# Science Driver:
# Indian Ocean Heat Export

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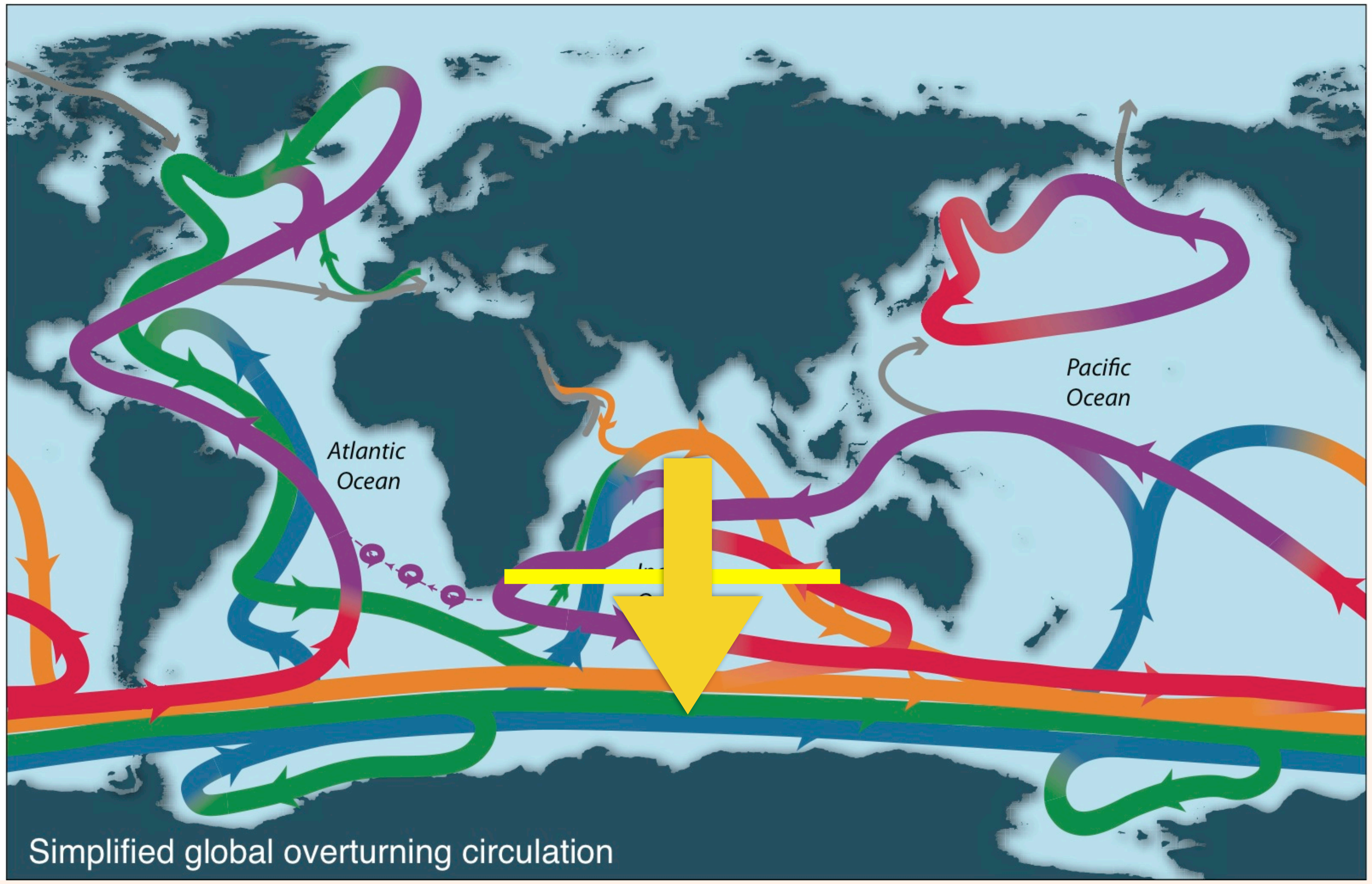
Recent focus on wind-driven Southern Ocean upwelling and AMOC has overshadowed the essential roles of diapycnal upwelling of intermediate, deep, and bottom waters in the Indian and Pacific Oceans.

