# INTEROCEAN EXCHANGE OF THERMOCLINE WATER: INDONESIAN THROUGHFLOW; "TASSIE" LEAKAGE; AGULHAS LEAKAGE

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***Abstract***: Interocean exchange of thermocline water is of central importance to the mass, heat and freshwater budgets of the major ocean basins. Fluctuations of interocean exchange may be expected to affect the global climate system by altering sea-air heat flux and associated large scale ocean overturning. Interocean exchange of thermocline waters include: Agulhas leakage which injects Indian Ocean water into the Atlantic Ocean; and the transfer of Pacific water into the Indian Ocean by way of the Indonesian Throughflow and along a route south of Australia, the Tassie Leakage. Observations and modeling work of the last few decades have informed us of the nature these key interocean exchanges and offer concepts for cost-effective approaches for sustained observing systems.

## 1. Introduction:

The ocean is segmented into three large basins. The interocean exchange of water between these basins, moves significant amounts heat and freshwater, affecting the large scale ocean stratification, with impact on ocean heat/freshwater inventories and the giant meridional ocean circulation cells of the Atlantic and the Southern Ocean [1,2]. Changes of interocean exchange are both a response and a driver to the climate system, and must be properly resolved in ocean and climate models.

The Antarctic Circumpolar Current (ACC) moves vast amount of cold water between the three oceans, with major impact on the Earth's climate system. However, smaller amounts of interocean transport of warm thermocline water also impact the climate and its fluctuations. The most significant (Figure 1) are transfer of Pacific water into the Indian Ocean by way of the Indonesian seas (ITF) [3], and along the southern margin of Australia [4], and the transfer of Indian Ocean subtropical water into the Atlantic around the southern rim of Africa [5]. The Bering Strait transfers substantial amount of Pacific cool freshwater into the Arctic Sea and ultimately in the North Atlantic. Observing the changes of mass, heat and freshwater transfer within these inter-ocean links is central to monitoring fluctuations in the earth's climate system.

It is anticipated that there will be much overlap between this White Paper and other contributions to OceanObs09. Topics related to the most relevant are: AMOC; Deep Observing networks; Southern Ocean Observing System; Indian Ocean Observing System; The Global Tropical Moored Buoy Array. Also, see: South Atlantic SAMOC web site: *http://www.aoml.noaa.gov/phod/SAMOC/*. For the Bering Strait, see: An Integrated International Approach to Arctic Ocean Observations for

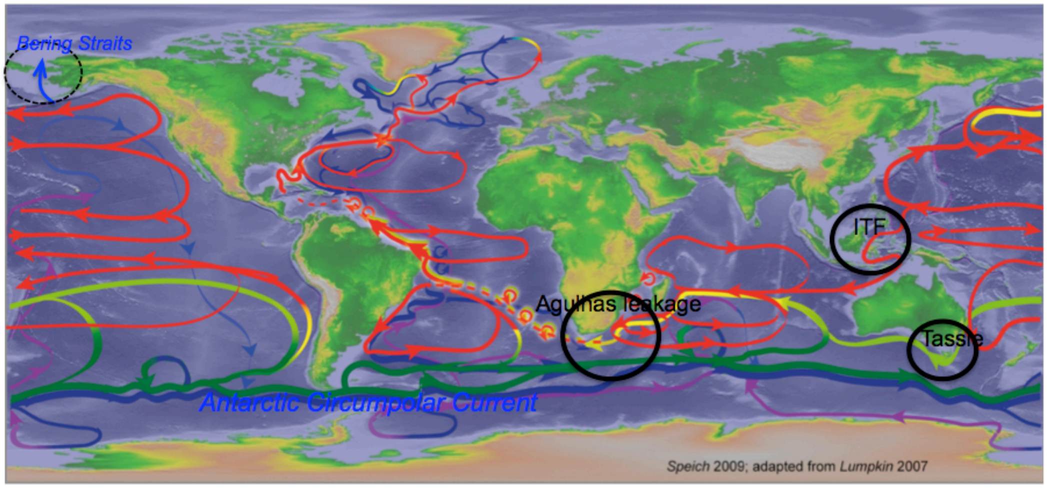

*Figure 1: The Pacific to Indian Ocean flow within the Indonesian seas, the Indonesian Throughflow (ITF); the Indian to Atlantic Ocean flow around the southern rim of Africa, the Agulhas leakage; the Pacific to Indian Ocean flow south of Australia are considered to play a significant role in the in the global ocean thermohaline balance and circulation (shown by the red, blue and green flow pathways in the figure). The figure is modified from [6], see: http://stockage.univ-brest.fr/~speich/SAMOC/SAMOC_2009.ppt; adapted from [7].*

Here we brief discuss the climate role and ingredients of a cost effective observing systems of the Indian to Atlantic transfer of warm water as represented by Agulhas leakage; and the transfer of Pacific to Indian transfer of warm water by way of the Indonesian Throughflow and along a route south of Australia which has been referred to as the Tassie Leakage.

