Hydrodynamic changes in the Agulhas Current and associated changes in the Indian and Atlantic Ocean

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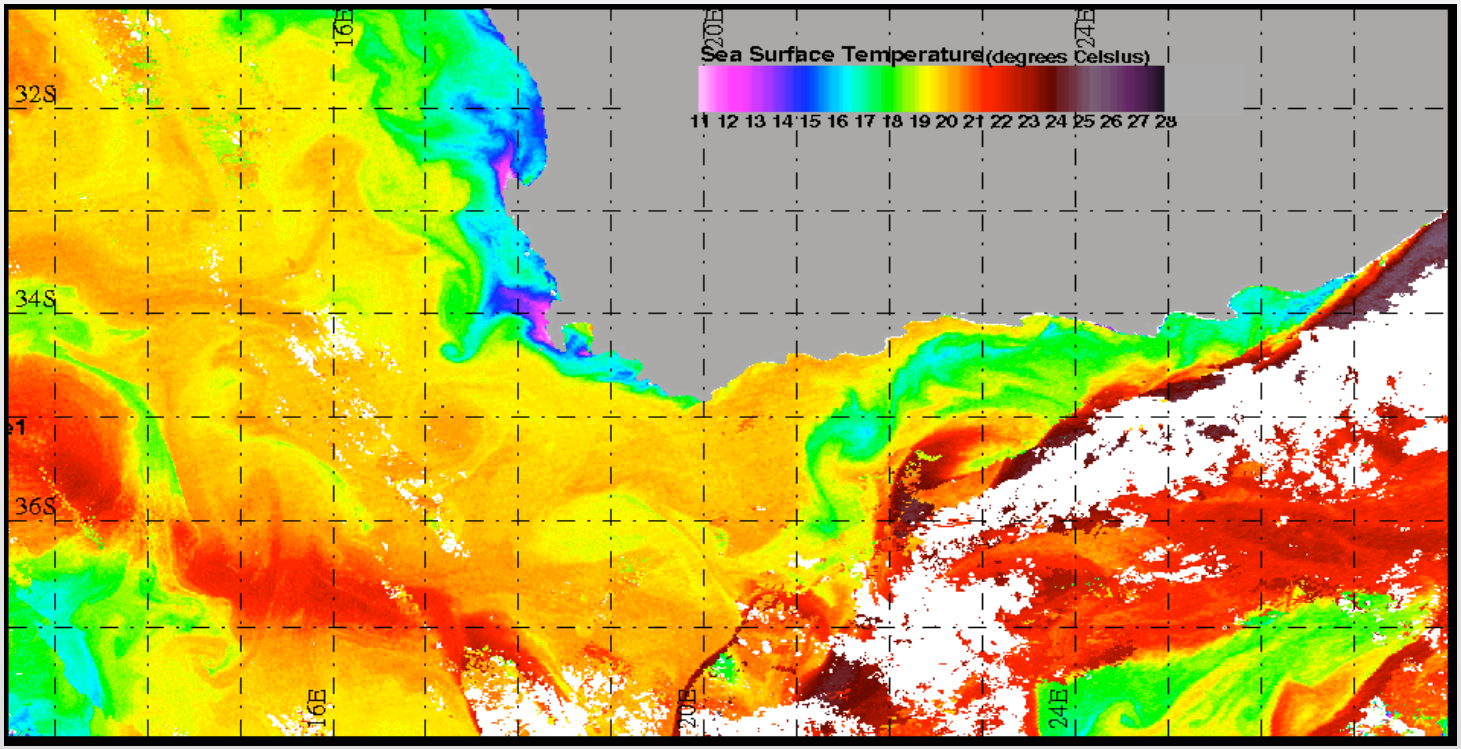
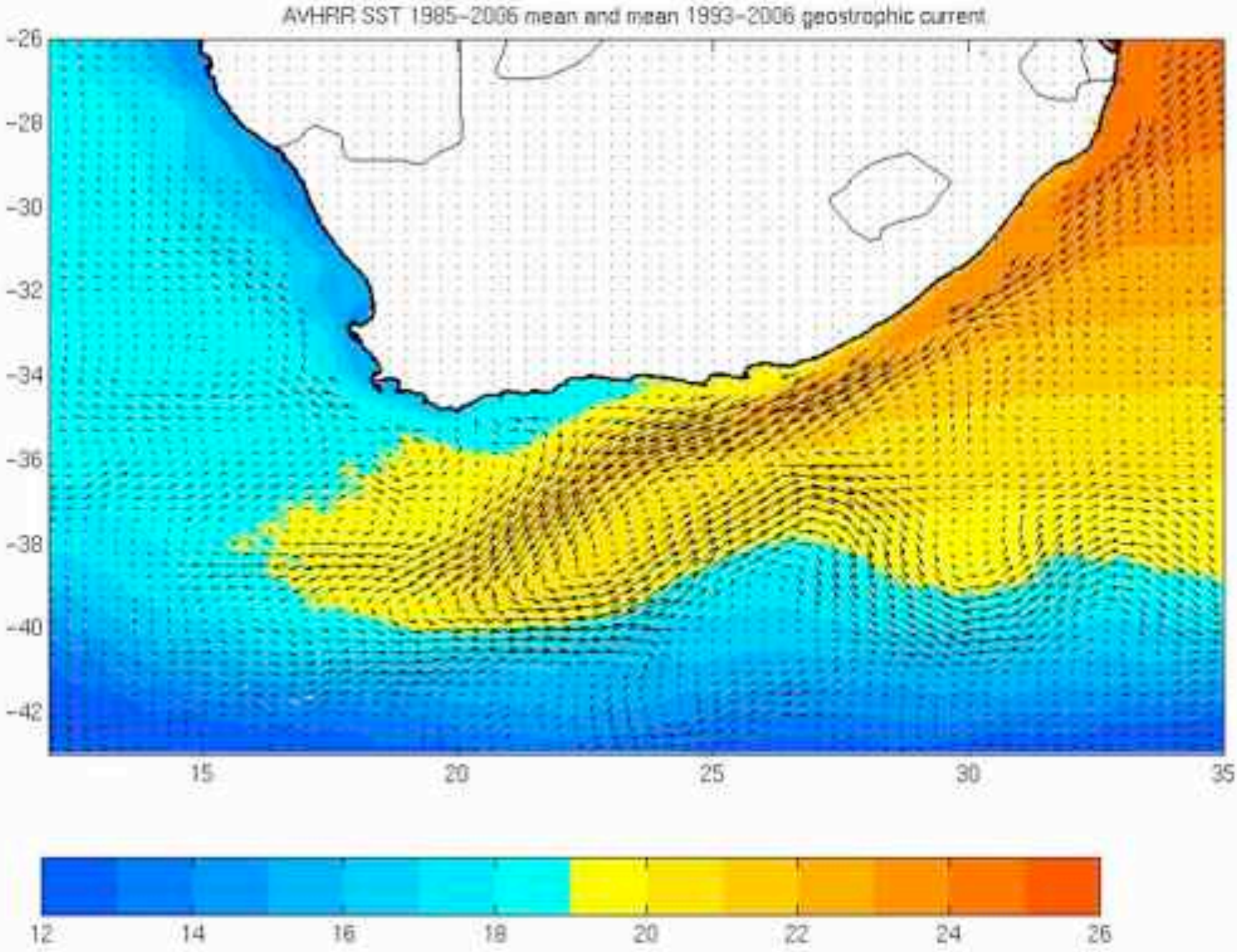
Contributions from Pierrick Penven, Benjamin Pohl, Bjorn Backeberg

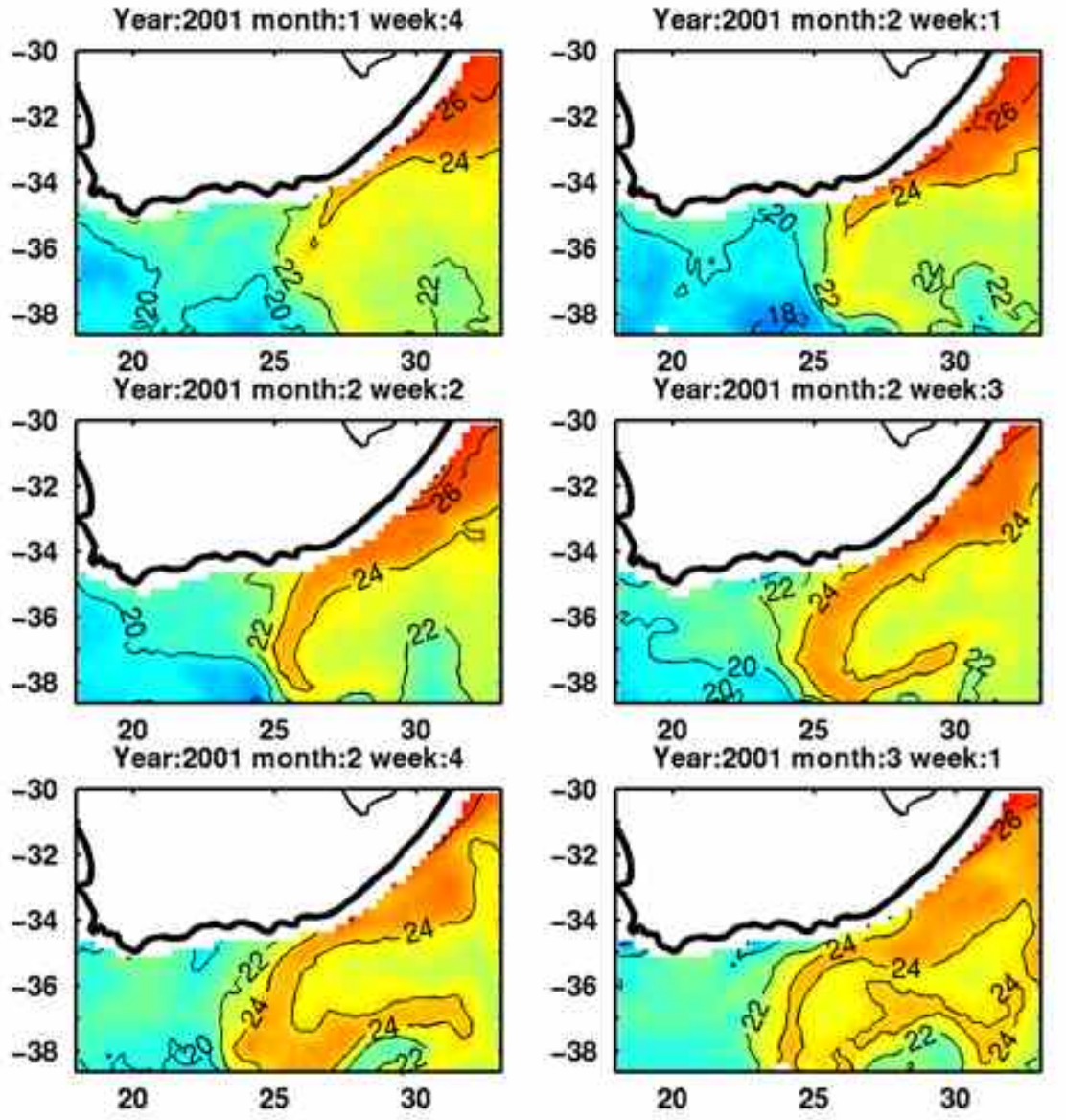


Sea surface temperature estimated by AVHRR aboard NOAA (1x1 km resolution)

