Wind Driven Circulation Indian Ocean and Southern Ocean

Lecture 18

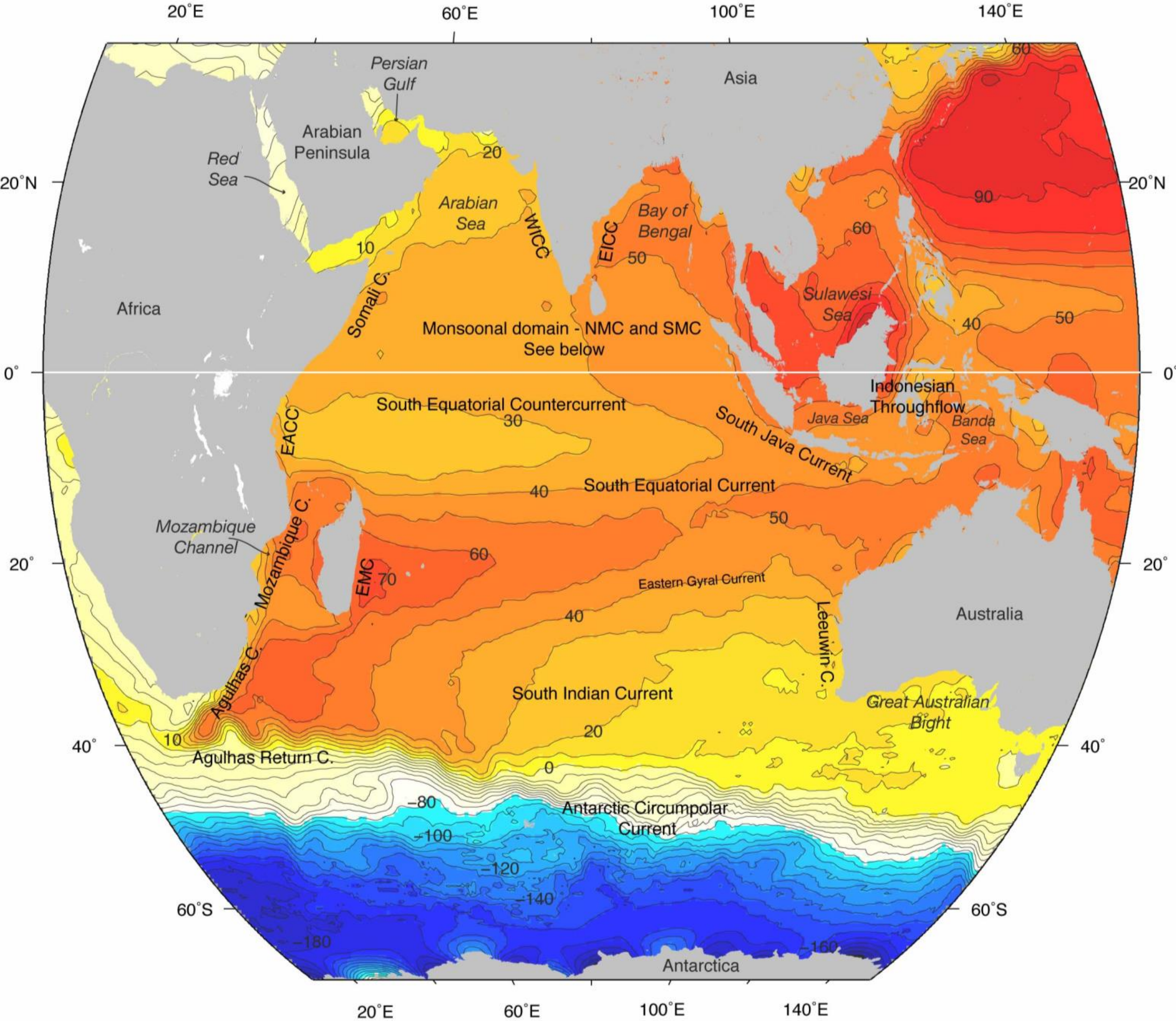
MAR 350 Spring 2017

Reading: Knauss Chapter 7

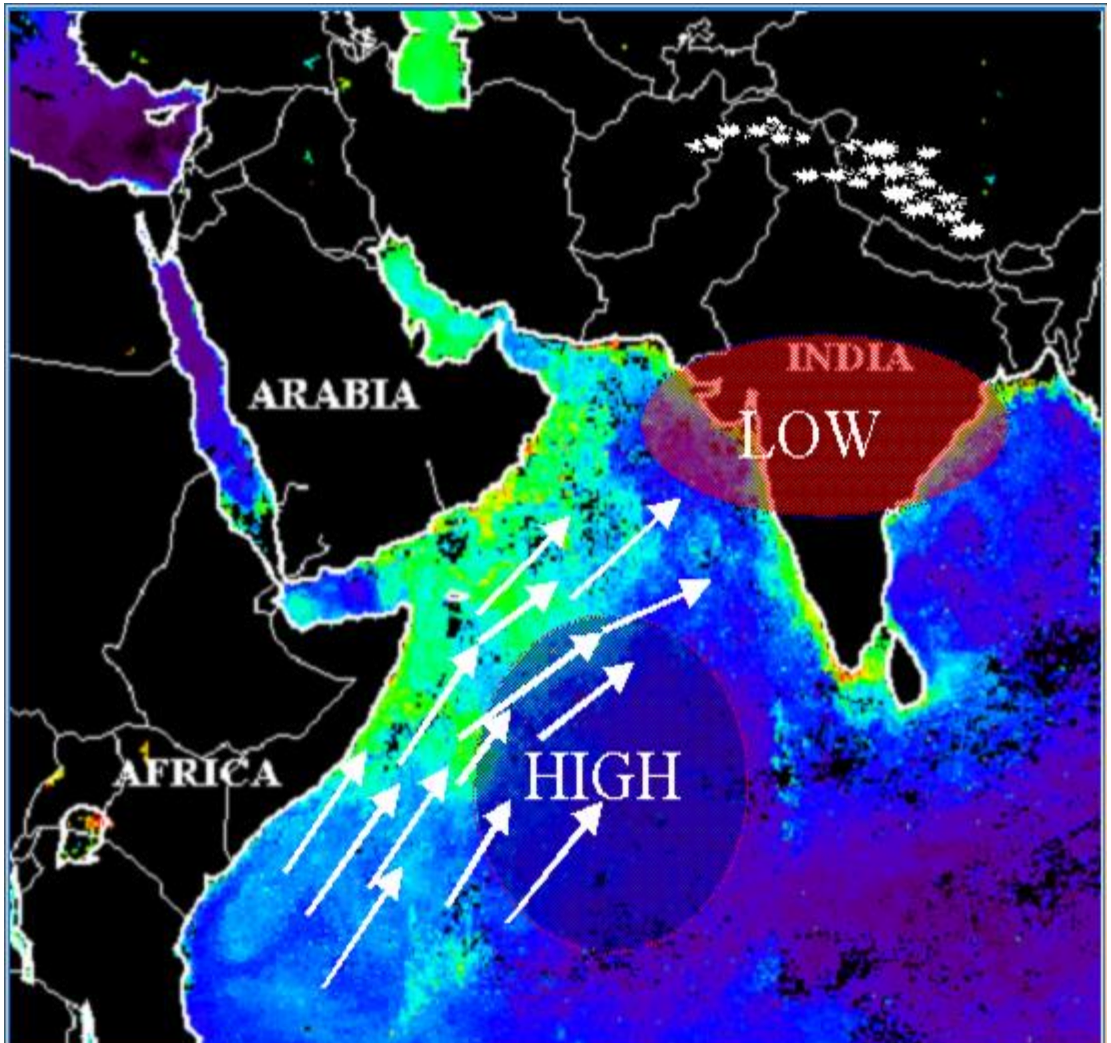
ECCO2 model animation

ecco2_sst_flow (2).mp4

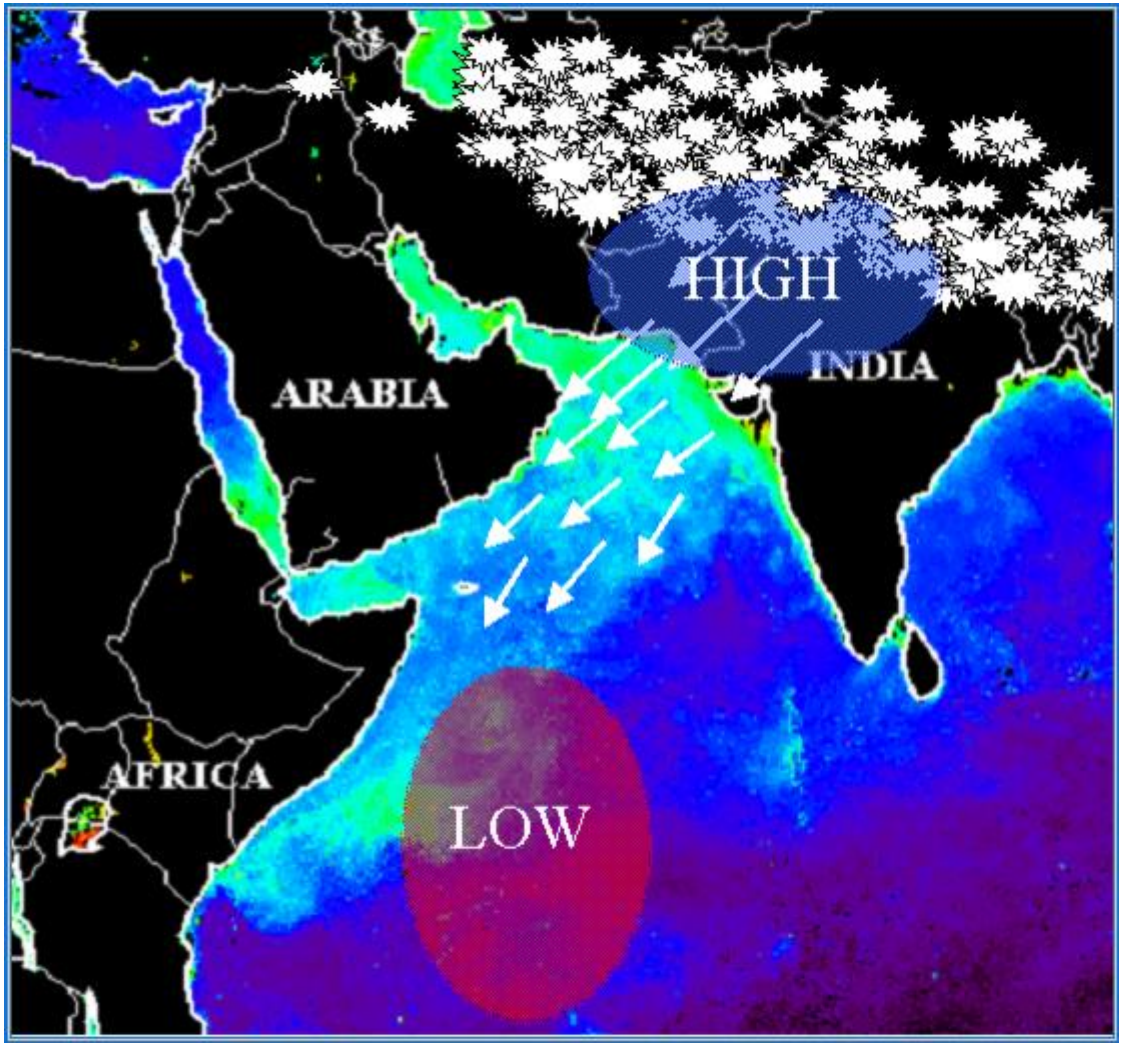
Mean surface height and currents



DPO Fig. 11.1



Wind direction resulting from differential pressure over sea and land superimposed on a SeaWiFS chlorophyll image for the southwest monsoon. High chlorophyll concentrations in the western Arabian Sea are due to coastal upwelling



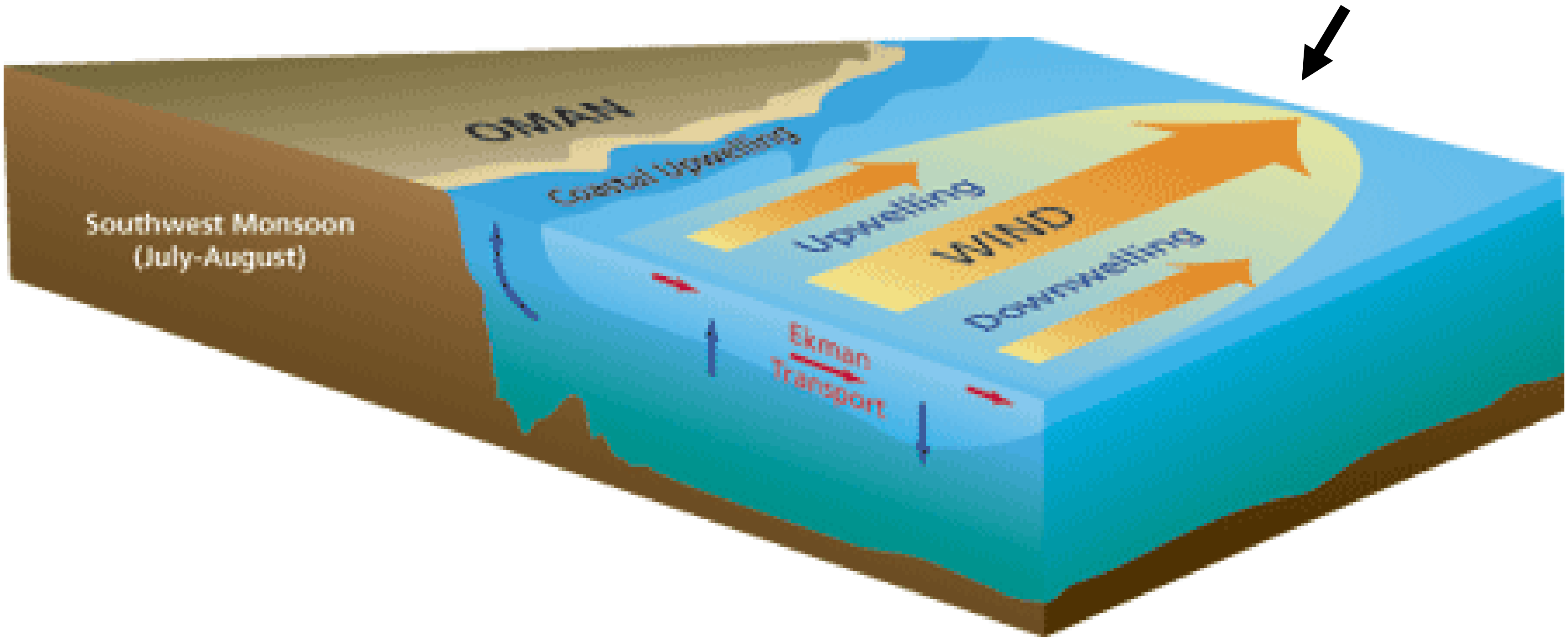
Schematic showing snow cover extent and wind direction superimposed on a SeaWiFS chlorophyll image for the northwest monsoon season. High chlorophyll concentrations sre due to nutrients inputs from of winter convective mixing

