Biogeochemical and Ecological Impacts of Boundary Currents in the Indian Ocean

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A review paper in review/revision for Progress in Oceanography

OCB Workshop
July 27th, 2016

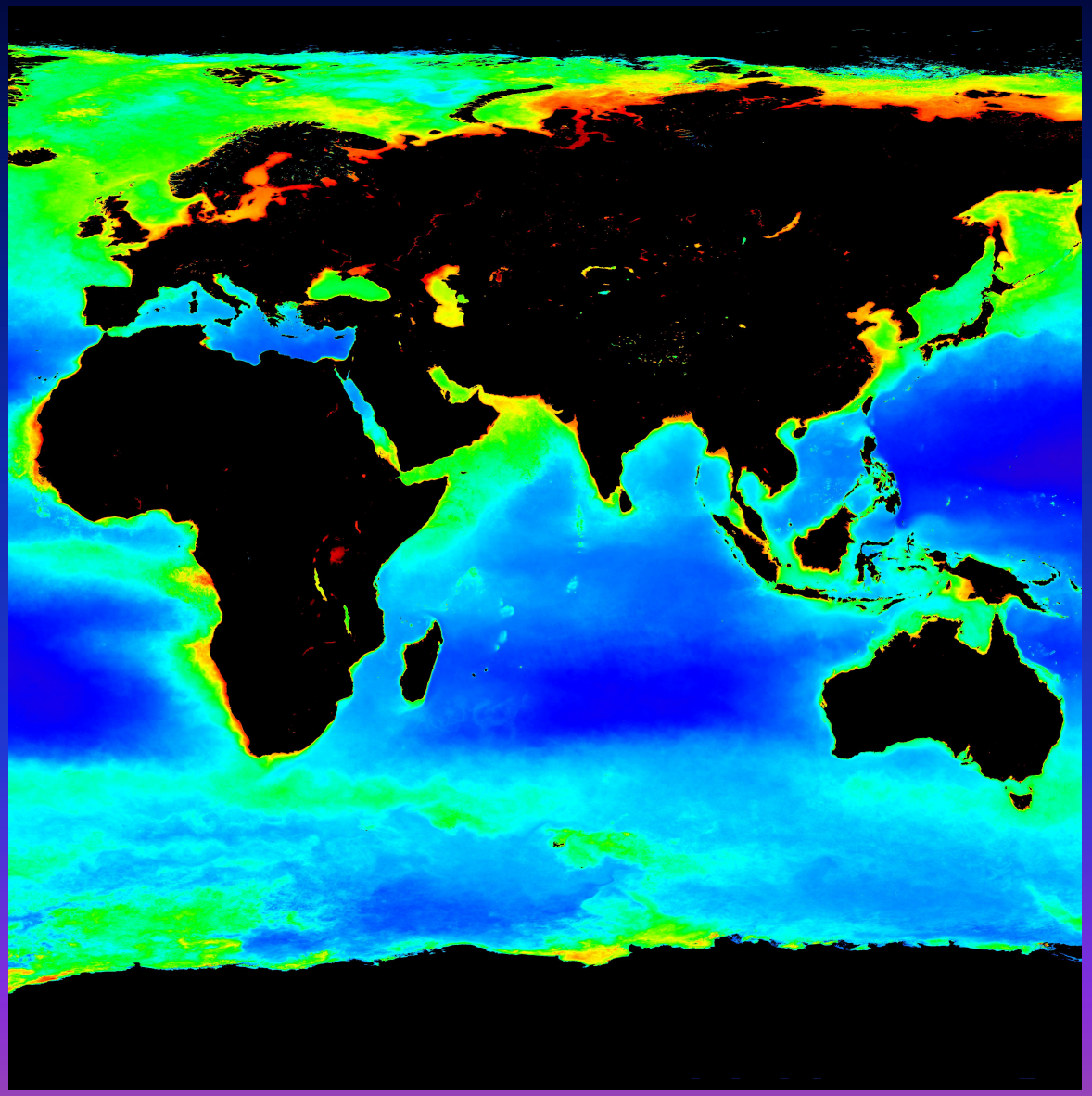
Outline:

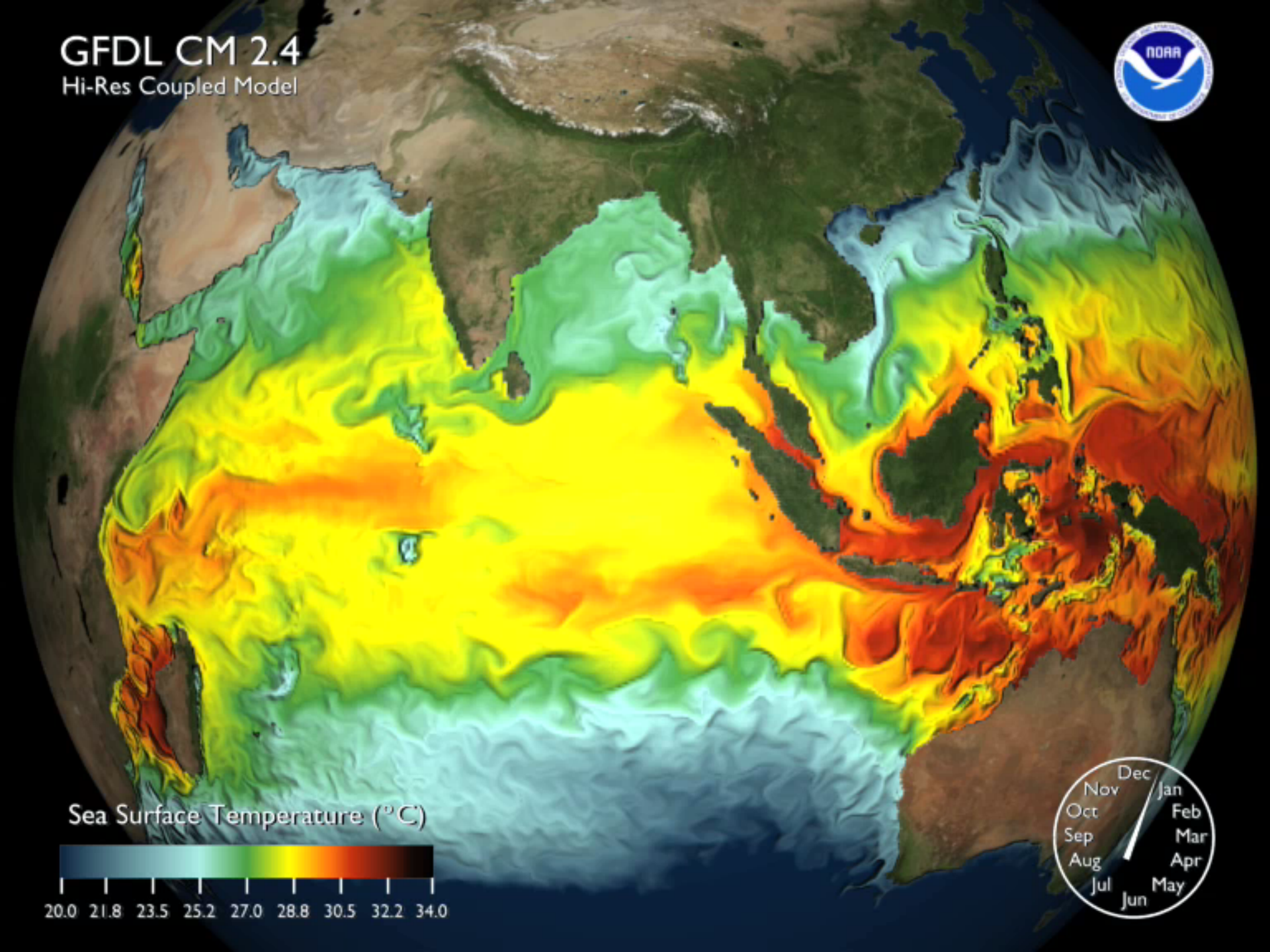
- Introduction to boundary currents in the Indian Ocean.
- Some of the biogeochemical and ecological impacts of seasonally reversing boundary currents in the northern Indian Ocean.
- The poleward-flowing Leeuwin Current and its anomalous biological signatures.
- In contrast, the huge Agulhas Current transport, productivity and higher trophic level impacts.
- Summary and conclusions.

Boundary Currents in the Indian Ocean

The Indian Ocean is different:

- It is bounded to the north by the Eurasian land mass (no temperate zones).
- The Eurasian land mass drives intense monsoon winds.
- The Northern basin is divided in half by the Indian subcontinent.
- The Indonesian Throughflow allows low latitude exchange with the Pacific Ocean.




