surface and in the deeper ocean. It is these boundary currents that are the subject of this paper.

Boundary currents are an important and integral part of the global oceanic three-dimensional circulation scheme. They advect substantial amounts of heat, fresh-water and mass between the two hemispheres. Their fluctuations are prime agents for climatic changes. There are a variety of boundary currents, including surface, intermediate and deep boundary currents on both the western and eastern sides of ocean basins, and also interior boundary currents. Surface western boundary currents, including the Gulf Stream, Kuroshio, East Australian Current, Agulhas Current and Brazil Current are swift, narrow and deep, with large transports. In contrast, surface eastern boundary currents, including the Canary Current, California Current and Benguela Current are relatively slow, wide and shallow, having relatively small transport. These boundary currents are

Table 1. Classification of boundary currents (BCs), with some examples

	Western BC		Eastern BC	
Surface BC: Intermediate influence on climate	Swift; O (100 cm/s) Deep (>2000 m) Large transport (>50 Sv) sharp boundaries with coastal circulation		relatively slow; O (10 cm/s) less deep (<500 m) low transports (<10-20 Sv) different regime near boundaries parts of upwelling regions	
	Examples: Gulf Stream Kuroshio East Australian Current Agulhas Current Brazil Current		Examples: Canary Current California Current Benguela Current	
Intermediate and deep BC: Indirect (long-term) impact on climate	Compensation currents as part of the global circulation (No-name)			
	IWBC of the South Atlantic or South Indian DWBC of the Atlantic	AAIW NADW	Poleward undercurrents	Upwelling related
Interior BC: Unknown impact on climate	Currents under control of mid oceanic ridges			

IWBC Intermediate Western Boundary Current

DWBC Deep Western Boundary Current

AAIW Antarctic Intermediate Water

NADW North Atlantic Deep Water

believed to have a considerable influence on climate change. There are a variety of intermediate and deep western boundary currents, although most of them have no identifiable names. Table 1 briefly summarises the features of boundary currents, according to Gross (1972).

The dynamics and physics of these boundary currents are different; so are the ways of measuring them. The following account reveals a variety of monitoring methods, including repeated expendable bathythermograph (XBT) sections, repeated expendable conductivity-temperature-depth profiler (XCTD) sections, moored current meters, inverted echo sounders (IESs), inverted echo sounders with pressure gauges (PIESs), conductivity-temperature-depth recorder (CTD) moorings, an underwater cable, shipboard acoustic Doppler current profilers (ADCPs), and a regional acoustic tomography array. There are a variety of float technologies, including neutrally buoyant floats such as RAFOS, profiling floats such as Argo, and self-steering profiling floats (gliders). Utilization of

satellite altimeter data from TOPEX/POSEIDON and other satellites will be crucial in conjunction with these technologies.

The large number and wide variety of boundary currents in the global ocean prevents a detailed review of the dynamics and measurement strategies in this paper. Instead, we choose to explore the strategies adopted for observing four representative boundary current systems that have been the subjects of detailed studies in recent years. These are the Kuroshio, the East Australian Current, the Indonesian Throughflow and the low-latitude boundary current system of the Atlantic.

The Kuroshio is the (surface) western boundary current of the subtropical gyre of the North Pacific. Recently, a group called 'Affiliated Surveys of the Kuroshio off Cape Ashizuri' (ASUKA) carried out a set of measurements across the Kuroshio south of Japan (Imawaki et al., 1997, 2001). The transport of the Kuroshio is

determined by geostrophic calculation using repeated hydrographic survey data, referenced to velocities observed by current meters moored at mid and abyssal depths. A procedure was developed to estimate a time series of volume transport of the Kuroshio from the TOPEX/POSEIDON altimeter data, based on a high correlation between the measured transport and the difference in sea surface height across the Kuroshio. The Kuroshio transport will be monitored also with tide gauge and submarine cables at several locations.

The East Australian Current is the (surface) western boundary current of the subtropical gyre of the South Pacific. Three high-resolution XBT transects have been maintained for 7–13 years across the East Australian Current: two transects (Brisbane–Fiji and Sydney–Wellington) along the Australian coast and one transect (Auckland–Fiji) where the current separates from the Australian coast and reattaches at New Zealand. Present analysis is focusing on monitoring the East Australian Current transport using a combination of the XBT data with TOPEX/POSEIDON altimeter and coastal tide gauge data.

The Indonesian Throughflow is closely related to western boundary currents of the Pacific and considered here as a boundary current. Due to the complexity of the bathymetry as well as the low latitude of the entrance channels, monitoring the Throughflow is challenging. The longest record of Throughflow mass and temperature transport is based on a repeated XBT transect between Australia and Java. Monitoring sea level on each side of the major Throughflow straits by a shallow pressure gauge array could be the most cost-effective means of monitoring transport.

The low-latitude boundary current system of the Atlantic consists of a confusingly large number of partly opposing surface and deep currents. In fact, the system covers the whole water column. These boundary currents can be seen as limbs of the global thermohaline circulation with its prime propulsion in the northern North Atlantic, i.e. the Greenland and Labrador seas. Besides more conventional tools of ocean observations such as current meter moorings, CTDs, ADCPs and the like, adequate modern methods such as autonomous current profilers and ‘geostrophic moorings’ are under discussion or have already been applied, in order to solve the puzzle of recirculation elements

and their impact on the variability of the net heat transport across the equator.

For more detailed accounts of the effect of bathymetry and regional current regimes, the reader is referred to traditional textbooks (e.g. Tomczak and Godfrey, 1994). A useful reference relating to the Gulf Stream is Rossby and Gottlieb (1998), which describes monitoring of the stream by an ADCP mounted on a merchant vessel.

The next sections describe the four selected boundary current regimes in detail and present examples of the application of various measurement techniques. They are followed by concluding remarks.

Kuroshio

The North Equatorial Current flowing westward broadly bifurcates in the westernmost region of the North Pacific, and the northern branch forms a strong western boundary current, the Kuroshio. The primary part of this current, in a shallow layer at depths above 1000 m or less, enters the East China Sea from east of Taiwan, proceeds north-eastward along the continental slope, and flows out to the North Pacific through the Tokara Strait (Fig. 1). The deep part of the boundary current flows along the eastern slope of the Ryukyu Ridge outside the East China Sea. This may partly or wholly join the Kuroshio flowing out from the East China Sea through the Tokara Strait, and may compose a deep part of the Kuroshio south of Japan.

Recent studies

Recently, the ASUKA Group endeavored to measure the Kuroshio and its recirculation south of Shikoku, Japan, and estimate their absolute volume and heat transports (Imawaki et al., 1997, 2001). The observation line (Fig. 1) was chosen to coincide with a subsatellite track of the altimetry satellite TOPEX/POSEIDON, which has been measuring the sea surface height since 1992 (Fu et al., 1994). During the period 1993–1995, nine moorings equipped with 33 current meters were maintained along the observation line to start the intensive survey. During this two-year period, the ASUKA Group carried out hydrographic surveys along the line repeatedly, using CTD and/or XBT, in order to estimate upper-layer velocities, which cannot be measured adequately by moored current

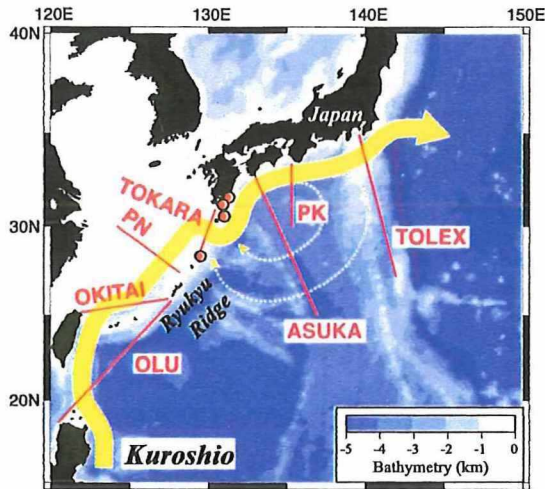


Figure 1. Observation lines across the Kuroshio, superimposed on the bathymetry. TOLEX: ferry ADCP line; PK: hydrographic section; ASUKA: *in situ* and satellite monitoring line; TOKARA: ferry ADCP line; PN: hydrographic section; OKITAI and OLU: underwater cable measurement line. Red dots are tide gauge stations at the Tokara Strait.

meters; in total, 42 repeat sections were obtained for the Kuroshio region. This field measurement was carried out as the PCM5 array of the World Ocean Circulation Experiment (WOCE), and for the Global Ocean Observing System (GOOS).

Geostrophic velocities are calculated from repeated hydrographic survey data, with reference to velocities observed at mid and abyssal layers. The profile of the sea surface dynamic topography (SSDT) is estimated on the basis of absolute geostrophic velocities at the sea surface. The volume transport of the Kuroshio for the upper 1000 m depth is estimated from the absolute geostrophic velocities obtained above. Here the Kuroshio is simply defined as the entire eastward flow.