SW and NE Monsoons

- Thermally direct circulation in the tropical atmosphere (like Walker cell and sea/land breeze). Rising air over warm earth and sinking over cool regions with surface air flow from sinking to the rising region.
- In summer, land is warmer than ocean so surface wind is from ocean to land. In winter, the reverse.
- Indian (Asian-Australian) monsoon: late summer conditions are strong air flow from the Arabian Sea northeastward into India ("Southwest monsoon"), accompanied by large precipitation over land. Wind along Arabia is especially intense ("Findlater jet"), like an atmospheric western boundary current.
- The Findlater jet forces major upwelling along the Arabian coast (offshore Ekman flow). Circulation in the Arabian Sea is anticyclonic and the northward Somali Current (western boundary current) is fully developed.
- In autumn, the sea-air temperature contrast decreases. The Findlater jet swings to the south and blows eastward ("Transition"). During the Transition, a strong eastward surface jet develops in the ocean along the equator.
- In winter, the wind blows from land to sea ("Northeast monsoon"). Upwelling in the Arabian Sea ceases. Circulation in the Arabian Sea weakens and the Somali Current can reverse.

SW Monsoon - coastal effects

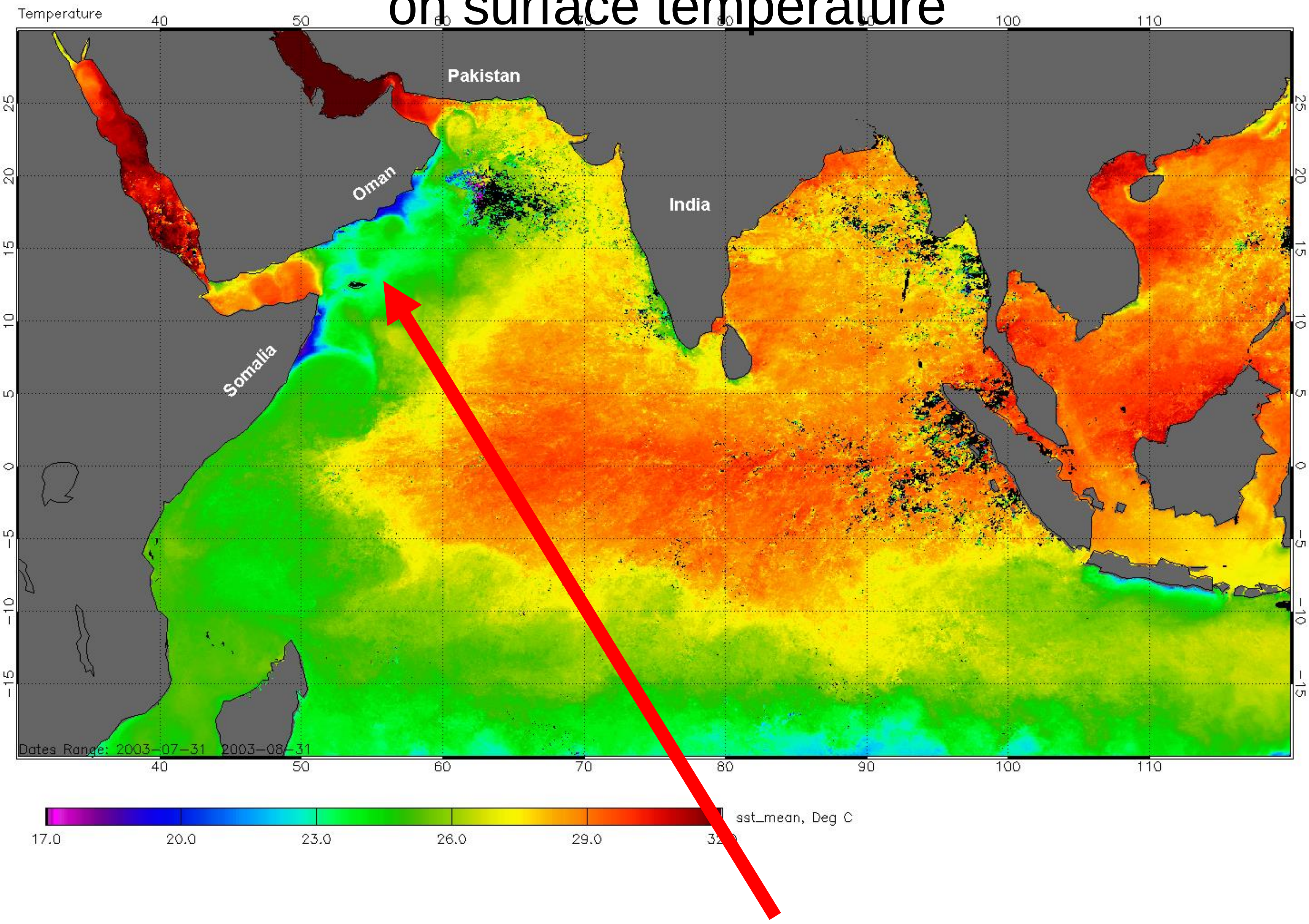
"Findlater Jet" (only during SW monsoon)



Honjo et al (1997)

An overview of the winds and directly forced ocean response associated with the Southwest Monsoon is provided by this schematic cross-section of the ocean taken perpendicular to the coast of Oman. The jet of the surface winds drives water to its right in the northern hemisphere as "Ekman transport" (red arrows). Along the coast because of the boundary this leads to cool water rising to the surface, or upwelling. Moving offshore, the varying strength of the wind leads to differences in the strength of the Ekman transport, causing a divergence of surface water and upwelling inshore of the wind maximum, and a convergence and downwelling offshore of the wind maximum (blue arrows).

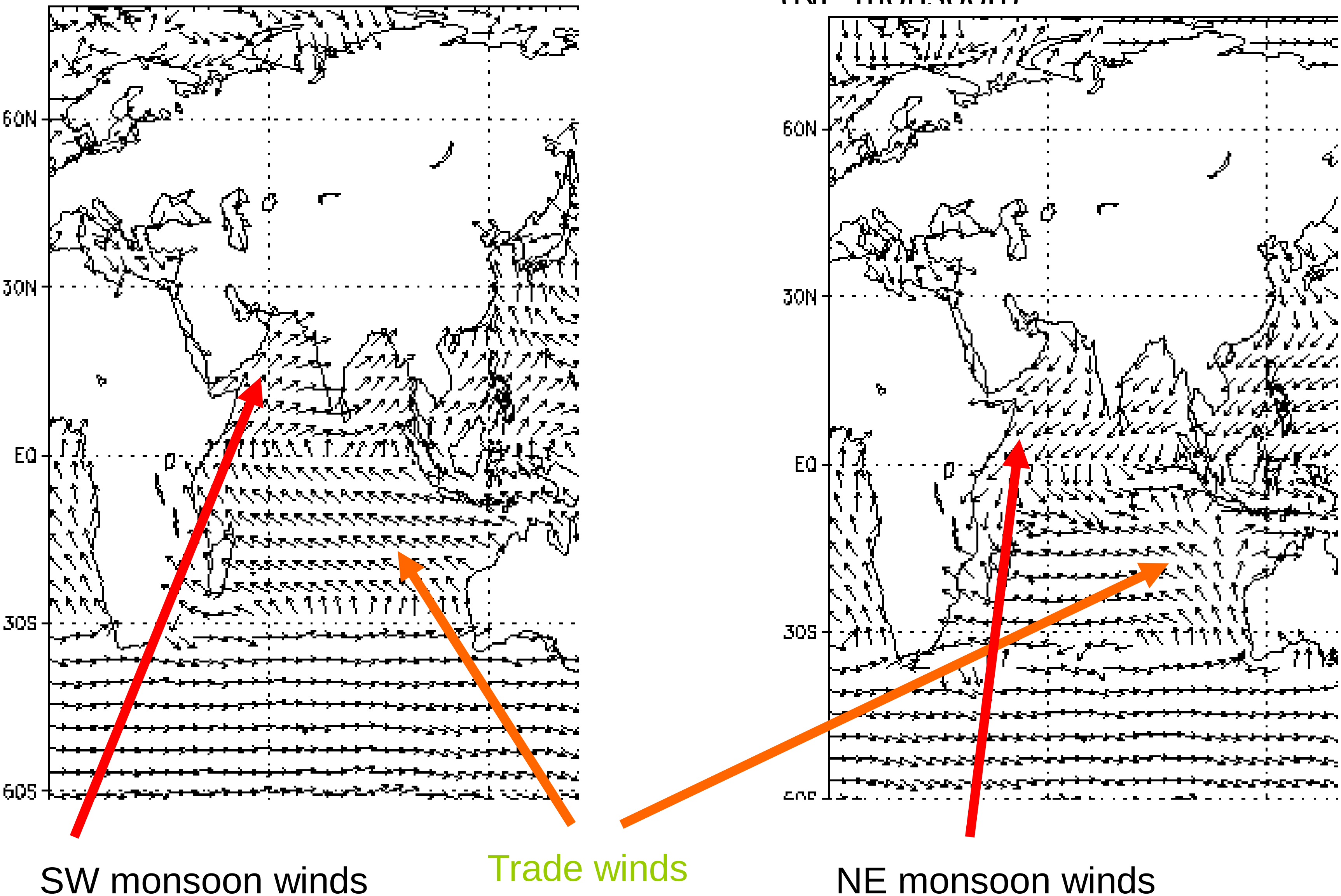
Asian (Indian) monsoon - effect of SW monsoon upwelling on surface temperature



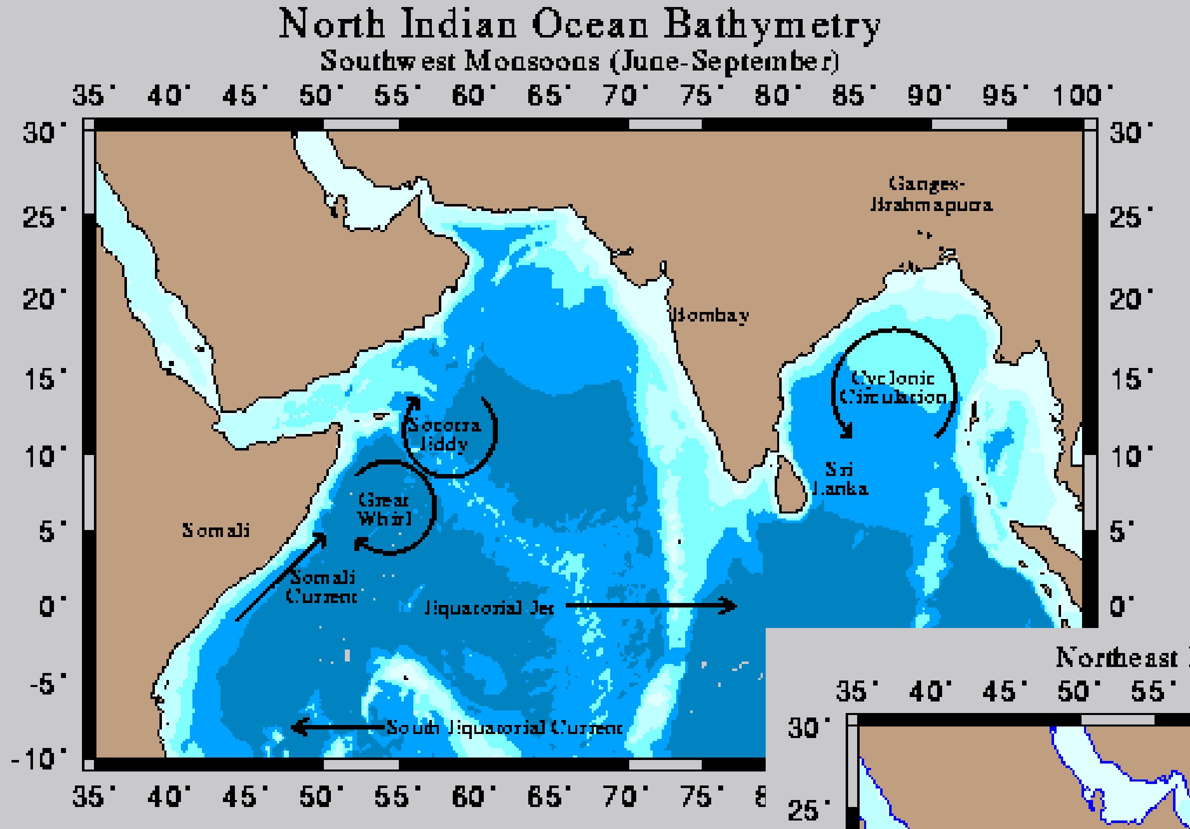
July 2003 SST: Low along Somalia and Arabian peninsula during SW monsoon. (NASA MODIS satellite, NASA GSFC)