GFDL CM 2.4
Hi-Res Coupled Model
NOAA
Sea Surface Temperature (°C)
20.0 21.8 23.5 25.2 27.0 28.8 30.5 32.2 34.0
Dec
Jan
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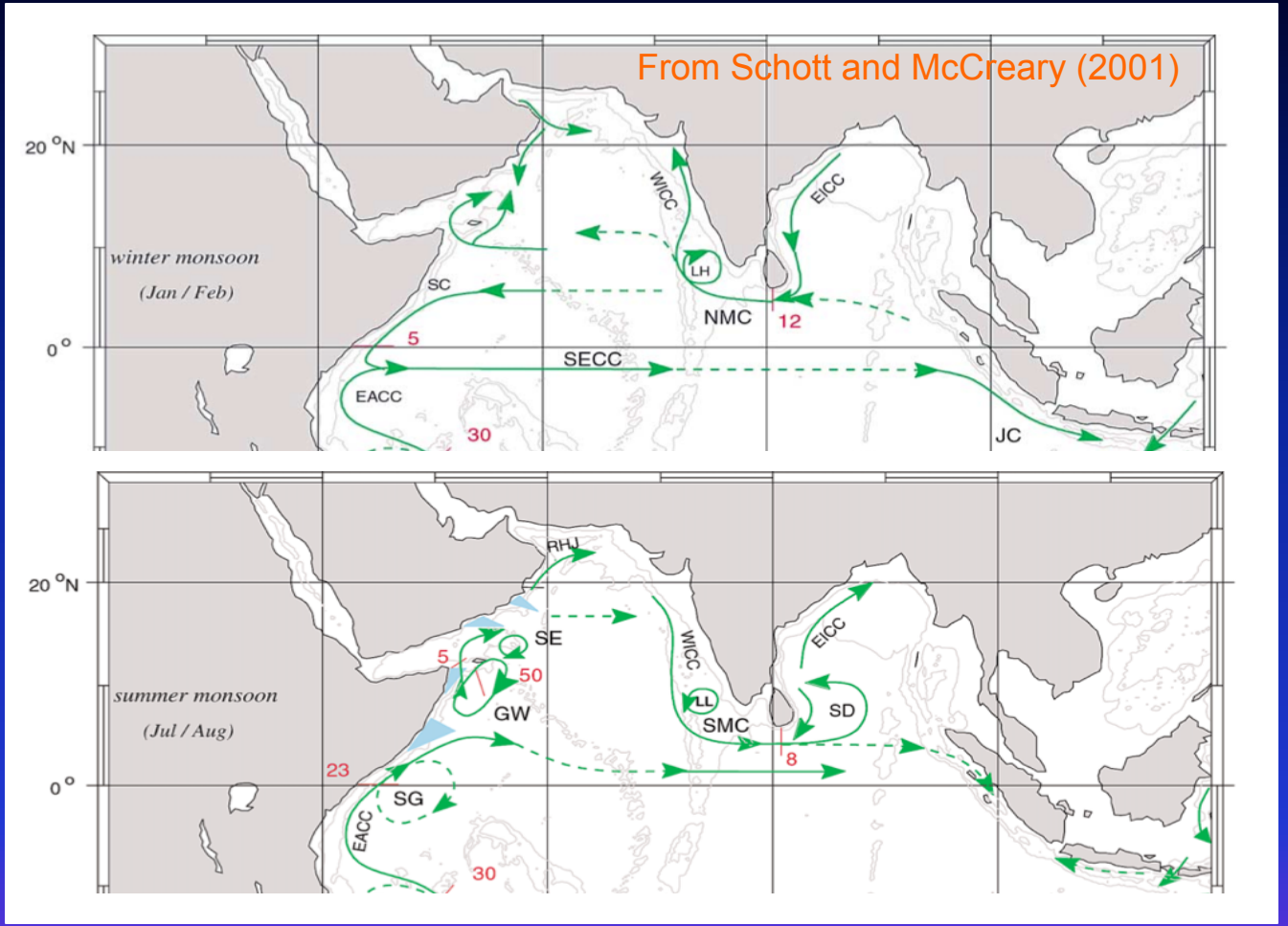
Northern IO Boundary Currents Reverse Seasonally

- Due to the influence of the Monsoon Winds.
- These include: the Somali Current and the East African Coastal Current, Coastal Currents in the western Arabian Sea, West and East Indian Coastal Currents, Southwest and Northeast Monsoon Currents, and the Java Current.
- All reverse partially or fully in response to the monsoon winds and tend to be upwelling favorable during SWM vs. downwelling favorable during NEM.



- Transports are relatively small (< 40 Sv) but some are very fast.
- Local wind forcing (monsoon) impacts can be very strong.
- Remote forcing by coastal Kelvin waves is also important.

Primary Production Response to Upwelling/ Downwelling and Boundary Current Reversals

- The Arabian sea transitions from a eutrophic coastal upwelling circulation during SWM.
- To more oligotrophic during intermonsoons.
- To downwelling and mesotrophic during the NEM.
- These kinds of effects are manifested throughout the northern Indian ocean

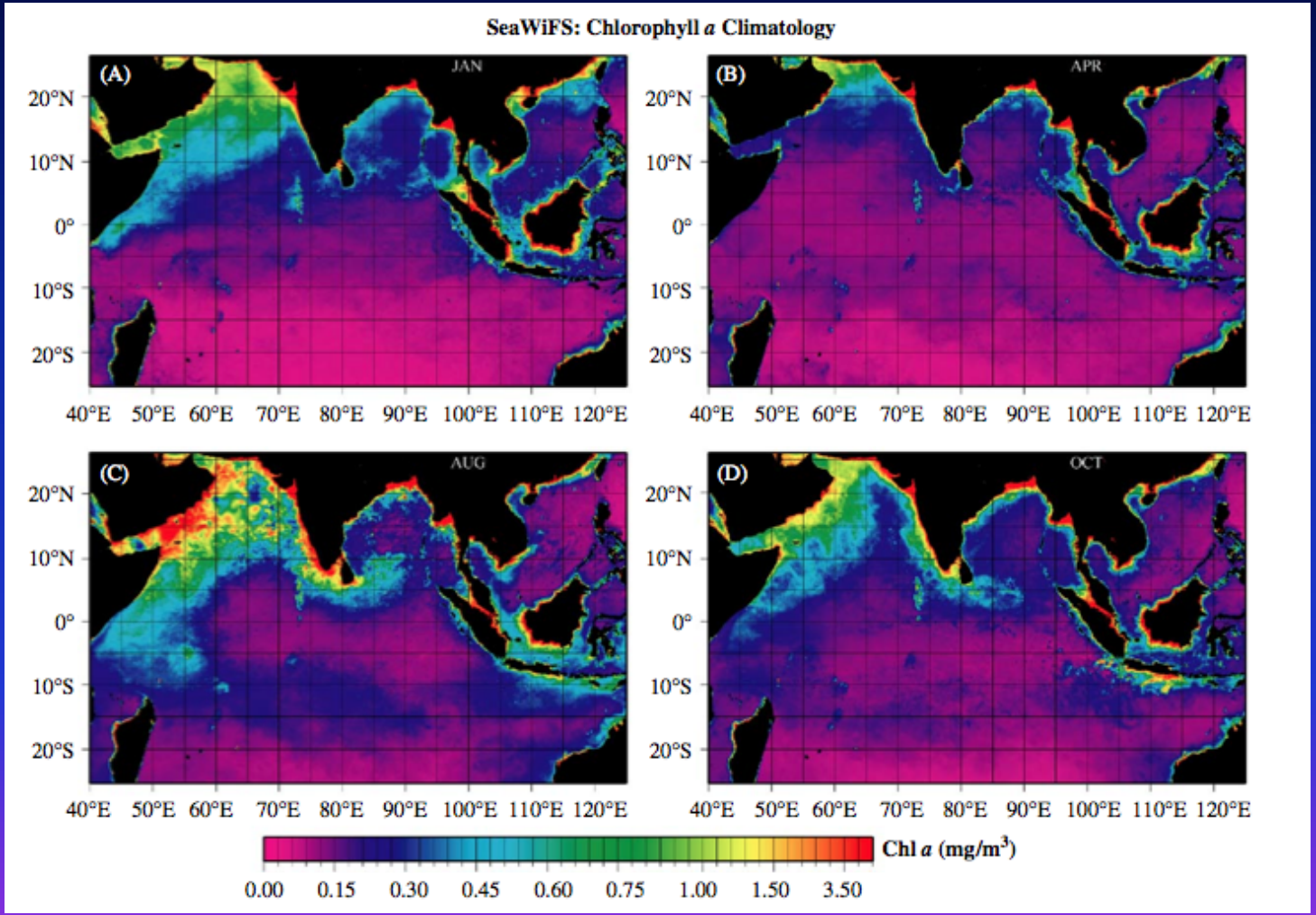


Figure from Wiggert et al. 2006

Changes in nutrient limitation and stoichiometry caused by SWM induced upwelling

- Reversals in the coastal currents and upwelling intensity also cause shifts in nutrient stoichiometry.
- Transitioning from potential N limitation in spring (red) to Fe and Si limitation in summer (blue).
- Due to upwelling and transport of Fe and Si depleted water during the SWM.
- Naqvi et al. (2010) argue that the western Arabian Sea transitions to an Fe-limited HNLC condition during SWM.