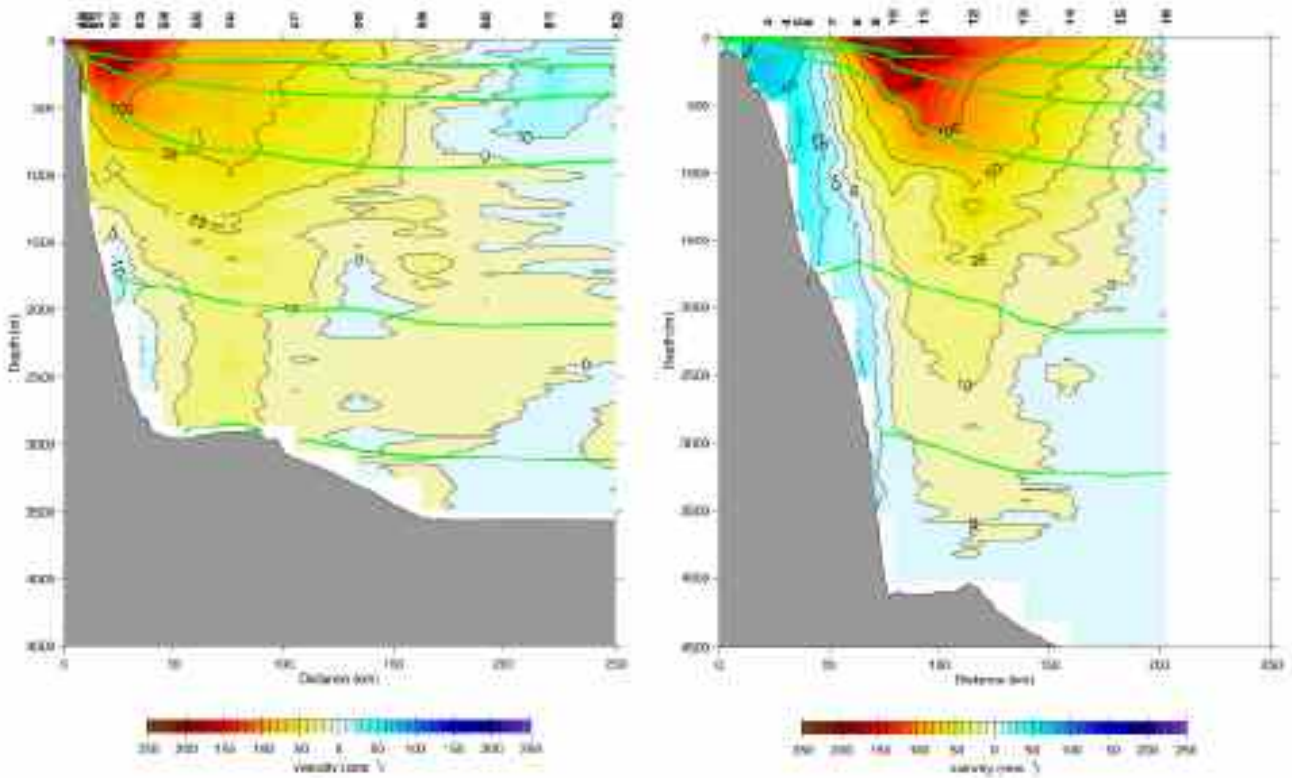
Funding from WRC, ACCESS, Nansen-Tutu Center



Mean AVHRR Pathfinder 4x4 km sea surface temperature and merged altimetry derived geostrophic currents

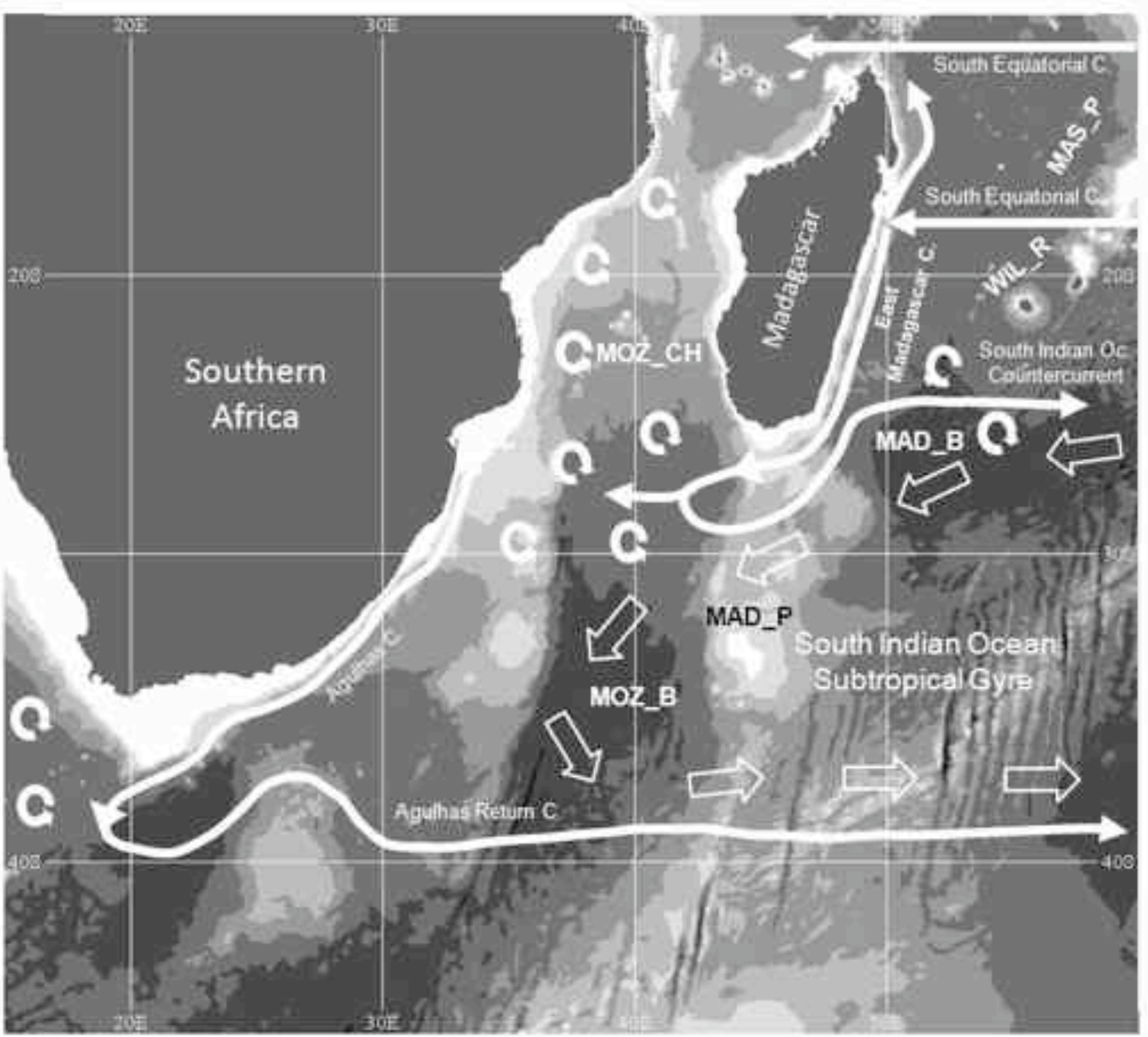


Sequence of weekly mean TMI TRMM sea surface temperature showing an unusual early retroflection of the Agulhas Current at a position more eastward and northwards than normal. Warm Agulhas water eventually re-enter the current. Data is shown each week from the last week of January 2001 to the first week of March 2001 (Rouault and Lutjeharms, 2003)

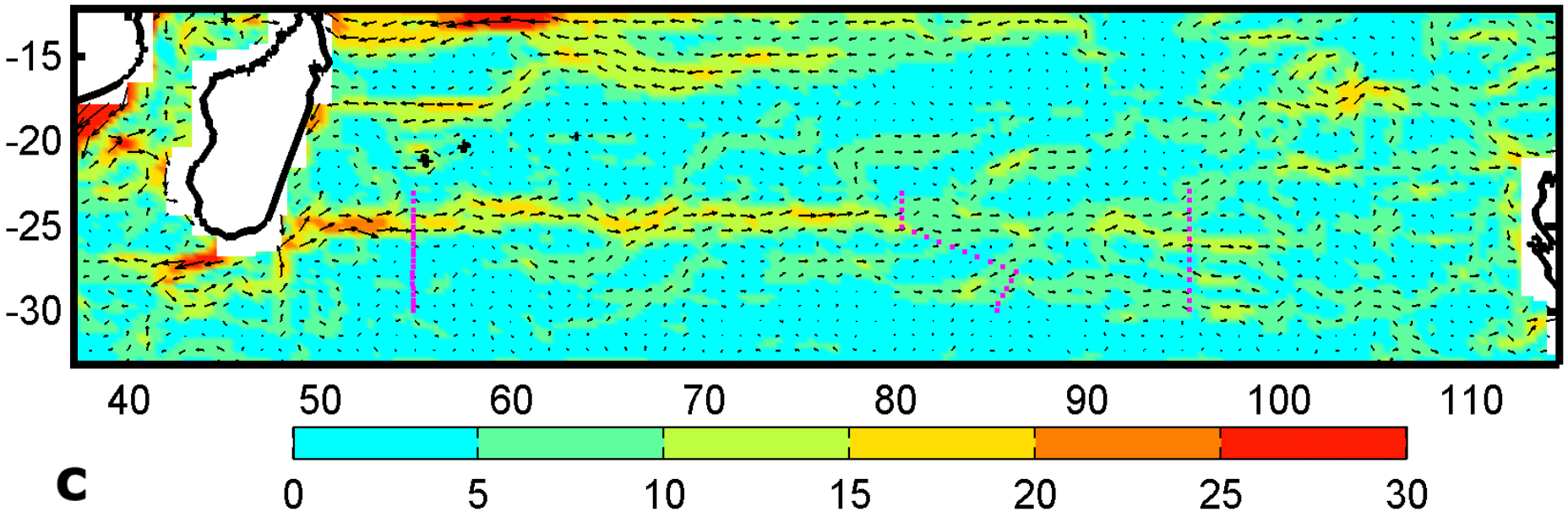


(a) (b)