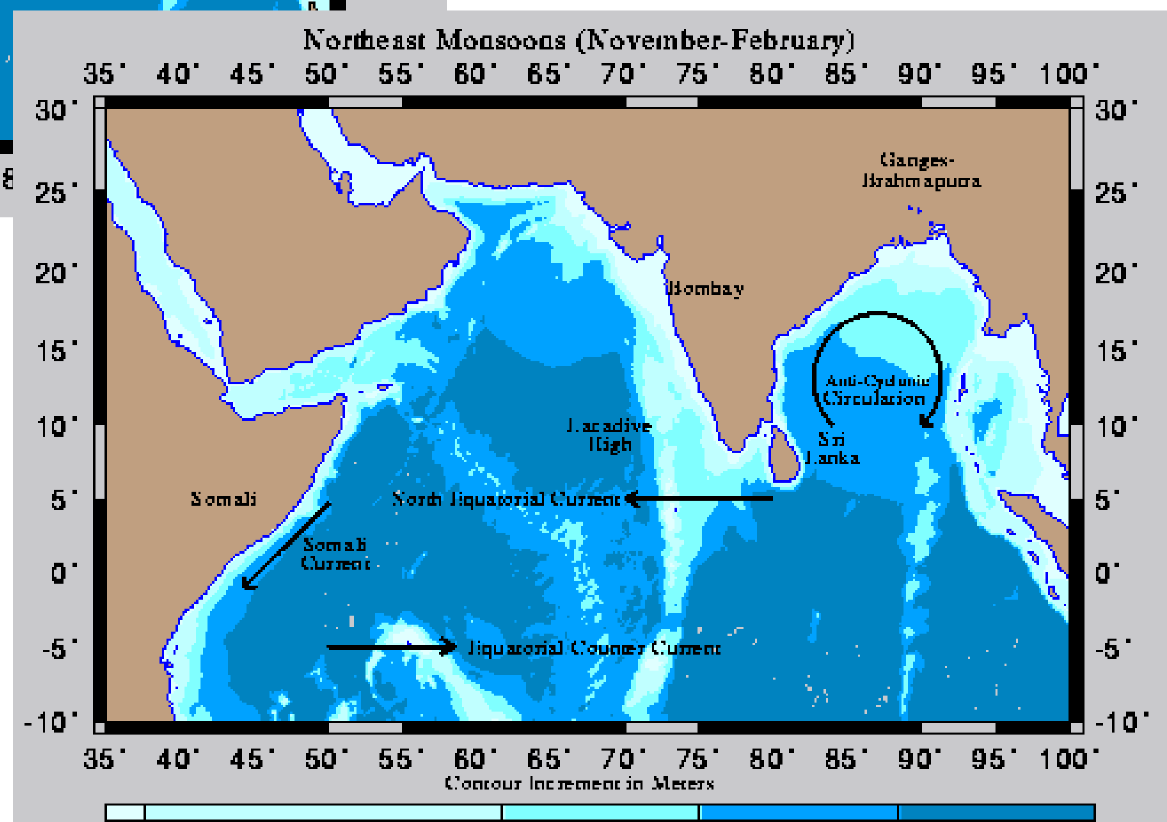
June-August winds Dec-Feb winds

(SW monsoon) (NE monsoon)



Several reversing circulations





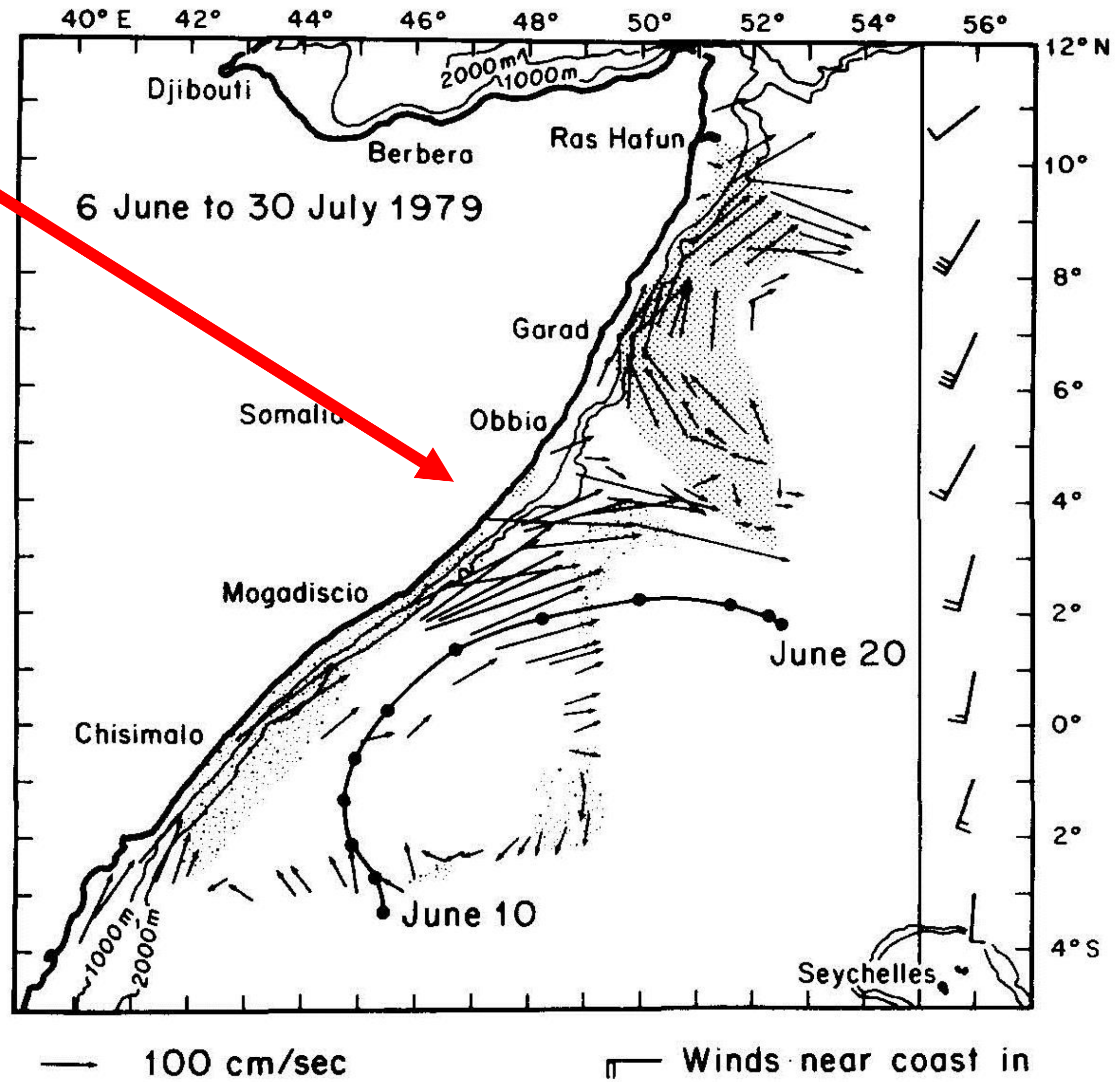
Graphic from Southampton Oceanography Centre website on Indian Ocean

http://indianocean.free.fr/tabmat.htm

Arabian Sea circulation

- Somali Current is the (reversing) western boundary current of the Arabian Sea
- NE monsoon - southward SC, starts in Dec, until April. Up to 1 m/sec. Only found south of 10N.
- SW monsoon - northward SC, May/June – Aug/Sept. Up to 3.5 m/sec (very strong).

R. A. KNOX and D. L. T. ANDERSON

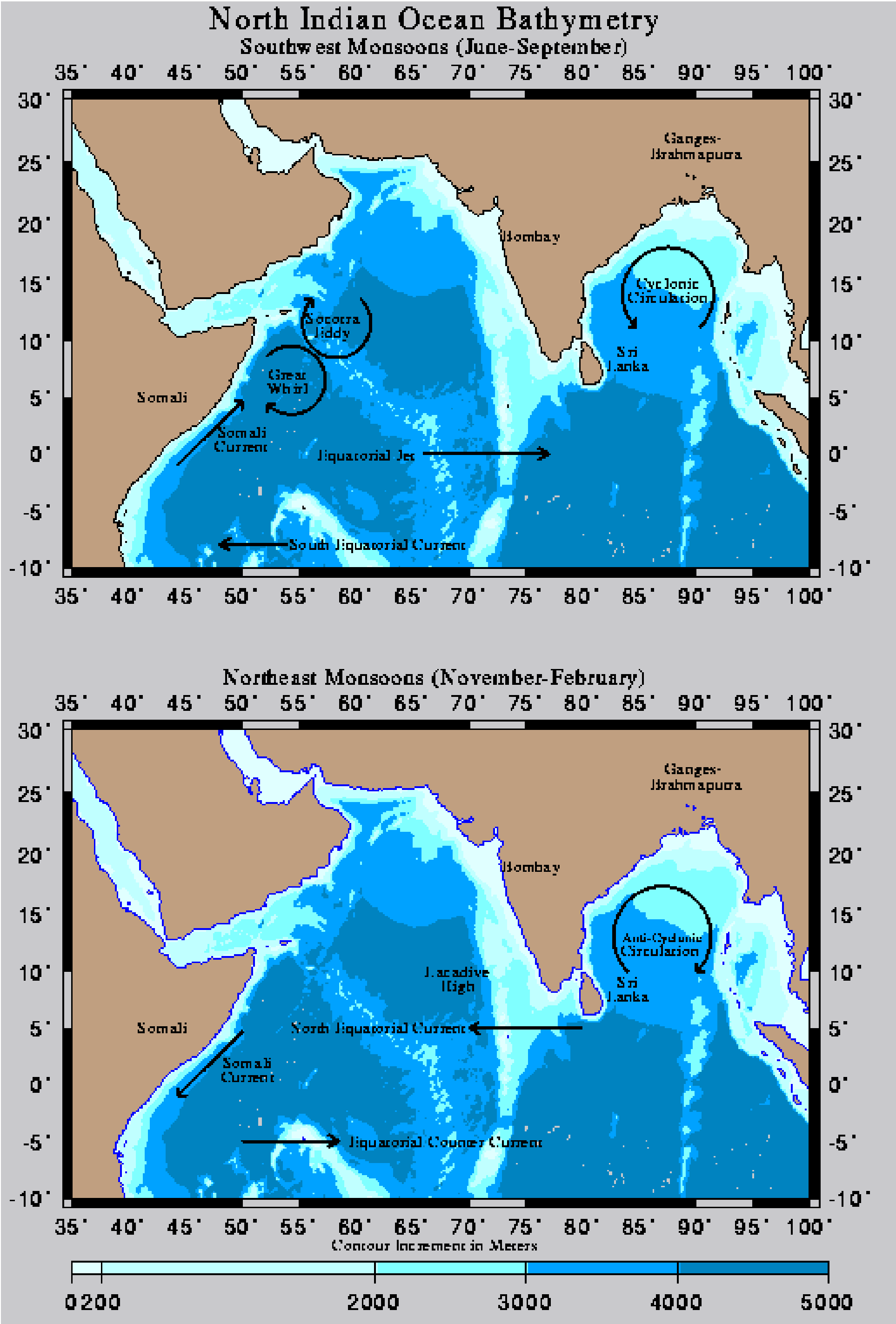


Bay of Bengal circulation

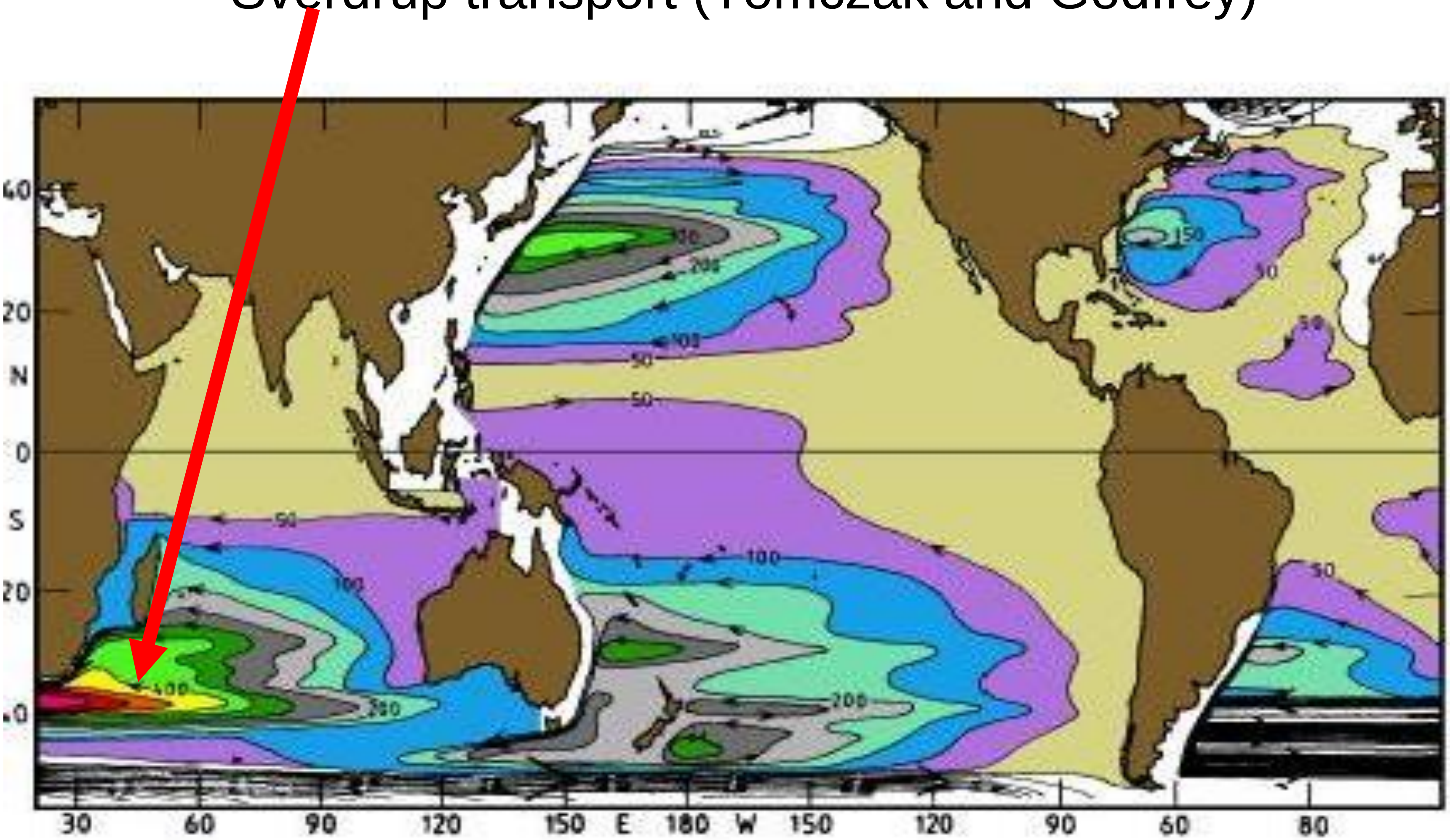
- Much weaker monsoonal forcing than Arabian Sea
- Reversing East Indian Current (the WBC for the Bay of Bengal)