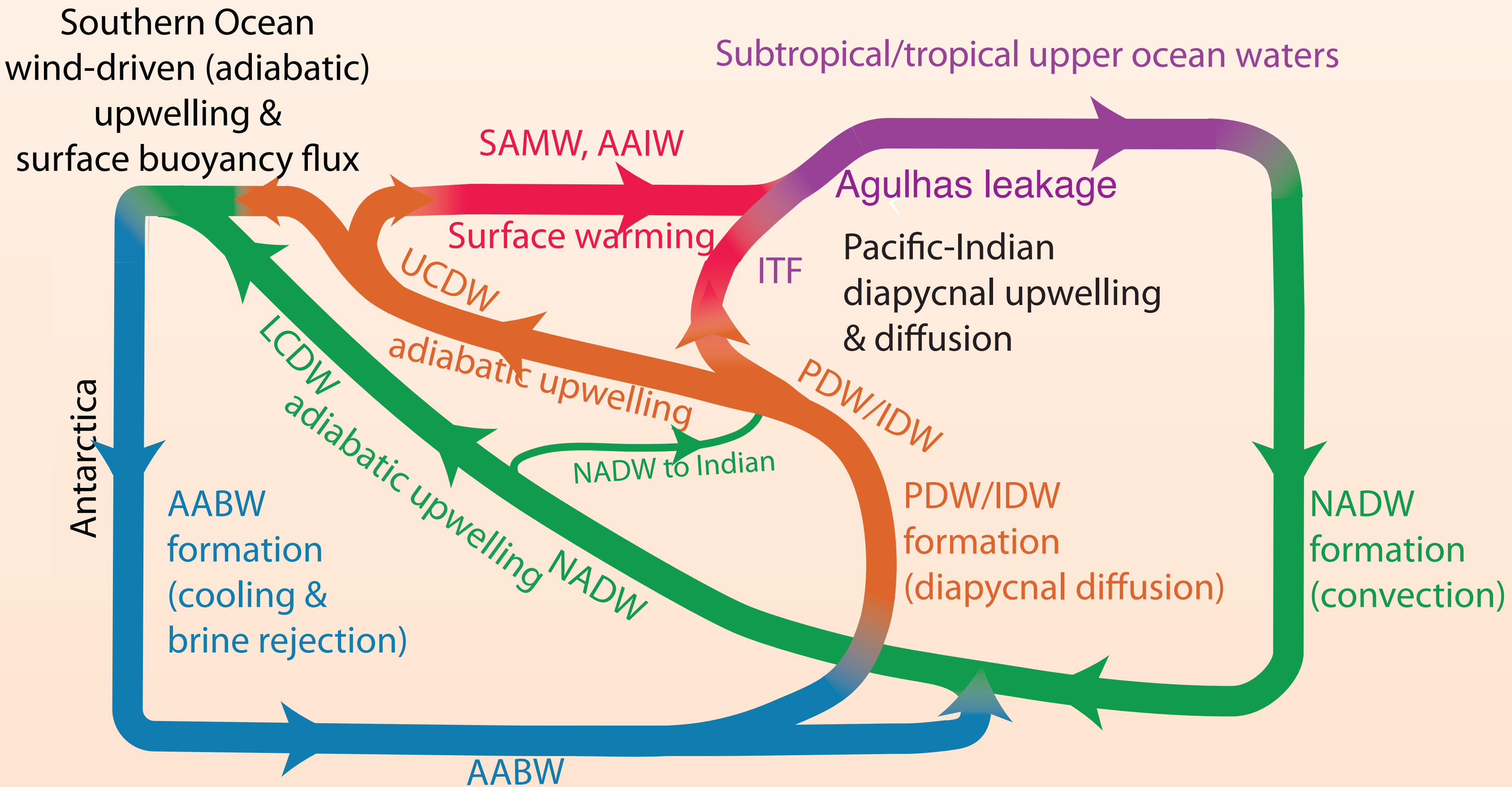
All basins contribute, in almost equal parts, to source waters of NADW.

Properties and heat content of upwelled waters depend strongly on mixing and diffusion in the Indian and Pacific Oceans.

**Important to decadal variability.**



Simplified global overturning circulation



Southern Ocean wind-driven (adiabatic) upwelling & surface buoyancy flux

Subtropical/tropical upper ocean waters

SAMW, AAIW

Agulhas leakage

Surface warming

ITF

Pacific-Indian diapycnal upwelling & diffusion

UCDW

adiabatic upwelling

PDW/IDW

LCDW

adiabatic upwelling NADW

NADW to Indian

Antarctica

AABW formation (cooling & brine rejection)

PDW/IDW formation (diapycnal diffusion)