Society; Combining satellite altimetry, time-variable gravity, and bottom pressure observations to understand the Arctic Ocean: A transformative opportunity; The Ocean and Sea-Ice Components of the Arctic Observing Network.

## 2. Pacific To Indian Ocean flow

### [A] Indonesian Throughflow [ITF]

The transfer of tropical water from the Pacific to the Indian Ocean through the Indonesian seas is considered to be a first order factor in the heat and freshwater inventories of these oceans, and as such are linked by sea-air fluxes to the larger scale climate system [8], specifically to El Niño-Southern Oscillation (ENSO), the Asian Monsoon, the Indian Ocean Dipole (IOD). The interocean exchange within the multiple passages of the complex archipelago configuration of the Indonesian seas is a challenge to observe as well as to simulate within numerical models. This challenge must be met so to better predict changing ocean and climate conditions as well as manage marine resources within Indonesian waters.

The Indonesian seas represent a complex array of passages linking shallow and deep seas (Figure 2). The literature, dating to 1961 [9], offers a wide range of annual mean transport values for the ITF, from near zero to 25 Sv (Sv = $10^6$ $m^3$/sec). Estimates based on observations obtained from the mid-1980s and mid-1990s suggest a mean ITF of ~10 Sv [3] (Figure 2) with interannual and seasonal fluctuations, as well as energetic intraseasonal (<90 days) variability and tides [3, 10, 11, 12, 13, 14, 15]. The ITF is a response to ocean-scale wind stress as characterized by the “Island Rule” [16], and to the phase of El Niño-Southern Oscillation (ENSO; [17, 18, 19] and its Indian Ocean “cousin”, the Indian Ocean Dipole, IOD [20, 19, 21] as well as the regional monsoonal wind pattern over southeast Asia [22, 23].

Model studies have investigated the ITF impact on the Indian and Pacific heat and freshwater budgets and on the ITF role in the climate system [24, 25, 26, 27, 28, 29, 30, 31, 32]. The model dependent results indicate changes in the ocean surface temperature and meridional circulation within the Indian and Pacific Oceans according to the characteristics of the ITF. The ITF affects atmosphere-ocean coupling with potential impacts on the ENSO and monsoon phenomena [33].

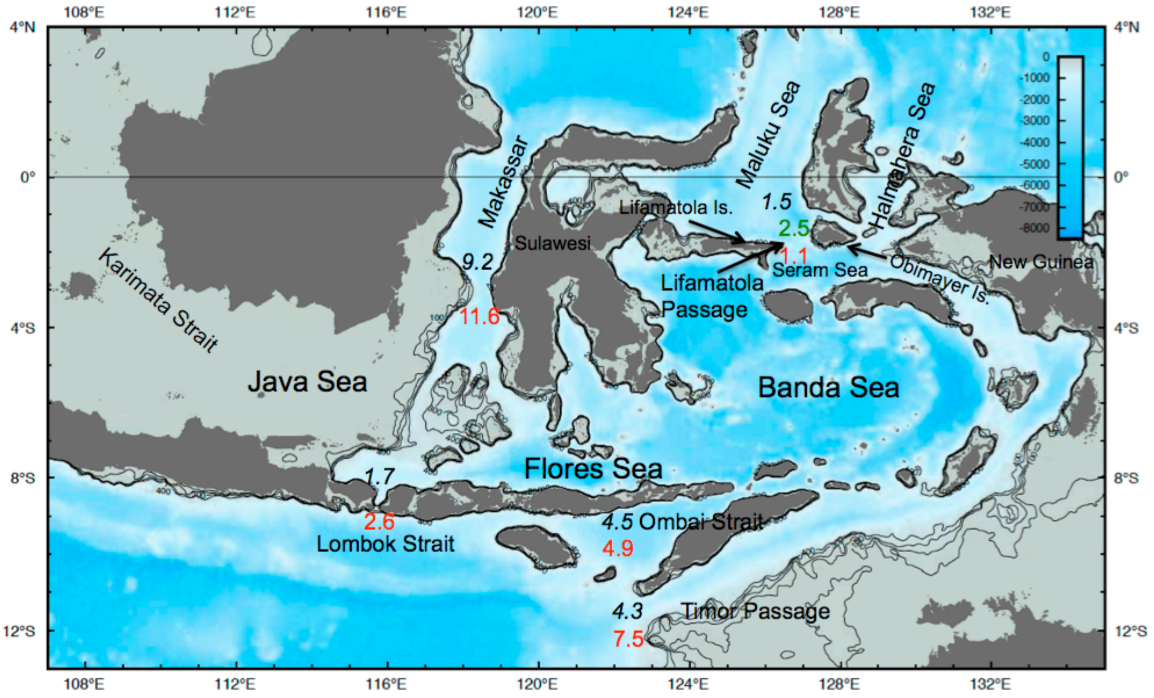

*Figure 2: Transport values in* $10^6$ $m^3$*/sec within the passages measured by the INSTANT program, 2004-2006. The italics numbers in black represent transport values based on pre-INSTANT data: Makassar Strait, 1997 [34, 35]; Lombok Strait, 1985 [36, 37]; Timor Passage (south of Timor) from March 1992 to April 1993 [38]; Ombai Strait (north of Timor) for 1996 [39]. The pre-INSTANT value of 1.5 Sv for the Lifamatola Passage represents overflow of dense water at depths greater than 1500 m based on 3.5 months of current meter measurement in early 1985[40]. The red numbers are the 3-year mean transports measured by INSTANT. In Lifamatola Passage, the green number is the INSTANT overflow transport >1250 m, and the red number is the total transport measured by INSTANT below 200 m. For details about the INSTANT moorings and transport values [41, 42, 43].*