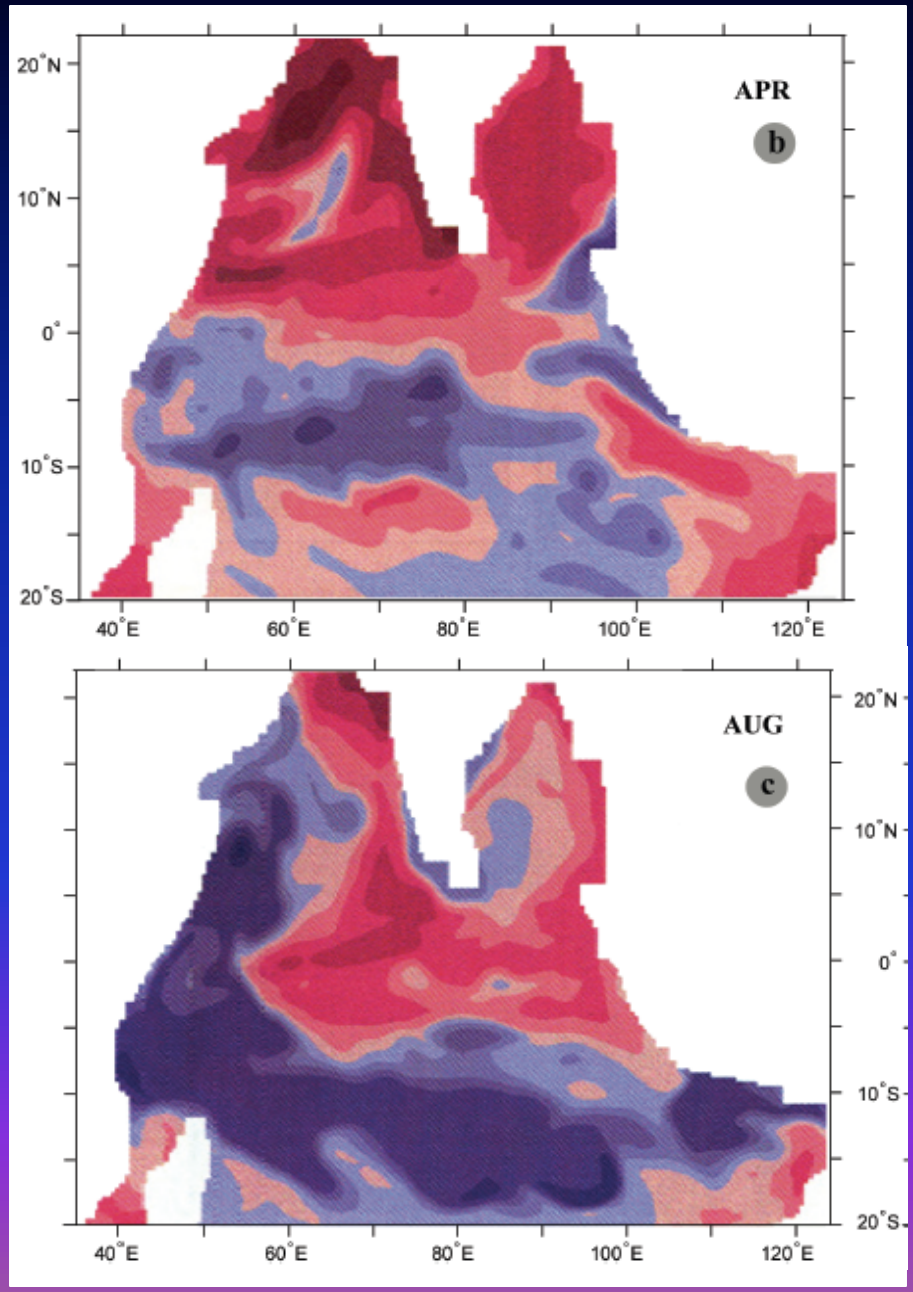


Figure from Wiggert et al. 2006

Higher Trophic Level Response to Upwelling and Boundary Current Reversals in the Arabian Sea

Calanoides carinatus

Southwest Monsoon

Transition to Fall Intermonsoon

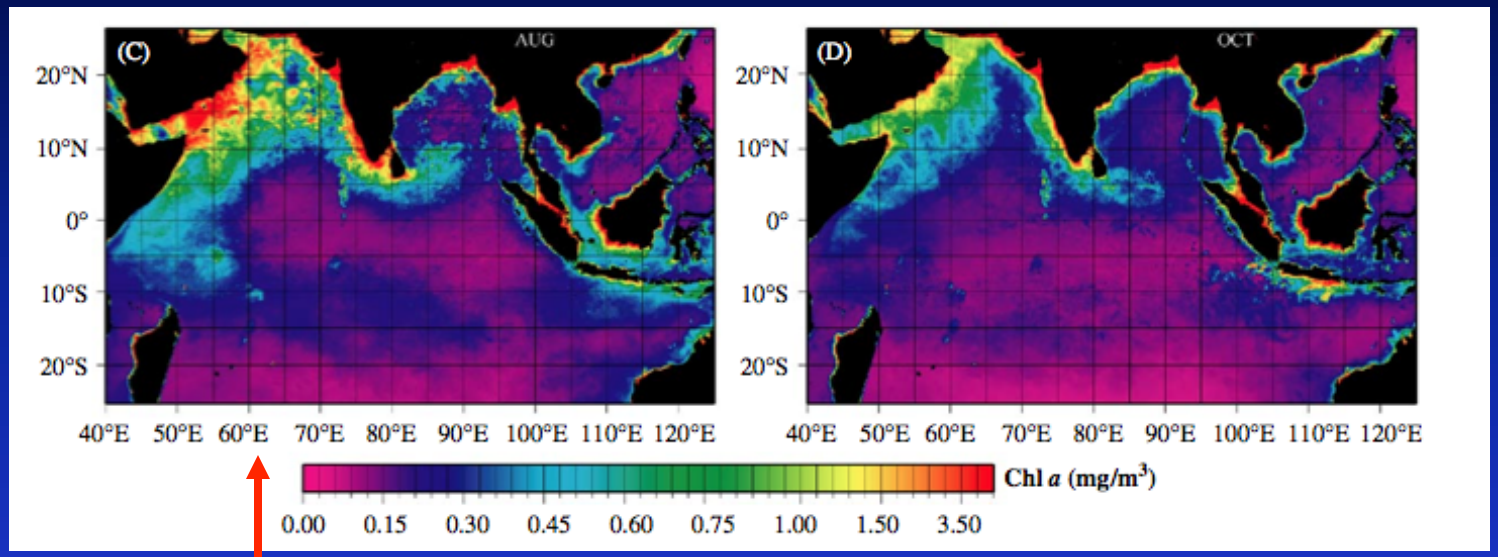


Figure from Wiggert et al. 2006

- At higher trophic levels crustacean zooplankton migrate from hundreds of meters depth to the surface during the SWM in the western central Arabian Sea to feed [Idrisi et al., 2004].

- It has been suggested that grazing control by this species slows accumulation of phytoplankton biomass in response to upwelling of nutrients [Smith, 2001].

Higher Trophic Level Response to Upwelling and Boundary Current Reversals in the Arabian Sea

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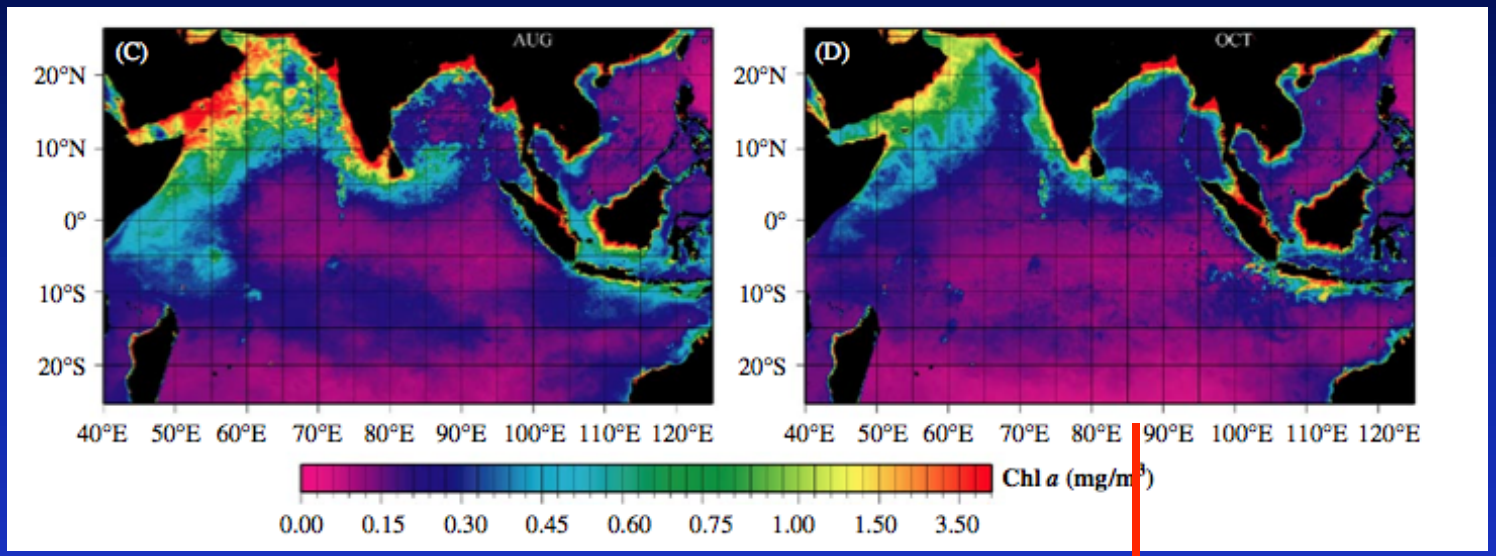


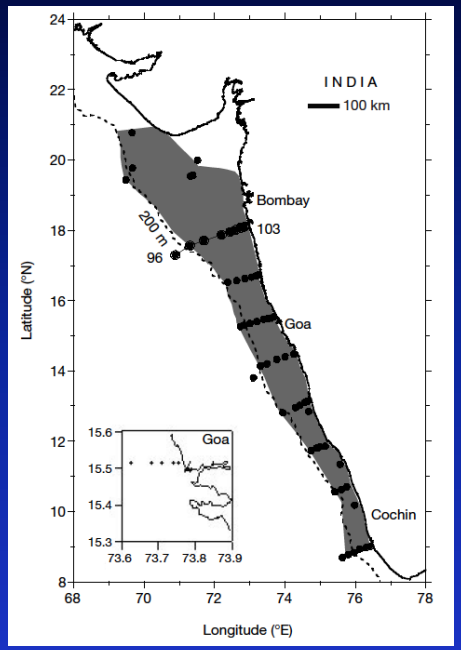
Figure from Wiggert et al. 2006

➢And that downward migration of zooplankton at the end of the SWM potentially enhancing the phytoplankton bloom and export.

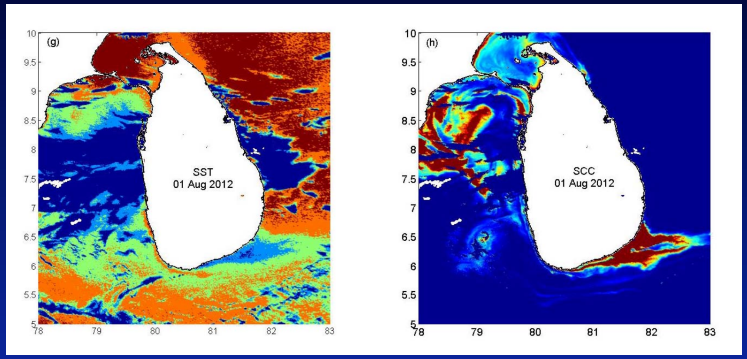
➢We also see behavioral responses in higher trophic level species as well, e.g., the kingfish (*Scomberomorus commerson*) has a single spawning period, peaking in May/June just prior to the onset of the SWM (Claereboudt et al., 2004) .