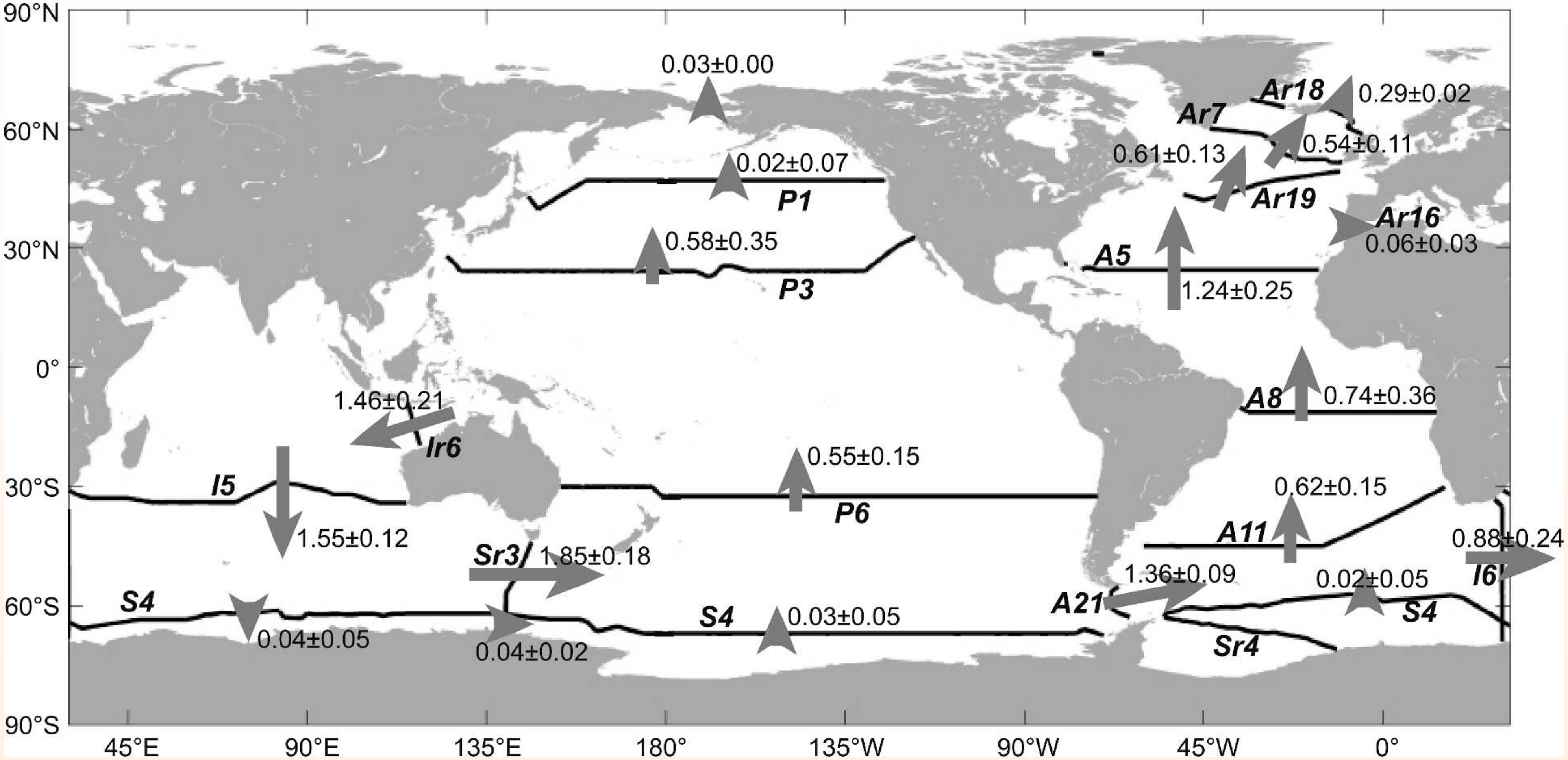
NADW formation (convection)