The Indonesian seas do not simply provide a passive conduit for interocean exchange, as the stratification of the inflowing Pacific water is modified before its export into the Indian Ocean. During the ~1 year residence of the Makassar transport ~10 Sv within the Banda Sea (above the sill depth of Makassar Strait, ~700 m), the inflowing Pacific profile is altered by mixing, with energy derived from dissipation of powerful tidal currents [44, 45, 14, 46, 47], by Ekman pumping [48], as well as heat and freshwater flux across the sea-air interface. This results in a unique Indonesian tropical stratification with a strong, although relatively isohaline, thermocline. The formation of the Indonesian stratification is further complicated as the inflow and outflow at the intraseasonal to seasonal time scales are not necessarily in balance, with water accumulating and modified within the Banda Sea from February to June and released during the rest of the year [48, 49].

The interocean fluxes of heat and freshwater induced by the ITF does not depend on just the net transport, but also on the form of the velocity, temperature and salinity profiles [50, 51]. The annual mean transport may not change, but if the transport profile varies relative to that of temperature and salinity, then the interocean heat and freshwater transports would change accordingly.

- *Recent observational programs of the ITF and suggestions for additional observing system:*

The International Nusantara Stratification and Transport (INSTANT) program [52, 41, 42, 43, 53] was established to directly measure the depth dependent ITF from the intake of Pacific water at Makassar Strait and Lifamatola Passage, to the Nusa Tenggara exit channels into the Indian Ocean. The collective merit of the INSTANT program over prior measurements of the ITF is the simultaneous, multi-year measurements in all the major inflow and outflow passages. INSTANT fieldwork began in December 2003/January 2004 and was completed in November/December 2006. ENSO during the three year INSTANT period was in a weak El Niño state, with a La Niña phase in late 2005 into early 2006, providing some confidence that the three year ITF mean might be a fairly good representation of a longer term mean. The IOD during the INSTANT period was near zero, but with a substantial positive phase in the latter half of 2006 [54]. The INSTANT ITF transport is about 30% greater than the ITF as revealed by non-synoptic measurement with specific ITF channels during the 1990s (Figure 2).

Three years cannot capture low frequency fluctuations of the ITF and its links to the climate system. From a research perspective, the existing ocean data can be developed to provide an estimate of the long-term behavior of the ITF. The INSTANT data set will be important in providing guidance of how to achieve this. For a more direct approach a cost-effective ITF monitoring system is needed. As the ITF has multiple streams and undergoes significant modification in its stratification en route through the Indonesian seas, a cost-effective, long-term monitoring system is no easy matter to design. We propose that a working group be established to consider the specifics of such a cost effective plan, using the INSTANT period of intensive observations as a base. What follows are elements of such a plan.

Development of a ITF plan would benefit from coordination with the IndOOS, so as to take full advantage of the basin scale observing system in the Indian Ocean. This coordination will provide the added value to ITF activities and will help emphasize the social benefits from ITF observation through better identifying the linkage between ITF with the IOD, MJO and Monsoon.

A long-term Makassar mooring site was established at the INSTANT Makassar – west mooring position in November 2006. This NOAA/OCO funded mooring was deployed on 22 November 2006 at 2°51' S; 118°28' E, was recovered on 31 May 2009, and re-deployed for another 2 years to continue to build the time series. With the 2004-2006 INSTANT program mooring at the same site, we now have a 5.5 year continuous time series of Makassar throughflow [55]. While this serves as an important part of the ITF monitoring array, it in itself is not sufficient. Moorings in other key passages should be considered. The Lifamatola deep overflow into the Seram [Banda] Sea of about 2.5 Sv is difficult to quite expensive to measure. As its inter-annual variability is small: the standard deviation of the annual mean flow is <0.5Sv, <20% of the 3 year INSTANT mean value [43], perhaps monitoring the deep Lifamatola transport is not cost effective? But this needs to be carefully considered. Other throughflow routes that should be considered for observing over long periods are from the Halmahera Sea to the Maluku Sea; the Karimata Strait linking the South China Sea to the Java Sea; and Singapore Straits. While Timor carries the bulk of the ITF into the Indian Ocean, the variability is largely governed by Lombok and Ombai. It would seem key to monitor at least one of these passages. We need to do an assessment of what inflow and outflow moorings are needed (which straits, # moorings in each strait etc.).

Other components of a ITF observation network may involve:

- A key element of any observational system is the larger scale and regional coverage offered by satellite based sensors, such as SST and SSS (the later expected once Aquarius is operational); altimeter [56], SAR and ocean color [57].