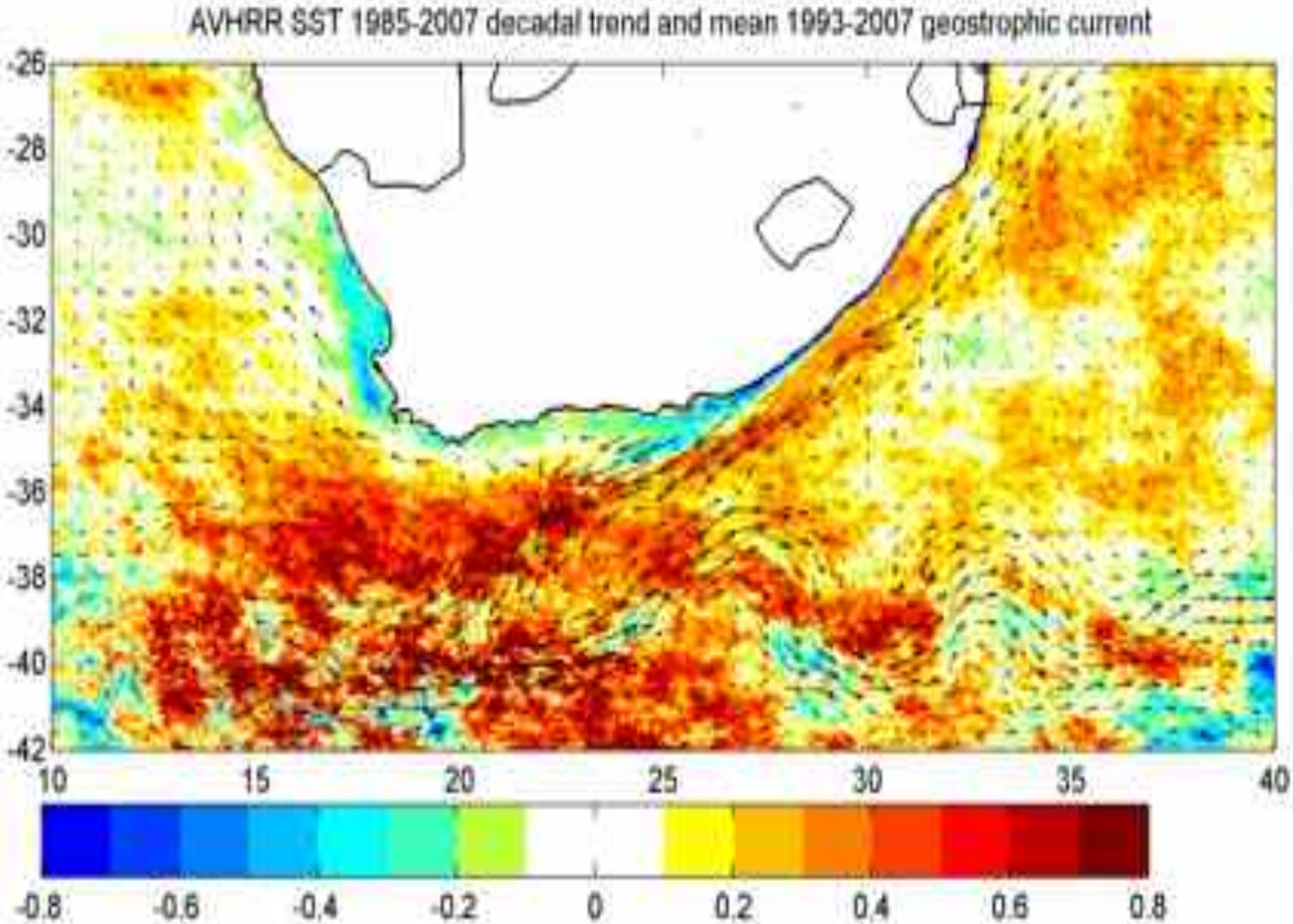
Figure 2.2: *Combined LADCP and ADCP measurements undertaken during the AUCE campaign in 2003 at 32°S (a) and 36°S (b). Colour contours show the vertical distribution of the along-shore velocity across the Agulhas Current. Green contours represent neutral surfaces separating layers of, from top to bottom, Tropical Surface Water (TSW), SubTropical Surface Water (STSW), thermocline waters (including SubAntarctic Mode Water), Red Sea (RSW) and AntArctic Intermediate Water (AAIW), and Upper/Lower North Atlantic Deep Water (NADW). Positive values in shades of red and yellow are indicative of the south-westward flow associated with the Agulhas Current. Shades of blue indicate the presence of a under-current flowing north-eastward under the Agulhas Current. The location of the Agulhas Current maxima moves offshore with increasing depth with the level of no-motion exhibiting a V-shape pattern. These images were downloaded from* `http://www.rsmas.miami.edu/personal/lbeal/current.html`.



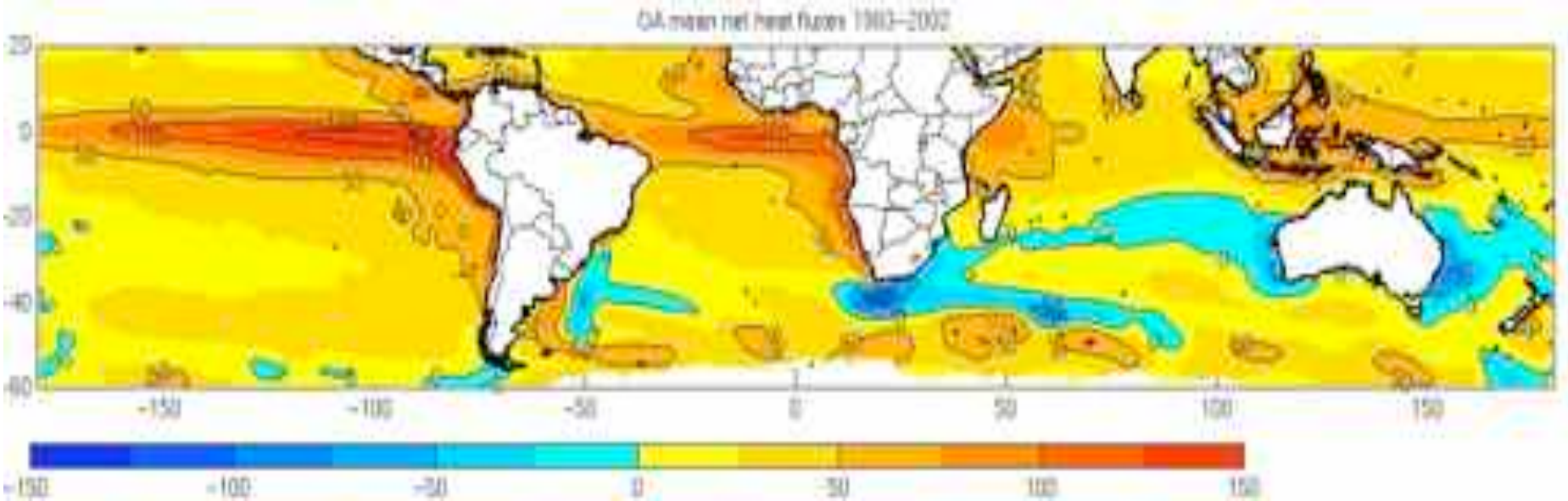
Siedler G, M Rouault, A Biastoch, B Backeberg, C J.C. Reason, and J. R. E. Lutjeharms 2009 Modes of the southern extension of the East Madagascar Current, *JGR Ocean*



Altimetry derived geostrophic currents averaged over five years from August 2001 to May 2006 showing the newly documented South Indian Counter Current and the related retroflection South of Madagascar . The magenta dots indicate the positions of the WOCE stations used for transport calculations (Siedler et al, 2009)



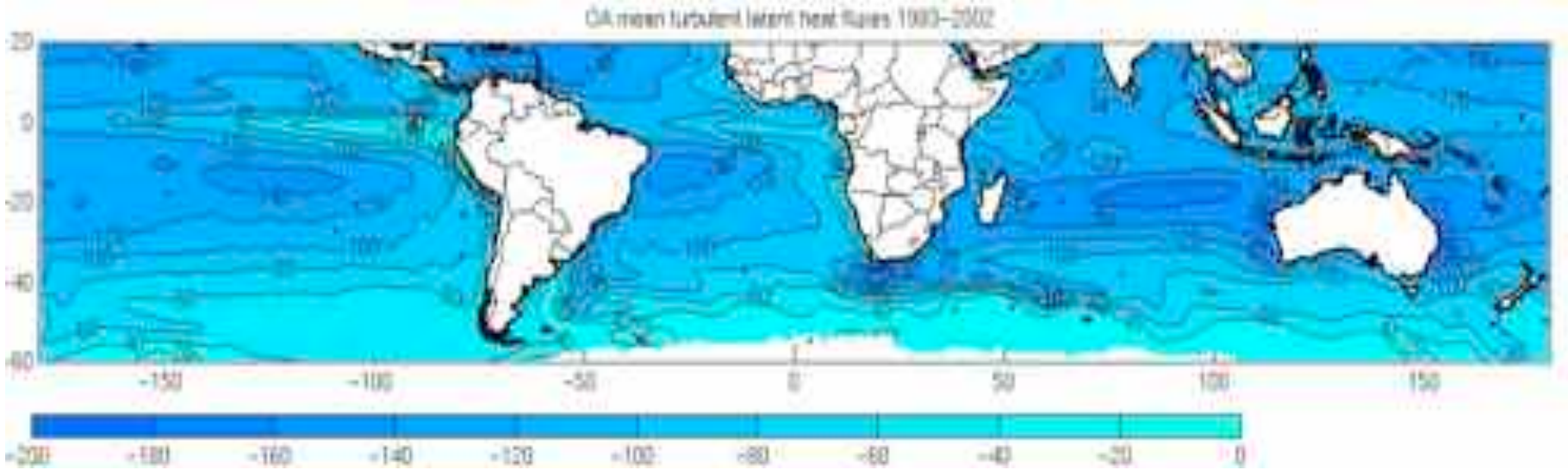
Change in sea surface temperature from 1985 to 2007 in C per 10-year using 4 km resolution AVHRR only. Superimposed is the mean ocean current (yellow to red: warming, green blue: cooling)



Net heat budget at the sea surface = latent heat and sensible (WHOI OA Fluxes) +shortwave and longwave radiative fluxes (ISCCP) from 1983 2002 at 1 deg resolution