The estimated transport of the Kuroshio is found to have a very high correlation with the SSDT difference across the Kuroshio (Imawaki et al., 2001). The estimated Kuroshio transport varies from 27 to 85 Sv ($1 \text{ Sv} = 10^6 \text{ m}^3/\text{s}$) for 25 selected hydrographic surveys carried out during the two years. Figure 2 is a scatter plot of the Kuroshio transport for the upper 1000 m and SSDT differences across the Kuroshio. The correlation coefficient between these two quantities is high, and the rms (root-mean-square) difference from the regression line (with a slope of 81 Sv/m) is small. This high correlation can be

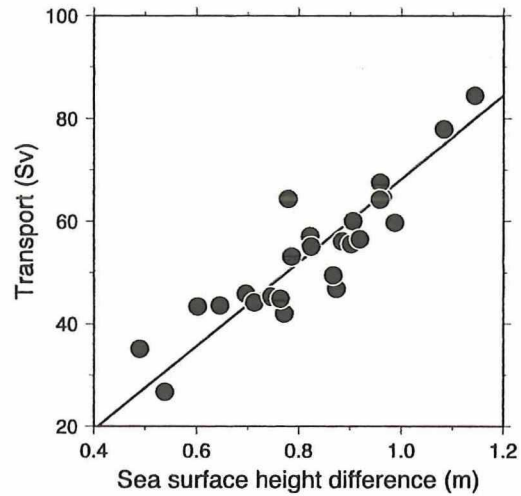


Figure 2. Scatter plot of the Kuroshio transport (in Sv) for the upper 1000 m and sea-surface dynamic height difference (m) across the Kuroshio. Twenty-five cases are shown. The correlation coefficient is 0.90 and the rms difference from the regression line (solid line) is 5.6 Sv. Adapted from Imawaki et al. (2001).

understood by examining the vertical profile of the Kuroshio transport per unit depth. Individual transport profiles vary greatly, but if the transport is normalized by the sea surface transport, the profiles become almost the same. Thus, the total transport is almost proportional to the sea surface transport per unit depth, which is proportional to the SSDT difference across the stream; in other words, the increase (or decrease) of the total transport results from a proportional increase (or decrease) of all the layers of the Kuroshio.

Having this relationship, the SSDT difference across the Kuroshio derived from TOPEX/POSEIDON altimeter data provides a time series of the Kuroshio transport with sufficiently fine resolution and as long a duration as the satellite operates. Figure 3a shows a 7-year record for 1992–1999 obtained in this way, the first long-term record of the Kuroshio transport with sufficient temporal resolution. Altimeter-derived transports agree very well with transports estimated from *in situ* data. Here, only anomalies from the temporal mean are used from the TOPEX/POSEIDON altimeter data. In the present analysis, the above-mentioned SSDT profiles estimated from *in situ* data along the ASUKA line are combined with SSDT anomalies from altimeter data, in order to obtain the mean SSDT profile. The

sum of this mean profile and anomalies from the altimeter data gives us the absolute SSDT profile. Tide gauge data at Cape Ashizuri (at the northern end of the ASUKA line) are used as sea surface heights on the coastal side of the Kuroshio, where the altimeter cannot work well.

The Kuroshio transport fluctuates greatly around a mean of 57 Sv. Part of the transport is associated with the transport of the stationary local anticyclonic warm eddy located on the offshore side of the Kuroshio (Hasunuma and Yoshida, 1978). The present estimate of the Kuroshio transport necessarily includes the eastward transport of the northern part of this eddy, which is assumed to be equal to the westward transport of its southern part, that is, the westward-flowing Kuroshio recirculation. Activities of propagating cyclonic and anticyclonic mesoscale eddies are very high in this region. Most of the fluctuations shown above are associated with those mesoscale eddies, whose contributions should also be excluded. The transport of the westward-flowing Kuroshio recirculation is estimated in a similar way using the altimeter data and the relationship between the transport and SSDT difference obtained for the Kuroshio recirculation. Here the Kuroshio recirculation transport is estimated between the offshore edge of the Kuroshio and 26°N latitude. The southern extent is fixed at this latitude, partly because it is close to the southern end of the stationary local anticyclonic warm eddy climatologically (Hasunuma and Yoshida, 1978) and partly because eddy activities were lowest there on the ASUKA line during 1992–1999, as deduced from altimetry. The throughflow transport is estimated by subtracting this recirculation transport from the above-estimated Kuroshio transport (Fig. 3b). The 7-year mean of the transport is estimated to be 42 Sv. The transport and its variability are reduced, in comparison with those of the Kuroshio as the eastward flow.

The present high correlation between the Kuroshio transport and SSDT difference across the Kuroshio provides a practical way of long-term monitoring of the transport using satellite altimeter data. A similar high correlation has been previously suggested between the geostrophic transport and SSDT difference for the Kuroshio (Nitani, 1975). A very similar combination of estimates of transport and SSDT difference for the Kuroshio south of Japan was found recently in a global ocean circulation model (P. Saunders, pers.

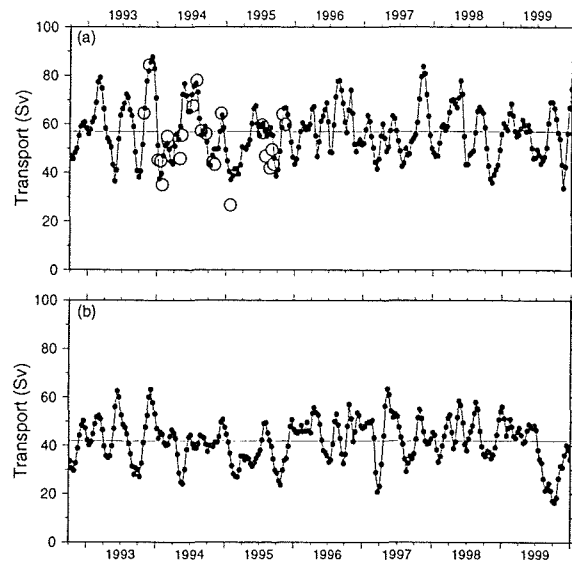


Figure 3. Time series of the Kuroshio transport (solid line with dots; in Sv) south of Japan during 1992–1999, estimated from TOPEX/POSEIDON altimeter data using the relationship between the transport and sea-surface dynamic height difference (Fig. 2). A Gaussian 3-point filter with weights (0.25:0.5:0.25) has been used. Panel (a) is the transport of the Kuroshio as the eastward flow. Also shown are transports (open circles) estimated from *in situ* data. Panel (b) is the transport of the Kuroshio as the throughflow (see text for definition). Adapted from Imawaki et al. (2001).

comm., 1998). A similar significant linear relationship has also been found for the Kuroshio east of Taiwan from recent field measurement of the WOCE PCM1 (Johns et al., 2001). Such a relationship may hold, more or less, for most western boundary currents.

Sea level data from tide gauges (Fig. 1) south of Kyushu are useful for monitoring volume transport of the Kuroshio in the East China Sea. Kawabe (1995) obtained regression equations of sea level for Kuroshio transport, by fitting these data to geostrophic transport at the PN line observed and computed by the Nagasaki Marine Observatory, Japan Meteorological Agency (JMA). They are quite effective, also, for monitoring interannual variations of Kuroshio transport, and were used to study the large meander of the Kuroshio (Kawabe, 1995, 2001). The regressions show that the volume transport is estimated well by the sea level difference from one side of the Kuroshio to the other.

Hydrographic surveys of the Kuroshio have been carried out since the mid-1950s at several

locations, including the PK and PN lines (Fig. 1) by the Kobe and Nagasaki Marine Observatories, respectively, of the JMA. Since the 1970s, surveys have been performed four times a year for these two lines. Upper-layer velocities of the Kuroshio have been measured by ADCPs on ferry boats along the Tokyo–Ogasawara Line Experiment (TOLEX) line maintained by Tohoku University (Hanawa et al., 1996) and the Tokara Strait line (TOKARA), maintained by Kagoshima University, since the early 1990s (Fig. 1).

Measurement of the voltage generated by electromagnetic induction due to ocean water movement, using a submarine cable, is an effective way to monitor the volume transport of the current flowing over the cable, and this method has been employed in the Strait of Dover, the Straits of Florida, the Tasman Sea, and so on. Monitoring the Kuroshio transport using this method is just beginning. Voltage measurements commenced in June 1998 for submarine cables between Okinawa and Taiwan (OKITAI cable) and between Okinawa and Luzon (OLU cable) (Fig. 1).

Prior to estimating transport using the induced voltage technique, close attention must be given to the following: First, noise from magnetic storms and spikes due to earth current must be removed from the voltage data. Corrections using geomagnetic data are being tried for this purpose. Second, voltages must be converted to volume transport. Equations for the conversion are being developed by observing the volume transport over the cables with a free-falling sonde, lowered and shipboard ADCPs, and CTD. The first such observation was made in September 2000 with the R/V *Hakuho Maru* (University of Tokyo).

Recommendations

- Satellite altimeter missions should be continued for more than decades.

It has been found that the volume transport of the Kuroshio can be estimated from altimeter data, using the high degree of correlation between transport and the difference in SSDT across the Kuroshio. The TOPEX/POSEIDON altimeter, which has been measuring the sea surface height since 1992, will be followed by JASON-1, to be launched by the end of 2001. (The reader is referred to a JASON-1 web site at <http://jason-1.jpl.nasa.gov/>.) JASON-1 will repeat exactly the

same orbit as TOPEX/POSEIDON. It is crucial to continue the altimeter observations along the same orbit; this will provide a very long time series of SSDT along the fixed subsatellite tracks, including the ASUKA line. The Kuroshio transport estimates will then be available every 10 days as long as these altimeter satellite missions continue.

- Intensive *in situ* observations of the Kuroshio and Kuroshio Recirculation should be repeated occasionally (every 10–15 years).

The high correlation, mentioned above, between the transport and difference in SSDT across the Kuroshio will hold in the future, but the slope of the regression line (Fig. 2) may change slightly in time. Therefore, it is preferable to repeat the Kuroshio and Kuroshio Recirculation observations similar to the past, including moored current measurements, repeated hydrographic surveys and others, in order to confirm the correlation, every 10 to 15 years.

- PIES observations in the Kuroshio region should be maintained.