*In situ* systems include (Figure 3):

- Moorings, discussed above.
- Shallow pressure gauges that offer a method to capture the surface layer flow [58].
- High Frequency Radar [e.g. CODAR] provides detailed views of the sea surface flow.
- Repeat XBT and XCTD sections offer snapshot views of the ITF stream entering the Indian Ocean [17, 19].
- The use of Inverted Echo Sounders with pressure gauges (PIES) should be evaluated to monitor the changing thermocline depth and sea level.
- Data telemetry from non-tethered instrumentation, such as drifters, Argo profilers and gliders offer regional views for the ocean condition.
- Instrumenting ships of opportunity, this includes VOS [e.g. 1997-2000 "WESTPAC ADCP Program" Japanese bulk carrier fitted with an ADCP on repeated traveling from Japan to western Australia, see http://www.ocean.hiroshima-u.ac.jp/wpadcp/index.html] as well as ferry between the various Islands of the Indonesia region, can be a cost effective observational method (see “FerryBoxes Begin to Make Waves” Science vol 322;1627-1629, 12 December 2008).

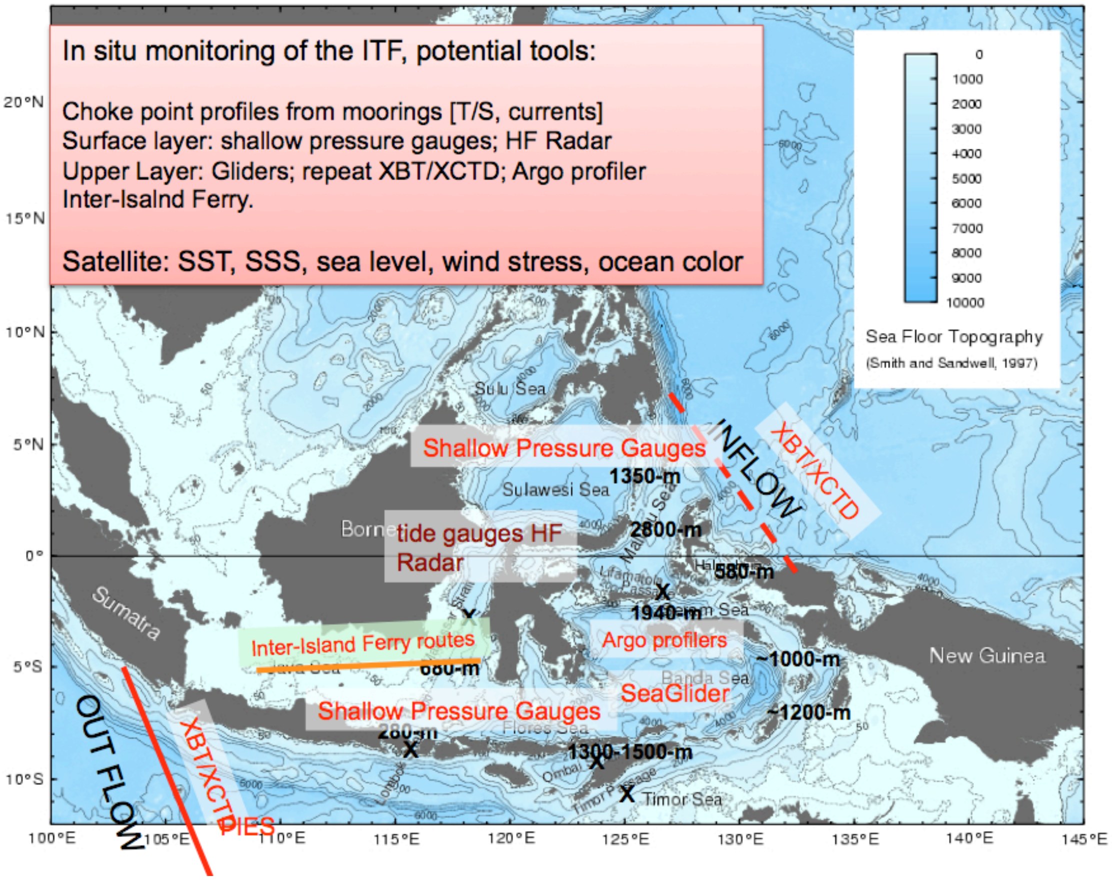

*Figure 3: Potential elements of a ITF observing system. As the ITF has multiple streams and undergoes significant modification in its stratification en route through the Indonesian seas, a cost-effective, long-term monitoring system is no easy matter to design. We propose that a working group be established to consider the specifics of such a cost-effective ITF monitoring plan, using the INSTANT period of intensive observations as a base. Coordination with the IndOOS is recommended.*

### [B] Tassie Leakage (Pacific to Indian flow south of Australia):

Warm Pacific water also enters the Indian Ocean along the southern margins of Australia, in a transfer often referred to as the Tasmanian or 'Tassie' Leakage. Data analyses and models, including quasi-Lagrangian observations, strongly suggest that the structure of the Atlantic Meridional Overturning circulation for the modern climate involves a strong link with the three subtropical gyres of the southern hemisphere, which merge into a "supergyre" spanning the three ocean basins [60, 61, 7, 4]. The Pacific/Indian link is by way of the Tassie leakage.