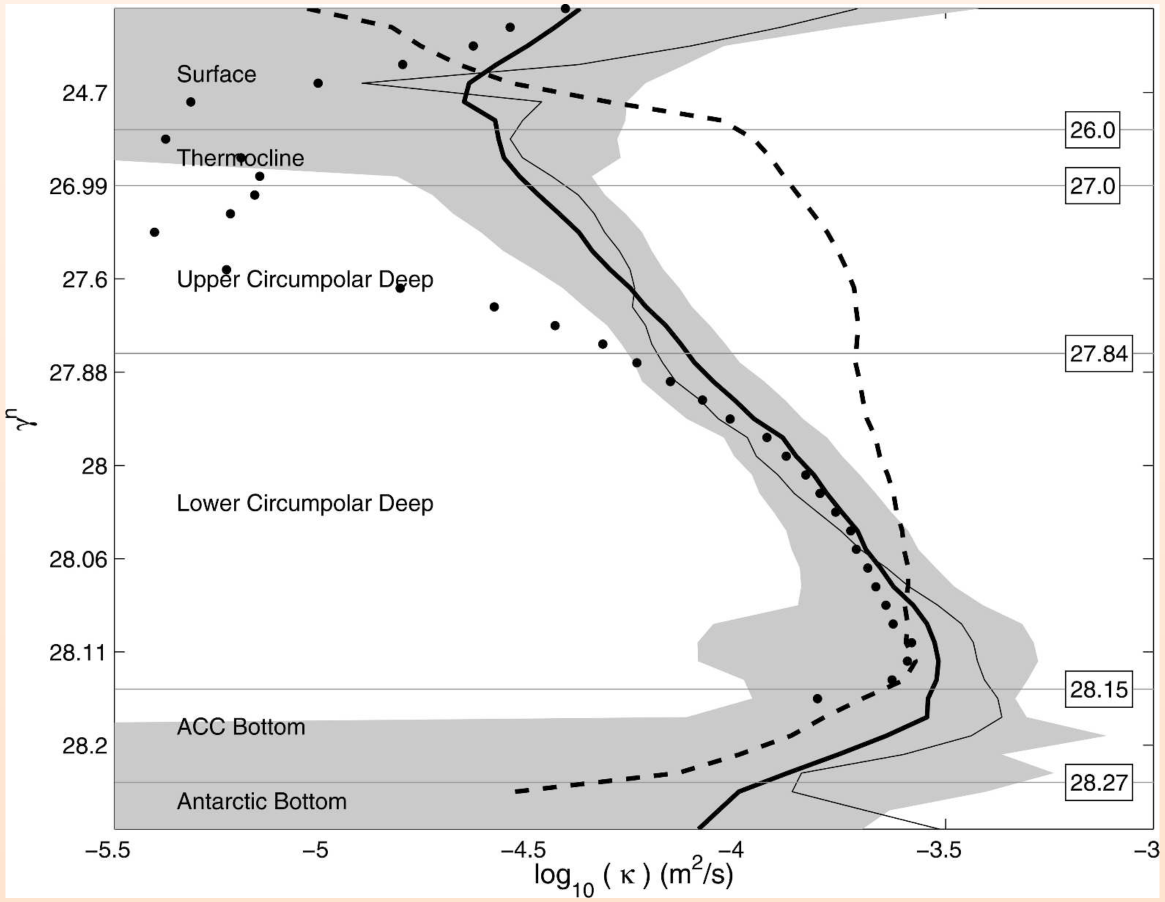
AABW

Talley, 2013

| Authors | Data source | Over-turning (gyre) (Sv) | Agulhas Current (Sv) | ITF (Sv) | Ekman trans. (Sv) | ZVS (max) (m) | Upwelling (cm/s) | Heat flux (PW) | Heat convergence (PW) | Fresh-water flux (Sv) |
|---|---|---|---|---|---|---|---|---|---|---|
| **Fu (1986)** | | ?? | | | | | | -0.25 | -0.25 | |
| **Toole & Warren (1993)** | 1987 | 25 | -87 | 6.7 (@24°) | 1.6 | ~2000 | 6.9 x10$^{-5}$ | | -0.98 | |
| **Robbins & Toole (1997)** | 1987 | 12 ± 3<br>(11.9 ± 2.7 x 10$^{9}$ kg/s) | -87 | 5.3 ± 3.5 | 1.6 | 2000, layer5 | 4.5 x10$^{-5}$ | MOC -0.41,<br>gyre -0.19,<br>ITF 0.18 | -0.42 ± 0.19 | 0.30 ± 0.09<br>MOC 0.12,<br>gyre 0.03,<br>ITF 0.16 |
| **McDonald (1998)** | 1987, global inverse | 17 ± 5 | -9 | | | | | -1.45 | | |
| **Zhang & Marotzke (1999)** | GCM | -5 deep cell (16 <500m) | -42 (baroclinic) | 2.7 | | <500 | | | | 0.05 |
| **Ganachaud et al (2000)** | 1987, global inverse | 10.6 ± 4 | -74 ± 7 | 15 ± 5 (posteriori) | 0.5 ± 1 | ~1000 | 1-3 x10$^{-5}$ | -1.5 ± 0.2<br>ITF: -1.36 ± 0.15 | -0.1 ± 0.2 | 0.35 ± 0.25 |
| **Bryden and Beal (2001)** | 1987 | 10.1 | -66.5 | 12.3 (@18°) | 1.65 | | | -0.12<br>MOC -0.62,<br>gyre -0.75,<br>ITF 0.7 | -0.66 | 0.54 |
| **Sultan et al (2007)** | 1987 | 14.4 | -55 | 1.5 ± 1 | | | 15.5 ± 8 x10$^{-5}$ | -0.33 | | |