Longwave=incoming longwave-outgoing longwave

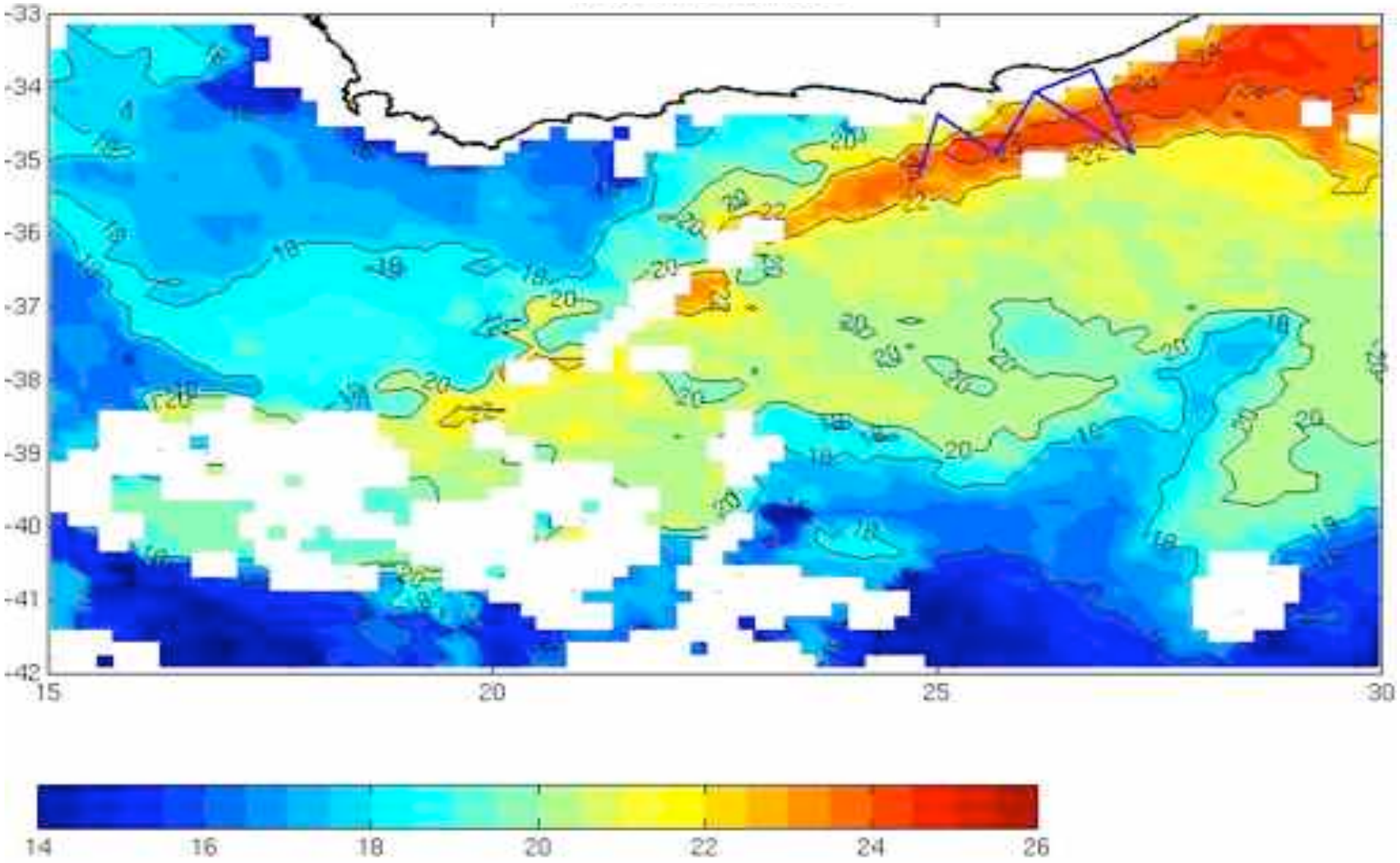
Western boundary current such as Agulhas Current are loosing energy all year long



Mean turbulent latent heat fluxes from 1983 2002

THE AGULHAS CURRENT AIR SEA EXCHANGE EXPERIMENT
Avril Mai 1995

SA ALGOA



18 km resolution AVHRR Pathfinder SST (Reynolds and Smith, 1994) averaged over the period 23-30 April 1995 during which the ACASEX field expedition took place. The ACASEX cruise track is shown in blue. The core of the Agulhas Current has SST > 22 C. White areas over the ocean correspond to those for which there was persistent cloud cover during the cruise

Air sea interaction

$$\tau = \rho_a C_D (U - U_s)^2$$

Wind stress

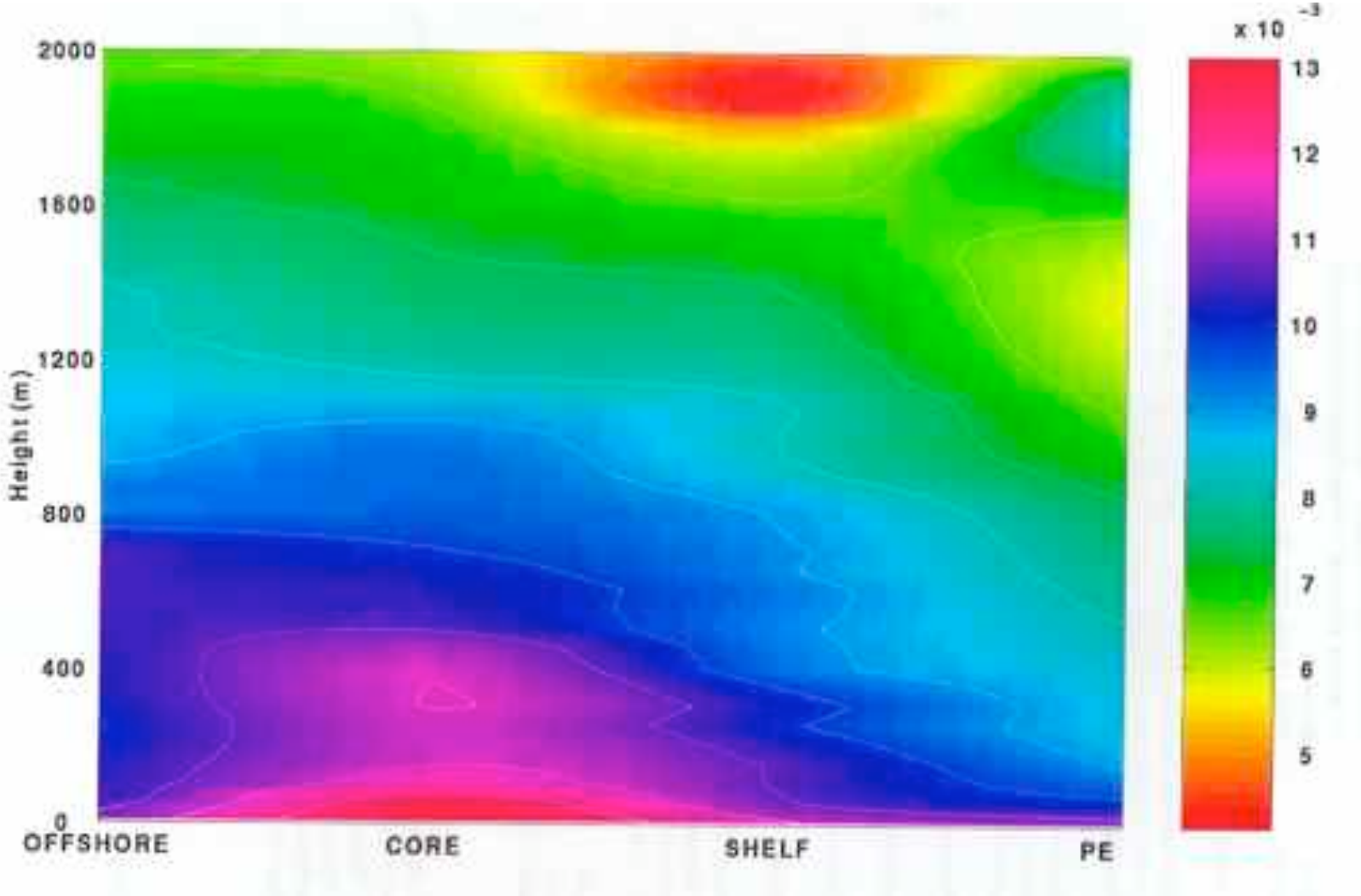
$$H = \rho_a c_p C_H (U - U_s)(T_s - \Theta)$$

Turbulent flux of sensible heat

$$E = \rho_a C_E (U - U_s)(q_s - q)$$

Turbulent flux of humidity aka turbulent latent heat flux

Specific humidity vertical profile derived from a transect of radiosondes.
Wind was alongshore that day



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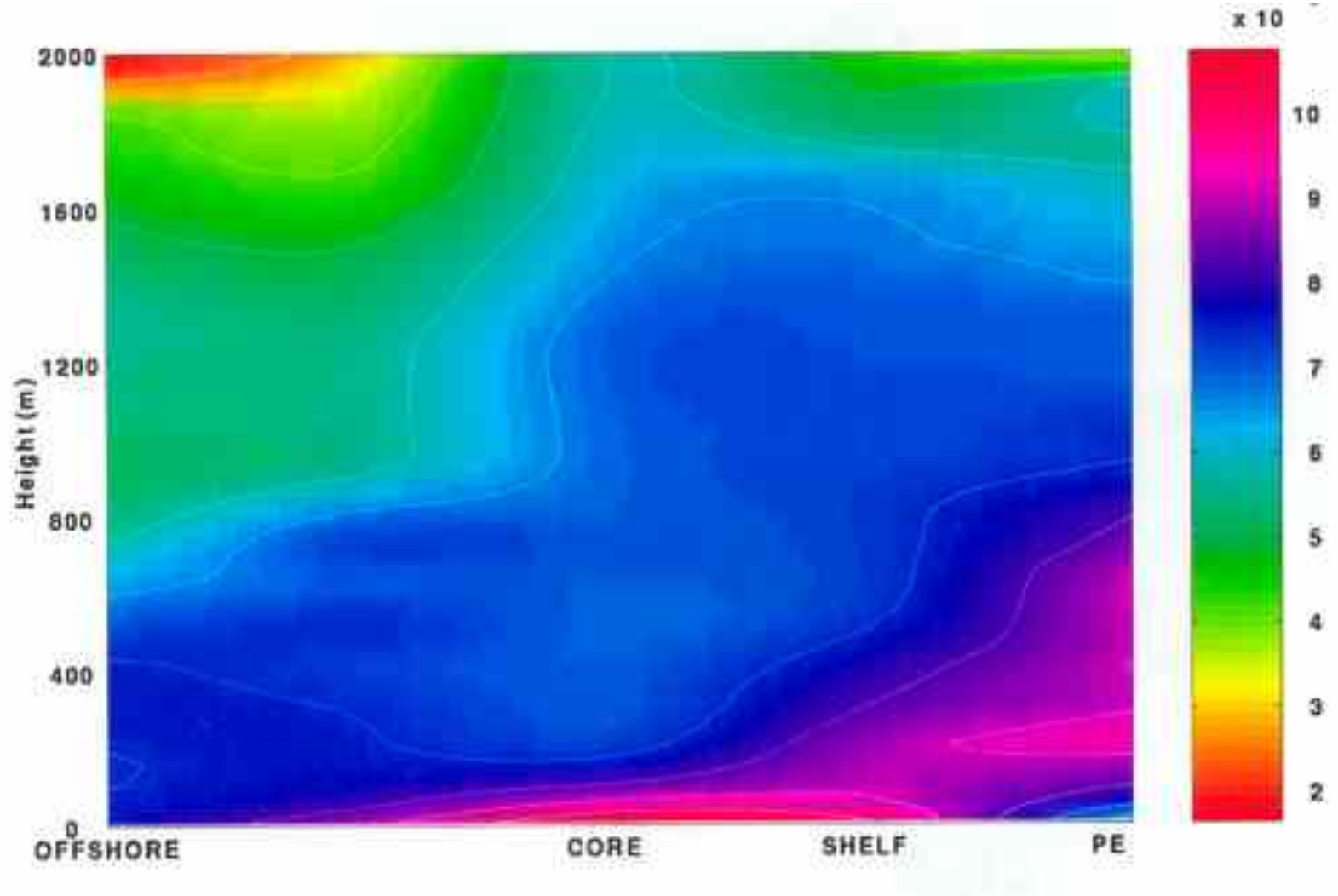