During the ASUKA observations in 1993–1995, nine IESs were maintained under the Kuroshio and Kuroshio Recirculation. Two sites on the coastal and offshore sides of the Kuroshio have been maintained following the ASUKA observations. Recently, a procedure has been developed to estimate vertical temperature profiles from IES data, using the regional gravest empirical modes (GEM), derived from numerous hydrographic profiles in that region (Meinen and Watts, 2000). This procedure has been found to be applicable to the Kuroshio region (Book et al., 2001) and will be able to estimate geostrophic velocity and transport fairly accurately, using historical temperature and salinity (T–S) relations. The two IESs on both sides of the Kuroshio will provide a time series of baroclinic transport of the Kuroshio. These IES/PIES measurements should be continued for decades.

- Tide gauges around Japan should be maintained in the future.

Sea level observations with tide gauges are very important for monitoring the Kuroshio in terms of current velocity, volume transport, and current axis variations (Kawabe 1995). Tide gauges have been maintained by the JMA, the Hydrographic Department of the Japan Coast Guard and the Geographical Survey Institute of Japan. We

emphasize that the heights of datum lines of tide gauges should be measured continuously using the Global Positioning System (GPS), in order to measure the vertical displacement of the ground and estimate the exact height of the sea surface. This is crucial to tide gauge observations at the coast and islands around the Kuroshio, for long-term Kuroshio variability studies.

- Hydrographic surveys of the Kuroshio around Japan should be continued.

The JMA and other organizations have maintained several hydrographic sections (Fig. 1). Some of these surveys date back to the 1950s and have been providing very important records, especially for decadal variability studies. Observations of upper-layer velocities of the Kuroshio by ADCPs on ferry boats along the TOLEX and TOKARA lines (Fig. 1) also should be continued in the future.

East Australian Current

Past and present studies

The western boundary current of the South Pacific subtropical gyre is sampled by a series of three high-resolution XBT transects crossing the current at widely spaced locations (Fig. 4); the reader is referred to a web site for the high-resolution XBT/XCTD networks at <http://www.hrx.ucsd.edu>. The East Australian Current flows southward along the east coast of Australia, crossing line PX30 at Brisbane (26.6°S) and line PX34 at Sydney (33.9°S). The current separates from the coast before reaching Sydney, but it overshoots the XBT line southward before turning back to the northeast and recrossing PX34. Part of the separated current flowing eastward in the Tasman Front reattaches to the northern coast of New Zealand (Fig. 4) as the East Auckland Current, crossing the PX06 line at 35.5°S. Thus, the XBT transects capture the boundary current in three distinctly different domains. Figure 4 shows the location of the three transects overlain on a map of dynamic height anomaly at the sea surface relative to 2000 dbar, objectively mapped from the National Oceanographic Data Center archive data supplemented by recent stations, as described by Roemmich and Sutton (1998). Quarterly sampling is carried out along each XBT transect; this began in 1986 along PX06 and in 1991 along PX30 and PX34. XBT profiles down to 800 m are collected at intervals of 10 to 40 km along-track, with sparse XCTD profiles along PX06.

The mean and standard deviation of temperature fields for the three boundary current crossings are shown in Fig. 5. In each case, the mean current axis is located by the offshore drop in the height of isotherms, with a recirculation also seen on the offshore side of each crossing. The overall variability is highest at Sydney and lowest at Auckland. Interestingly, the variability is relatively low near shore in each transect, increasing to a maximum at the offshore side of each crossing.

The quarterly sampling of the high-resolution XBT transects does not resolve variability in the boundary currents occurring on timescales of days to months. While the focus of the sampling program is on seasonal to interannual variability, it is necessary to account for the aliased frequencies. Present analyses focus on using TOPEX/POSEIDON altimeter data to supplement the XBT transects in the time domain. Figure 6 shows a comparison of XBT and TOPEX/POSEIDON transport estimates for the East Auckland Current at the PX06 line. In the upper panel, a time series of surface geostrophic velocity is shown, integrated from the inshore edge of the transect near the 200 m isobath, to the mean location of the offshore side of the current (35.6°S to 33.6°S). Geostrophic velocity from XBT data is relative to 800 dbar, using historical temperature/salinity (T-S) relations supplemented with XCTD casts to estimate salinity (see. Gilson et al., 1998, for example). Surface geostrophic velocity from TOPEX/POSEIDON is adjusted to have the same temporal mean as for the XBT data. Good agreement is seen between the two time series, including the disappearance of the current in mid-1997, when it meandered offshore. One can also see that the altimeter captures substantial variability on timescales shorter than three months, for example in late-1994 and early-1995. The lower panel of Fig. 6 shows similar time series, except that the transport is over the depth range 0–800 m. For this estimate, TOPEX/POSEIDON surface height is used, together with a correlation function relating surface height anomalies to subsurface density structure to estimate the subsurface flow field down to 800 m (Gilson et al., 1998). Again, it is seen that the TOPEX/POSEIDON and XBT series are in reasonable agreement.

A second limitation of the XBT transects is their 800 m depth range. It is clear from the mean

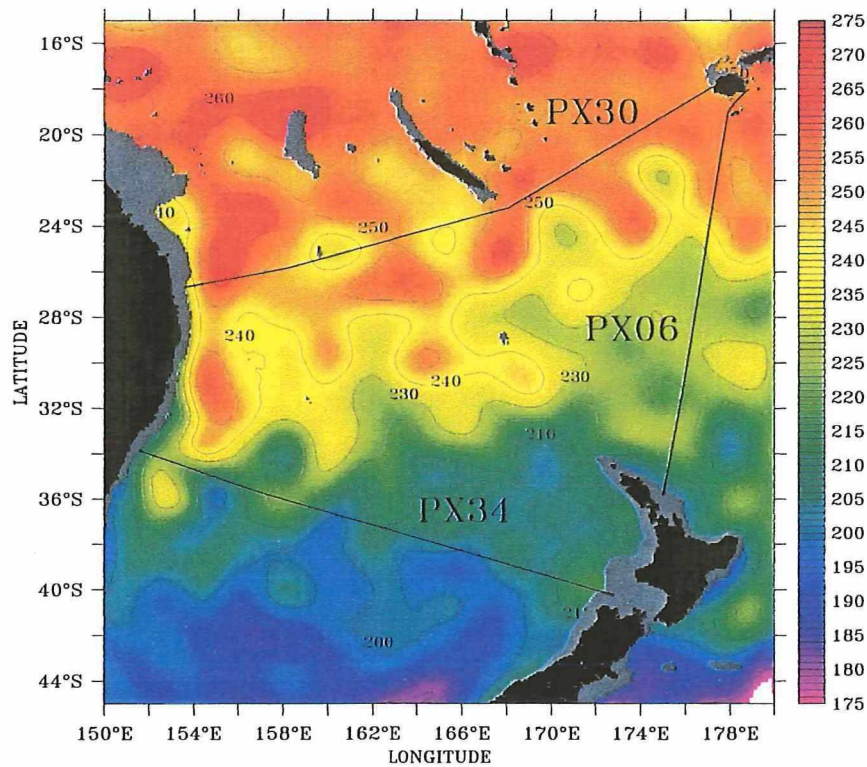


Figure 4. Three XBT sections for monitoring the East Australian Current, superimposed, for illustrative purposes, on a map of dynamic height anomaly (dynamic cm) at the sea surface relative to 2000 dbar. Adapted from Roemmich and Sutton (1998).

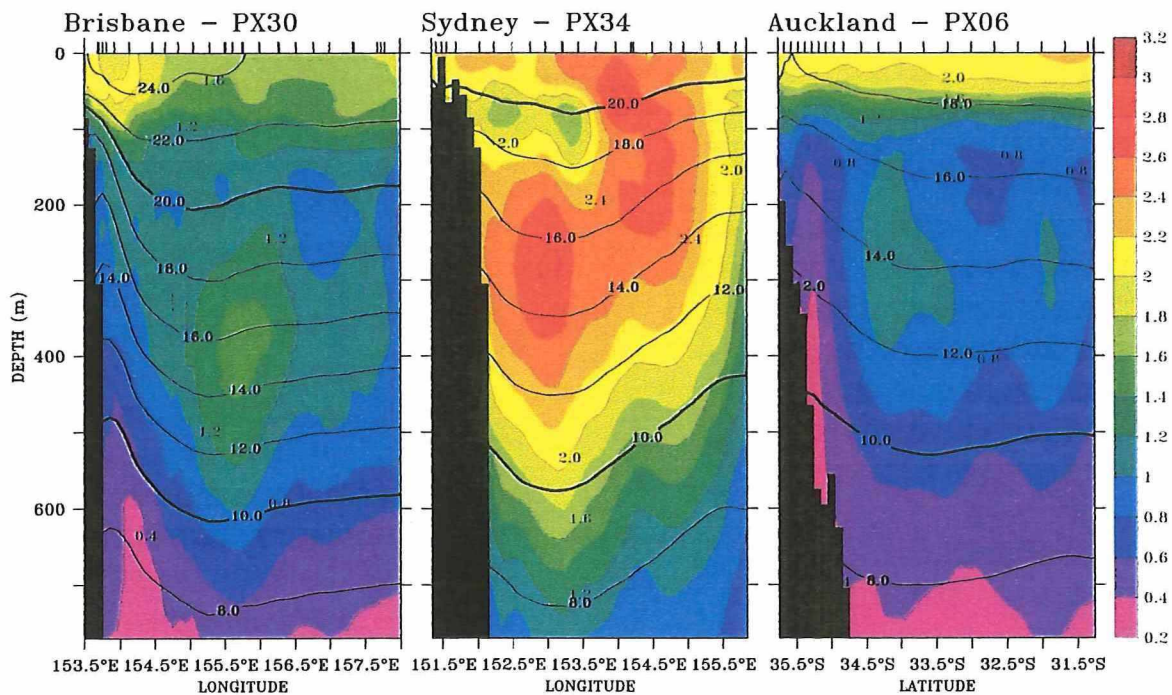


Figure 5. Mean (solid lines) and standard deviation (colors) of temperature ($^{\circ}\text{C}$) of the East Australian Current off Brisbane and Sydney (1991–1999) and the East Auckland Current north of Auckland (1986–1999). Adapted from Roemmich and Sutton (1998).

temperature structure (Fig. 5) that the boundary currents extend deeper than 800 m. To date, top-to-bottom CTD measurements have been made along two of the lines. WOCE hydrographic project line P14C followed XBT line PX06 in September 1992. Line PX30 was occupied with deep CTD stations by the R/V *Franklin* (CSIRO) in January 1999. Plans are for a similar occupation of the PX34 line in 2001 along with a repeated deep survey along PX30. These transects provide valuable information on the deep structure of the boundary currents that is useful in interpreting the XBT and TOPEX/POSEIDON datasets.