Biogeochemical and Ecological Impacts of Some Other Northern Indian Ocean Boundary Currents

- The West Indian Coastal Current reverses seasonally, promoting upwelling, hypoxia and fish kills during the late SWM.
- The Southwest / Northeast Monsoon Currents reverse seasonally off Sri Lanka promoting upwelling / downwelling and changes in productivity and CPUE.
- The East Indian Coastal Current reverses seasonally, promoting upwelling, and changes in primary production, zooplankton biomass & community composition during the SWM.
- The Java Current reverses seasonally, promoting upwelling, primary production, zooplankton migration and enhanced sardine catch during the Southeast Monsoon.

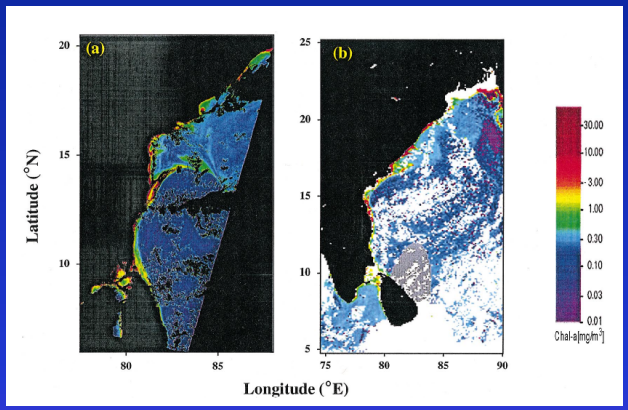


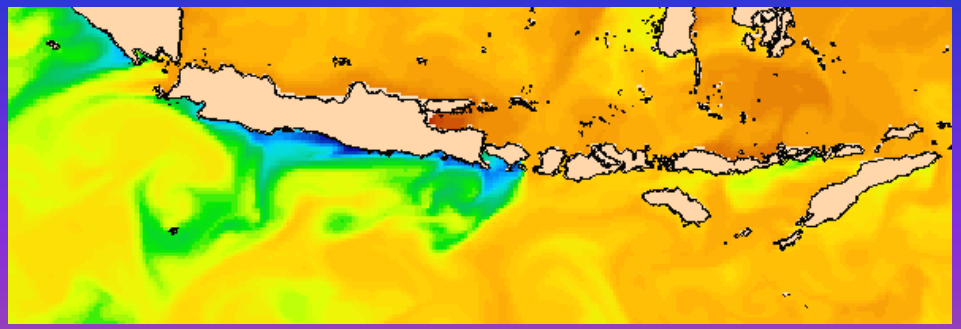
From Naqvi et al. 2006



From de Vos et al. (2014)

Gomes et al. 2000



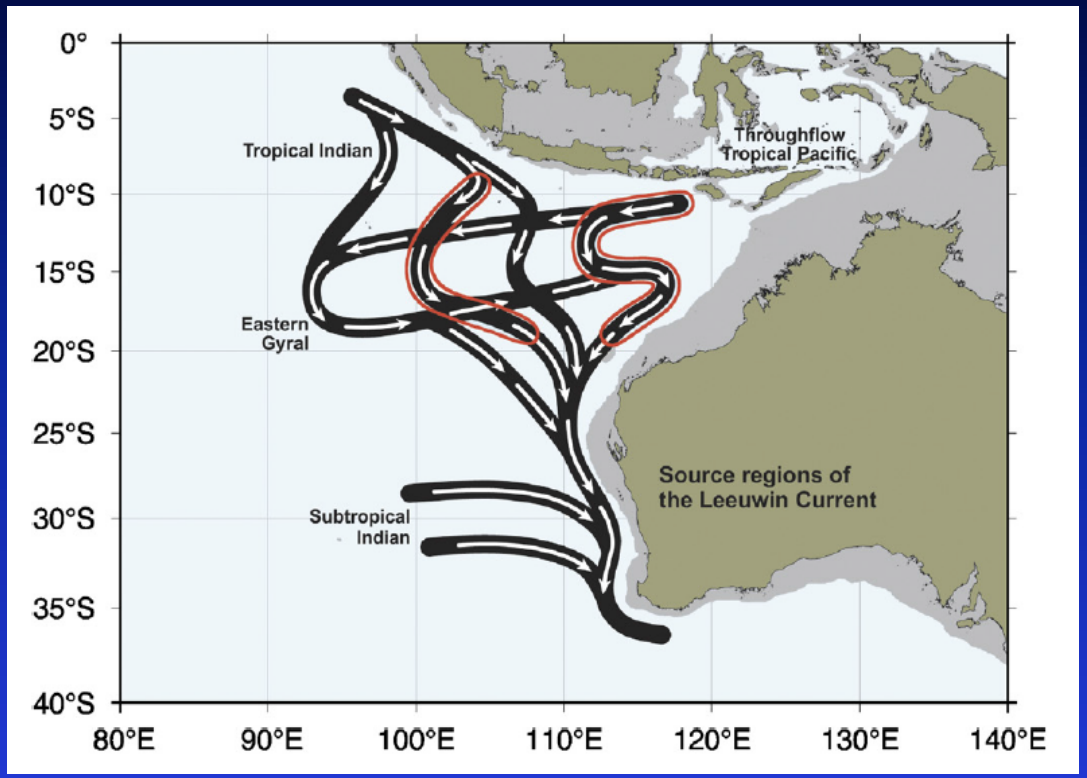


From OFAM courtesy of Andreas Schiller

The Leeuwin Current is Anomalous in Almost Every Respect

From Domingues et al. (2007)

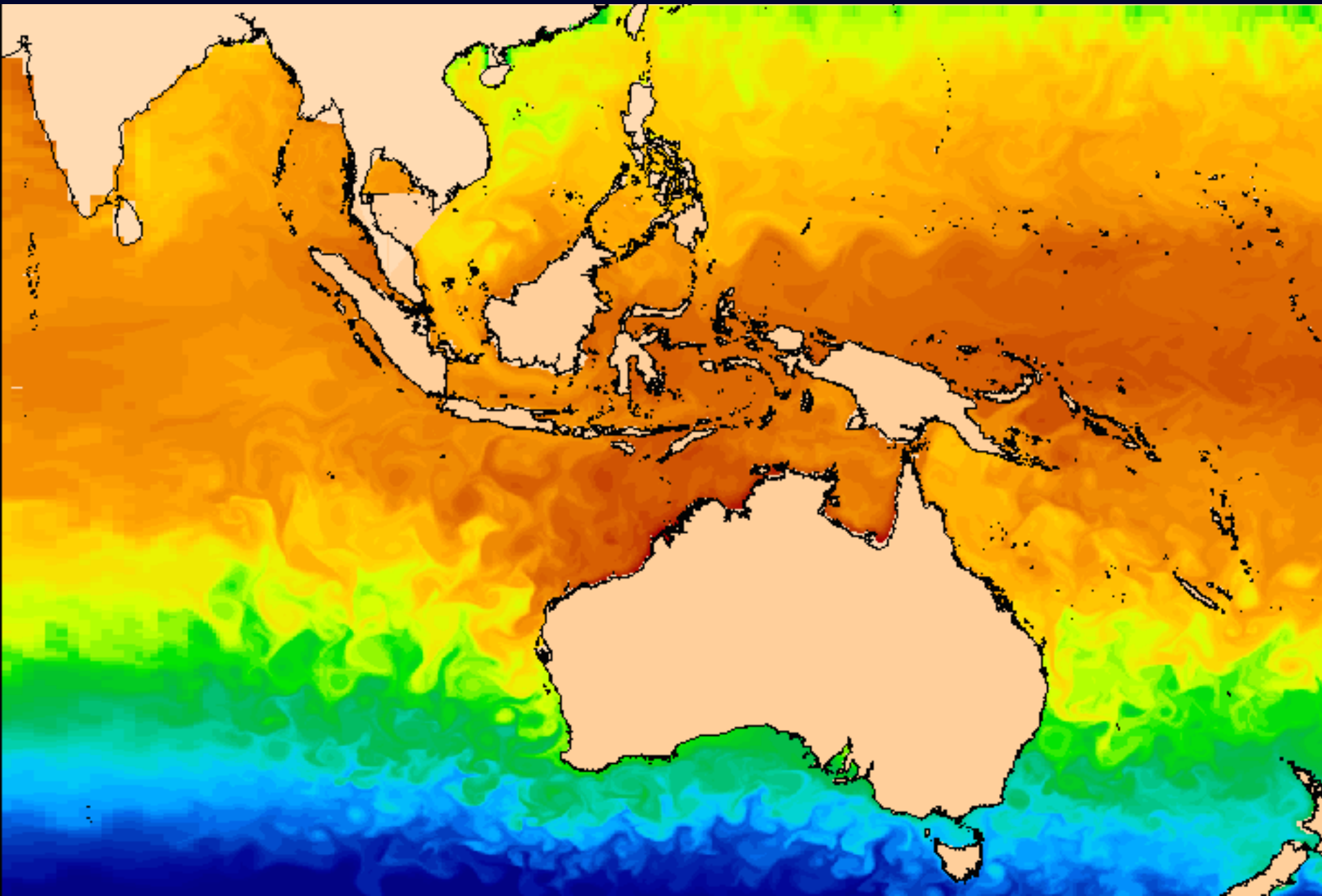
- The only poleward flowing eastern boundary current in the world.
- Source regions are from the northeast through the ITF and the SEC and the west via the Eastern Gyral Current.
- Warm and fresh. Shallow (~300 m deep). Relatively small (<5 Sv).
- Significant seasonal variability in transport.
- Downwelling favorable (Coriolis to the left).
- Remote forcing (large scale pressure field) from the ITF drives this southward flow.
- But local wind forcing can lead to upwelling and current reversals near the coast.