The coupling between the upper ocean wind-driven circulation and the overturning in the model suggests that changes in the southern hemisphere winds can alter the pathways of the AMOC, and therefore the water properties and the associated heat and freshwater transports. In the Pacific Ocean, the wind and local bathymetry separates the inflowing waters from the south (the southern branch of the subtropical super-gyre) in two branches. One, in the easternmost part of the subtropical gyre, ends up in the Indian Ocean through the Indonesian Throughflow after been taken in the Pacific STC. The other one, emerges from the western part of the basin where the southern branch collides with the New Zealand plateau (Figure 4). This branch feeds the westward flowing water south of Tasmania [62, 63, 64]. This flow is relatively deep, centred around 600-800 m of depth and has a transport varying between 6 and 24 Sv [62, 64].

An important number of recent models simulating the modern-climate ocean circulation for which the upper-branch of the AMOC has been derived, show that a relatively significant fraction of the total transport to the North Atlantic originate from the Tasman outflow [61]. The core of the "Tasman leakage" crosses the subtropical Indian Ocean remaining at the base of the thermocline and eventually reaching the surface layers in the North Atlantic. Because of their deep run, the largest fraction of these waters are isolated from air-sea exchanges with the atmosphere along their trajectory to the North Atlantic.

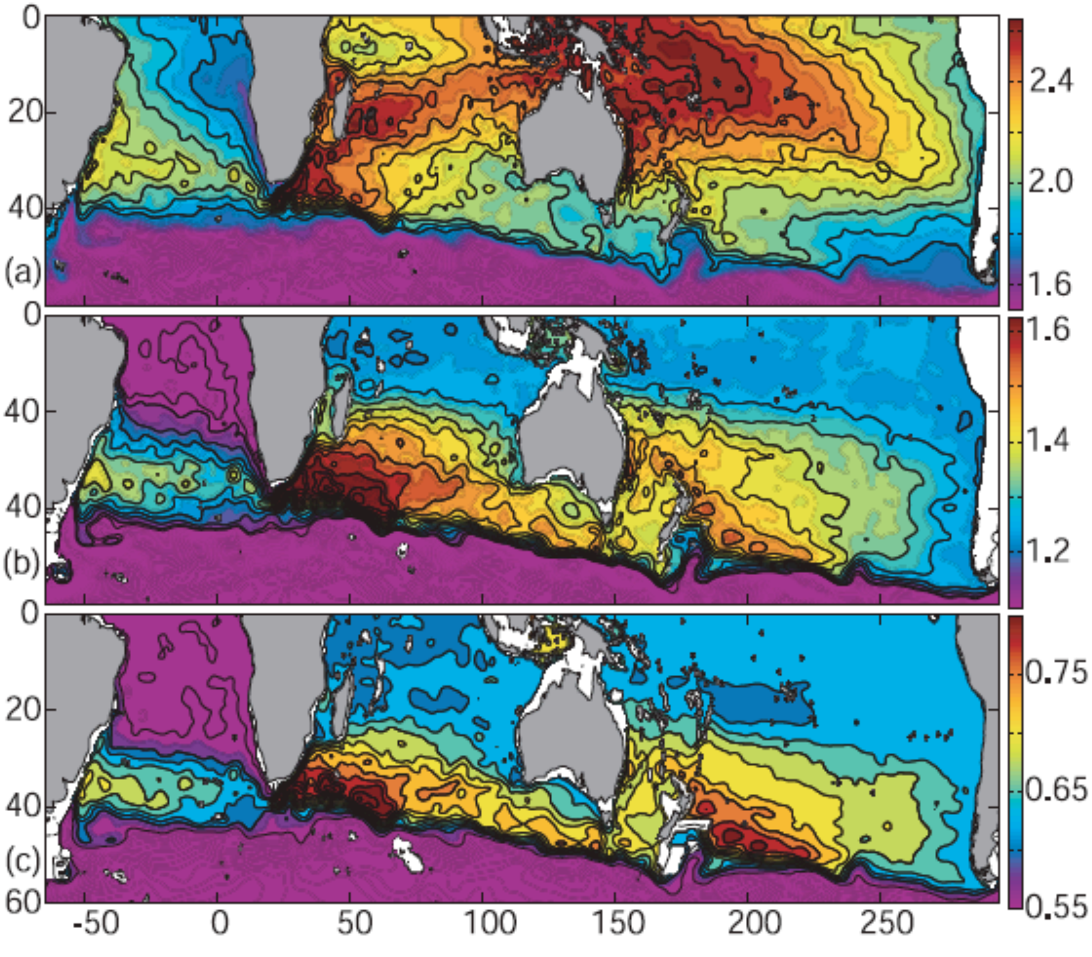

*Figure 4: The mean steric height, (a) h0/2000 (contour interval 0.02-m), (b) h400/2000 (contour interval 0.01-m), and (c) h1000/2000 (contour interval 0.01-m [4].*