High-resolution XBT transects provide a cost-effective means of observing western boundary current structure and variability on seasonal to interannual timescales. Similar sampling is being carried out along tracks in the North Pacific and North Atlantic, with plans for comparable crossings in the South Indian and South Atlantic. An advantage of these transects is that they do not end on the offshore side of the current. They extend far offshore—in most cases to the other side of the ocean—in order to enable calculation of the net transports of mass and heat for the

combination of western boundary and interior ocean circulations. One of the cost-effective and practical ways of boundary current monitoring for heat and freshwater transports is a high-resolution XBT/XCTD transect combined with a shipboard ADCP.

Recommendations

Deeper sampling

A deeper (down to 2000 m depth, at ship speed of 20 kn) and more accurate XBT, the T-12, is presently being tested. Shear in the Tasman Sea region typically extends to about 2000 m depth, below which it is limited by several major topographic barriers. If the T-12 proves successful, then 2000 m sampling along the XBT lines in the East Australian Current should be initiated.

Salinity and reference velocity from Argo

Deployment of Argo floats in the Tasman Sea region will begin in 2001. The floats will provide salinity information on broad spatial scales. This is important both in the calculation of geostrophic velocity and SSDT for comparison with TOPEX/POSEIDON, and for studying the hydrological

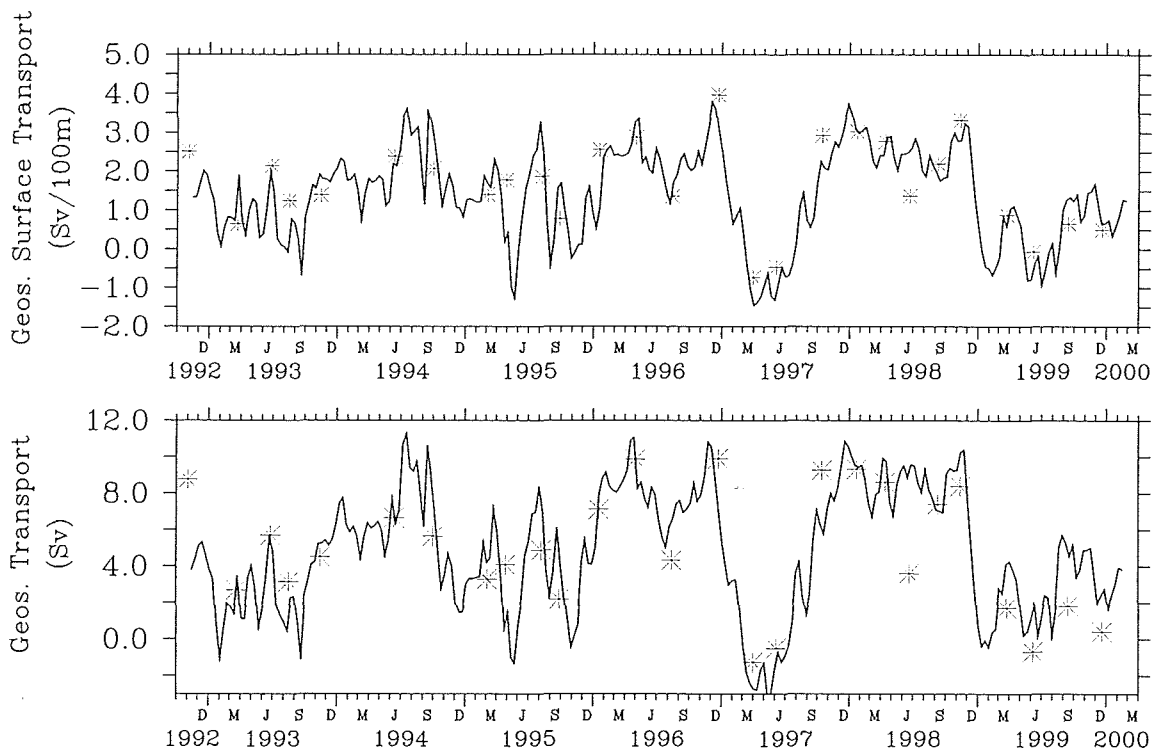


Figure 6. Comparison of XBT (* symbols) and TOPEX/POSEIDON (solid line) transport estimates for the East Auckland Current at the PX06. The upper panel is the sea-surface transport per unit depth and the lower is the transport integrated over the depth range of 0–800 m. Adapted from Gilson et al. (1998).

cycle (e.g. freshwater transport) in the region. The float array will also provide an accurate mean velocity field at the 2000 m reference level.

Glider transects

The developing glider technology will provide a means of obtaining more frequent upper-ocean T-S transects across the East Australian Current. It is suggested that glider sampling be carried out along all three XBT lines crossing the East Australian Current and the East Auckland Current in order to resolve transport variability on timescales of about 10 days.

Occasional deep hydrographic transects

The upper-ocean XBT, Argo, and glider projects should be supplemented by occasional (5–10 year) repeats of the deep ocean hydrographic transects crossing the boundary currents.

Indonesian Throughflow

The passages in the Indonesian Island chain allow the exchange of mass, heat and freshwater between the tropical Indian and Pacific oceans and so comprise the only major low-latitude inter-basin ocean pathway. This Indonesian Throughflow (ITF) impacts on the heat and freshwater budgets of these large ocean basins, both their long-term means and on interannual timescales (Godfrey, 1996). Coupled modelling work by Schneider (1998) reveals the large impact of the ITF on the global climate system (Fig. 7). By removing heat from the equatorial Pacific Ocean and warming the Indian Ocean, deep atmospheric convection moves to the far western Pacific and eastern Indian oceans. This shift in convection drives changes in the global atmospheric circulation and affects midlatitude winds. Thus, the ITF is a major player in controlling the heat content of the tropical Pacific and Indian oceans and so likely plays a role in the growth and dissipation of interannual anomalies such as El Niño.

Efforts to constrain the heat and freshwater budgets of the Indian and Pacific oceans using ocean data are greatly hampered by lack of knowledge of the long-term mean ITF (Bryden and Imawaki, 2001; Wijffels, 2001), which is estimated to affect a heat transport of about 0.5 PW (Godfrey, 1996) from the Pacific to the Indian oceans.

Monitoring the ITF and its associated heat and freshwater fluxes are thus needed:

- to close the heat and freshwater budgets of the Pacific and Indian ocean basins and therefore better constrain integral surface fluxes;
- to understand how anomalies of heat and freshwater content are exchanged between the Pacific and Indian oceans and what impact they have on air–sea interaction in these basins; and
- to constrain climate models and so gain confidence in their ability to simulate the above.

Meyers et al. (this volume) consider the broader issues of heat storage and air–sea exchange in the ITF region, while this paper concentrates on monitoring the inter-ocean exchange.

Past and present attempts

Attempts to measure the ITF directly must grapple with the fact that the flow occurs in a topographically complex region, where several possible pathways exist. The entrance channels on the Pacific side are near the equator, making it impossible to rely on geostrophy as a means of estimation of the ITF and associated climate fluxes there. In the Indian Ocean, the outflow channels are at latitudes of 6°S or higher, thus supporting the use of geostrophy. Meyers (1996) has monitored the upper portion of the ITF using an XBT line established in 1984 as part of the Tropical Ocean–Global Atmosphere (TOGA) network. This line, designated as IX1 (Fig. 8a), is the basis for constructing the longest continuous estimate of the upper part of the ITF (Meyers and Pigot, 1999). With roughly fortnightly sampling, this dataset has been used to resolve changes in transport and heat content on bimonthly timescales, adequate for resolving the seasonal and interannual changes in the ITF (Fig. 8b). Due to the depth limitation of XBTs, only geostrophic transport from 0–400 m has been estimated, and density was derived using climatological salinities (Levitus, 1982). The latter is known to be problematic due to large smoothing scales. There is also a general lack of high quality salinity data at the northern end of IX1, increasing the uncertainty in estimating the T–S relation.