Graphic from Southampton Oceanography Centre website on Indian Ocean

http://indianocean.free.fr/tabmat.htm



Sverdrup transport (Tomczak and Godfrey)



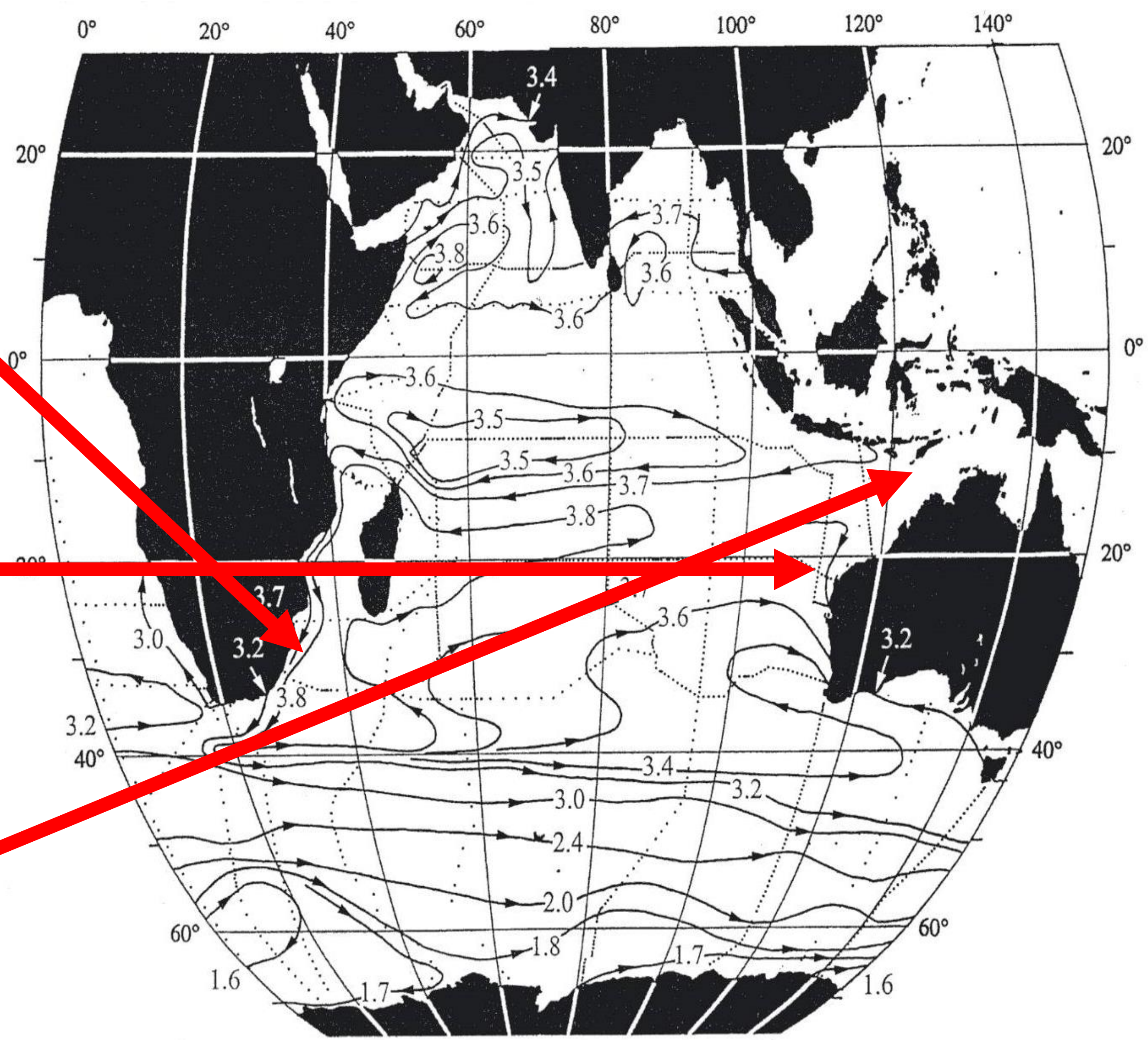
ig. 4.4. Depth-integrated steric height P, calculated from the right-hand side of the Sverdru lation (eqn (4.5)), using the data from Hellerman and Rosenstein (1983). Units are 10^1 m^2. Fo etails of the integration procedure see Godfrey (1989).

Indian surface circulation (adjusted steric height) (Reid, 2003)

Subtropical gyre (Agulhas is the WBC)

Leeuwin Current

Indonesian Throughflow (from Pacific)

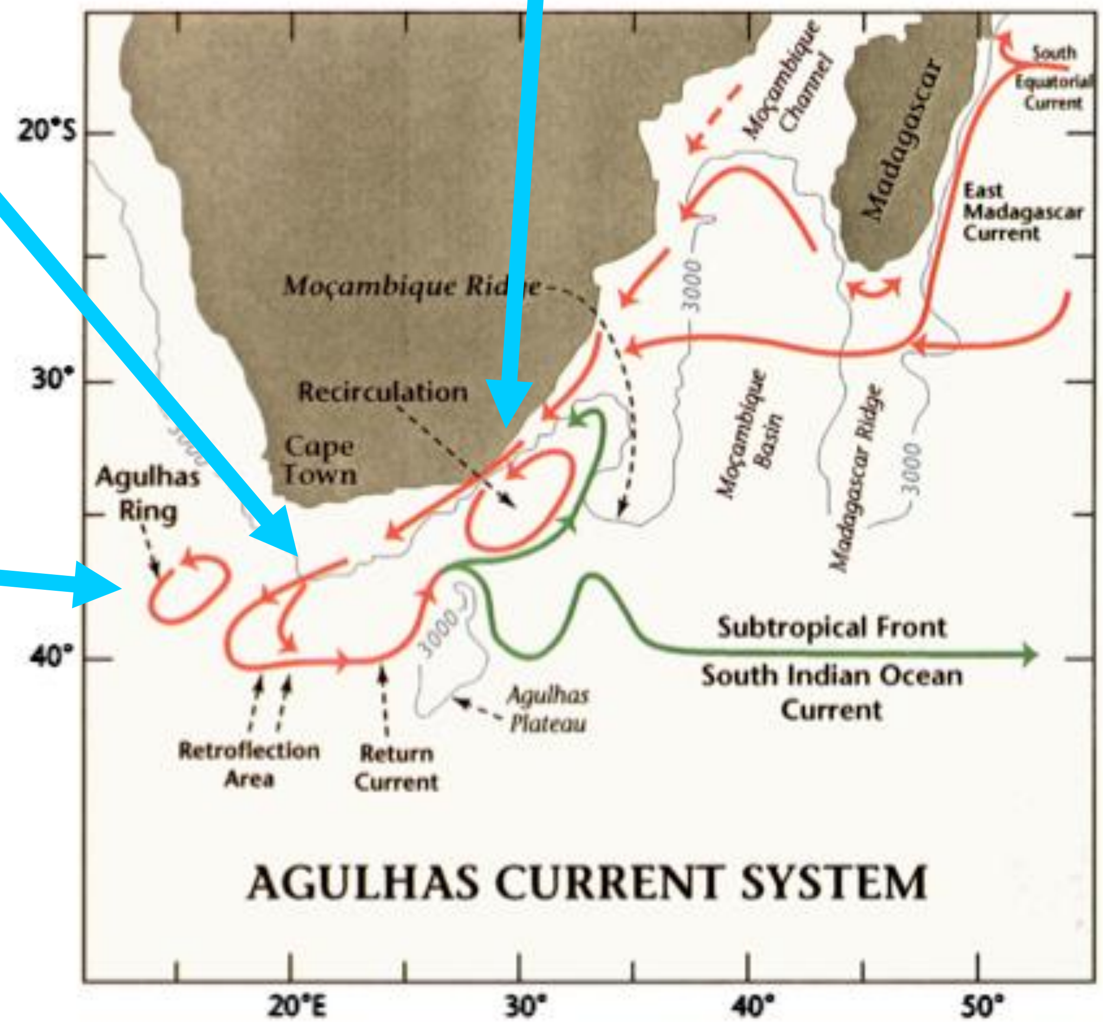


Subtropical gyre WBC: Agulhas

Agulhas retroflection:
Western boundary current wishes to continue further southward, but Africa ends, so current passes to the west, retroflects back to the east.

Agulhas rings: shed at the retroflection.

Rings and part of transport continue westward into the South Atlantic, including Benguela Current



(DPO Fig. 11.12 from Schmitz, 1995)

Agulhas

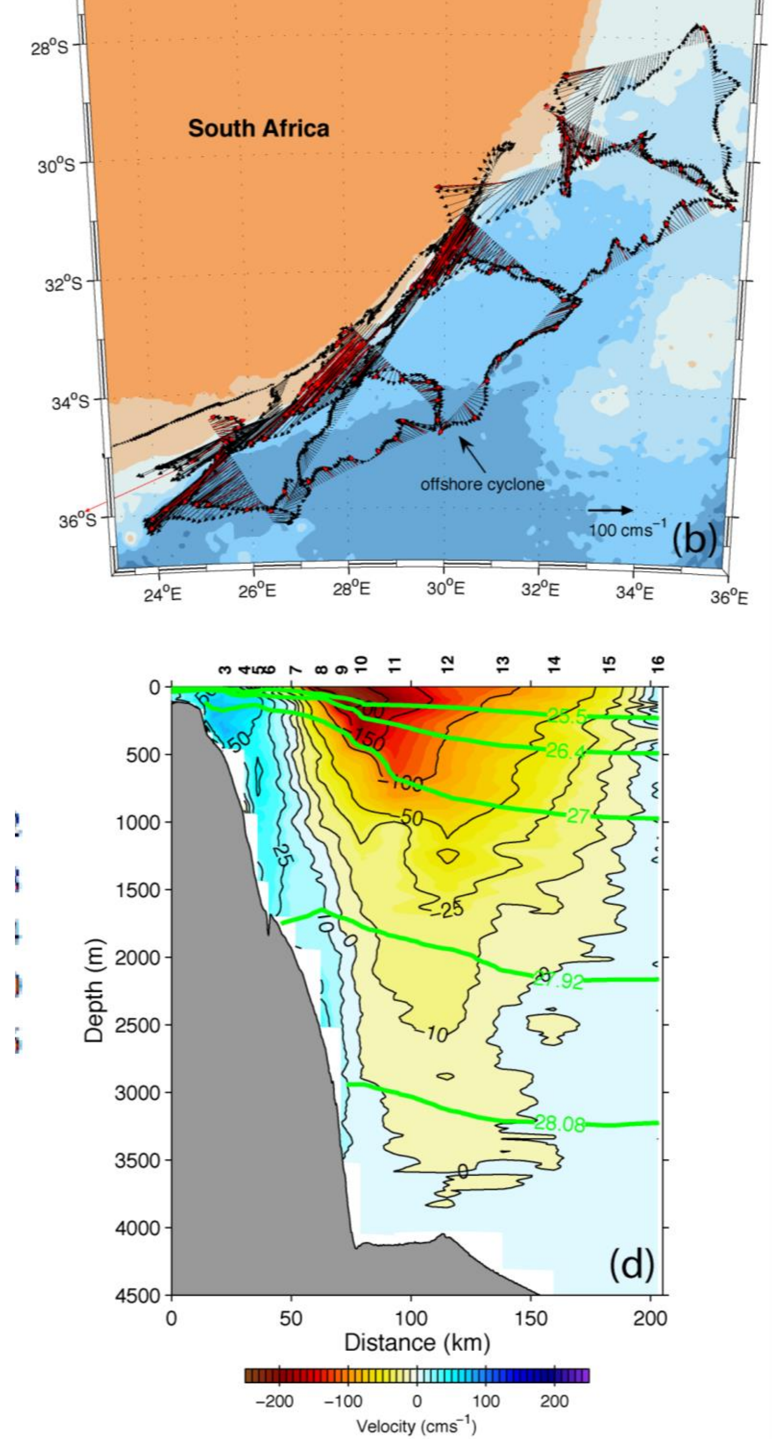
Strong western boundary current

> 200 cm/sec at surface

~ 100 km width

Southward flow extends to bottom

Northward countercurrent inshore

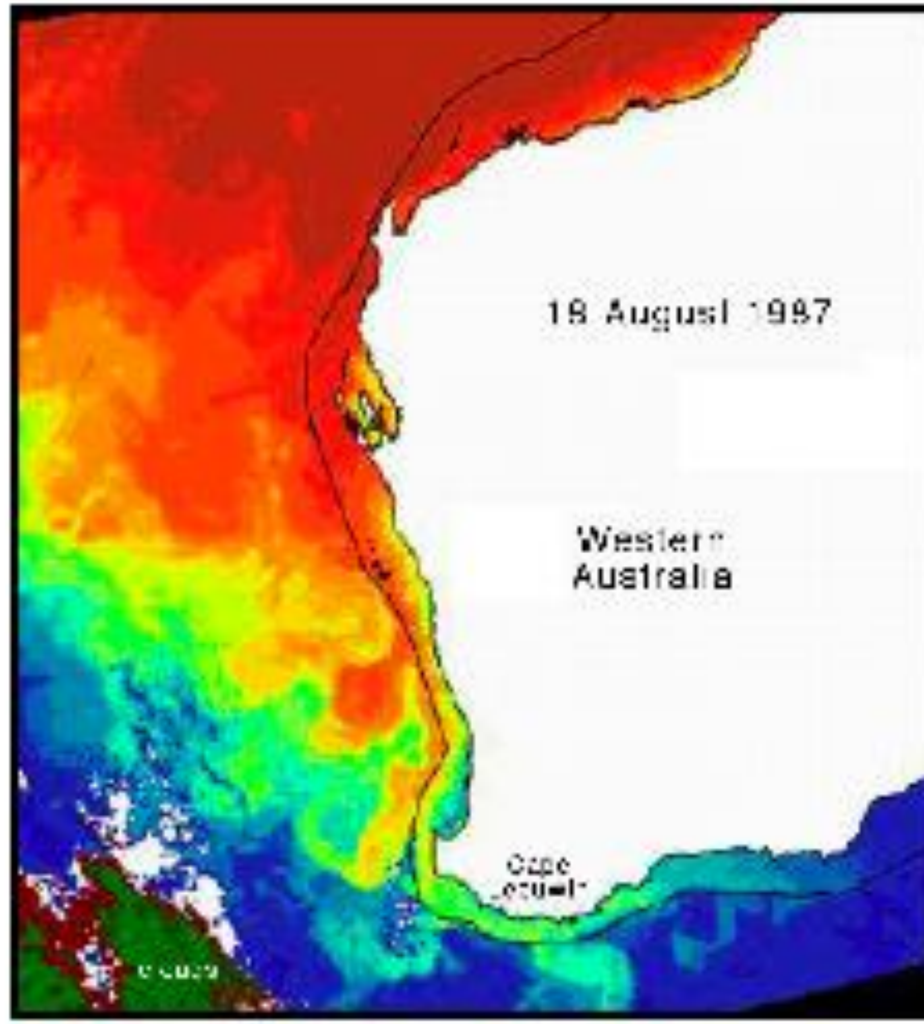


(DPO Fig. 11.12 from Beal et al.,

Eastern Boundary Current: Leeuwin Current

The ONLY eastern boundary current that flows poleward (despite the usual EBC equatorward winds!).