Completely different AMOC structures, essentially reduced to a circulation pattern confined between the North Atlantic and the South Atlantic are obtained only for past glacial conditions [6]. This suggests that Tasman Leakage and more importantly the wind forcing that structure the return flow to the North Atlantic in a southern hemisphere supergyre for the actual climate conditions, are important to the global ocean circulation, the AMOC and also the Earth Climate. Because advection of water masses affects heat and freshwater transports, variations of the wind pattern could affect the dynamical regime and stability of the AMOC [65, 66, 67]. Hence, in a changing climate, trends of the southern hemisphere winds could represent an additional process to which the AMOC is sensitive [68]. Now, very recent analyses of data from the recently launched ARGO programme, of ocean drifters together with trends derived from altimetry as well as climate change scenarios suggest that the subtropical gyres of the southern hemisphere (and therefore the "supergyre") are extending southward. This change could affect at a relatively short-term, mass, heat and fresh-water exchanges between the ocean basins, the AMOC itself and affect in turn the varying climate.

• *Tassie Leakage Observational time series:*

While the feedbacks involving the SH ocean circulation, have the potential to significantly affect the global circulation and climate change they remain poorly understood. However, the short and incomplete nature of existing time series means that the causes and consequences of observed changes are difficult to assess. Sustained observations are required to detect, interpret and respond to change.

The Tasman outflow is currently observed by a seasonal High Resolution XBT line (SURVOSTRAL project), a repeated (5 to 7 year frequency) hydrological line (CSIRO), Argo floats, and, by inference, altimetric sea surface height.

Ideally an observing network dedicated to monitor changes in ocean circulation could be based on a system of relatively dense array of Current – Pressure Inverted Echo Sounders across the Tasman flow south of Tasmania (Figure 5) and southward across the local recirculation (to be able to compute the net inflow of Tasman waters in the Indian Ocean).

South of Tasmania the hydrography transect SR3 is repeated on a low frequency base (5 to 7 year). altimetry. In addition, even if between the South-East Indian Ocean and South-West Pacific the differences in water masses is not so dramatic as it is between the Agulhas Current System and the South Atlantic, Tassie leakage transfer water masses slightly different than the ambient South-East Indian ocean ones. Moreover, this transfer happens in the subsurface and not at the sea surface (it is centered around 800 m). Because of this it is not detectable from surface dynamic height (Figure 4). Therefore, we cannot just use altimetry derived proxies (as they make use of the surface dynamic height) but we need to put together two independent integral estimates of the thermohaline structure of the water column (therefore altimetry-GEM + C-PIES-GEM ). The best way to combine the two independent estimates should be methods as used in GEM-ETTA and ASTTEX program [69].

As the Tassie leakage could be made of eddies, to get robust estimates from the mooring/altimetry proxies, it would be appropriate to get a more frequent and high resolution hydrology sampling than produced by SR3, XBT or ARGO sampling. Glider lines added to the mooring array and complementary to all other observations, should improve estimates of both proxies derived from the mooring array and those from altimetry.

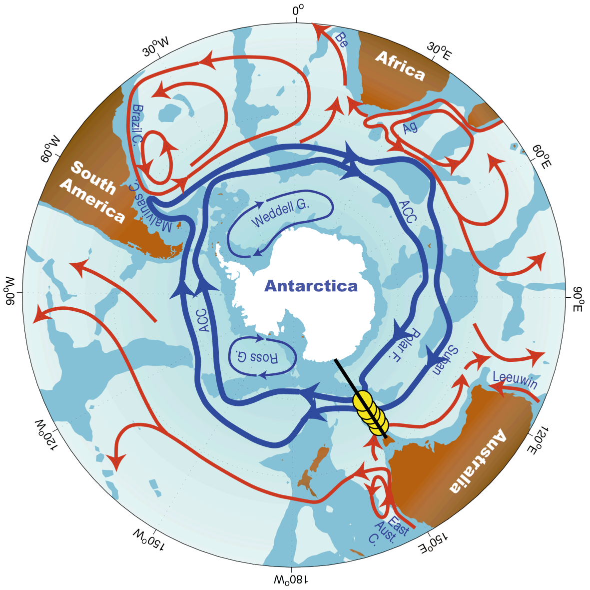

*Figure 5: The proposed observing network for the Tasman outflow that allies already ongoing repeated observations (hydrography undertaken by CSIRO, HR XBTs in the framework of SURVOSTRAL, Argo floats, altimetry). We suggest adding an order 10 of C-PIES, together with repeated intraseasonal glider lines (at a monthly frequency or higher due to the mesoscale nature of the flow in the region)*

## 3. Indian to Atlantic flow: Agulhas Leakage

An interocean exchange route considered as important to larger-scale thermohaline circulation lies not within the confines of a channel, but rather in the gap between the southern shores of Africa and the ACC, a gap occupied by the Agulhas Retroflection. The Agulhas Current flows westward along the southern rim of Africa, with a transport approaching 100 Sv. Rather than continuing into the South Atlantic, Agulhas water curls back to the Indian Ocean, in what is referred to as the Agulhas Retroflection. The significant of the Agulhas Retroflection does not end with its momentary loop into the southeast corner of the South Atlantic: there is considerable transfer of Indian Ocean water into the upper kilometer of the Atlantic Ocean. This is often referred to as the Agulhas leakage (Figure 6) [5].