- Transport is also influenced significantly by planetary (Kelvin) waves.
- High kinetic energy generates "productive" warm core eddies and jets.

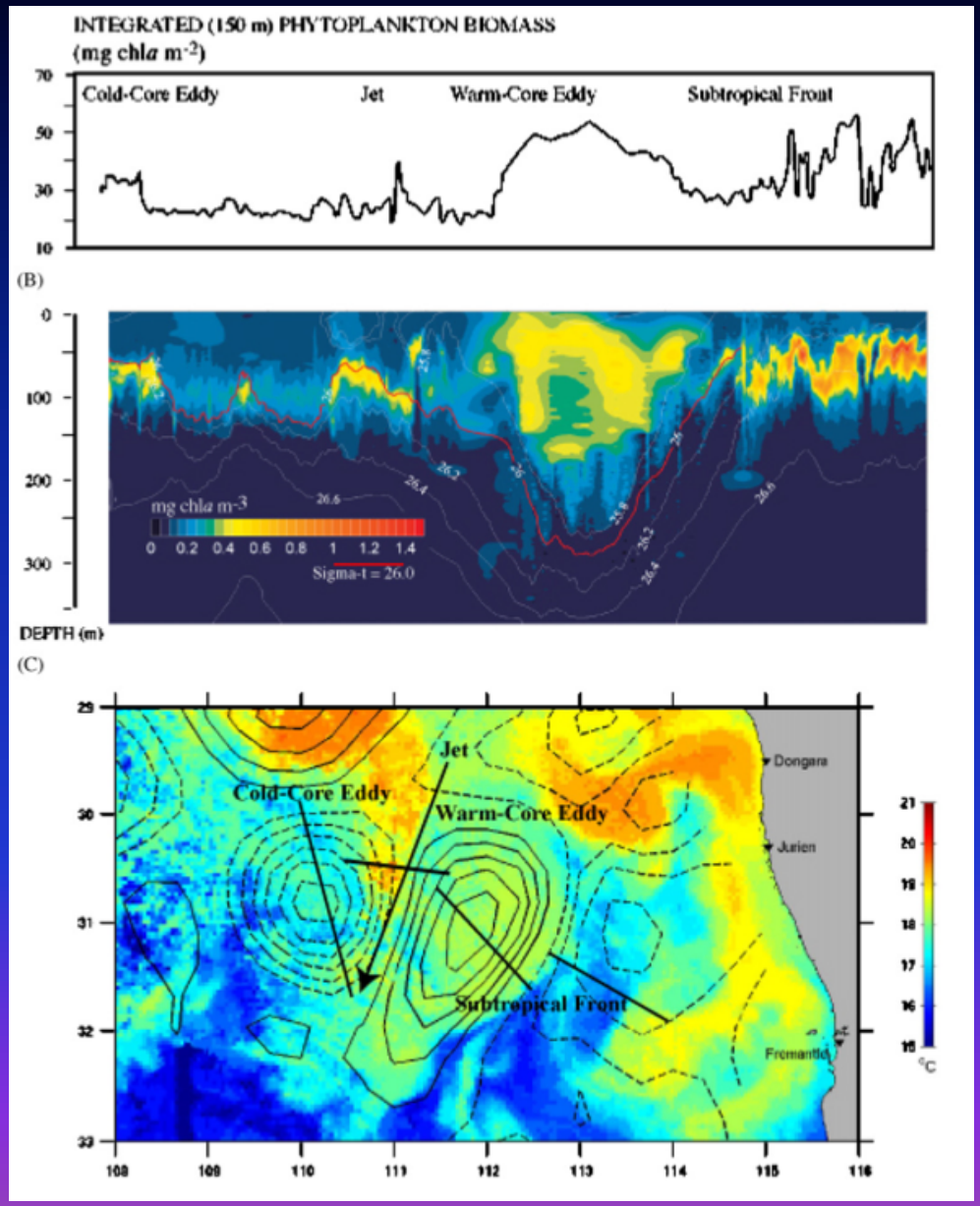
The Leeuwin Current:

OFAM simulation courtesy of A. Schiller



The Leeuwin Current productive warm core eddies

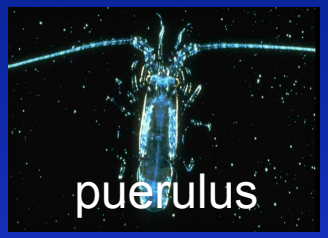
- These warm core eddies transport high chlorophyll, "productive" coastal diatom communities westward.
- Into relatively cold oligotrophic waters dominated by small open ocean species.
- It's an anticyclonic downwelling circulation! Where are the nutrients coming from?
- Lateral supply? Recycling? Vertical trapping?

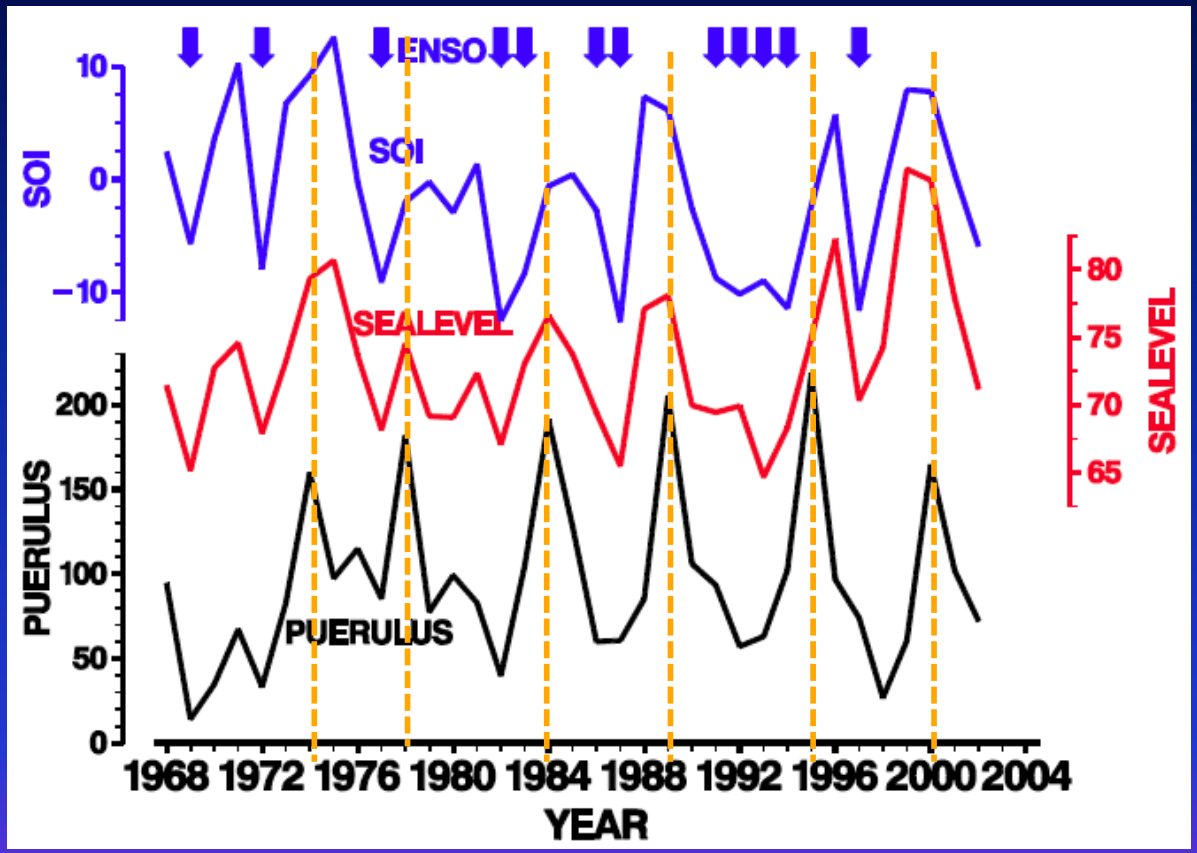


From Waite et al., 2007

Rock Lobster puerulus settlement linked to Leeuwin Current transport variability

ppt slide courtesy of L. Beckley





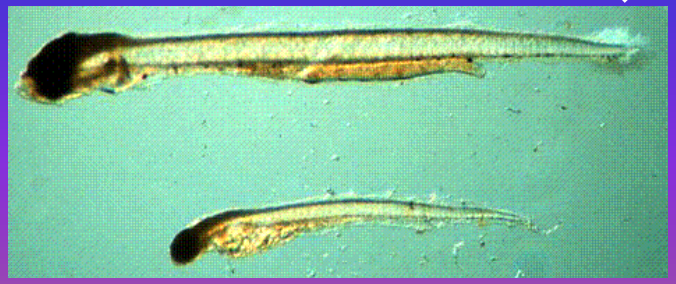
Southern Oscillation Index, or **SOI**, gives an indication of development and intensity of El Niño or La Niña events in the Pacific Ocean. The SOI is calculated using the pressure differences between Tahiti & Darwin

ENSO-related upper ocean variations propagate poleward as internal coastal Kelvin waves along the WA coast. They generate higher coastal sea levels and induce strong LC flow in La Nina years.

- Higher trophic level impacts of the LC include southward transport of rock lobster larvae.
- Historically there has been a positive correlation between puerulus settlement and LC transport (Caputi et al. 2001)
- But correlations with settlement have broken down in recent years (Brown 2009, Feng *et al*. 2011)
- Could this be related to subtle changes in the flow that now transport larvae offshore?

Some other examples from the Leeuwin Current

- The Leeuwin Current may enhance poleward transport of some marine populations (e.g., Rock Lobster).
- But the high kinetic energy associated with the eddy field of the Current can also disrupt long-shore connectivity and induce cross-shelf transport.
- For example, larvae of coastal anchovies can be advected offshore by such eddies, far away from their normal shelf environment.