Backwards flow due to pressure gradient around Australia, partially driven by Indonesian Throughflow



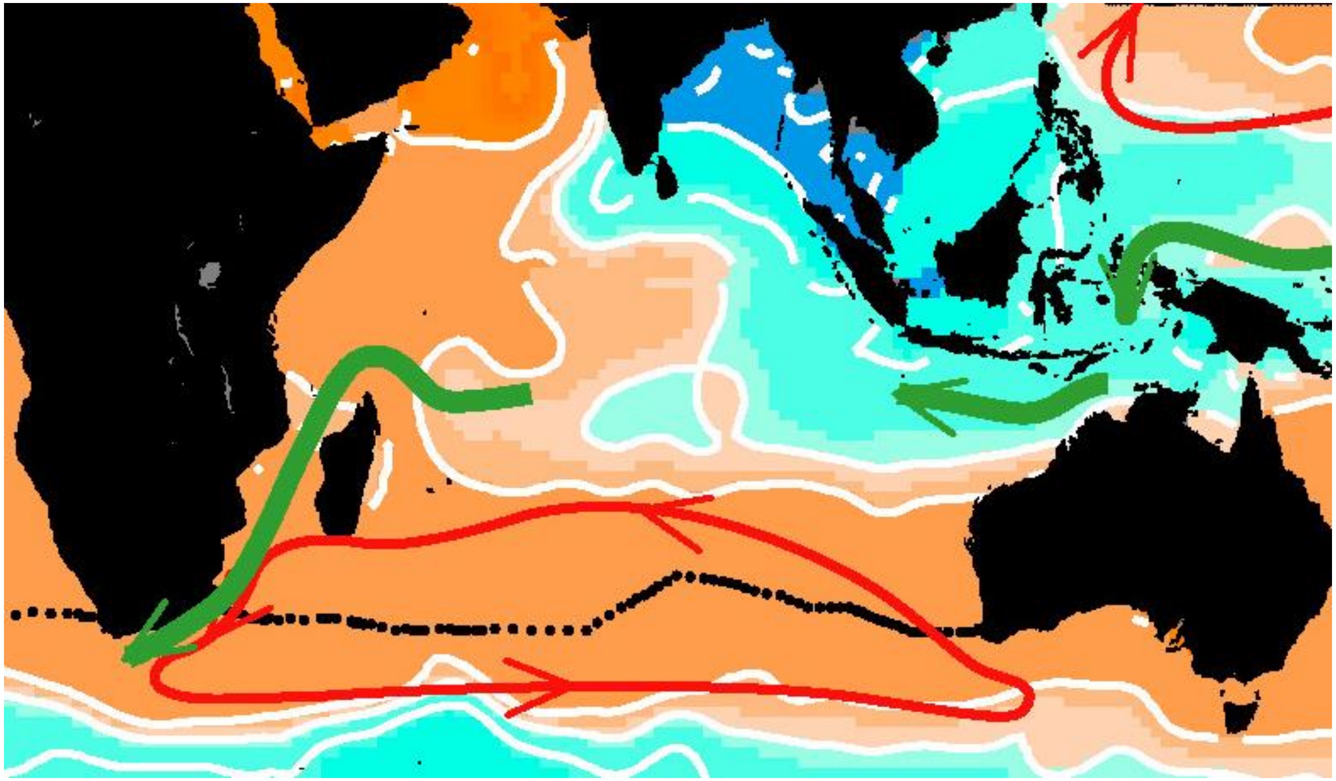
Sea surface temperature showing southward advection of warm water (Tomczak and Godfrey online text)

Indonesian Throughflow

Connection of upper ocean waters from Pacific to Indian Ocean.

Complicated set of straits, maximum depth about 1200 m.

Low salinity Pacific water evident in zonal jet across Indian tropical region, following the South Equatorial Current

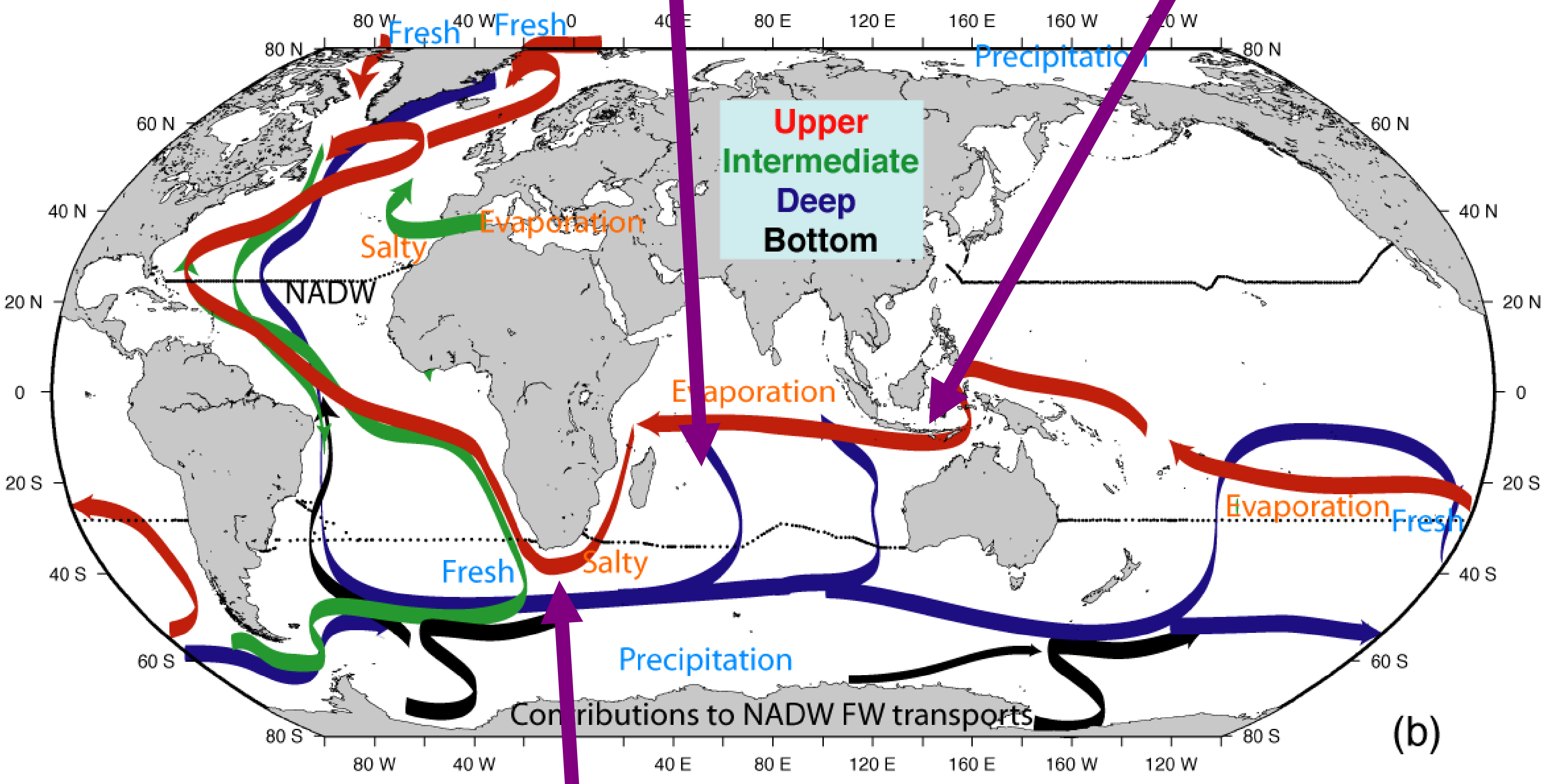


Talley (2008)

Indian Ocean role in global overturn

Upwelling of abyssal waters to upper ocean

Indonesian Throughflow



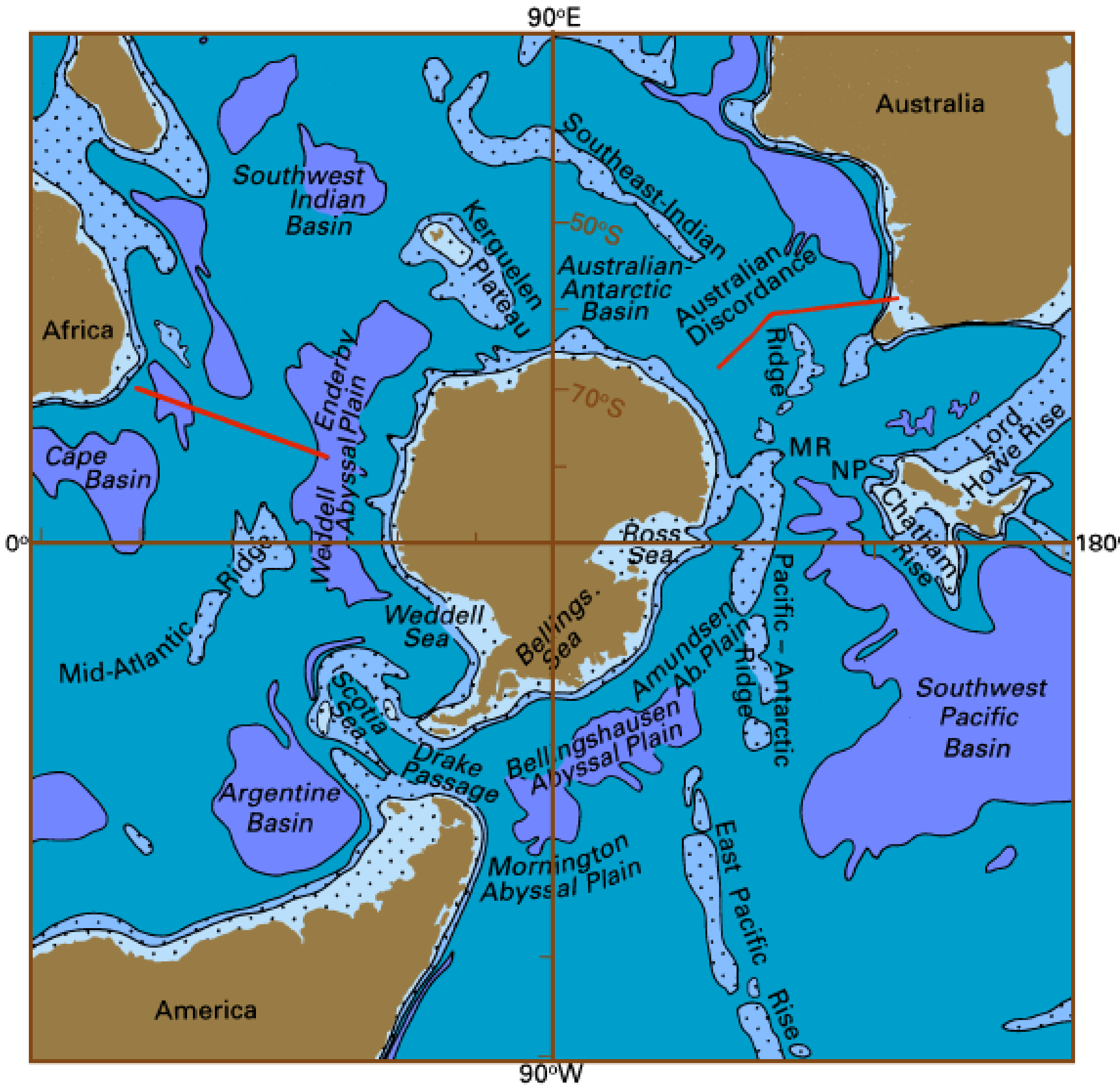
Agulhas retroflection, eddy shedding and transport of warm water into S. Atlantic

Summary Points

- Indian Ocean monsoons & associated circulation in northern part of Indian Ocean
- Subtropical gyre in S Indian Ocean
- Equatorial current system
- Western BC Agulhas Current - retroflection
- Eastern BC Leeuwin Current – unique direction
- Indonesian throughflow and contribution to global overturn