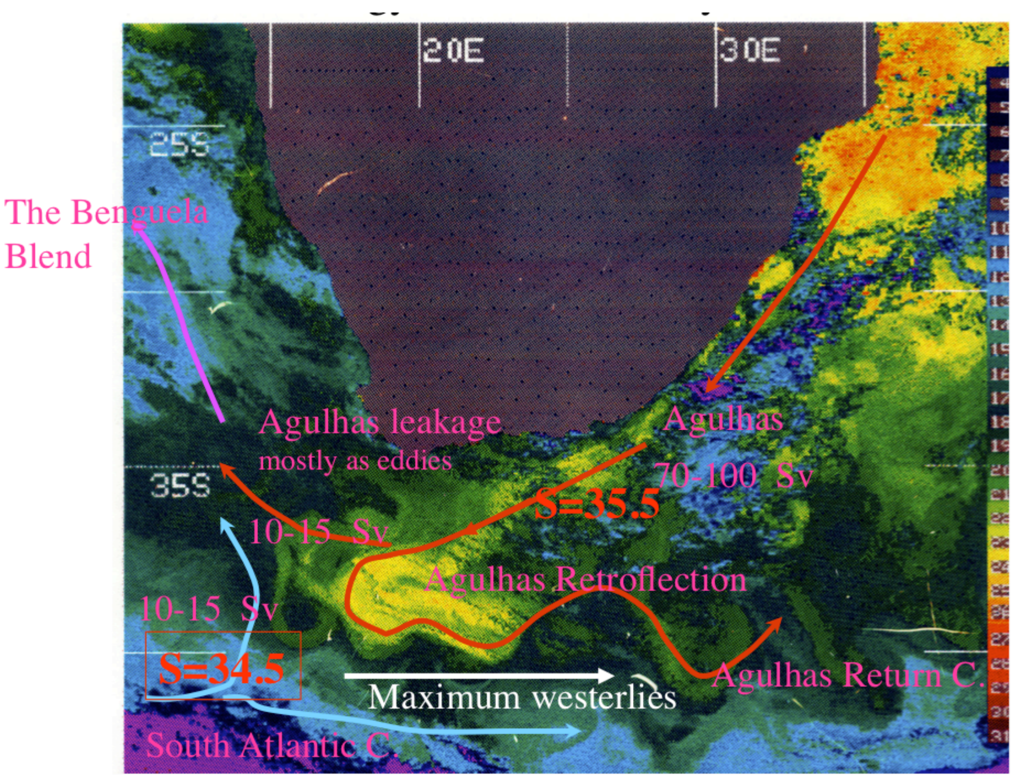

*Figure 6: Schematic of the Agulhas Retroflection and leakage into the South Atlantic Ocean*

The magnitude of Agulhas leakage, and its relationship to the larger scale present day and glacial/inter-glacial climate system, as related to the equatorward heat flux within the South Atlantic and to the formation of North Atlantic Deep Water and associated Meridional Overturning circulation has been the subject of numerous debates marked by conflicting results over the last 20 years [70].

Modeling studies reveal the potential impact of leakage on the strength and stability of the Atlantic MOC [66, 71, 72]. Increased Agulhas leakage is linked to the poleward shift of the southern hemisphere westerlies [73]. At shorter time scales (years) variability from the retroflection propagates via Rossby and Kelvin waves toward the Atlantic equatorial region and further north [74, 75] .

Recent modeling studies have confirmed our earlier theoretical work that if Agulhas transport goes up leakage goes down and vice versa [76]. In the extreme case a large enough Agulhas transport could lead to zero leakage by Inertial choking [77] which may have been the case during glacial periods [78, 79].

The impact of leakage on the MOC is strongly dependent on how the characteristics of leakage water (temperature, salinity and potential vorticity) mix and blend in the Cape Basin (the Cape Cauldron). This determines the involvement of the leakage in the broader scale MOC versus that that closes into the subtropical supergyre.

- *Agulhas Leakage Observational Time Series:*

As the Agulhas leakage is a significant component of interocean exchange in terms of the climate system, specifically to the Atlantic Meridional Overturning Circulation (AMOC) [72], a sustained observational program is recommended.

In recent years a number of programs have been effective in investigating aspects of the Agulhas leakage behavior. These include the GoodHope program [80], the Bryden/Beal moorings in the Agulhas Current [81], the ASTTEX moorings [69] and the earlier the BEST array [82, 83]. A rather wide selection of oceanographers have noted the critical importance and the need for proper monitoring of Agulhas leakage. The OceanObs09 program should build upon and expand these endeavors.