Under the Java–Australia Dynamics Experiment (JADE), and WOCE programs, hydrographic lines were completed along or near IX1 and so

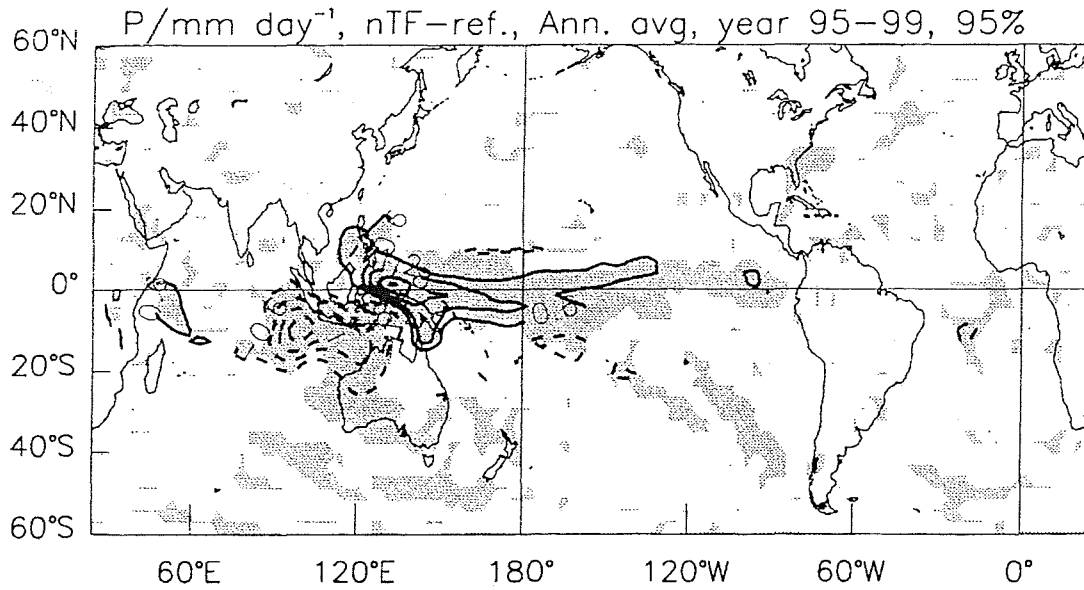


Figure 7. Differences in average precipitation (mm/day) between two coupled model runs with and without the Indonesian passages closed. Increase (decrease) of rainfall is shown by solid (dashed) lines with contour intervals of 0.6 mm/day; the zero contour is omitted for clarity. Shading highlights changes significant at the 95% level. Closed passages and no Throughflow are associated with lower rainfall over Indonesia and the eastern Indian Ocean, and much higher rainfall over the western and central Pacific. Adapted from Schneider (1998).

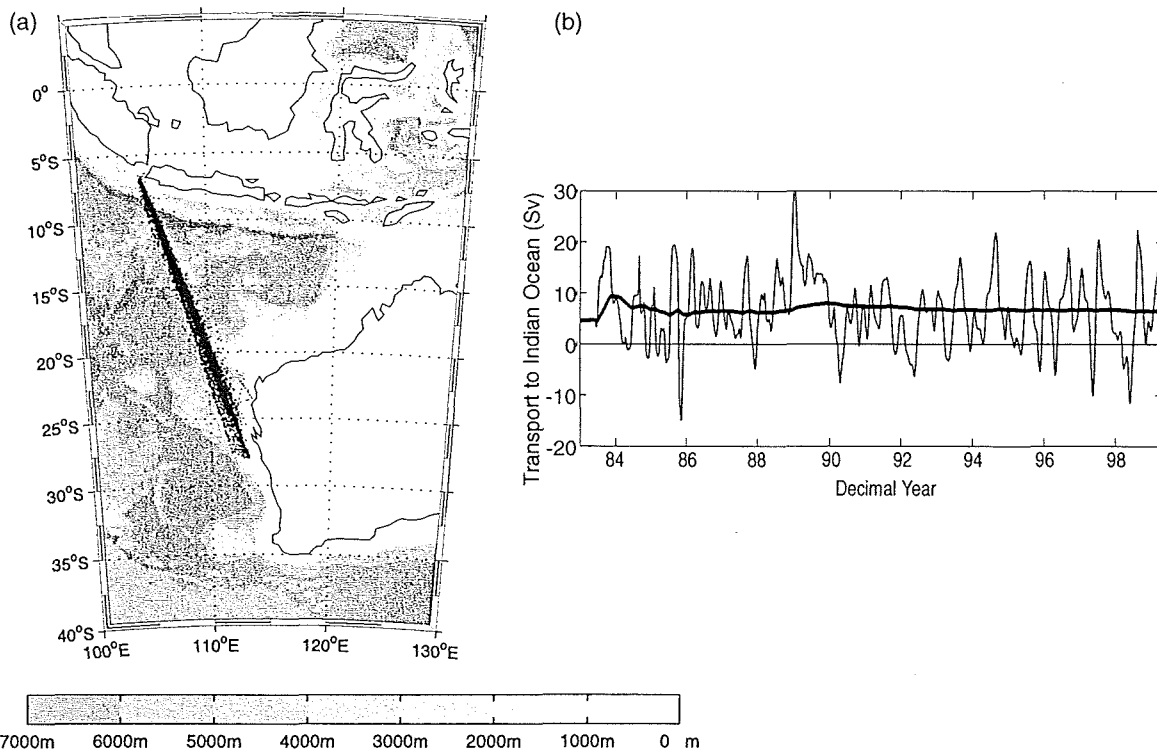


Figure 8. (a) Location of XBT casts along the repeat line IX1. The ocean bottom bathymetry is grey shaded. (b) Geostrophic transport (Sv) relative to 650 m between Australia and Indonesia based on the data shown in panel (a). Positive is towards the Indian Ocean. A cumulative mean transport is shown by the thick line. Adapted from Meyer and Pigot (1999).

provided synoptic estimates with full salinity (Fieux et al., 1996a; Wijffels et al., 1996). As was found by Fieux et al. (1996a), use of climatological salinity data in the upper 800 db results in transport errors of up to 5 Sv (Bray et al., 1997). The largest contributor to these errors is at the northern end of the section where a poorly understood boundary flow exists—the South Java Current. Within this current, at the northern endpoint of IX1, conditions exist that are characteristic of the eastern equatorial Indian Ocean: an extremely thin thermocline separates a freshcap from salty North Indian subthermocline waters below. From a 1-year pilot mooring, Sprintall et al. (1999) showed large variations in salinity in the South Java Current where, at times, the freshcap disappears altogether under upwelling conditions. Hence, there appears to be considerable variability in the T–S relation at the northern end of IX1 which, in turn, must impact on the accuracy of the resulting transport estimates.

Despite this, Meyers (1996) has been able to link changes in thermal structure and transport along IX1 to large-scale wind-field variations over the tropical Pacific and Indian oceans. Meyers' results support predictions based on simple theory that remotely forced wind-driven Kelvin waves in both the Pacific and Indian oceans can drive changes in the ITF (Clarke and Liu, 1994; Hirst and Godfrey, 1994). The 1984–1995 record-average ITF estimated between 0 and 400 m is only ~5 Sv, much lower than the ~15 Sv estimate based on observed wind stresses and the modified Sverdrup theory of Godfrey (1989). Along with errors due to salinity, this highlights the possibility of IX1 not sampling a large deep contribution to the ITF.

Several short 1–2 year direct velocity estimates have been obtained in various throughflow straits (Murray and Arief, 1988; Cresswell et al., 1993; Molcard et al., 1996; Aung, 1999; Gordon and Susanto, 1999; Gordon et al., 1999). These direct measurements, with their high temporal resolution, resolve the short-term variability that the XBT data misses. In many of the straits, tidal variations are very large (e.g. Gordon and Susanto, 1999) and so likely dominate any single velocity measurement. In addition, the heave associated with large internal tides (Field and Gordon, 1992) can introduce errors into geostrophic estimates based on profile data taken in the internal seas.

Variability on intraseasonal timescales (40–60 days) has been shown to be ubiquitous in the Indonesian Seas (Molcard et al., 1996; Watanabe et al., 1997) and along the Sumatra–Java coasts (Arief and Murray, 1996; Chong et al., 2000). These oscillations impose a minimum temporal resolution of about 15 days (2–4 points per cycle) in order to avoid aliasing.

The vertical extent of the ITF, crucial to the associated heat flux, is still very poorly known. Cresswell et al. (1993) and Molcard et al. (1996) find 2–3 Sv flowing west in the Timor Passage below about 400 m. Fieux et al. (1996b) found weak westward flow below 400 m in August 1989 but deduced eastward flow at these depths in February 1992.

An attempt has been made to use PIESs in Makassar Strait. This approach is still being assessed. The occurrence of seasonal shear reversals in the upper 250 m complicates the relationship between the integral measures obtained from the PIES and transport.

To date, it has not been possible to assess the accuracy of the transports measured by the IX1 line with direct measurements in the straits themselves. Except in the surface layers (Chong et al., 2000), the outflow channels (Lombok, Ombai and Timor) have never been simultaneously monitored, while the inflow channels (Makassar, Maluku, Lifamatola and Halmahera) are more numerous and much wider. Based on water-mass distributions, however, Gordon et al. (1999) suggest the bulk of the thermocline ITF flows through Makassar Strait. Strong coherence between two moorings placed on either side of the Libani Channel (a constriction in Makassar Strait) suggests a single mooring might be sufficient to monitor the Makassar Transport (Gordon and Susanto, 1999; Gordon et al., 1999). Due to storage effects between the IX1 line and the straits, it is not expected that transports will match, except at frequencies low enough for storage rates to be minimal, say 1–2 years.

Below, we suggest monitoring activities aimed predominantly at measuring the oceanic fluxes. A more thorough discussion of these and other options is needed. The potential exists that inexpensive proxy estimates of transport based on sea level, depth of thermocline or other indices, might be found, but these will require a relatively long and accurate direct estimate as a basis for calibration.

Recommendations

Geostrophic estimates of the upper ITF

We recommend continuing the IX1 XBT line at fortnightly sampling in order to reduce aliasing by the intraseasonal energy. Sampling should be supplemented with XCTDs, especially north of 15°S. Inclusion of a thermosalinograph might also help reduce errors due to large salinity variations in the surface layer. Model data could be used to determine the optimal mixture of XCTDs, XBTs and thermosalinographs required to achieve accurate monthly estimates of mass, heat and freshwater fluxes.