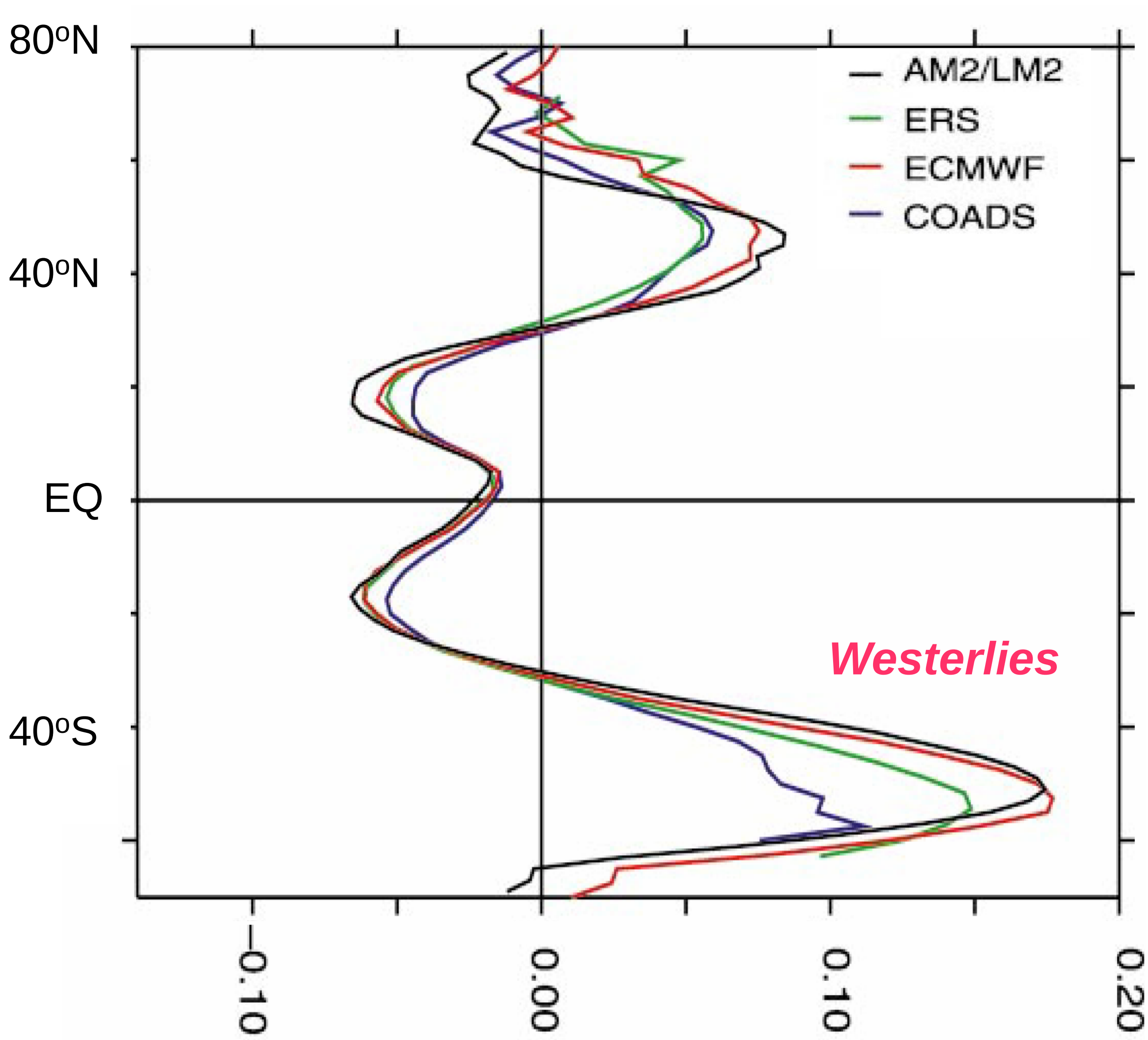
Wind Driven Currents in the Southern Ocean

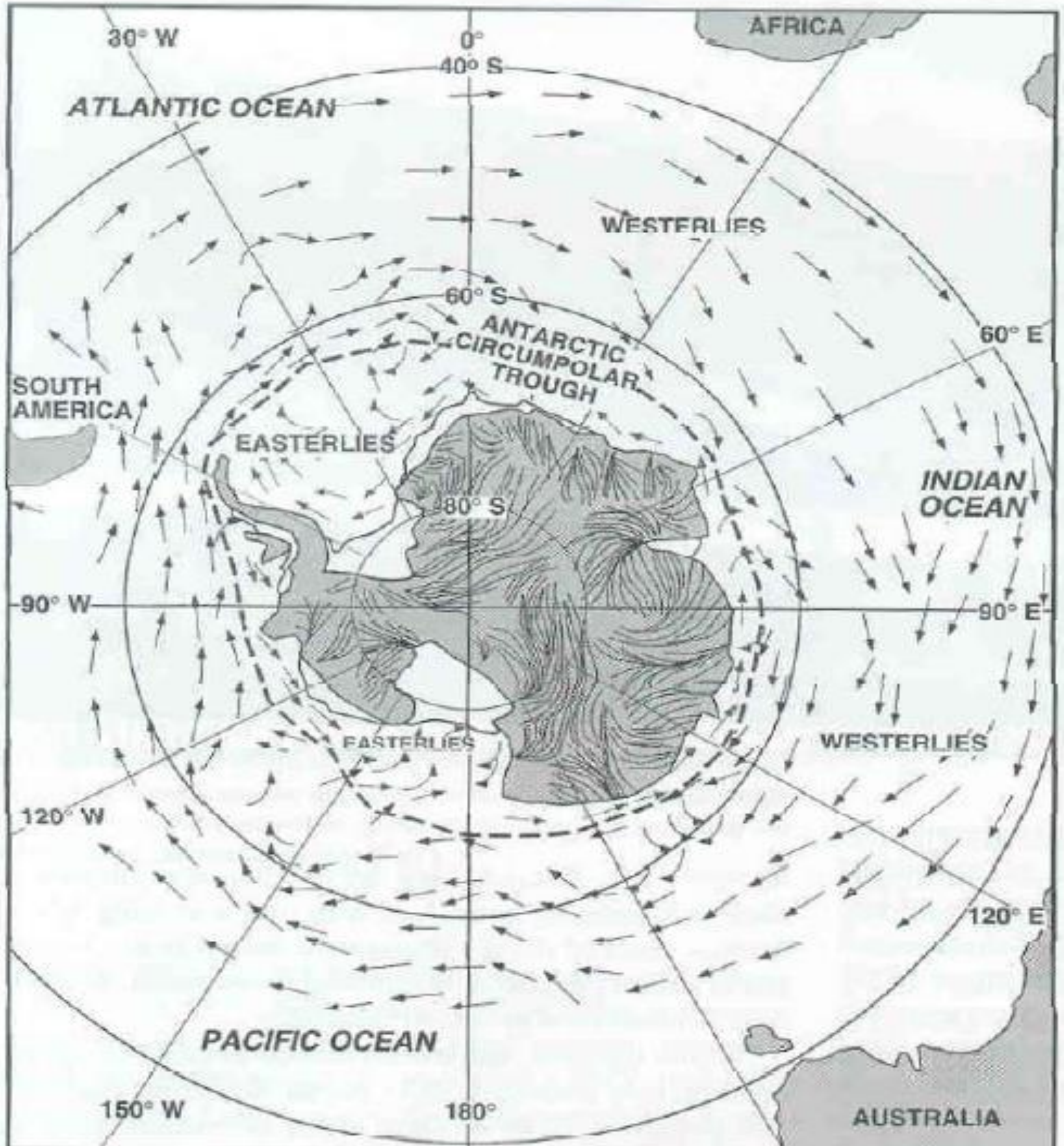
- Drives Antarctic Circumpolar Current ACC
- Produces upwelling and downwelling



90°E
0°
180°
90°W
Australia
Africa
America
Southwest Indian Basin
Kerguelen Plateau
Southeast-Indian
50°S
70°S
Australian-Antarctic Basin
Australian Discordance
Ridge
Enderby Abyssal Plain
Weddell Abyssal Plain
Cape Basin
Mid-Atlantic Ridge
Weddell Sea
Bellings. Sea
Ross Sea
MR
NP
Lord Howe Rise
Chatham Rise
Pacific-Antarctic Ridge
Amundsen Ab. Plain
Bellingshausen Abyssal Plain
Southwest Pacific Basin
Scotia Sea
Drake Passage
Argentine Basin
Mornington Abyssal Plain
East Pacific Rise

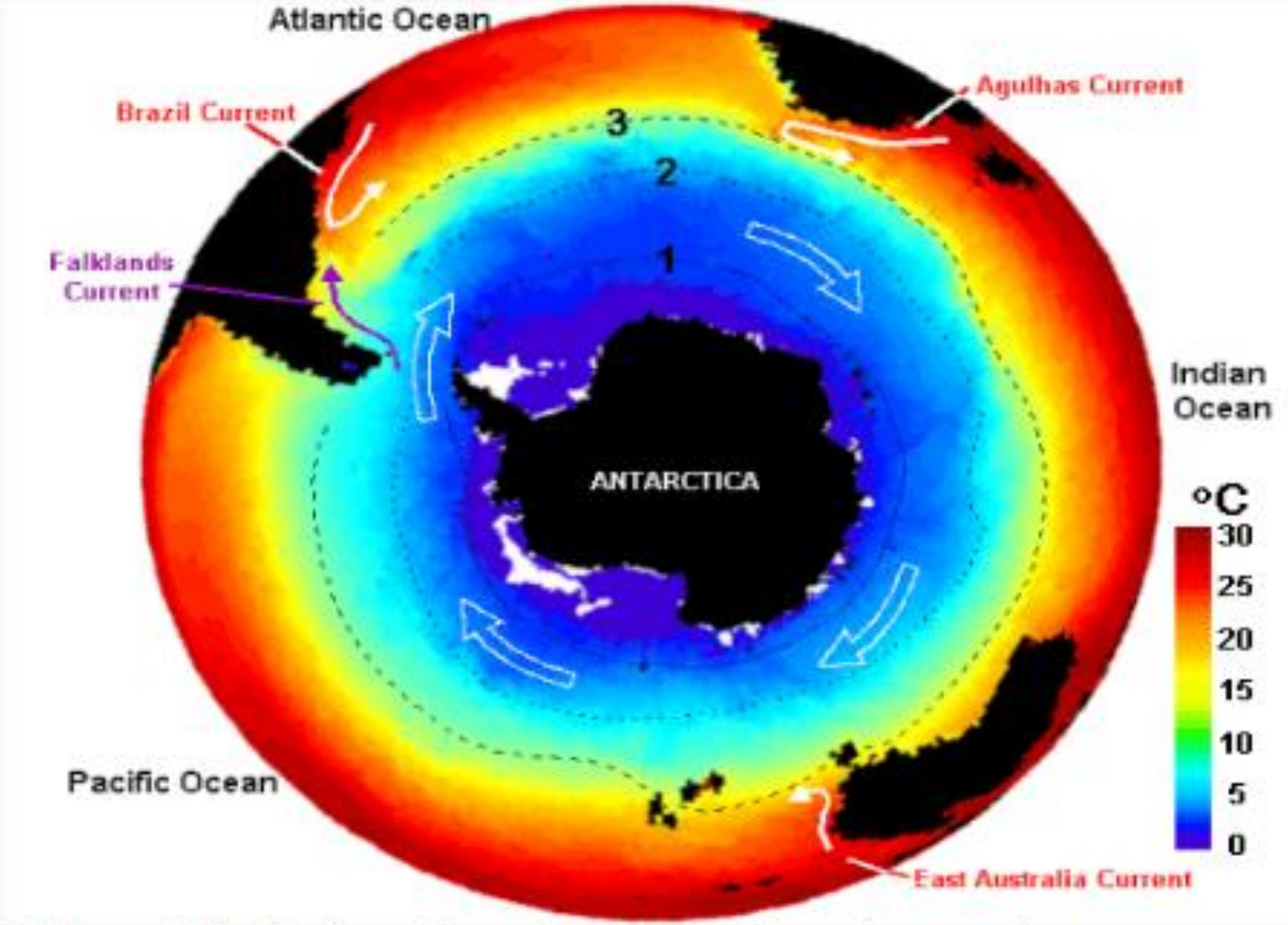
Mean zonal-averaged wind stress (Pa) over the ocean from different datasets





30° W
0°
40° S
AFRICA
ATLANTIC OCEAN
WESTERLIES
60° S
ANTARCTIC
CIRCUMPOLAR
TROUGH
60° E
SOUTH
AMERICA
EASTERLIES
80° S
INDIAN
OCEAN
90° W
90° E
EASTERLIES
WESTERLIES
120° W
120° E
PACIFIC OCEAN
150° W
180°
AUSTRALIA

Fronts in temperature data



SST map of the Southern Ocean in summer. Three fronts can be seen as areas where the temperature change from North to South is particularly fast. 1)The polar front 2) The subantarctic front, 3) The subtropical front - the northern boundary of the Southern Ocean. White outline arrows indicate the flow of the Antarctic Circumpolar Current. Source: NOC from SST climatology data