| **Lumpkin & Speer (2007)** | 1987, global inverse | 12.4 ± 2.6 | 67 ± 5 (constraint) | 13.2 ± 1.8 | 0.5 | | k=2 x 10$^{-4}$ m$^{2}$/s | -1.55 ± 0.12<br>ITF: -1.46 ± 2.1 | -0.1 ± 0.2 | 0.5 ± 0.01 |
| **Meijers et al (2007)** | GCM | 10 | <-70 | 10 | | | | -1<br>ITF: -0.9 | | 0.2,<br>ITF: 0.2 |
| **Talley (2008)** | 1987, global Reid circ’n | 16.4 ± 6.1 | -73 | | | | | | | |
| **McDonagh et al (2008)** | 2002 | 10.3 (52) | -69.7 ± 4.3 | 12 | | ~1500 (3300) | | | | |
| **Mazloff et al (2010)** | SOSE | | | 11 ± 1 | | | | -1 | | |
| **Katsumata et al (2013)** | 1987, 2009 + SODA, K7,OFES, Indo-Pacific | 1987:-23 ± 6<br>2009:-27 ± 6<br>above γ=27.4 including ITF | | increasing trend since 1990s | | initialised at γ=28.1 | | | | |
| **Sprintall et al (2014)** | synthesis of all ITF experiments | | | 15 Sv @ 17.6 C | | | | | | |
| **Hernandez & Talley (2016)** | 2002 & 2009, Indo-Pacific inverse | 2002: -12 ± 9<br>2009: -8 ± 7 | 2002: -75<br>2009: -92<br>(posteriori) | 2002: 11 ± 11<br>2009: 11.9 ± 8.3<br>(apriori 14± 5 ) | | ~1000 | | 2002: -1.1 ± 0.2<br>2009: -1.5 ± 0.2 | 2002: -0.47<br>2009: -0.82<br>(ITF @ 17.6 C) | |

Heat flux across 32 S



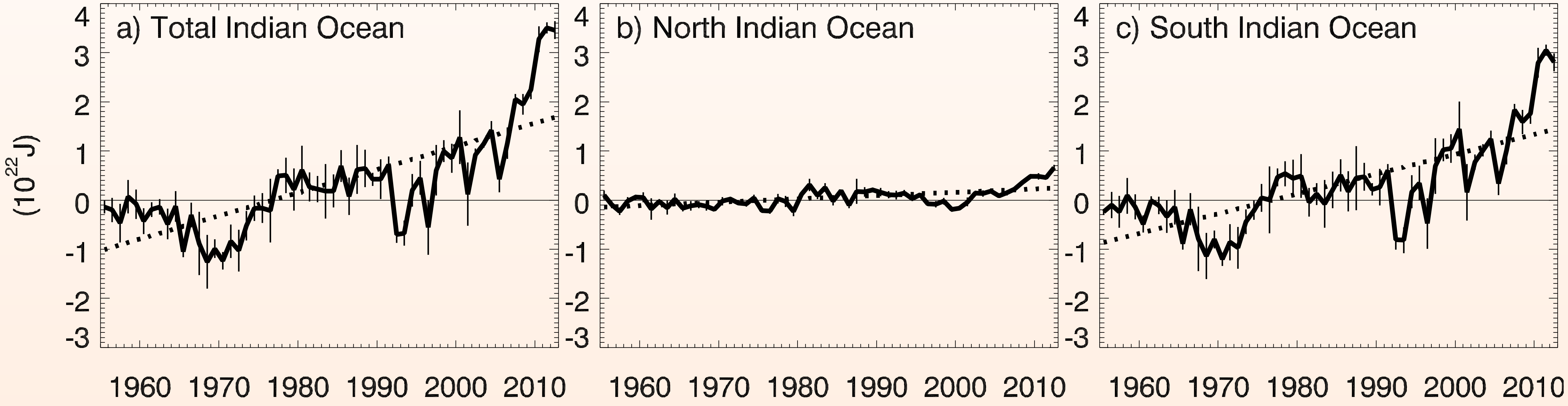


IO heat export has been estimated as strongest global meridional heat transport: Balances heat loss in Atlantic and Southern Oceans

IO has largest implied diapycnal mixing through thermocline and deep water: Implies water mass transformation.