The idea of monitoring the ITF by measuring cross-strait pressure gradients is being explored through the shallow pressure gauge array established by Bray and colleagues (Chong et al., 2000). This array potentially represents an inexpensive means of monitoring near-surface transports of mass, heat and freshwater through the straits, with high temporal resolution. Results are still preliminary, however, and more *in situ* verification of the deduced fluxes is required. The major problem with this technique is lack of information about flows at depth that can be directed oppositely to those at the surface (Chong et al., 2000). Multi-month mooring time series are recommended to help 'calibrate' the pressure gauge array under various seasonal and tidal regimes.

Direct estimates

The geostrophic monitoring should be complemented by a direct estimate as an independent check and to fully resolve intraseasonal and higher frequency events. There are several locations where this could be achieved: long-term direct monitoring of the Makassar and Lifamatola Throughflow, and moorings in the three major outflow channels (Lombok, Ombai and Timor Straits). Gordon et al. (1999) show that monitoring the Makassar Throughflow could be feasible with a single mooring. Less is known about the structure of the throughflow in Lifamatola Strait, which is quite wide at thermocline levels. However, water-mass measurements suggest this strait is a significant pathway for the deep throughflow.

Directly monitoring the deep throughflow—the part not passing through Makassar Strait—is a challenge and requires further study. It is likely that new fieldwork is required to determine the primary pathways of the deep throughflow and to

assess the feasibility of various monitoring approaches.

Profiling mooring technology (Fougere and Toole, 1998) could offer an alternative means of efficiently monitoring the full-depth baroclinic component of the ITF. Profiling moored CTDs are capable of delivering full depth profiles daily, or less frequently. Four such instruments moored on either side of the Savu Basin (Ombai out flow) and the Timor Trough would provide the basis for bottom relative estimates of the ITF through these basins. Because full-depth temperature and salinity profiles are obtained, heat and freshwater transports could also be derived. Such an array would have to be suitably programmed to avoid tidal aliasing. Along with a complementary means of monitoring the Lombok outflow through either a mooring or shallow pressure gauge array, full-depth estimates of the throughflow would be possible.

Low-latitude boundary current system of the Atlantic

Scientific issues and the need for observations

The objectives of the preceding examples of oceanic boundary currents dealt with their immediate impact on climate by heat advection and fluxes between the sea and the atmosphere or by the exchange between two oceans. When considering the associated meridional heat transport in the tropical Atlantic, we cannot neglect farther interactions between the deep-reaching boundary current regime and the abyssal. As the northern North Atlantic plays a key role in driving the variable thermohaline circulation (THC), low-latitude regimes of this ocean, where opposing flows are in close vicinity, appear particularly suitable for monitoring heat transport fluctuations on a larger scale. A burning question concerns the sensitivity of the tropical limb of the THC in respect to surface boundary conditions in high latitudes where freshly ventilated water is transformed into various types of Deep Water.

Supporting evidence for the decisive role of the variable THC in climate change comes from different sources, including model studies by Delworth et al. (1993). In a coupled model they show a maximum of the decadal oscillations at the northern rim of the tropical North Atlantic. There are further indications of 'sudden flips' of the THC within a decade based on numerical models (Rahmstorf, 1995) or from paleoceanographic sources (e.g. Sarntheim et al., 1994).

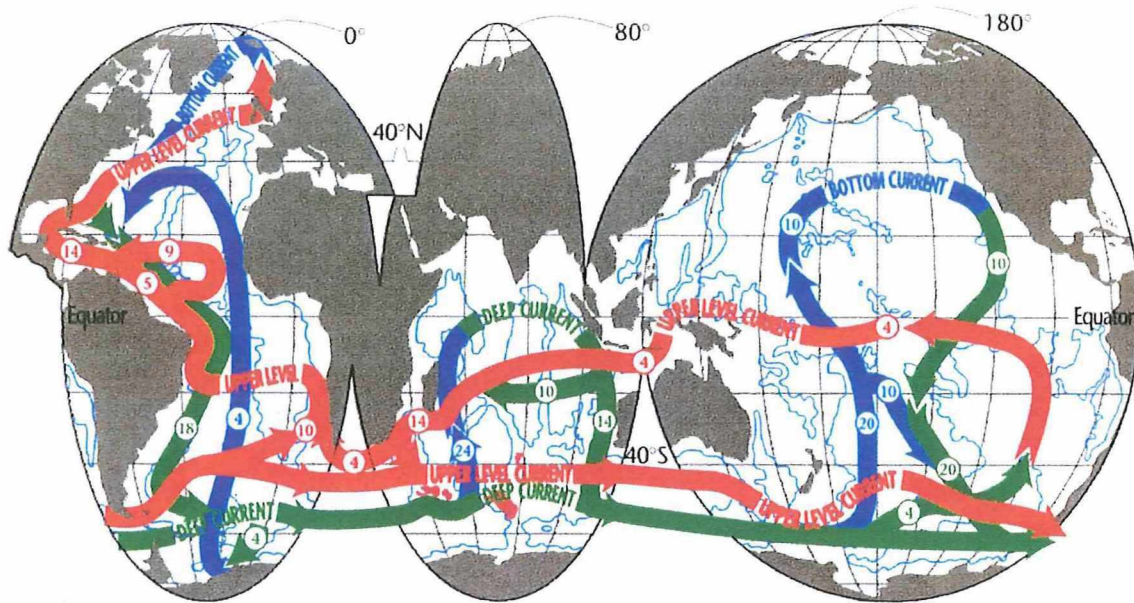


Figure 9. Conceptual diagram of the three-dimensional general oceanic circulation. Adapted from Schmitz (1995).

Generalized circulation schemes like the conceptual diagram (Fig. 9) by Schmitz (1995) suggest the southward-flowing North Atlantic Deep Water (NADW) to be the most constrained limb in the THC. The drifts of Antarctic Intermediate Water (AAIW) and Antarctic Bottom Water (AABW), bracketing the NADW pathway in the vertical achieve the compensating northward cross-equatorial transports.

More recently, an altimeter data analysis from TOPEX/POSEIDON has shown minimal eddy kinetic energy distributions in the tropics (Stammer, 1997). Such observations are also in agreement with the independently observed, limited spatial variability in the boundary current regions off Brazil.

Studies during WOCE in the western tropical South Atlantic between 5° and 20°S have revealed flow characteristics of well-defined boundary currents (Stramma et al., 1995; Schott et al., 1998; Zangenber and Siedler, 1998; Stramma and England, 1999; Weatherly et al., 2000). From the depth level of NADW upward they confirm the expected minor spatial variations and seem, at least in case of the AAIW, to be isolated from interior flows by an extended outer zone of persistent eddy activities (Boebel et al., 1999a)

without considerable augmentation from the subtropics.

However, the picture of a clear-cut western boundary regime with little interaction with the interior may be misleading. In comparing deep mass transports entering lower latitudes of the western North Atlantic with the export at the northern end of the Brazil Basin, one finds a discrepancy of a factor 2–3. The apparent deficit across the export region caused Schmitz (1995) and McCartney (1993) to postulate the existence of high-volume recirculation cells. So far, direct observations have failed to demonstrate such basin-wide cells. However, before an alternative solution for the mass imbalance in the Guyana Basin emerges, their impact on abyssal upwelling and their buffer effects must be kept closely in mind.

Schott et al. (1998) have studied repeatedly the system of major tropical currents in the Atlantic. Figure 10 demonstrates the limited eastern extent of the boundary current system in three stacked layers above 1000 m. Shown schematically are the North Equatorial Current (NEC), the North Equatorial Countercurrent (NECC), different branches of the South Equatorial Current (SEC), the Equatorial Undercurrent (EUC), the North Brazil Current (NBC), the Brazil Current (BC)

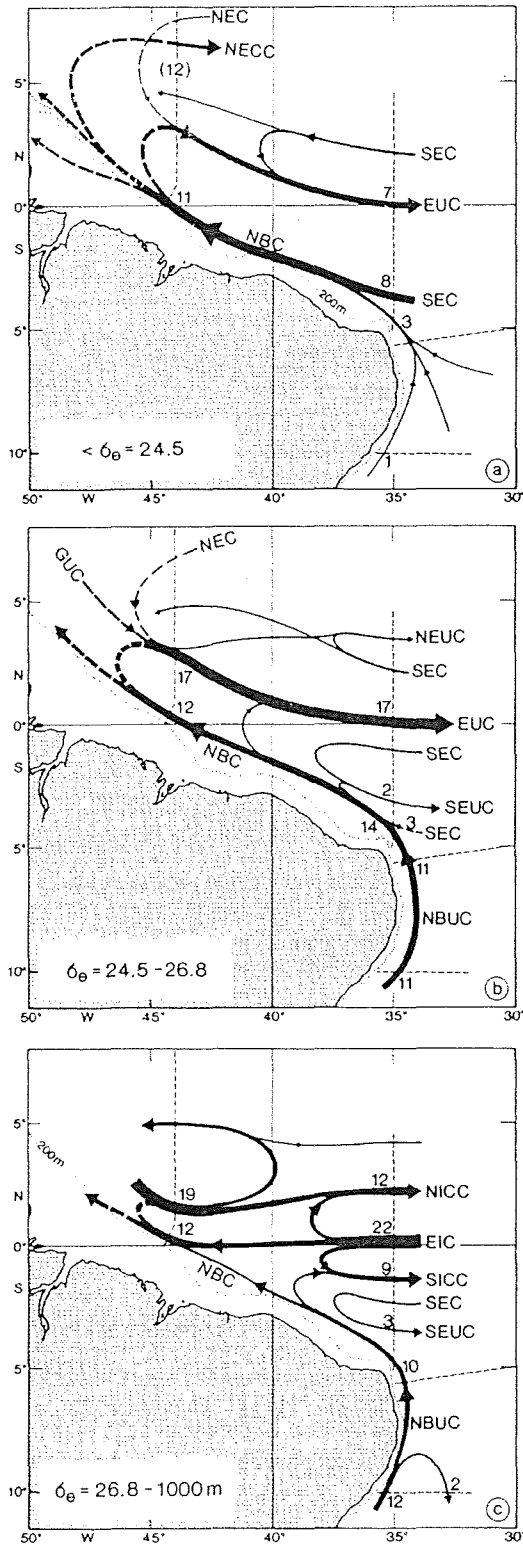


Figure 10. Schematic maps showing the major tropical currents of the South Atlantic for (a) the Tropical Surface Water layer down to 100 m for northern fall, (b) the Central Water layer at about 100 to 500 m depth, and (c) the AAIW range at about 500 to 1 150 m depth. Adapted from Schott et al. (1998).