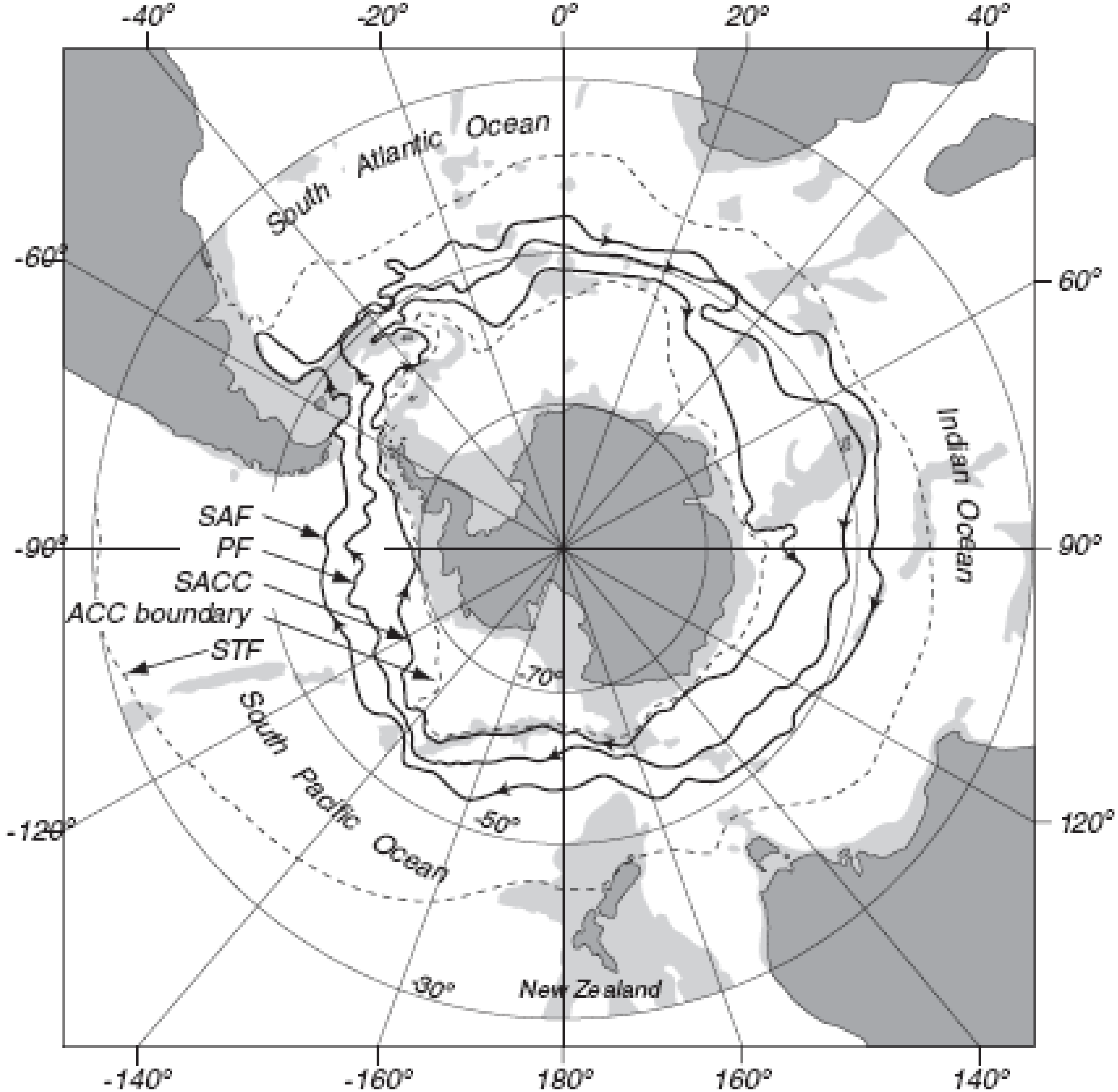
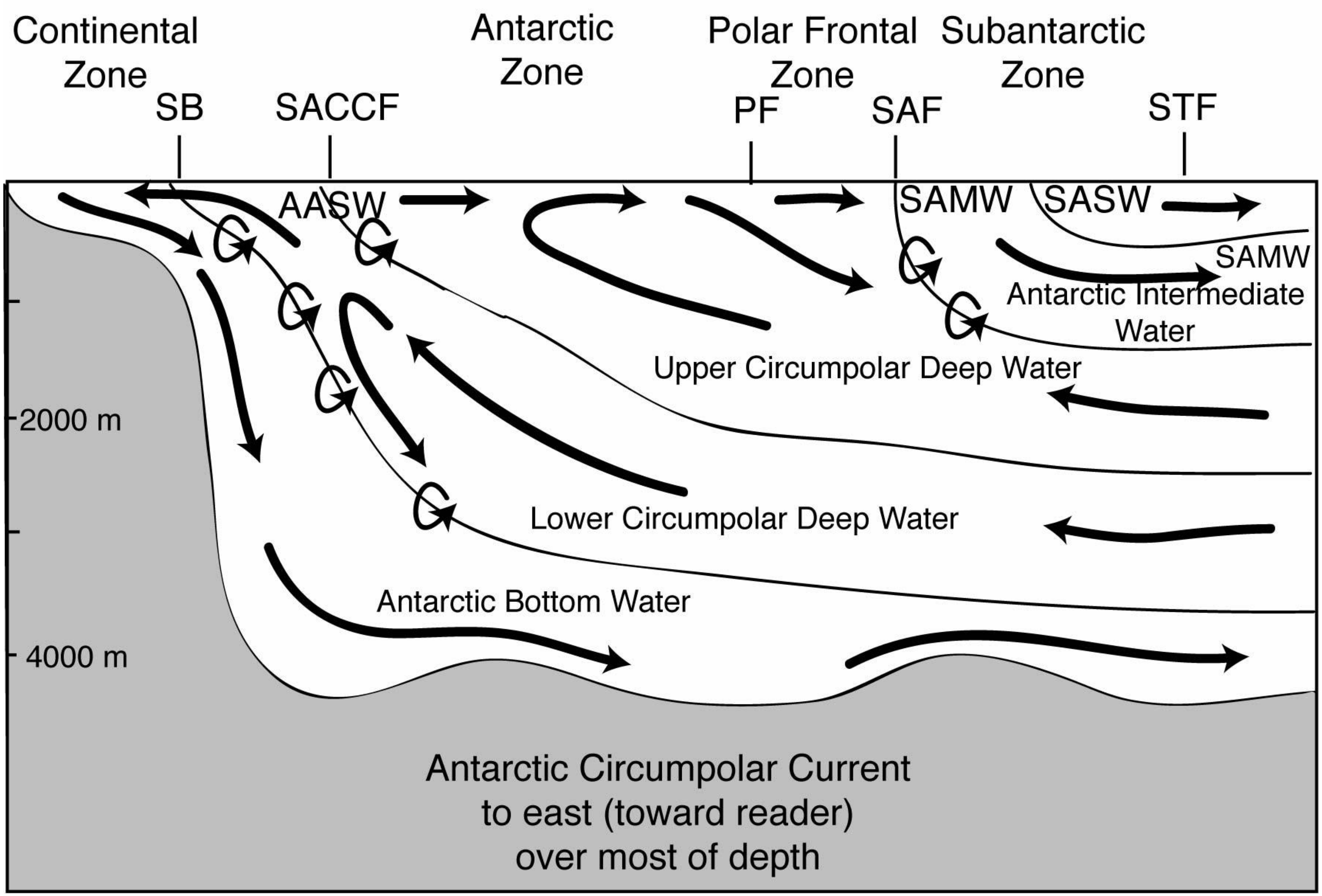


Figure 13.13 Distribution of fronts around Antarctica: **STF**: Subtrobical Front; **SAF**: Subantarctic Front; **PF**: Polar Front; **SACC**: Southern Antarctic Circumpolar Front. Shaded areas are shallower than 3 km. From Orsi (1995).

Southern Ocean: meridional view of water masses and overturn



DPO Fig. 13.4 (after Speer et al. 2000)

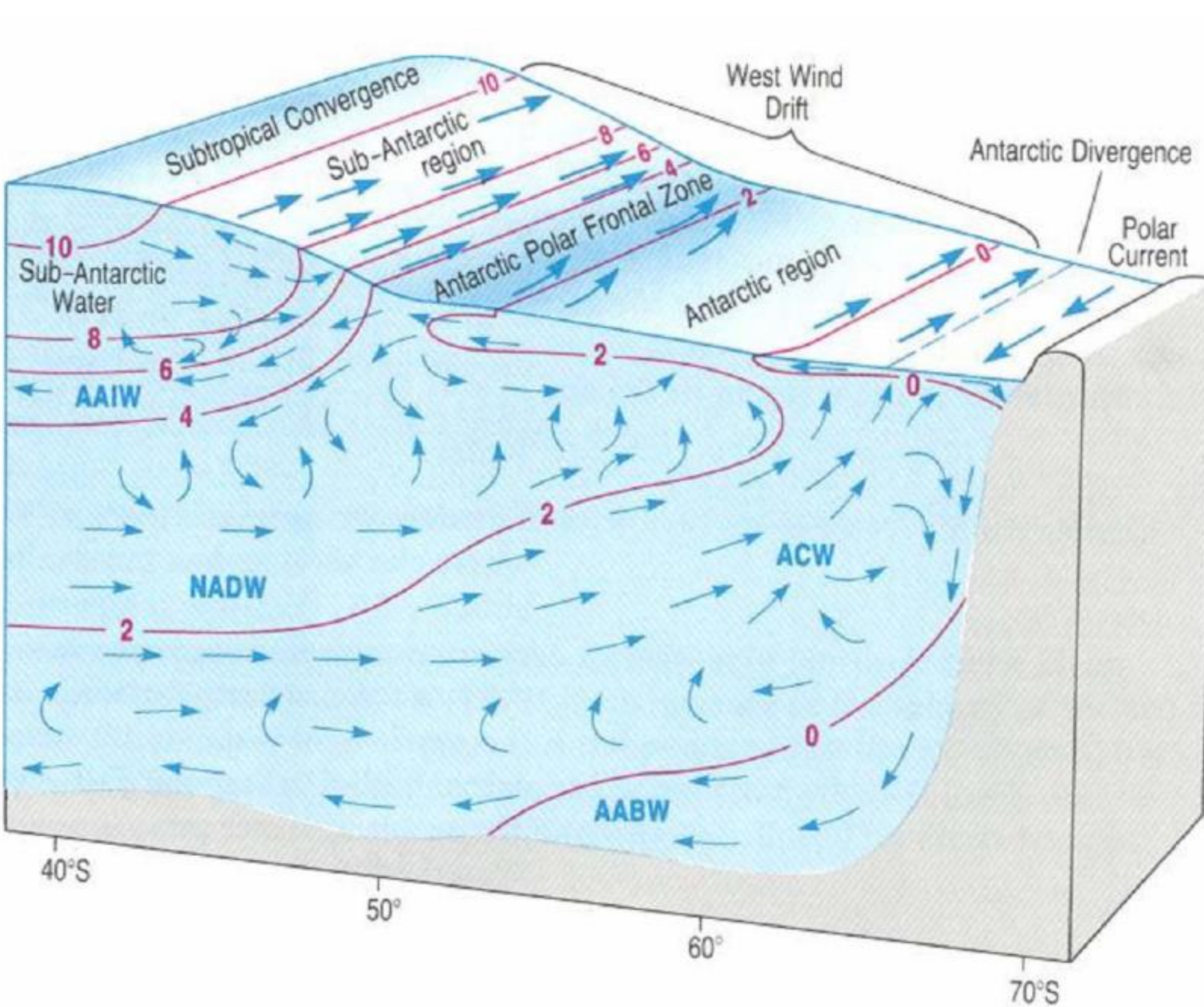
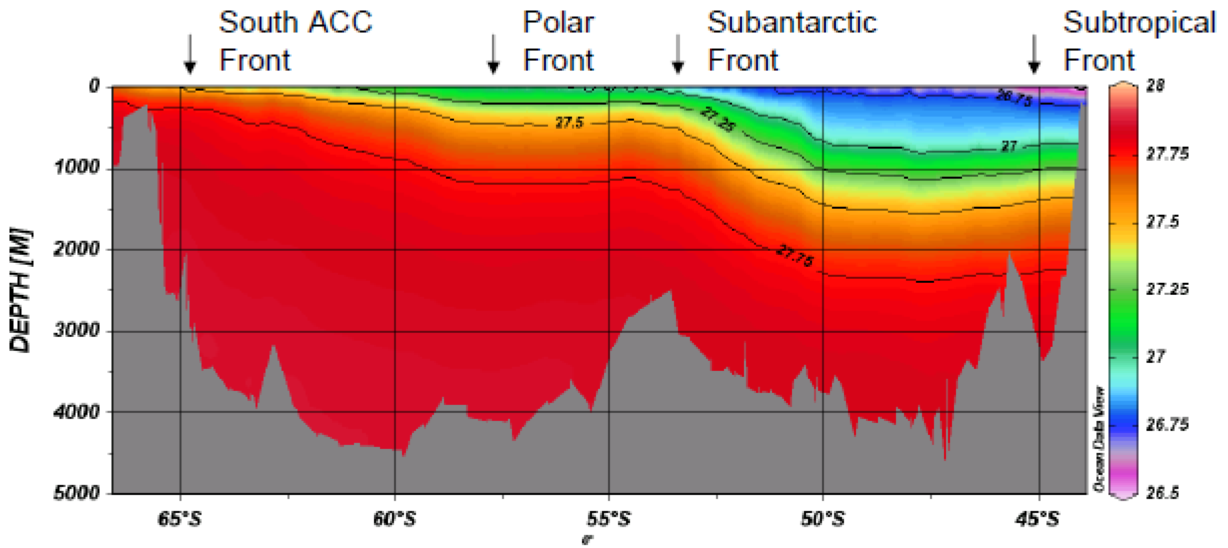
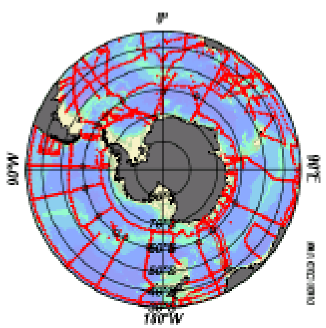


Figure 4. Schematic of circulation patterns and water masses surrounding the **Antarctic** margin poleward of ~40°S. One of the most prominent features is the transition **of NADW** into ACW and upwelling at the site of Antarctic divergence, followed by north**ward** Ekman transport and subduction as AAIW.

Density section crossing the ACC





•Isopycnals are slanted in the ACC.