Lumpkin & Speer, 2007

# Indian Ocean Heat Gain: What is the role of heat export across the open southern boundary?

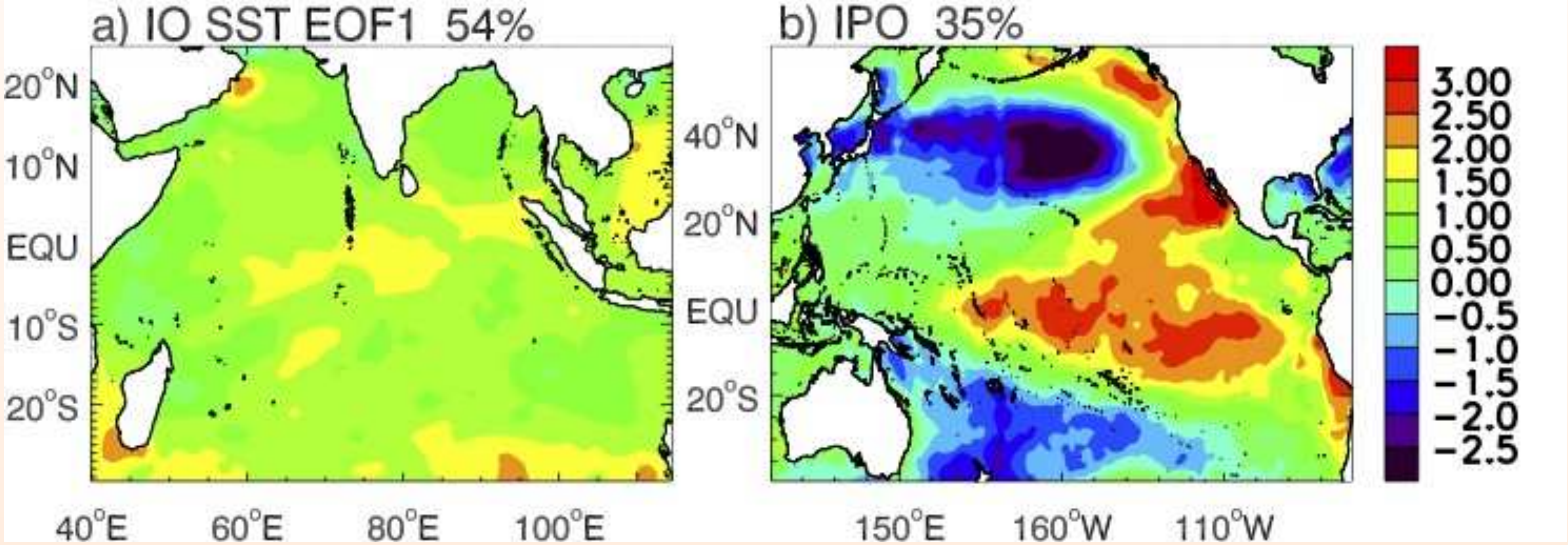


- Since 1998 Indian Ocean heat storage accounted for >30% of global ocean heat gain, while only 12% of area. Increased heat flux into basin via Indonesian Throughflow due to stronger Trade winds is implicated (Feng et al, 2011; Revelard & Sprintall, 2014; Lee et al, 2015).
- Storage is concentrated in the southern IO and is a balance of ITF import and export via subtropical gyre and overturning at open southern boundary, plus basin-wide air-sea flux.