Meteosat visible Image during the cruise

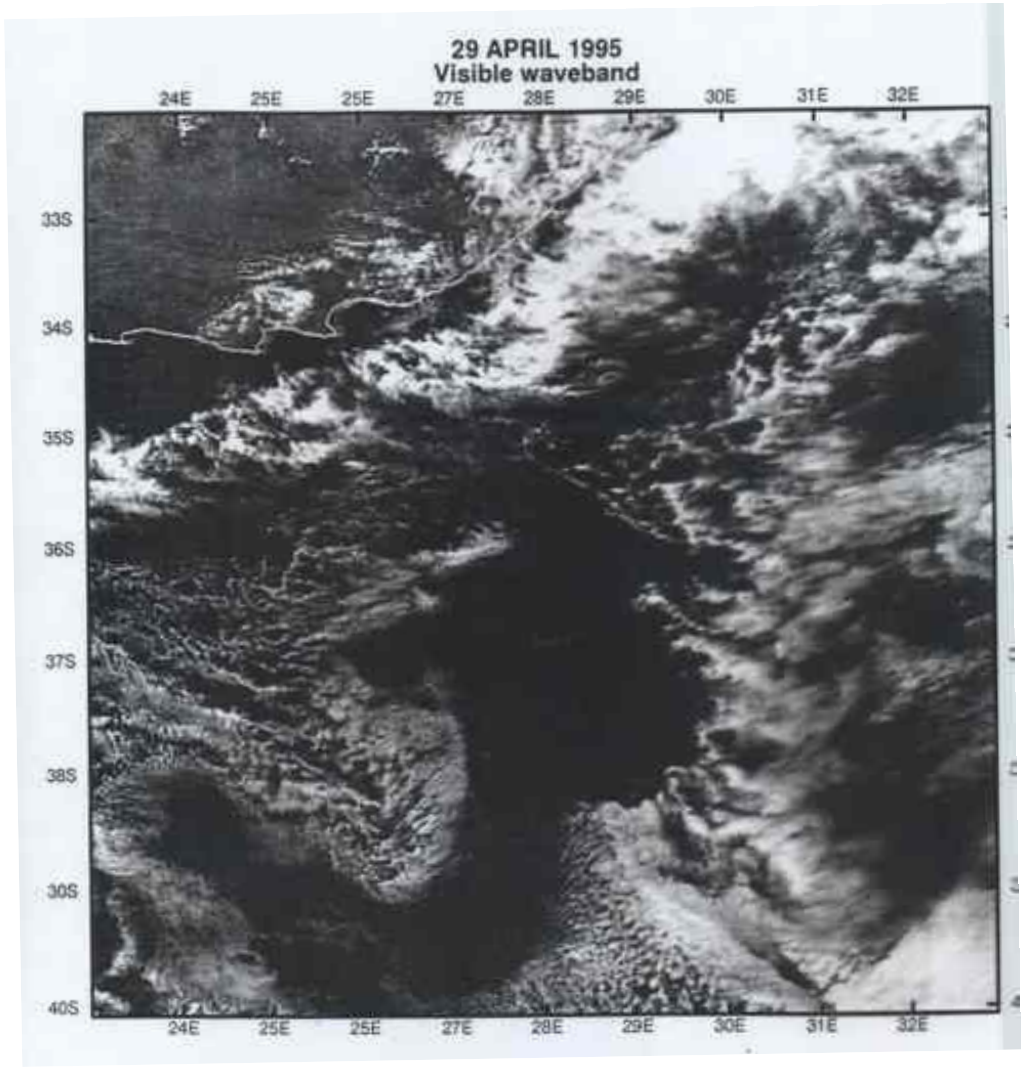
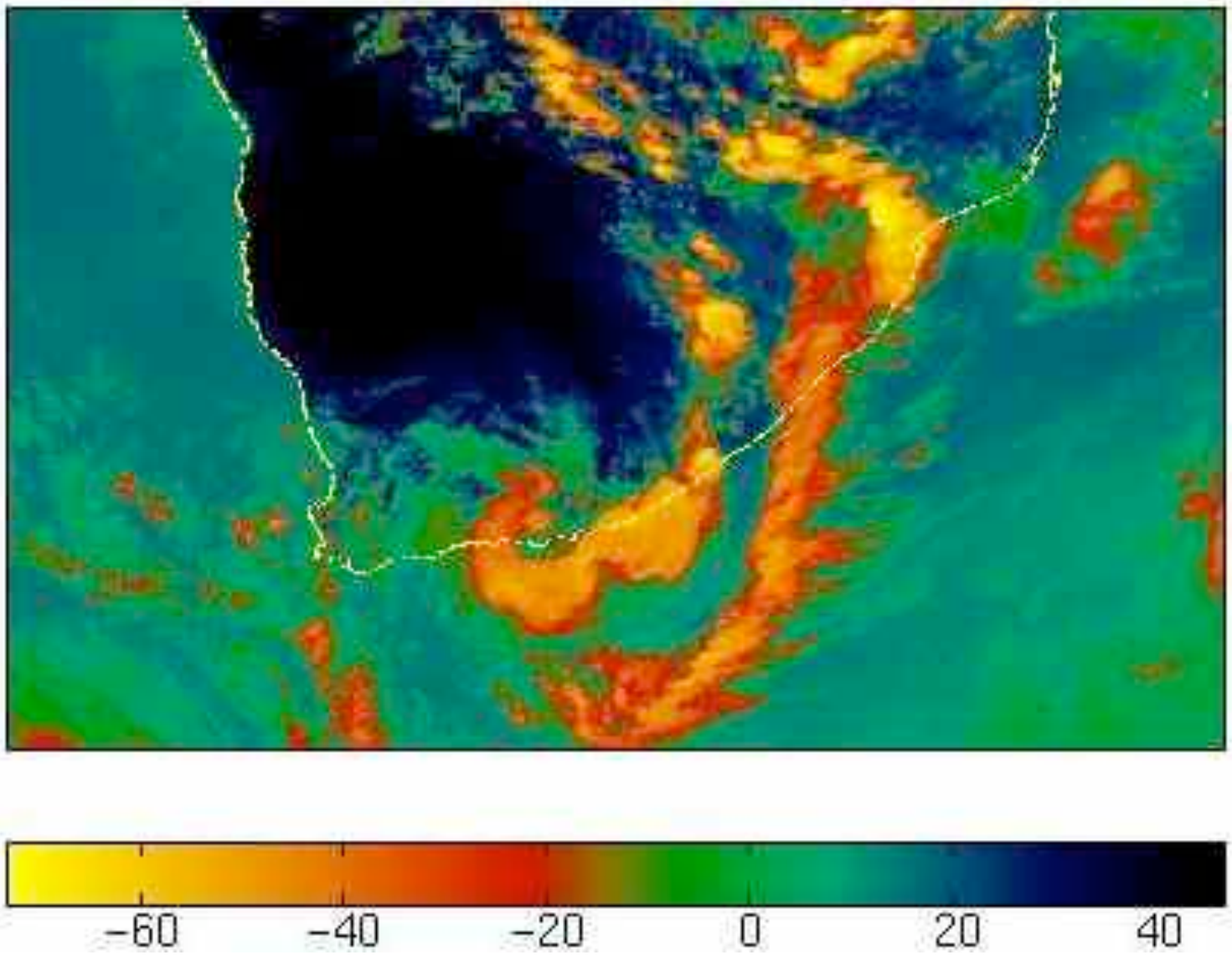


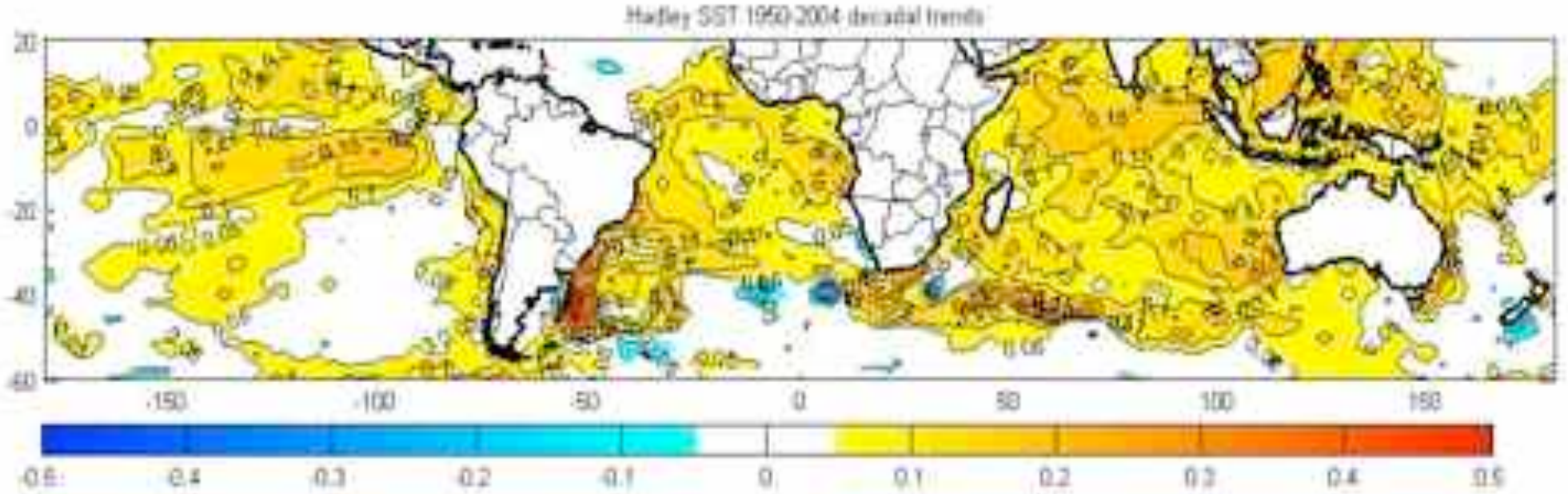
Figure 6.61: Photographs of cumulus formation over the shelf, Agulhas Current and seaward regions. The photographs are from top to bottom, left to right: facing west toward the coast from the shelf (fair-weather conditions); facing east toward the Agulhas Current from the shelf (where the edge of the current is clearly demarcated by cumulus formation); cumulus formation over the Agulhas Current; facing seaward from the current where cumulus becomes more scattered.