the Guyana Undercurrent (GUC), the North Brazil Undercurrent (NBUC), the South Equatorial Undercurrent (SEUC), the Equatorial Intermediate Current (EIC), the Northern Intermediate Countercurrent (NICC) and the Southern Intermediate Countercurrent (SICC). Numbers in the figure indicate transports in Sv. The confusingly large number of identifiable currents and their interdependency give an impression of the complexity of the THC at low latitudes and the difficulty of catching relevant climate signals by individual instruments or surveys. The subthermocline boundary current regime near the equator is subject to a detailed study by Rhein et al. (1995).

Pathways and space-averaged mean velocity values of the western South Atlantic were also observed by intermediate float observations during WOCE (Boebel et al., 1999b). Figure 11 is based on 170 float-years of velocity data preferably from the level of AAIW. Note the observed, confined lateral extension of the intermediate western boundary current in the form of the North Brazil Undercurrent at 10°–12°S.

As another illustration of boundary currents in the subtropical northwestern South Atlantic, we reproduce (Fig. 12) a schematic circulation pattern of NADW transports on the basis of WOCE sections. Note the broad drift of the NADW south of 15°S. Under the topographic control of the Vitória-Trindade Ridge, its core seems to be separated from the continental slope. Zangenberg and Siedler (1998) inferred from a conceptual model that a splitting of the incoming NADW transport is required by a simple vorticity argument. The 20 Sv from the north at 19°S appears to be balanced by only one-third of this transport progressing southward. The remaining two-thirds may be advected east and northeastward across the Mid Atlantic Ridge and/or recirculate and upwell in the Brazil Basin.

We conclude that the series of stacked boundary currents in the tropical Atlantic, with their far-reaching impact on the global THC, are suitably constrained areas in which to monitor surface and subsurface transports. Both play key roles in climate variability. With well-organized observations this region may play a future indicator role for climate changes on a decadal or longer scale. A monitoring project focused on the boundary current regions off Brazil to supplement and support the existing equatorial array—Pilot

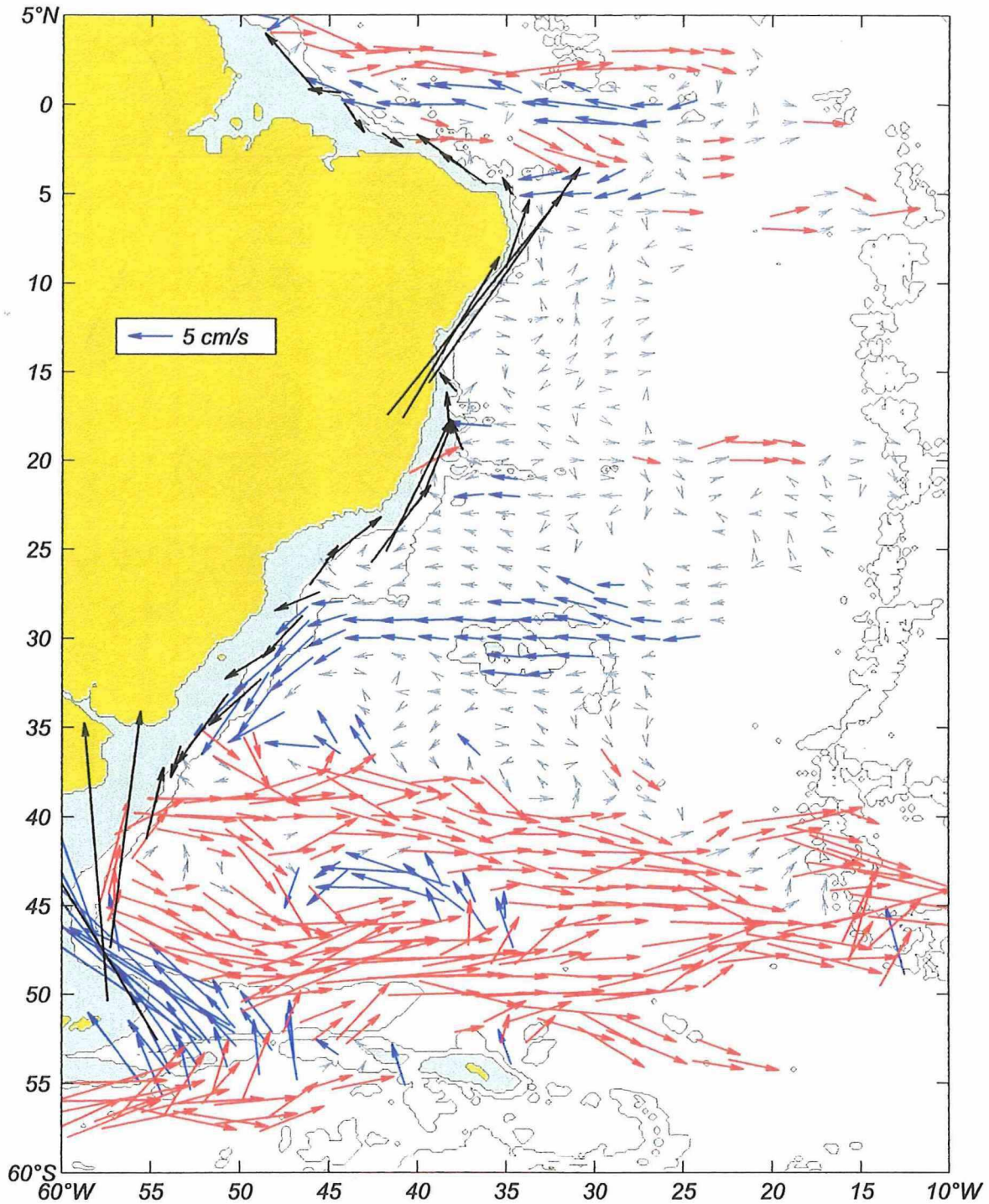


Figure 11. Space-time averaged mean velocities at intermediate depths (800–900 m) of the western South Atlantic. For the interior ocean, away from the 1500 m isobath, the box size is 2° of latitude x 4° of longitude on a 1° x 1° grid. Color and black arrows, based on at least 60 days of data and with mean speeds of greater than 3 cm/s, are displayed at the respective box centre (red and blue arrows indicate eastward and westward directions, respectively). Along the western boundary (black arrows) data between the coast and the 1500 m isobath were averaged within 200 km radius based on at least 15 days of data. Undersampled mean directions are displayed as grey arrows. Adapted from Boebel et al. (1999a).

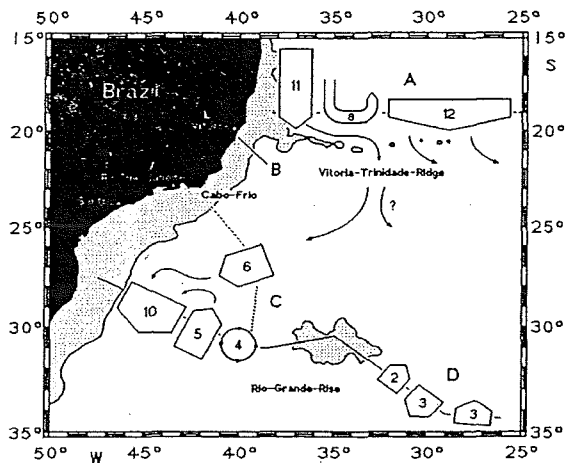


Figure 12. Generalized transport pattern of North Atlantic Deep Water (NADW) in the Brazil Basin. Values are rounded to full Sv. Water depths less than 2000 m are shaded. Adapted from Zangenberg and Siedler (1998).

Research Moored Array in the Tropical Atlantic (PIRATA)—is essential for a better understanding of climate fluctuations, and the reader is referred to the PIRATA web site: <http://www.ifremer.fr/orstom/pirata/pirataus.html>. We have a vision of an observational system in the tropics whose results can be related to high-latitude boundary conditions in convective regions such as the Labrador Sea enabling climate prediction estimates.

The oceanic current system in this western equatorial Atlantic will be surveyed in detail under the program of the Climate Observing System for the Tropical Atlantic (COSTA: <http://www.aoml.noaa.gov/phod/COSTA/>) and other internationally coordinated Climate Variability and Predictability (CLIVAR) programs such as the Meridional Overturning Variability Experiment (MOVE) or the Guyana Abyssal Gyre Experiment (GAGE). In these programs, adequate modern methods such as autonomous current profilers and 'geostrophic moorings' (see below) are under discussion to solve the puzzle of recirculation elements and their impact upon the variability of the net heat transport across the equator.

Recommendations

We have already discussed a number of methods in earlier recommendations. Most apply to intermediate and deep boundary currents in the tropical Atlantic as well. Once critical regions for

subsurface current observations have been identified during pilot studies, expensive arrays of moored current meters often can be reduced in quantity. They can still cover critical pathways along flanks or channels. However, long-term series are essential for monitoring the variable strength of the THC. Compromises in sampling schemes are unacceptable and time series ought to be maintained as uninterruptedly as possible.