# Decadal SST: What is the role of heat export across the open southern boundary?

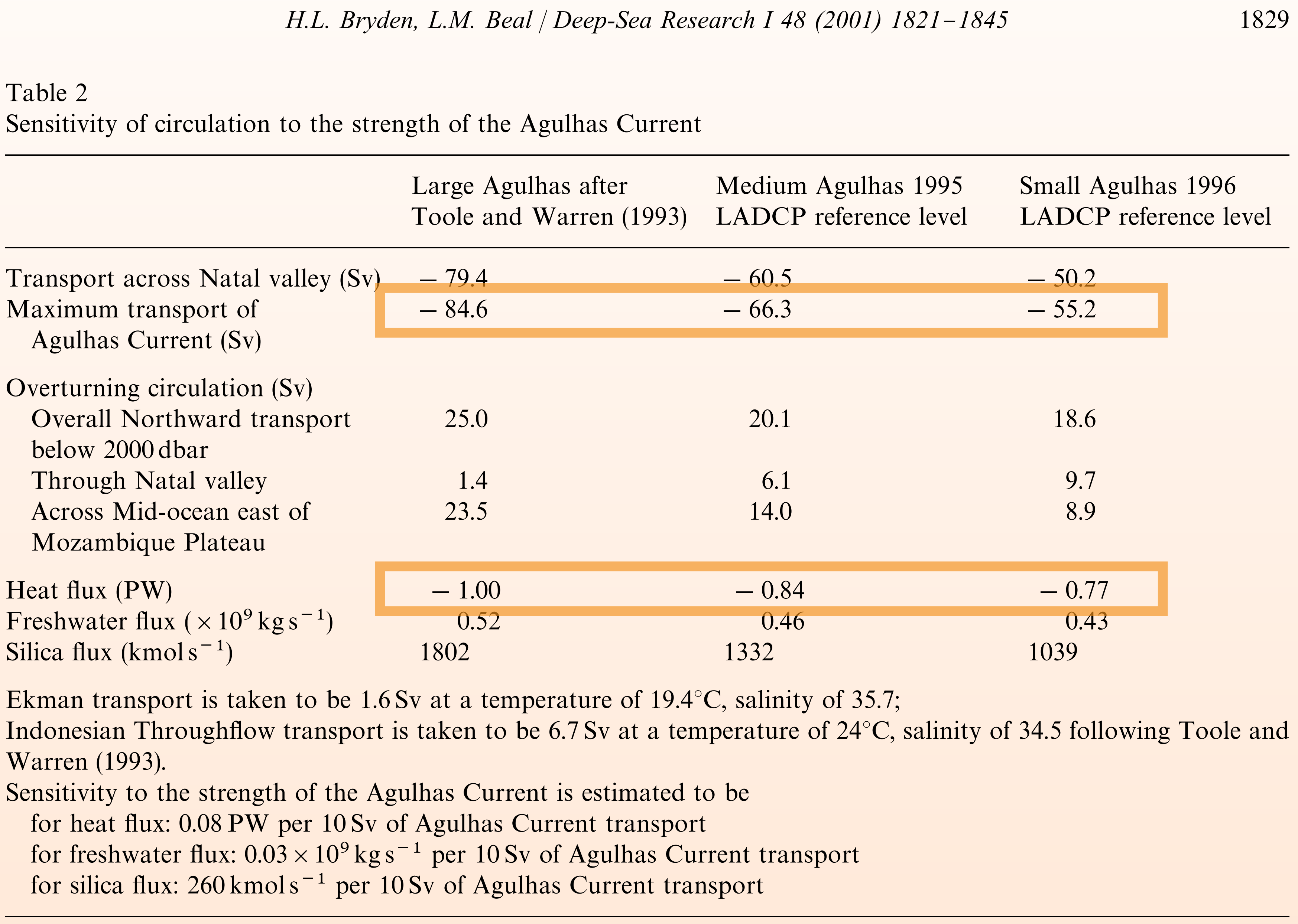
Indian

Pacific



- Leading signal in decadal SST is uniform across the basin and influences climate and extreme weather events for Indian Ocean rim countries (Han et al., 2014).
- In the North Atlantic, decadal SST (AMO) tied to subtropical overturning (AMOC)

# Indian Ocean Heat flux sensitive to Agulhas Current



*H.L. Bryden, L.M. Beal / Deep-Sea Research I 48 (2001) 1821–1845* 1829

Table 2
Sensitivity of circulation to the strength of the Agulhas Current

| | Large Agulhas after Toole and Warren (1993) | Medium Agulhas 1995 LADCP reference level | Small Agulhas 1996 LADCP reference level |
|---|---|---|---|
| Transport across Natal valley (Sv) | − 79.4 | − 60.5 | − 50.2 |
| Maximum transport of Agulhas Current (Sv) | − 84.6 | − 66.3 | − 55.2 |
| Overturning circulation (Sv) | | | |
| Overall Northward transport below 2000 dbar | 25.0 | 20.1 | 18.6 |
| Through Natal valley | 1.4 | 6.1 | 9.7 |
| Across Mid-ocean east of Mozambique Plateau | 23.5 | 14.0 | 8.9 |
| Heat flux (PW) | − 1.00 | − 0.84 | − 0.77 |
| Freshwater flux ($\times 10^9\,\mathrm{kg\,s^{-1}}$) | 0.52 | 0.46 | 0.43 |
| Silica flux ($\mathrm{kmol\,s^{-1}}$) | 1802 | 1332 | 1039 |