Cloud top temperature derived from Meteosat infrared channel is a good proxy for rainfall on 15 December 1998

15 DECEMBER 1998 UMTATA, AFTER THE TORNADO

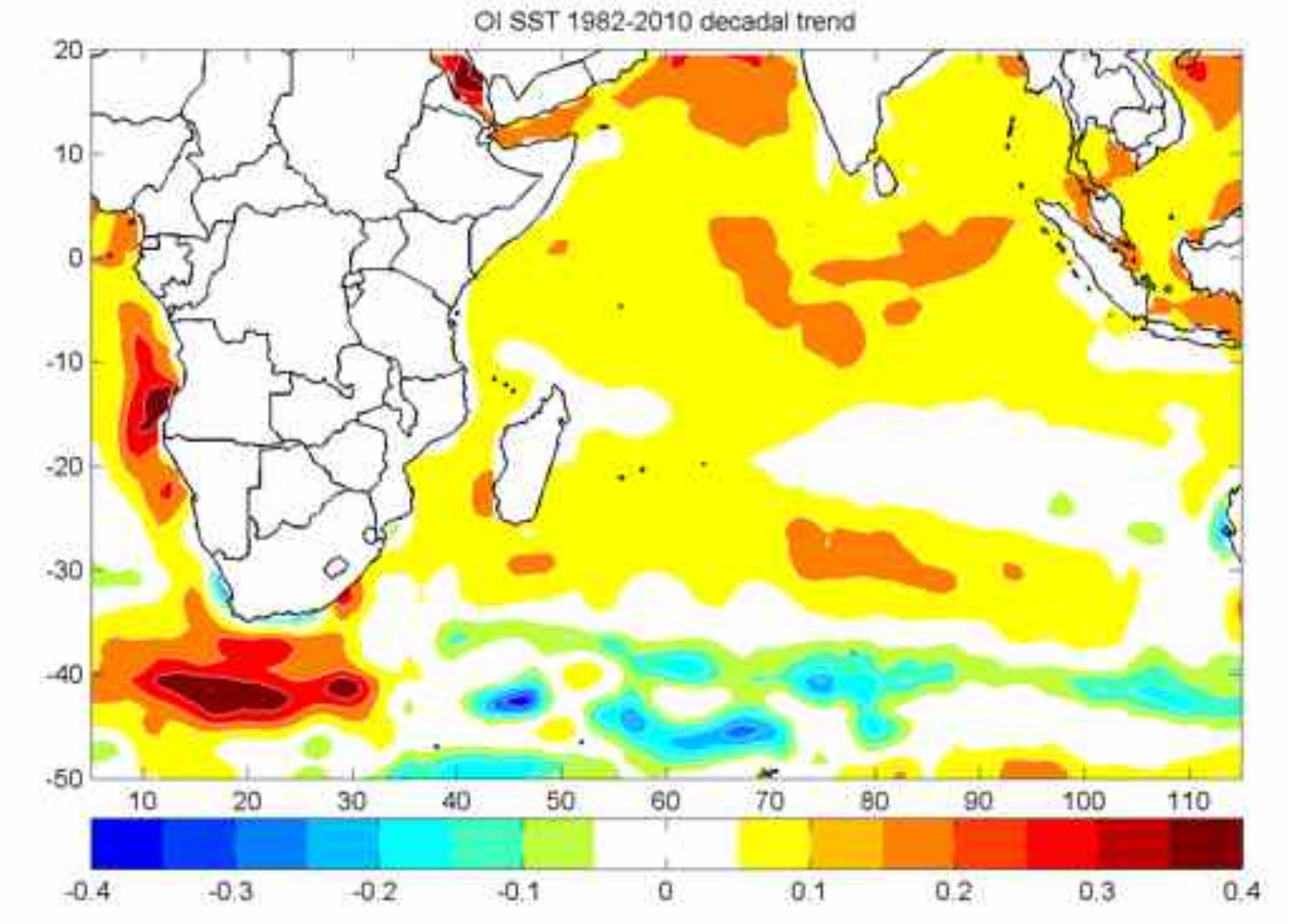
WARMING OF THE OCEAN SINCE 1950



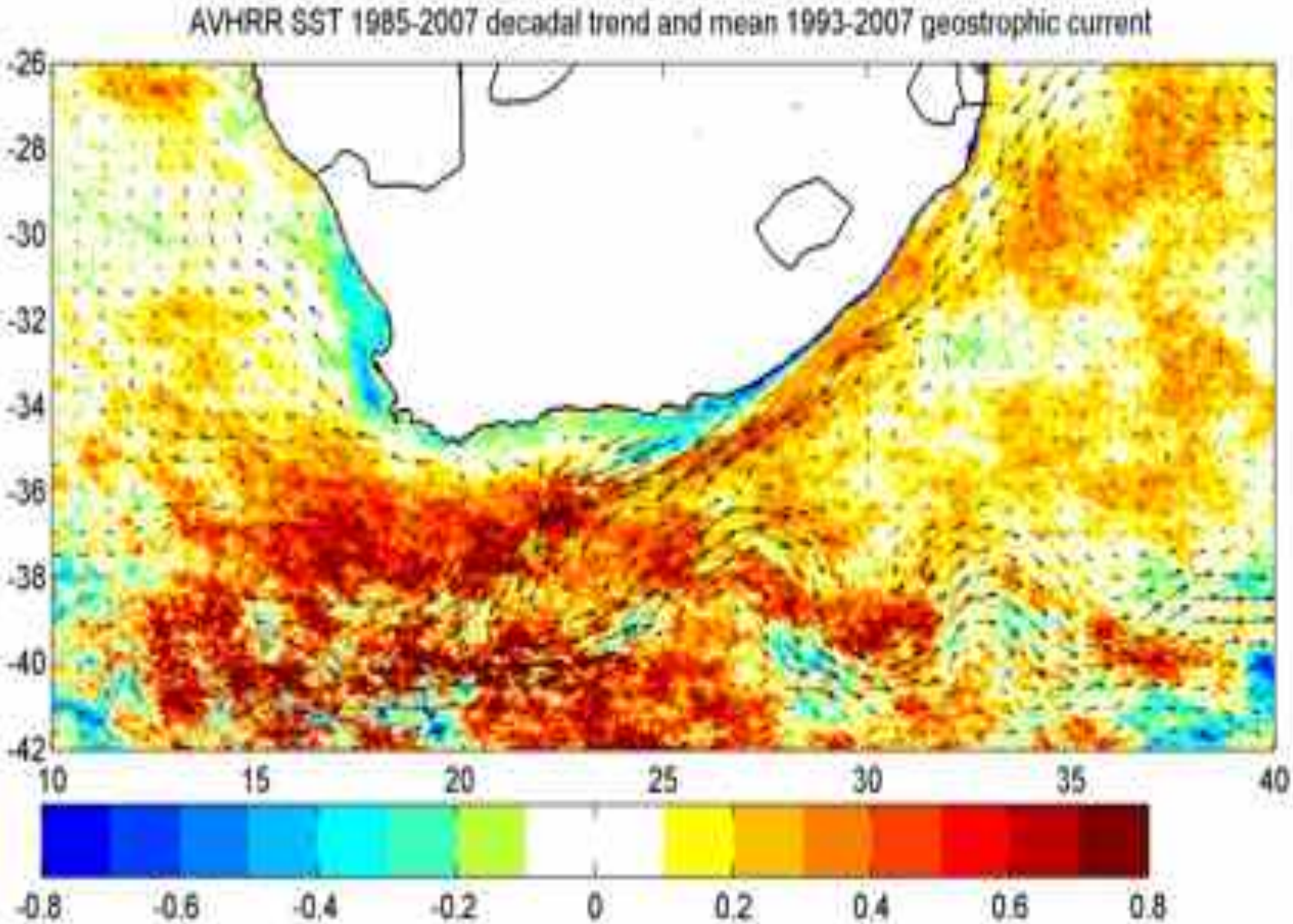
Linear trend in C per 10 year 1950-2004

- Since 1950 sea surface temperature warming using Hadley SST (UKMO, ex GISST, Rayner et al, 2003))
- Caution SST reconstruction along ship track and filling gap with statistics (EOF)
- Not many observations south of 35 S in the South Indian Ocean

Linear trend in SST 1982-2010 in C per decade using 1x1 degree Reynolds SST

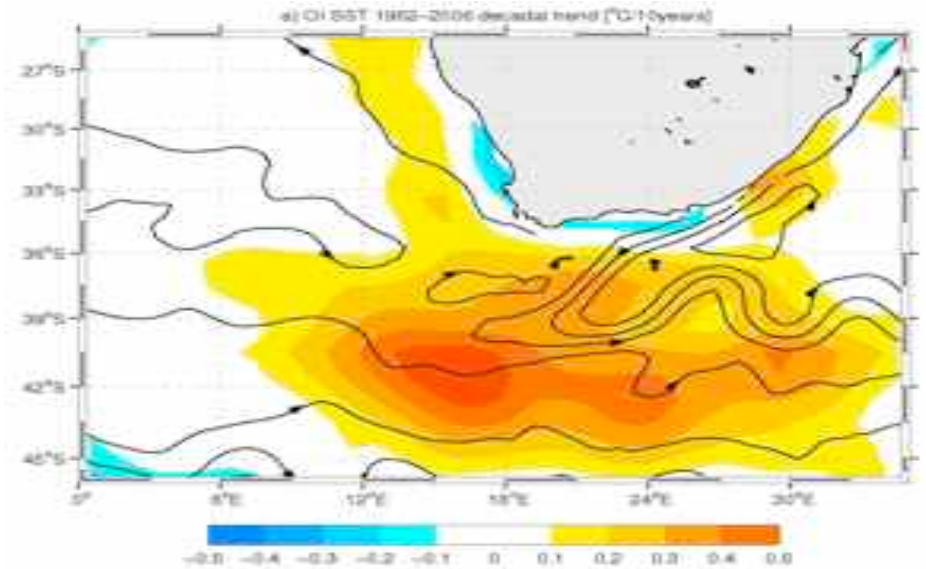


The Agulhas Current system and South Angola have significantly warmed up by up to 1.5 °C since the 1980's.