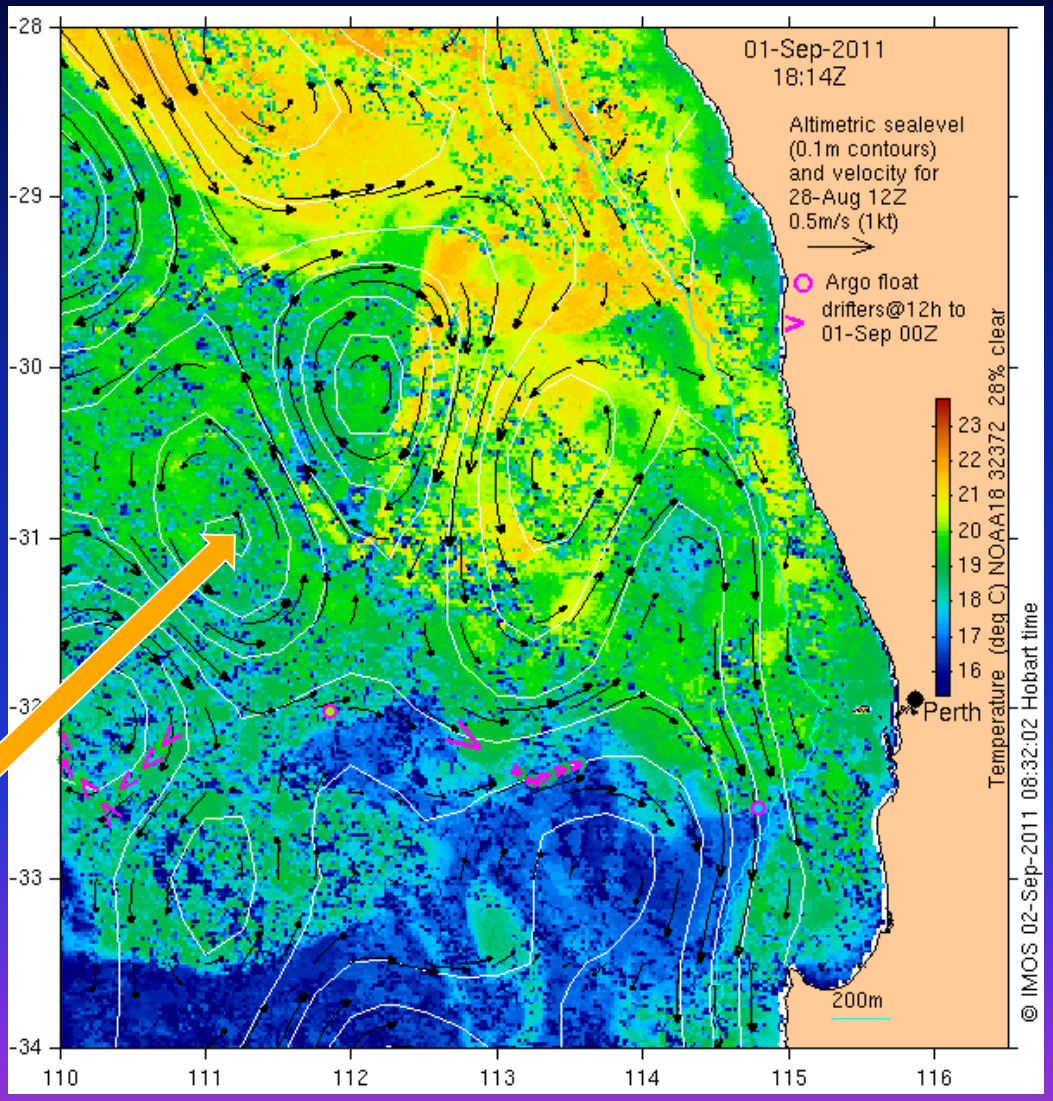
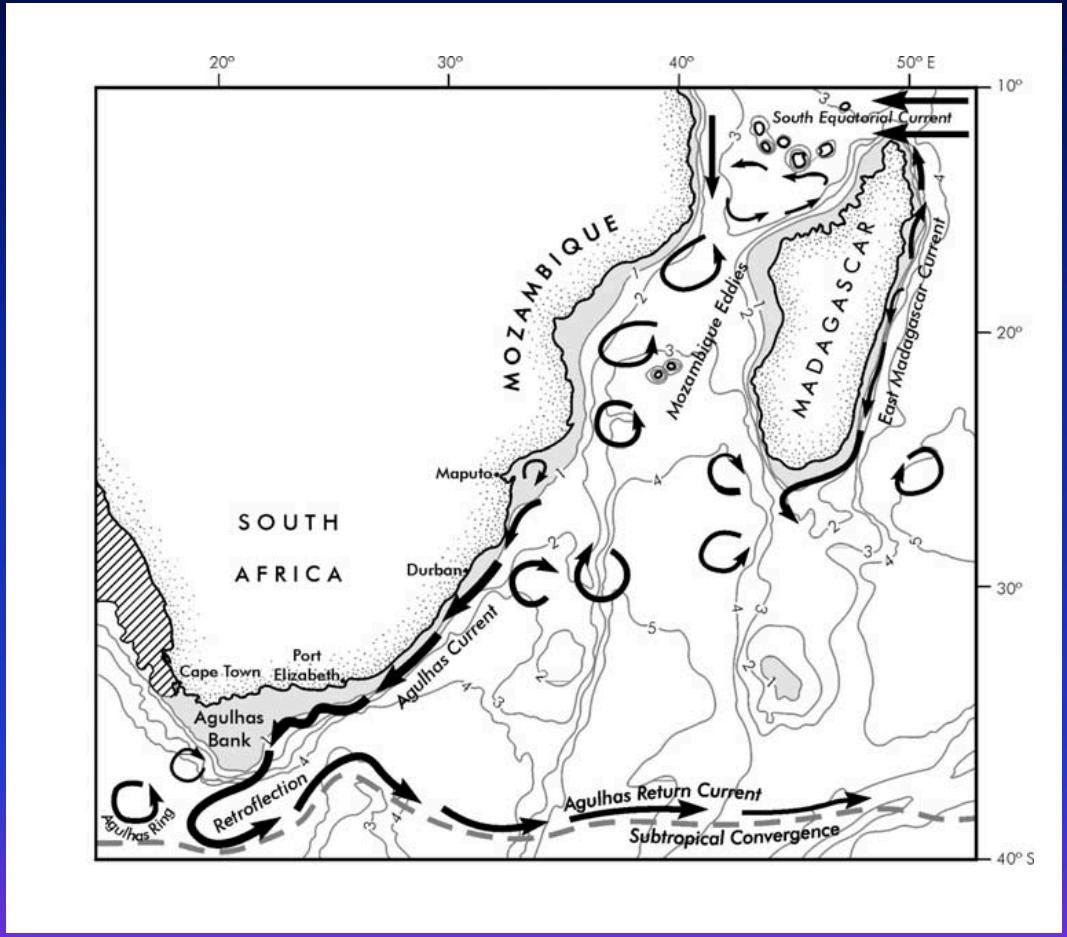


Figure courtesy of BlueLink

In Contrast, the Agulhas Current is Huge

- A warm southward-flowing western boundary current in southern hemisphere.
- Source regions from the Mozambique Channel and East Madagascar Current and recirculation in the southwest Indian Ocean sub-gyre.
- Deep (>1000 m depth).
- Its huge, one of the largest boundary currents in the world (~80 Sv).
- "Upwelling favorable" though surface expressions of upwelling are largely controlled by wind and topography.
- No filaments or seaward propagating eddies along the southeast coast.
- Rather it generates alongshore propagating eddies and sheds warm core anticyclonic rings into the Atlantic.