Ekman transport is taken to be 1.6 Sv at a temperature of 19.4°C, salinity of 35.7;
Indonesian Throughflow transport is taken to be 6.7 Sv at a temperature of 24°C, salinity of 34.5 following Toole and Warren (1993).
Sensitivity to the strength of the Agulhas Current is estimated to be
for heat flux: 0.08 PW per 10 Sv of Agulhas Current transport
for freshwater flux: $0.03 \times 10^9\,\mathrm{kg\,s^{-1}}$ per 10 Sv of Agulhas Current transport
for silica flux: $260\,\mathrm{kmol\,s^{-1}}$ per 10 Sv of Agulhas Current transport

- Inverse models using one-time trans-basin hydrographic data show basin-wide heat transport is carried by overturning and sensitive to the size of the Agulhas Current (Bryden & Beal, 2001; McDonagh et al, 2008).

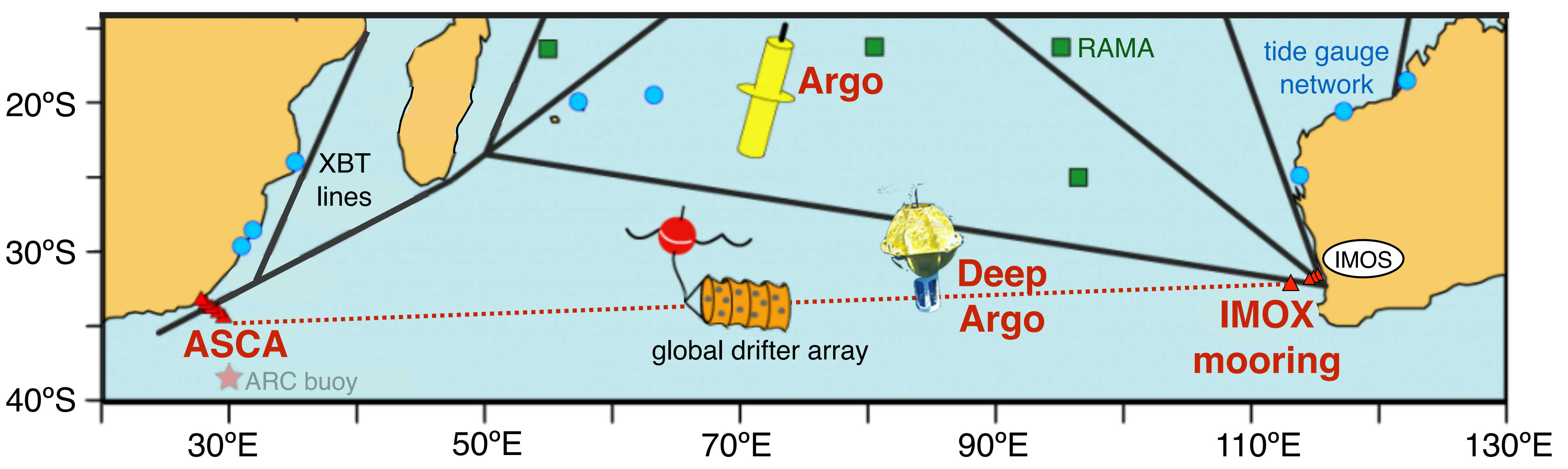
**Hypothesize decadal SST and heat storage related to ITF AND IO heat export across open southern boundary.**

(Heat export includes basin-wide air-sea flux convergence, which is difficult to measure directly)

# Actionable Recommendations towards capturing Indian Ocean Heat Export as part of IndOOS

- Observing system experiment: Across 34 S what time/space scales need to be resolved to capture meridional heat transport?
- T, S, p, v within Agulhas Current at 10-50 km horizontal, 100 (upper)-1000 m(deep) vertical, and daily? temporal resolution, to full depth. Moorings, gliders, CPIES??
- T, S, p, v at single point off western Australia (~4000 m?) with same vertical and temporal resolution: This forms a “geostrophic endpoint” mooring for overturning, following principles of AMOC observing system. Mooring, moored profiler, glider, CPIES??
- T,S,p,v at monthly, 200 km resolution across interior to capture gyre transport and inflows of bottom waters. Deep Argo? XBTs?
- Silicates at decadal? resolution to help constrain overturning. GO-SHIP??
- Sustained satellite observations of sea level and wind stress for barotropic fluxes and Ekman transport.

# Actionable Recommendations towards capturing Indian Ocean Heat Export



# Components of an IMO Measuring System

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