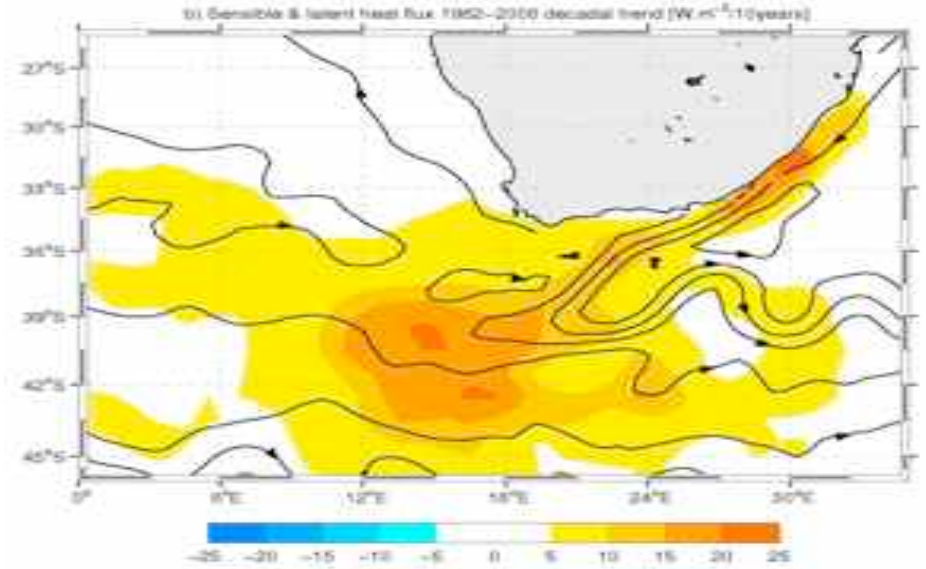


Change in sea surface temperature from 1985 to 2007 in C per 10-year using 4 km resolution AVHRR only. Superimposed is the mean ocean current (yellow to red: warming, green blue: cooling)

linear trend in SST from 1982 to 2006 [C/decade] showing a warming of up to 0.5 C per decade using OI Reynold SST



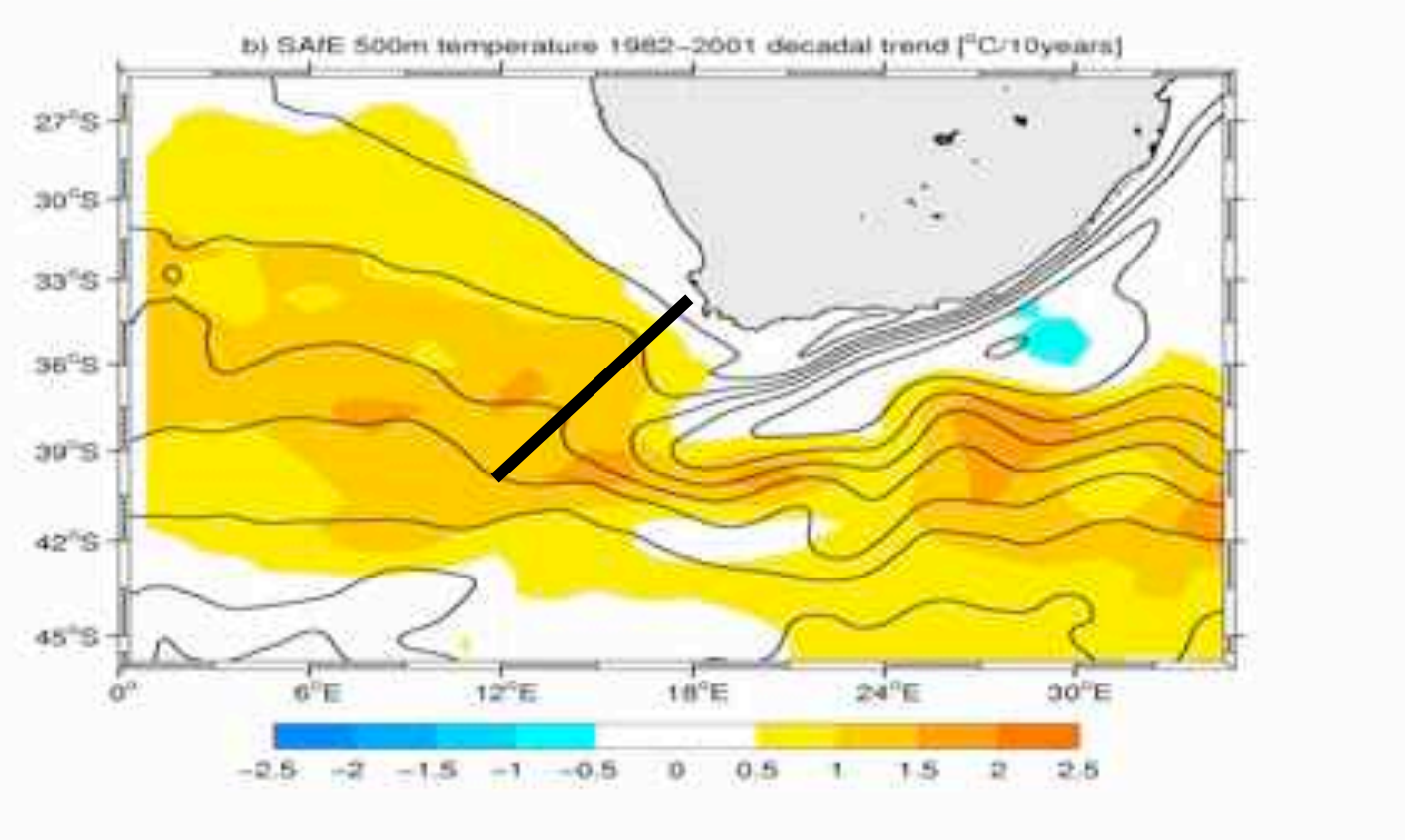
Linear trend in sensible and latent heat flux [W.m-2/decade] for the same period using OA WHOI fluxes (positive values represent a loss of energy for the ocean).



Observations of the recent warming in the Agulhas Current system and related increase in sensible and latent heat fluxes. The black contours represent an observed mean dynamic topography (1 contour per 20 cm) accounting for the mean surface currents. Arrows indicate the direction of the flow.

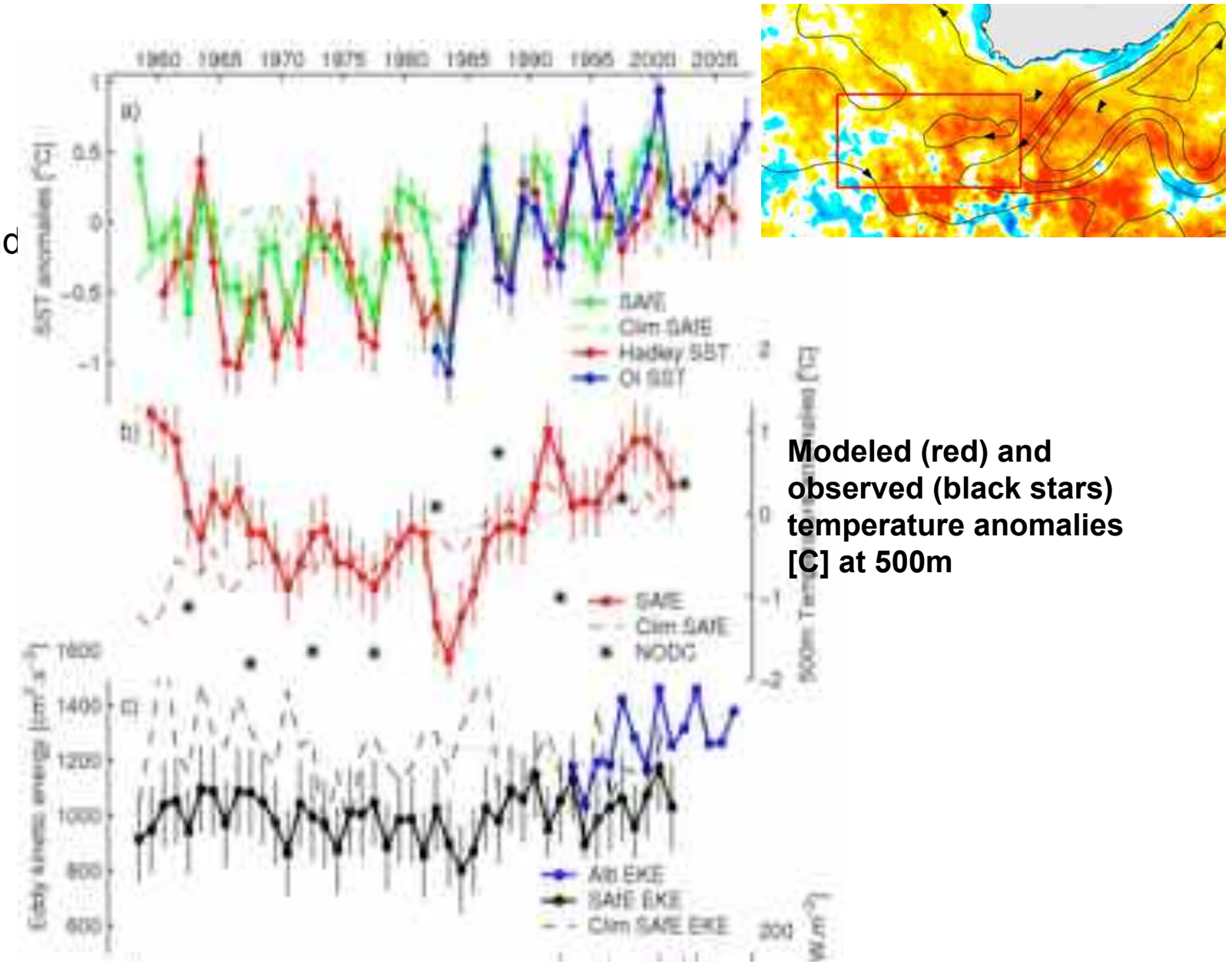
Rouault, Penven, Pohl, GRL, 2009

Linear trend in modelec
temperature at 500 m
from 1982 to 2001



Modeling the warming in the Agulhas Current system. Temperature trend, at 500 m showing a stronger temperature increase. Black line will be used to calculated the leakage of Indian Ocean water to the Atlantic Ocean (Rouault et al, 2009)