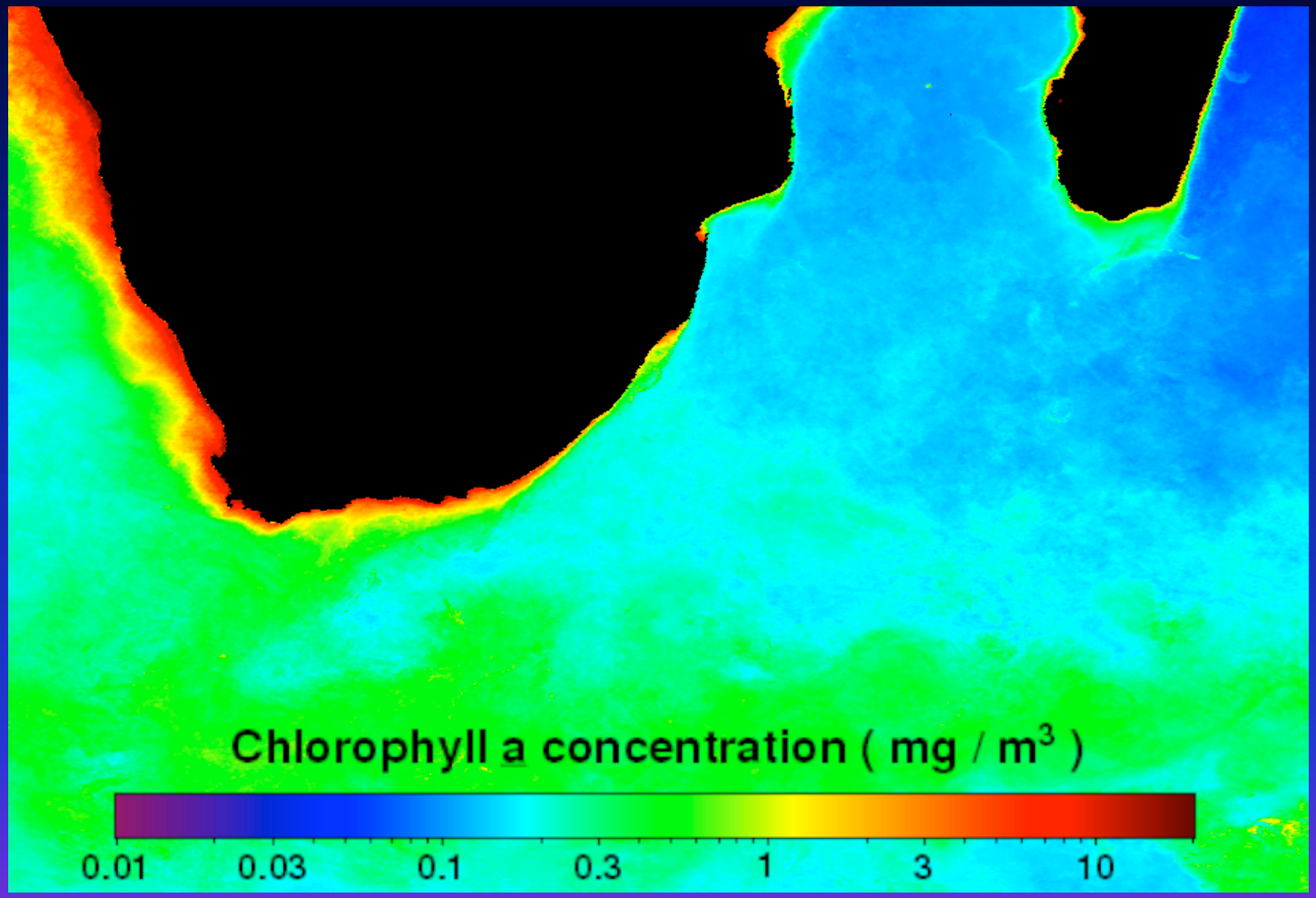
From Lutjeharms, 2006



- Strongly remotely forced.

The Agulhas Current

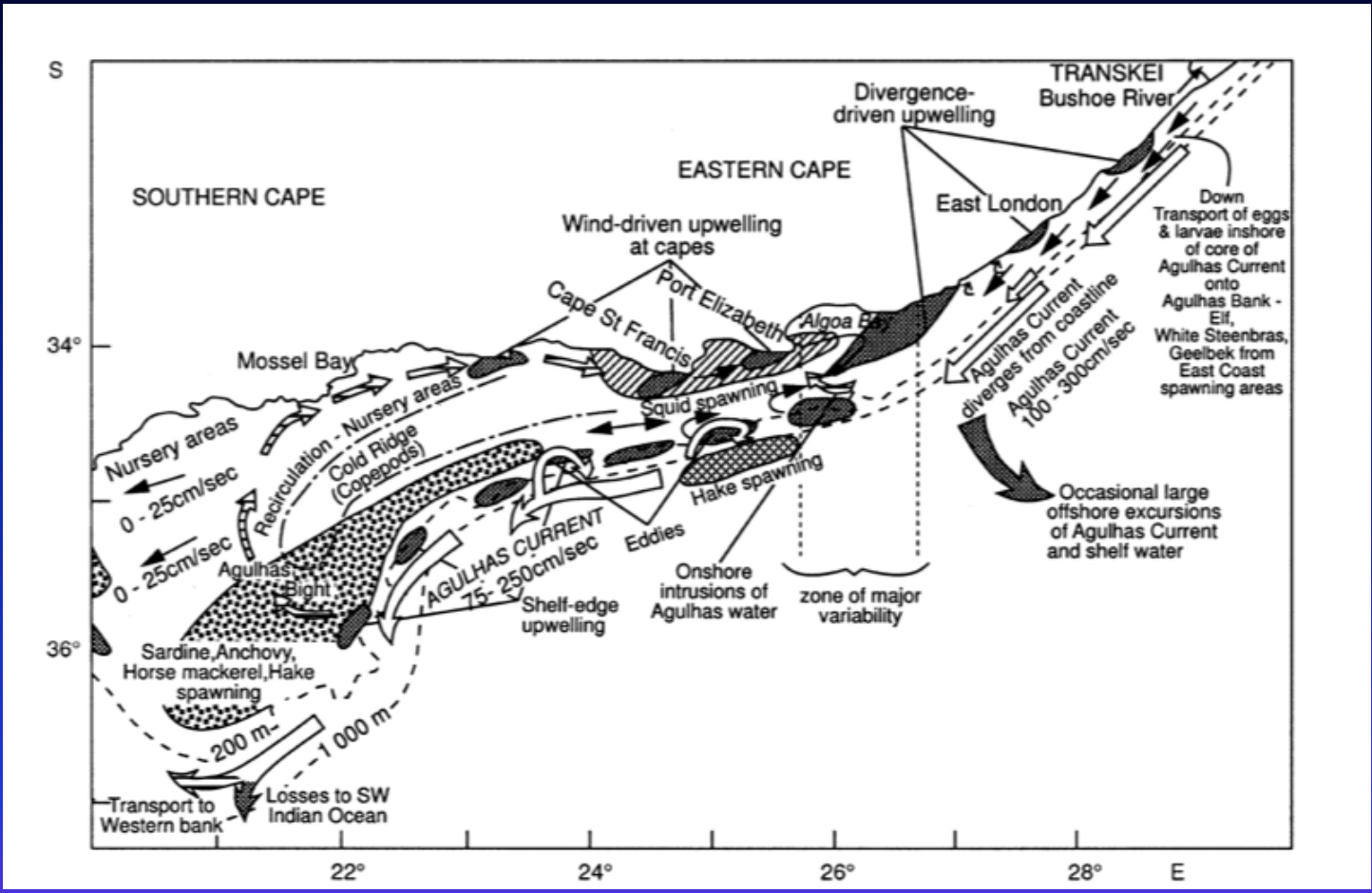
SeaWiFs Chlorophyll 2009 mean



- Enhanced productivity in the coastal zone and in the retroflection.
- But no seaward filaments or eddies along the southeastern coast.
- Rather, alongshore propagating eddies (Durban Eddies and Natal Pulses)

The Agulhas Current

From Hutchings et al. (2002)



- Most fish species in southern Africa have evolved highly selective reproductive patterns for successful retention of planktonic eggs and larvae.

- These ensure that sufficient progeny are retained or can enter the nursery grounds along the coastline in the face of alongshore transport associated with the Agulhas Current.

Example, the KwaZulu-Natal Sardine Run

- The KwaZulu-Natal sardine run off southern Africa occurs from May through July when billions of sardines (the Southern African pilchard *Sardinops sagax)* spawn in the cool waters of the Agulhas Bank and move northward along the east coast of South Africa.

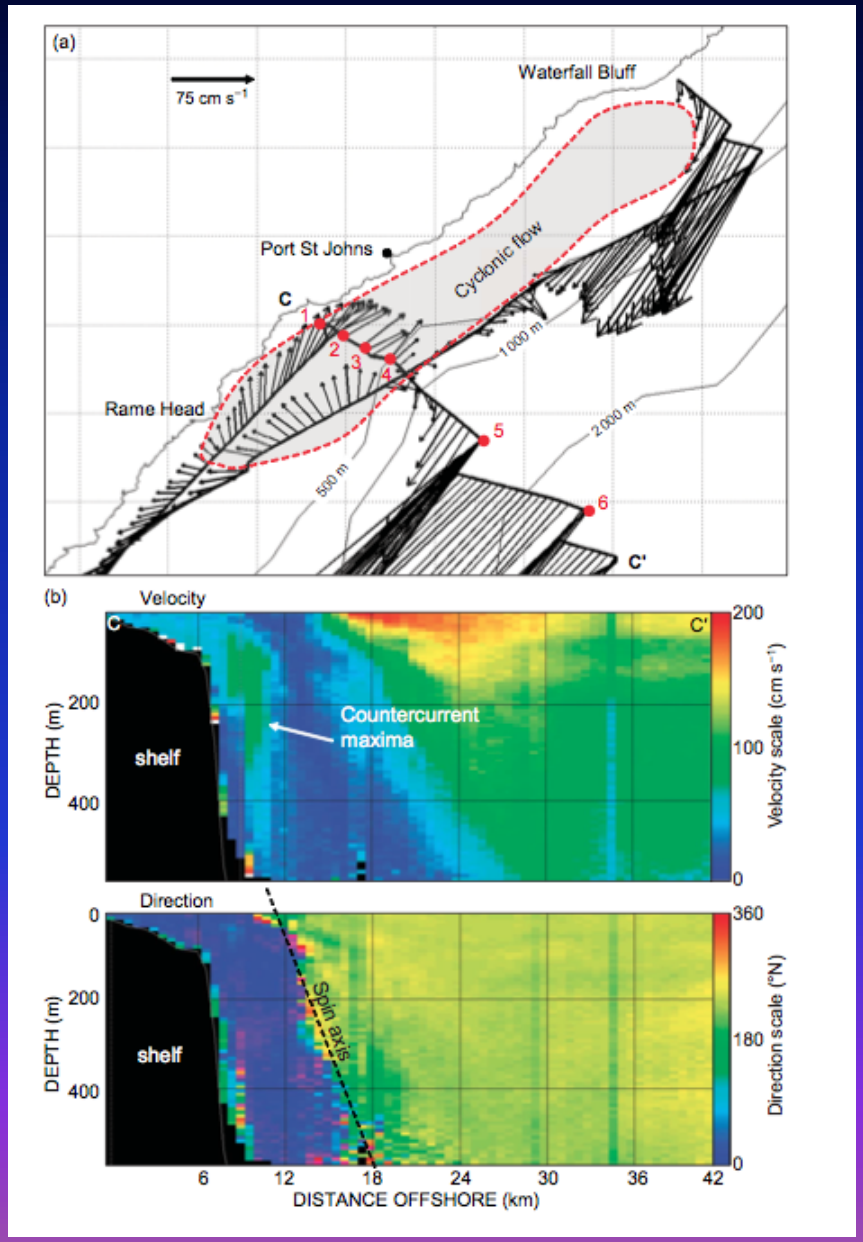
- There are dramatic higher trophic level responses (sharks, birds, dolphins, whales and people).

- How do they do it against the Agulhas Current?