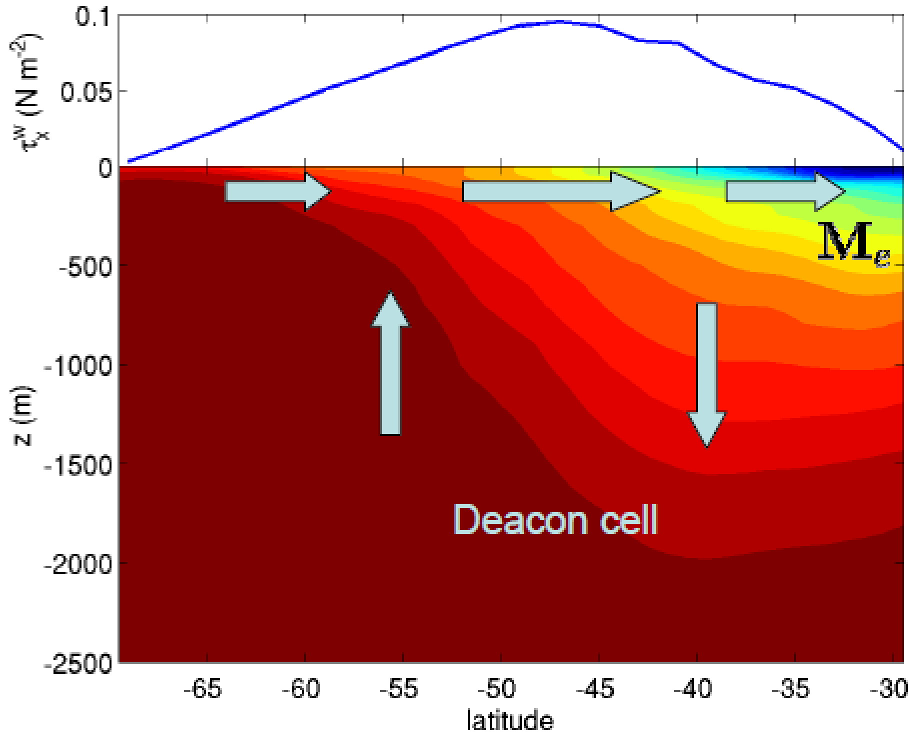
•By the thermal wind balance this implies that the current is surface intensified.

•Isopycnal outcrops mark the location of fronts.

•Fronts mark the boundaries between water masses.

- •SAF:Subantarctic Mode Water (SAMW) and AAIW
- •PF: AAIW and Circumpolar Deep Water (UCDW).

Formation of fronts in the Southern Ocean



Ekman transport

$$\mathbf{M}_e = \frac{\boldsymbol{\tau}^w \times \hat{k}}{\rho_o f}$$

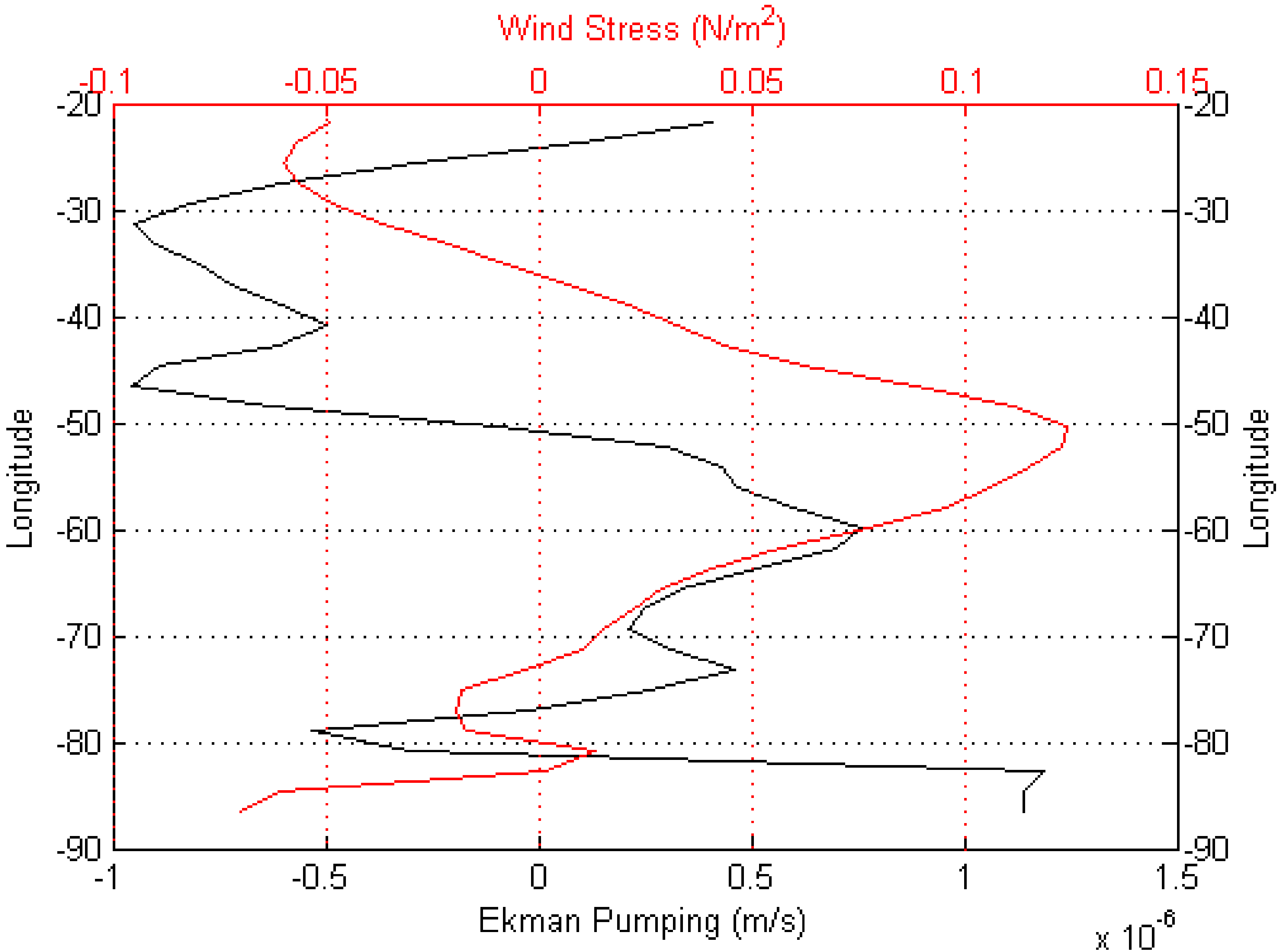
f Coriolis parameter

ρ density

•Convergence/divergence of the Ekman transport drives downwelling/upwelling which tilts density surfaces (isopycnals) upward, forming a front.

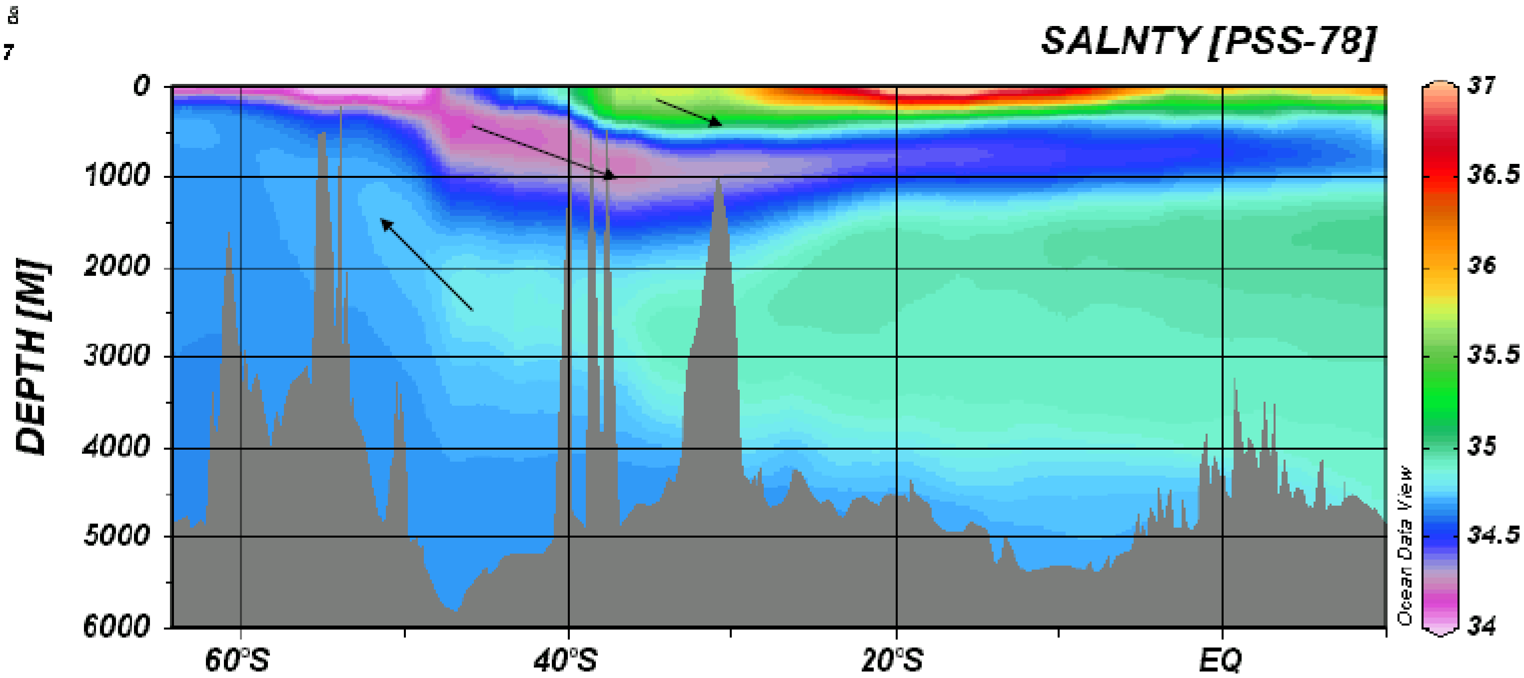
•The wind-driven overturning is known as the *Deacon* Cell

•This causes an increase in the potential energy of the system.



Wind Stress (N/m2)
-0.1
-0.05
0
0.05
0.1
0.15
-20
-30
-40
-50
-60
-70
-80
-90
Longitude
Longitude
-1
-0.5
0
0.5
1
1.5
Ekman Pumping (m/s)
x 10-6

The residual circulation in the ACC



•The sum of the eddy and wind driven circulations is known as the *residual circulation.*

•The interleaving of the water masses reflects the structure of upwelling and downwelling associated with the residual circulation.

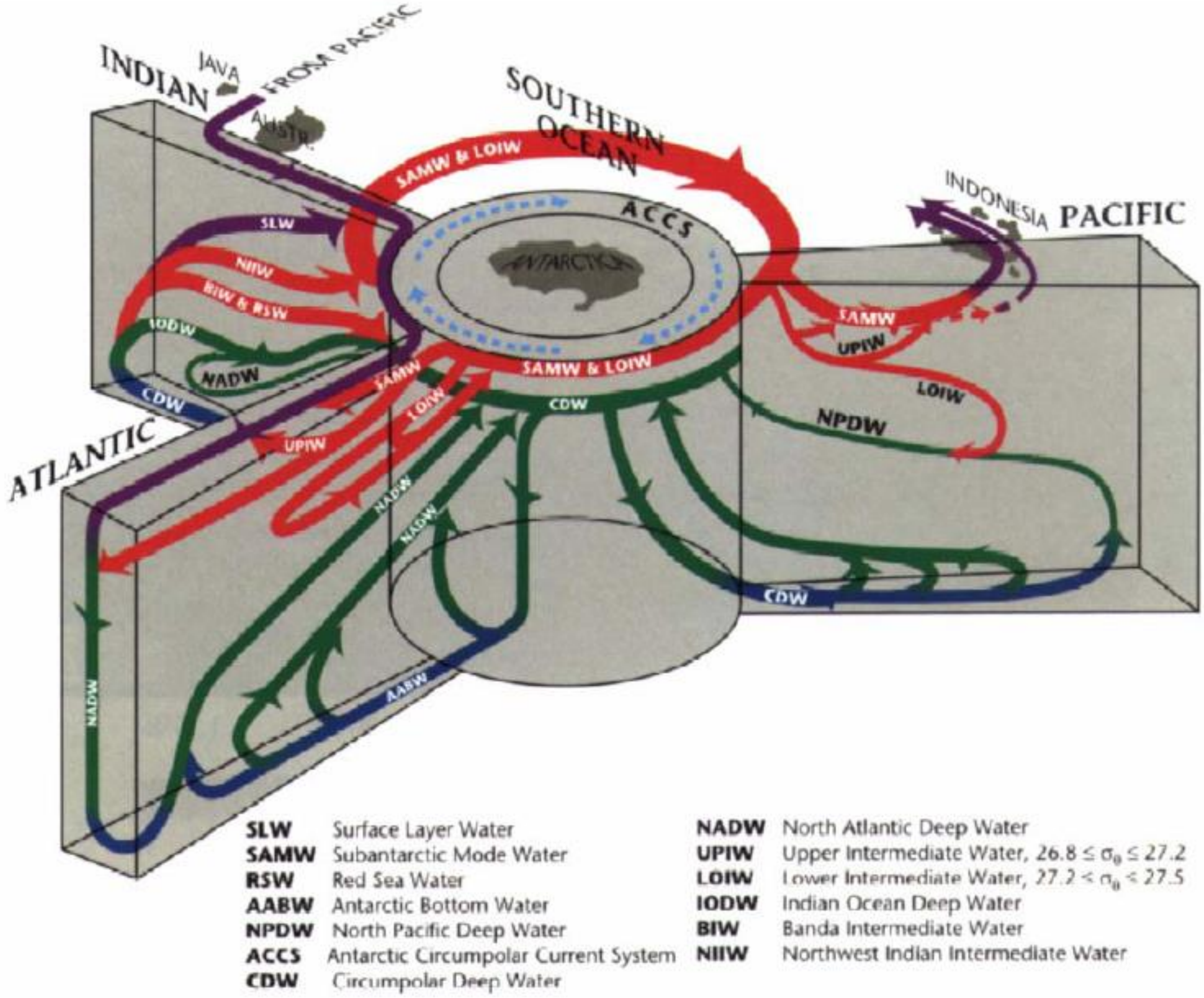


Figure 3. **Schematic** of global ocean circulation. The Southern Ocean plays a key role in the mixing of waters from different high-latitude and tropical locations.

Summary Points

- Up-welling and down-welling in Southern Ocean related to meridional variations in zonal winds
- Frontal structure
- Meridional circulation
- ACC facilitates communication between the south Atlantic, south Pacific, and Indian Oceans.