A newly funded program is Agulhas Current Time-series (ACT): Towards a multi-decadal index of Agulhas Current transport." (Lisa Beal, Paolo Cipollini, Johann Lutjeharms). ACT is a US-led, NSF-funded project with the goal of building a multi-decadal time series of Agulhas Current volume transport as a contribution to the Global Ocean Observing System. The ACT mooring array will be positioned southwest of East London, South Africa, where it will follow the trajectory of descending TOPEX/Jason ground track #96. Monitoring the upstream transport of the Agulhas by ACT will provide essential information for interpretation the Agulhas leakage observational time series.

An Agulhas leakage observational program a would include satellite and in situ observational components. These components should lend themselves to provide critical information required to validate and improve numerical simulations of the Agulhas Retroflection and of the transfer of Indian Ocean into the South Atlantic Ocean, and its involvement in the AMOC as well as other aspects of the climate system. In the ideal case one would like to design an in situ experiment to determine the relation between transport variability and amount of leakage.

Figure 7 provides a minimal observational approach to monitor the Agulhas leakage. The Agulhas leakage observational program needs to be coordinated with existing and OceanObs09 encouraged South Atlantic, southwest Indian Ocean, Agulhas current observational programs. The South Atlantic SAMOC array is most relevant to the Agulhas leakage issue, see http://www.aoml.noaa.gov/phod/SAMOC/ /. Also, of relevance is the new ACT program, discussed above and the Dutch INATEX program, which will continue the coming years monitoring the meridional transport through the Mozambique Channel with a mooring array (it began in 2000) and will soon add a mooring array to the East Madagascar Current near 25°S. These locations are upstream of the Agulhas Current proper. They have recorded strong inter-annual changes of the transport.

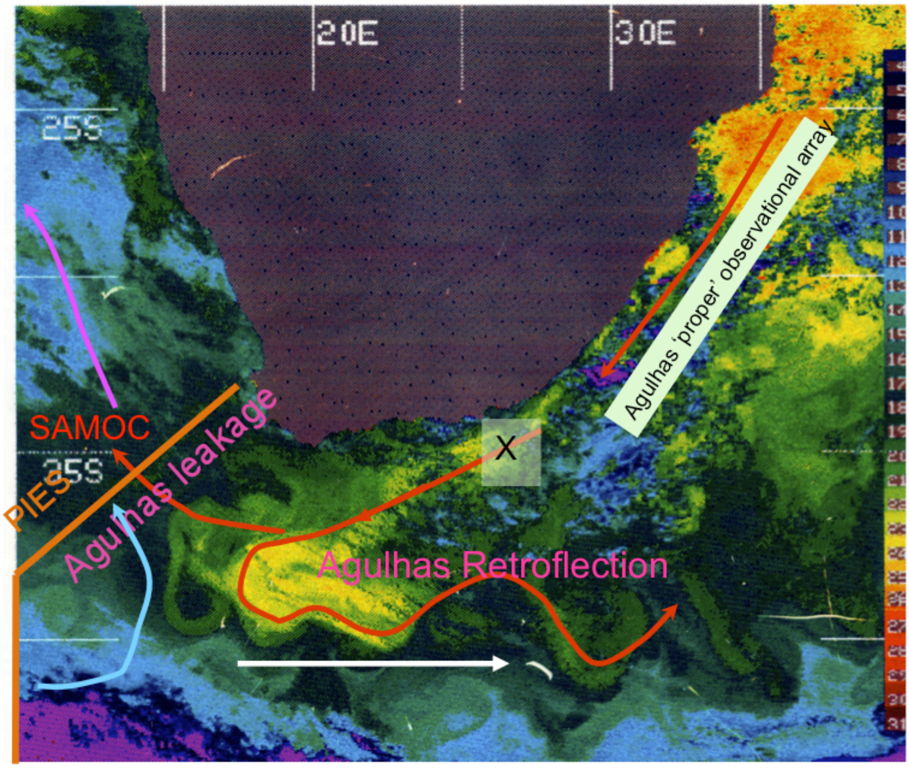

*Figure 7: Observational time series directed at the Indian to Atlantic leakage would be coordinated with the observational array designed to monitor the Agulhas Current. It would include Agulhas transport between the Agulhas Plateau and the African continental margin [X] as a series of inverted echo sounders with pressure gauges than can be linked to satellite derived altimetric measurements. This can be considered an element of the South Atlantic Meridional Overturning Circulation, SAMOC [http://www.aoml.noaa.gov/phod/SAMOC/]*

Feeding into the Agulhas Current is the southward flow within the Mozambique Channel (MC) and the East Mozambique Current (discussed in the IndoOOS CWP). IndoOOS CWP states: "The southward transport through the MC takes place mostly by a regular train of large and deep reaching mesoscale eddies [84, 85]. The eddies travel southward into the Agulhas retroflection region at the southern tip of Africa and affect the interocean exchange" and "satellite altimeter observations have shown significant interannual variation of the eddy activity in the Mozambique Channel and east of Madagascar [86]. It appears to be a lagged response to the Indian Ocean Dipole cycle (IOD)".

A strategy to monitor the Agulhas leakage must be coordinated with programs with these systems, specifically with the LOCO mooring array within MC (see: IndOOS CWP).

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