KwaZulu-Natal Sardine Run

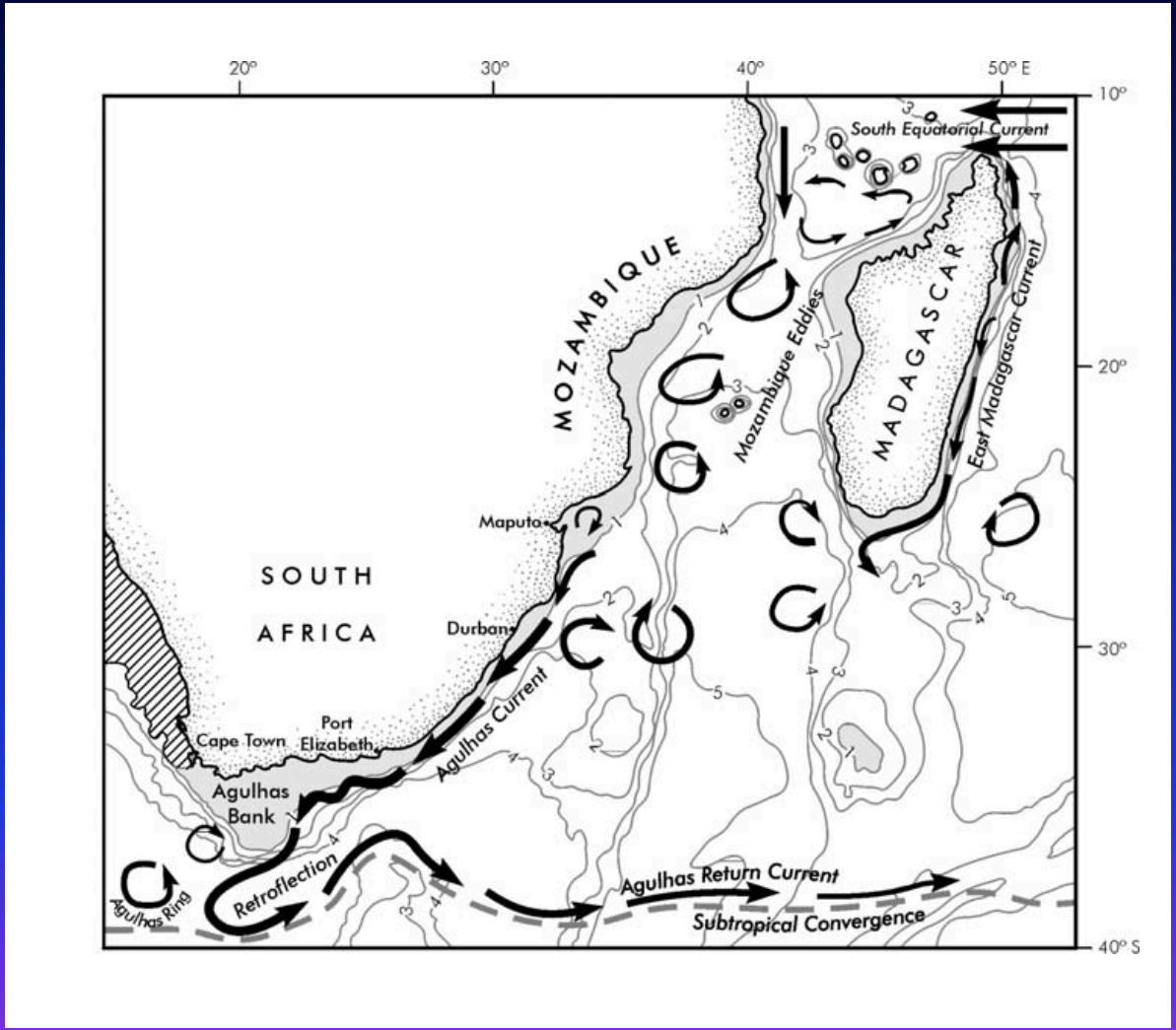
From Roberts et al. (2010)

- They can swim upstream near the coast in cold water.
- Northward-flowing, cold coastal countercurrents exist at times between the Agulhas Bank and the KZN Bight.
- These cold water pathways are enhanced by westerly winds in winter.
- These pathways are also enhanced by transient cyclonic eddies that move downstream in the inshore boundary of the Agulhas Current.
- i.e., break-away Durban eddies and the well-known Natal Pulse.



Some other examples from the Southwestern Indian Ocean

From Lutjeharms 2006



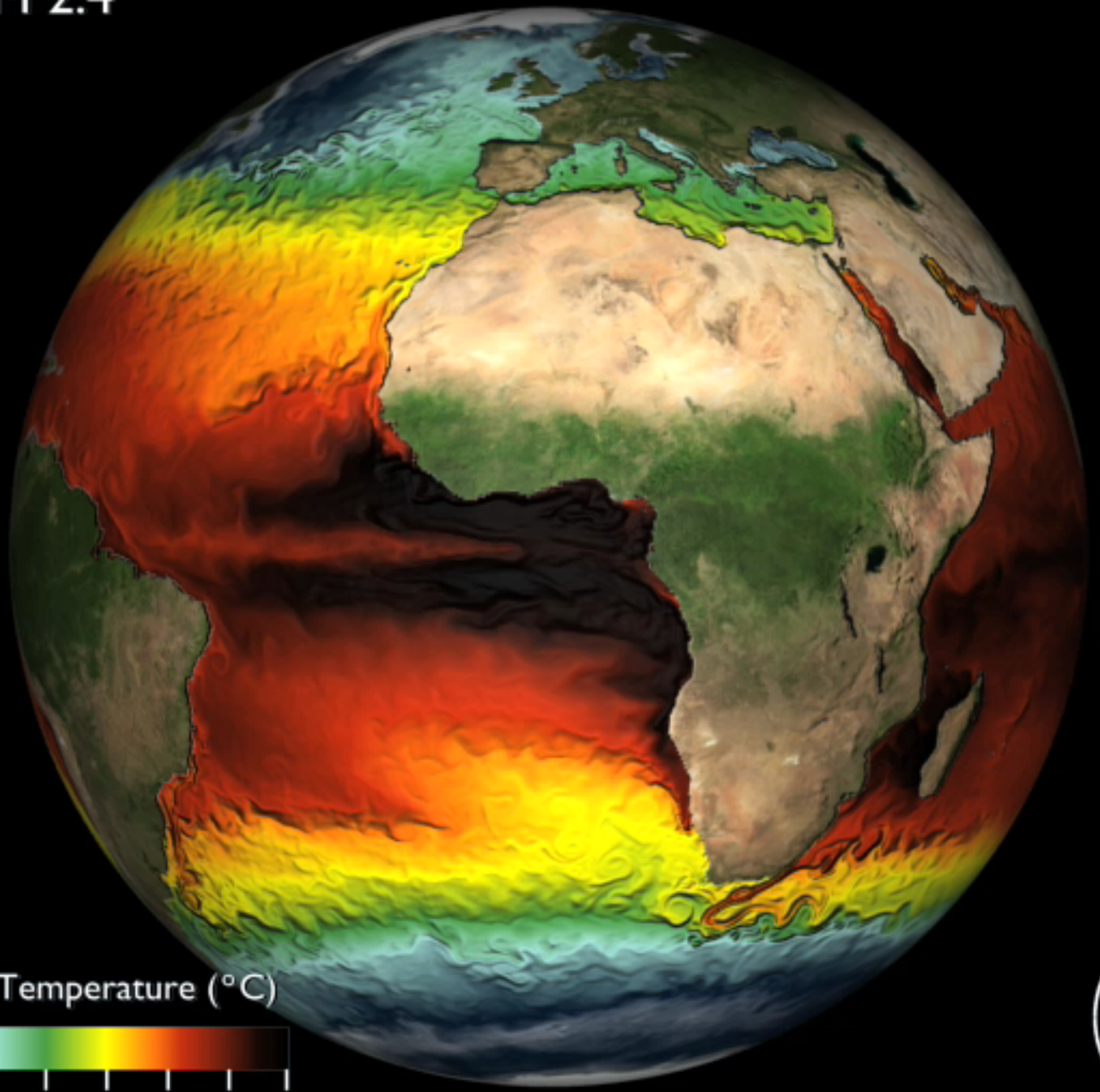
- Mozambique eddies: upwelling and downwelling drive changes in productivity and higher trophic level response (e.g., Great Frigate Birds).

- Togographically-forced coastal upwelling and productivity response on the inshore side of the East Madagascar Current, influences upwelling, productivity and higher trophic level response.

- The biogeographical distributions of zooplankton species off of South Africa clearly reflect the influence of the Agulhas Current.

- The Current transports *Indo-Pacific* zooplankton species into waters over the Agulhas Bank.

GFDL CM 2.4



Sea Surface Temperature (°C)

-1.0 3.1 7.2 11.4 15.5 19.6 23.8 27.9 32.0

Dec Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov

Summary and Conclusions:

- The Indian Ocean boundary currents are complex and unique in many respects and they provide interesting contrasts in terms of mesoscale variability, relative influences of local vs. remote forcing and biogeochemical and ecological responses.

- The northern basin is dominated by seasonally reversing currents that have very significant biogeochemical and ecological impacts. These include seasonal switching from upwelling to downwelling circulations, and modification of productivity, nutrient stoichiometry and higher trophic level species behavior.

- In the southern basin the small Leeuwin current is backwards in almost every respect. It is a remotely forced southward-flowing, downwelling current but local wind forcing is very important as well. It sheds “productive” westward-propagating warm core eddies and it influences higher trophic level larval recruitment and fate.

- In contrast, the upwelling favorable Agulhas Current is huge, among the largest boundary currents in the world. Although remotely forced, seasonal winds can enhance upwelling and production in the coastal zone. This current influences the behavior of many fish species (like the African pilchard) which respond to ensure that progeny are retained in the face of potent mechanisms for alongshore transport.

Thank You