The shallow tropical thermocline gives easy access to intermediate currents for vessel-mounted ADCPs. Their limited coverage of several hundred metres in the vertical can be overcome with station work, featuring self-contained ADCPs mounted on a CTD probe with rosette sampler. We recommend that all repeat cross-sections be supplemented with lowered ADCPs (Fischer and Visbeck, 1993).

In spite of occasional concerns, Lagrangian methods can be well suited to surveying boundary currents, as Boebel et al. (1999b) have shown off Brazil with neutrally buoyant floats. In addition, they represent useful options in the search for recirculation elements. Further technical developments are necessary to reduce piece costs and to convert them into more affordable expendable instruments.

The eddy-resolving property of most one-time floats (RAFOS; SIVOR—the expendable version of MARVOR; and others) allows no cycling between their mission depth and the surface (Davis and Zenk, 2001). This option remains restricted to profiling floats such as the Profiling Autonomous Lagrangian Circulation Explorer (PALACE), MARVOR, its profiling version PROVOR, the Sounding Oceanographic Lagrangian Observer (SOLO) and the Autonomous Profiling Explorer (APEX). Large quantities of the latter are expected to populate the ocean in the near future (Argo Science Team, this volume). Their unique profiling capabilities allow regular sampling of climate-relevant parameters like heat content and proxy drifts of intermediate currents. It is presently not clear how far they are suitable for monitoring deeper boundary currents. Fischer and Schott (2001) recently set an illuminating example by studying the drift of APEX floats in the deep Labrador Current off the Grand Banks. None of their drifters circumvented the Banks; instead, they all ended up in the east, in the interior of the subsolar North Atlantic.

In future versions, profiling floats will be able to actively determine their position (a 'virtual' mooring) or to move on predetermined paths, such as cross-current sections in boundary regions. Such 'gliders', with automatic data downloads and facilities for external control, appear eminently suited to systematic surveys of intermediate and near-surface boundary currents as well as to time series of observations that monitor heat and salt content.

A general shortfall of the above-mentioned methods, as well as conventional repeated XBT and CTD sections, lies in their limited representativeness. An elegant way of overcoming high-frequency or high wavenumber-contaminated observations is the application of integral methods. These can prevent aliasing (introduced by meanders, eddies or entrainment) by suitable averaging over certain temporal and spatial scales before samples are taken. The cable measurement mentioned for monitoring the Kuroshio transport fluctuations is an example of this category of observational tools. Observations with cycling CTD probes tethered on separate moorings allow calculations of integral density changes between mooring pairs. A different technical approach features larger numbers of moored CTD recorders (50 devices distributed over a depth interval of 2000 m, for example) which act as a virtual line sensor without moving parts. Pairs of such 'geostrophic moorings' yield valuable series of geostrophic current fluctuations, again representative of the region between the two moorings.

IESs with precision deep-sea gauges specified to absolute oceanic pressure accuracy of mbar (PIESs) are challenging integral sensors for long-term change observations. They also allow a conversion of relative geostrophic current profiles from moored quasi-line sensors into absolute profiles perpendicular to the gateway between the moorings considered. Such a combination of integral sampling instruments is presently being tested on a zonal section in the western tropical Atlantic along 15°N between Guadeloupe (Lesser Antilles) and the Mid-Atlantic Ridge.

Finally, the analysis of natural and anthropogenic tracer distributions and their variability belongs to one of the most promising integral methods for the observation of long-term changes (Fine et al., this volume). This technique, however, lies beyond the scope of this paper.

Concluding remarks

As has been shown in previous sections, a variety of observational strategies have been, and will continue to be, adopted for monitoring the different boundary current systems. Some strategies are common to all systems, others differ between them.

Moored instruments

Long-term measurements of velocity and water property are essential for understanding the variability of boundary currents, and critical pathways and key locations should be monitored continuously using moored instruments such as current meters, IESs, PIESs, CTDs and the like. In some cases, satellite altimeter data may assist in the monitoring. The continuous measurements exclude the possibility of aliasing due to strong mesoscale eddy activities, common in most boundary current regions.

IESs and PIESs are promising instruments for monitoring the baroclinic fields of a boundary current. The recently developed procedure to estimate vertical temperature profiles from IES data using a regional GEM will be very useful for some areas such as the Gulf Stream and Kuroshio; such profiles will yield geostrophic velocity and transport fairly accurately when combined with historical T-S relations. However, the procedure is limited to areas where the major variation is of a single lowest mode in the vertical, for example, the vertical displacement of the main thermocline. In cases where the major variation is associated with multiple modes in the vertical, conversion of IES data to information relating to density structure fluctuations is difficult, and the GEM technique is not applicable. An example is Makassar Strait, where seasonal shear reversals occur in the upper layer.

Vertical profiles of temperature and salinity can be monitored directly with a newly developed profiling mooring technology of CTD. The profiling moored CTD is able to deliver full-depth profiles with daily or lower frequency. A different technical approach is to use a set of numbers of CTD recorders (~50 devices) on a single mooring line, without moving parts. Using profiling moored CTDs and sets of moored CTD recorders can give vertical profiles of temperature and salinity without any assumptions, provided that they are moored successfully in a strong boundary current.

XBT and hydrographic surveys

Repeated high-resolution XBT/XCTD transects from voluntary ships provide a cost-effective means of monitoring the boundary current structure and variability on seasonal to interannual timescales. An advantage of these transects is that they do not end on the offshore side of the current but extend far offshore, in most cases to the other side of the ocean, in order to enable calculation of net transport of mass and heat for the combination of western boundary and interior ocean circulations. One of the cost-effective and practical ways of boundary current monitoring for heat and freshwater transports is repeated high resolution XBT/XCTD transects combined with a shipboard ADCP.

The frequent upper ocean measurements with XBT/XCTD, floats, gliders, etc. should be supplemented by occasional repeats (~ every 10 years) of deep hydrographic sections across the boundary current as a reference. This should preferably be accompanied by moored current meter measurements.

Floats and gliders

Profiling floats such as Argo will provide temperature and salinity information on broad spatial scales. This is important and effective for studying the global heat and freshwater transport. However, floats may not be so effective for boundary currents in shallow regions such as the ITC, the Kuroshio in the East China Sea, and the Florida Current. At present, it is not clear how far they are suitable for monitoring deeper boundary currents. The developing technology of self-steering profiling floats (i.e. gliders) could be more effective for sampling narrow, swift boundary currents repeatedly, by actively relocating their nominal positions or by progressing on cross-stream tracks, with external control facilities. The glider is one of the most cost-effective tools for systematic surveys of intermediate and near-surface boundary currents, and heat and salt content observations.

Altimeter and tide gauges

Sea level data from satellite altimeter and tide gauges are very useful for monitoring boundary currents for a long period. The altimeter data can provide information about variations of the surface geostrophic flow field, and, in some cases,

variation of the transport of boundary currents. It is crucial to continue the altimeter observations along the same orbit as the TOPEX/POSEIDON and JASON-1; only in that case, the data from consecutive satellite altimeter missions are fully utilized, providing us with a very long time series of SSDT along fixed subsatellite tracks. Tide gauge observations should be continued in future near the boundary currents as well as the world-wide oceans. The datum-line height of the tide gauge should be monitored with GPS to clarify the exact sea surface height.

Transport estimates

It is worthwhile to try to find inexpensive proxy estimates of transport of a boundary current based on sea level, depth of thermocline or other indices, like the Kuroshio transport estimates from SSDT differences across the stream. However, these will require a relatively long and accurate direct estimate as a basis for calibration. Such calibration should preferably be repeated occasionally (every ~10 year) for the relationship to be re-examined.

Definition of transport of a boundary current is usually not straightforward. Most of the boundary currents are accompanied by recirculations except when flowing very close to the coast. Estimates of transport are fully dependent on the horizontal extent of integrals. As for the local dynamics, the entire transport of the boundary current may be meaningful, but when the western boundary current of the basin-wide gyre is concerned, the simple entire transport of the boundary current may be meaningless and contributions from local recirculations should be excluded. Further, the transport varies at different locations in the same boundary current system. Therefore, discussions about transport of a boundary current should start with its definition. In practice, mesoscale eddy activities contaminate the transport estimates of a boundary current seriously.

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Question and Answer Session

Kessler: Speaking of the low-latitude boundary currents, like the Mindanao Current and the New Guinea Coastal Current, can you discuss the differences in measuring these currents as opposed to measuring the mid-latitude boundary currents?

Zenk: Obviously, we cannot use geostrophic methods. Two years ago we used floats in the Bismarck Sea to monitor the New Guinea coastal undercurrent, this is one way to do it. Near the equator is an excellent place to use gliders to monitor currents.

Talley: You showed quite different variability at different locations along the Kuroshio. Are these measurements in phase? Obviously, the Kuroshio is very well measured, but other boundary currents may not be as well measured. Perhaps, only one location will be used to monitor the transport in some cases. Do you have to be careful about measurements in different locations along a boundary current system?

Imawaki: Yes, there is a great deal of variability along the Kuroshio. For example, the transport adjacent to the East China Sea is quite different from the transport south of Japan. We have found that you have to be very careful about the locations where the transport is measured.

Rintoul: Many of the western boundary currents have strong recirculations off stream. Is there a need to measure across the re-circulations, or can we get away with just measuring the western boundary current itself?

Imawaki: There are several recirculations. We did some estimates to include the local recirculation. In this case the mean reduces to a mean of 42 Sv. It is a very important issue to evaluate the impact of the recirculations in the western boundary current transport.