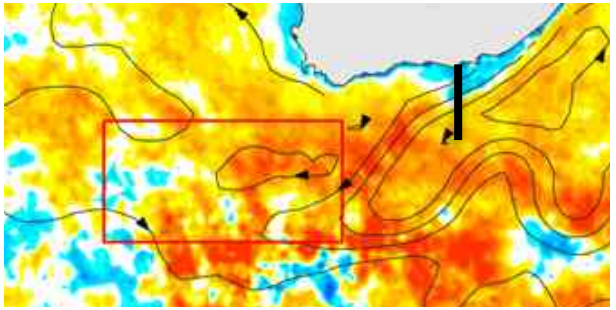
SST anomaly observed (green,and red) and modeled(green) in from 1960 to 2006

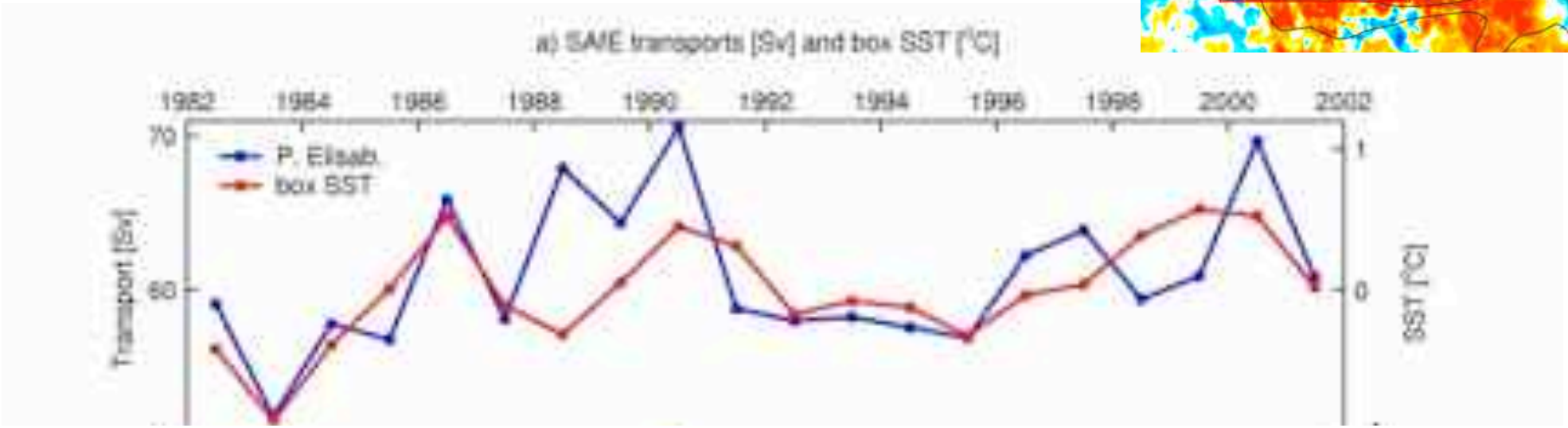


Modeled (red) and observed (black stars) temperature anomalies [C] at 500m

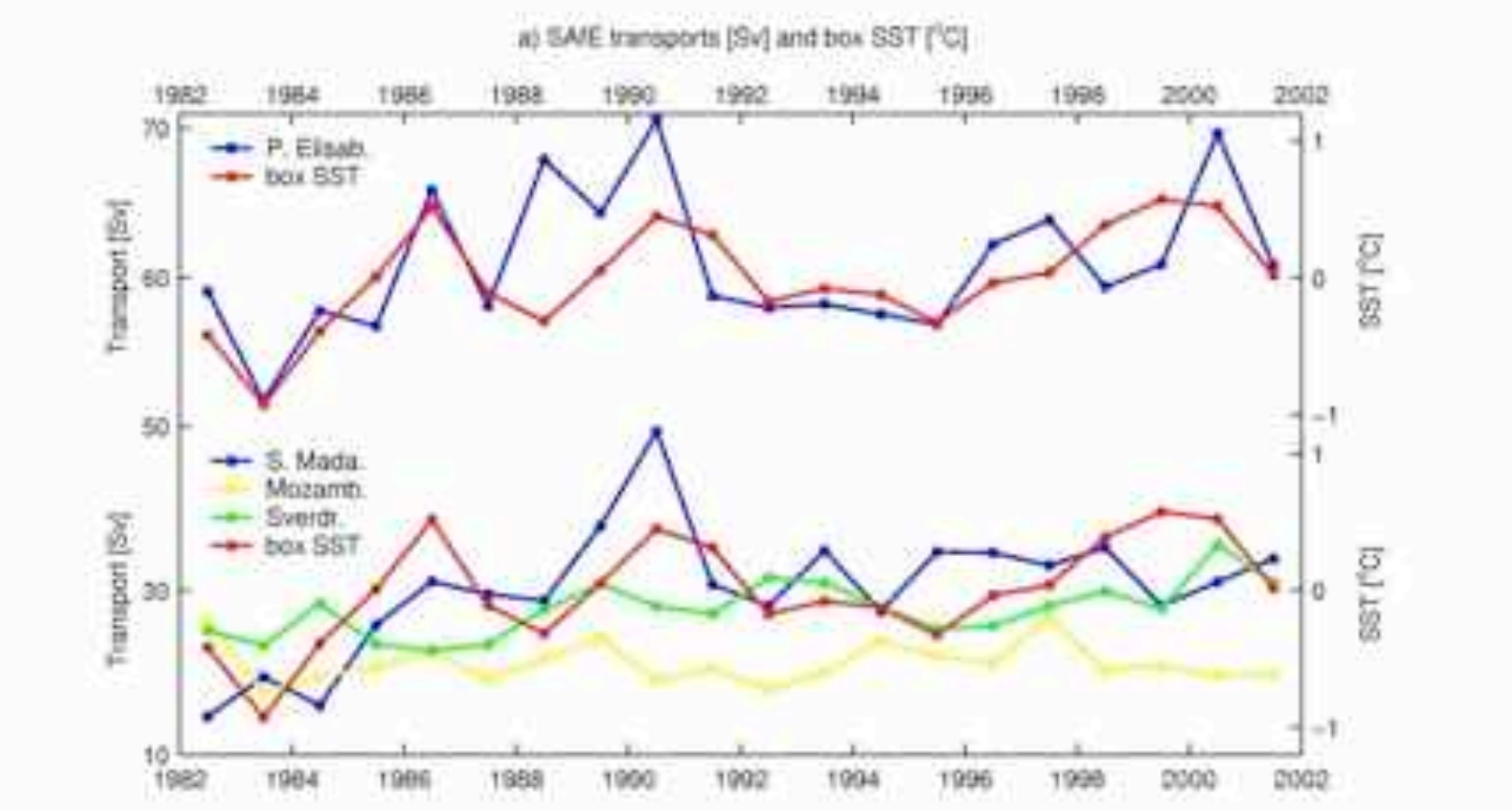
Modeled (black) and observed (blue) geostrophic eddy kinetic energy derived from sea surface height

Changes in the Agulhas Retroflection region (36S to 41S and 10E to 20E) from 1960 to 2006

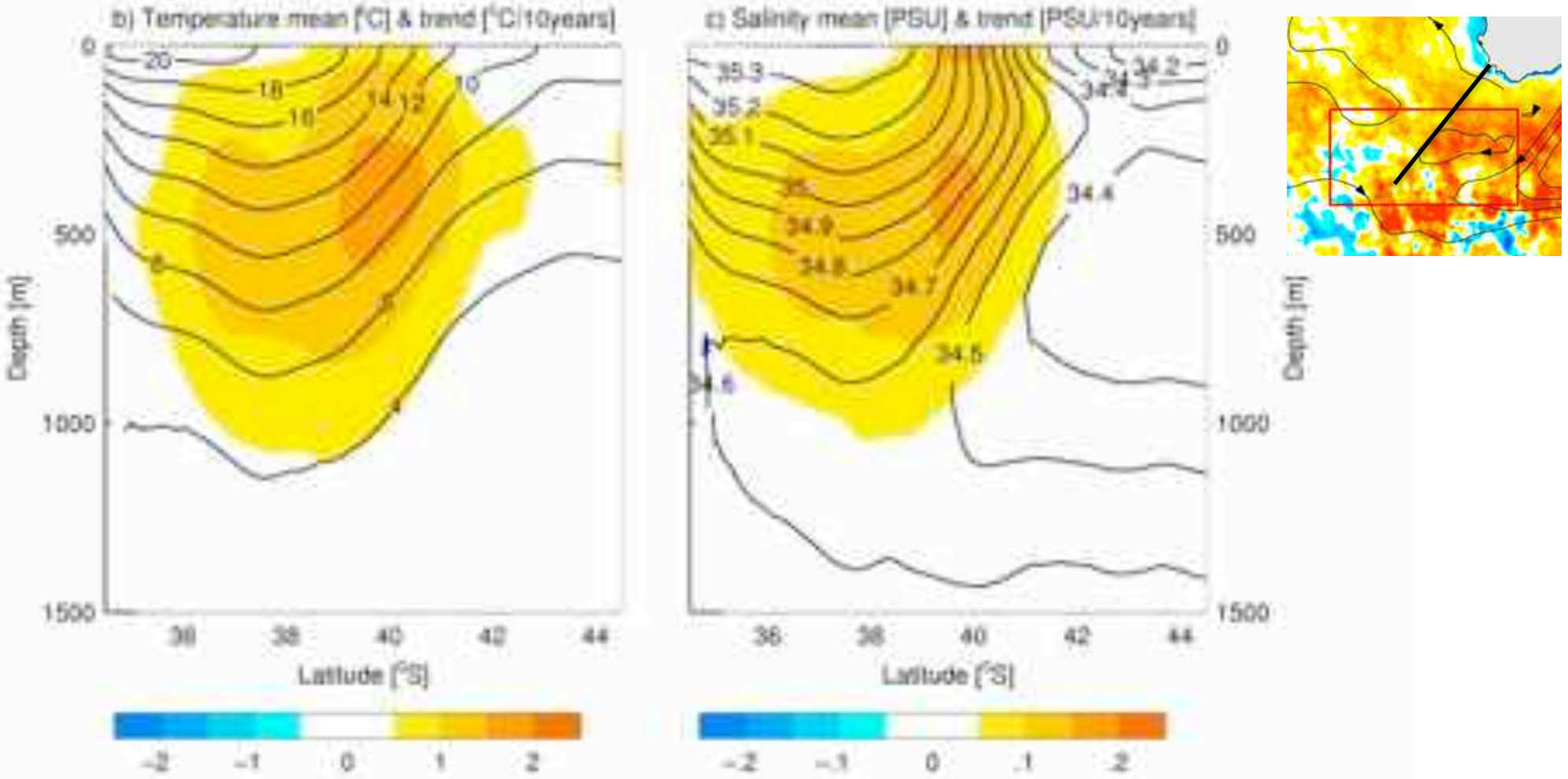




Modeled ocean transport in SV from 1000m to the surface: across a coastal section off South Africa (Port Elizabeth) (blue). The red line represents the modeled SST over the Retroflection



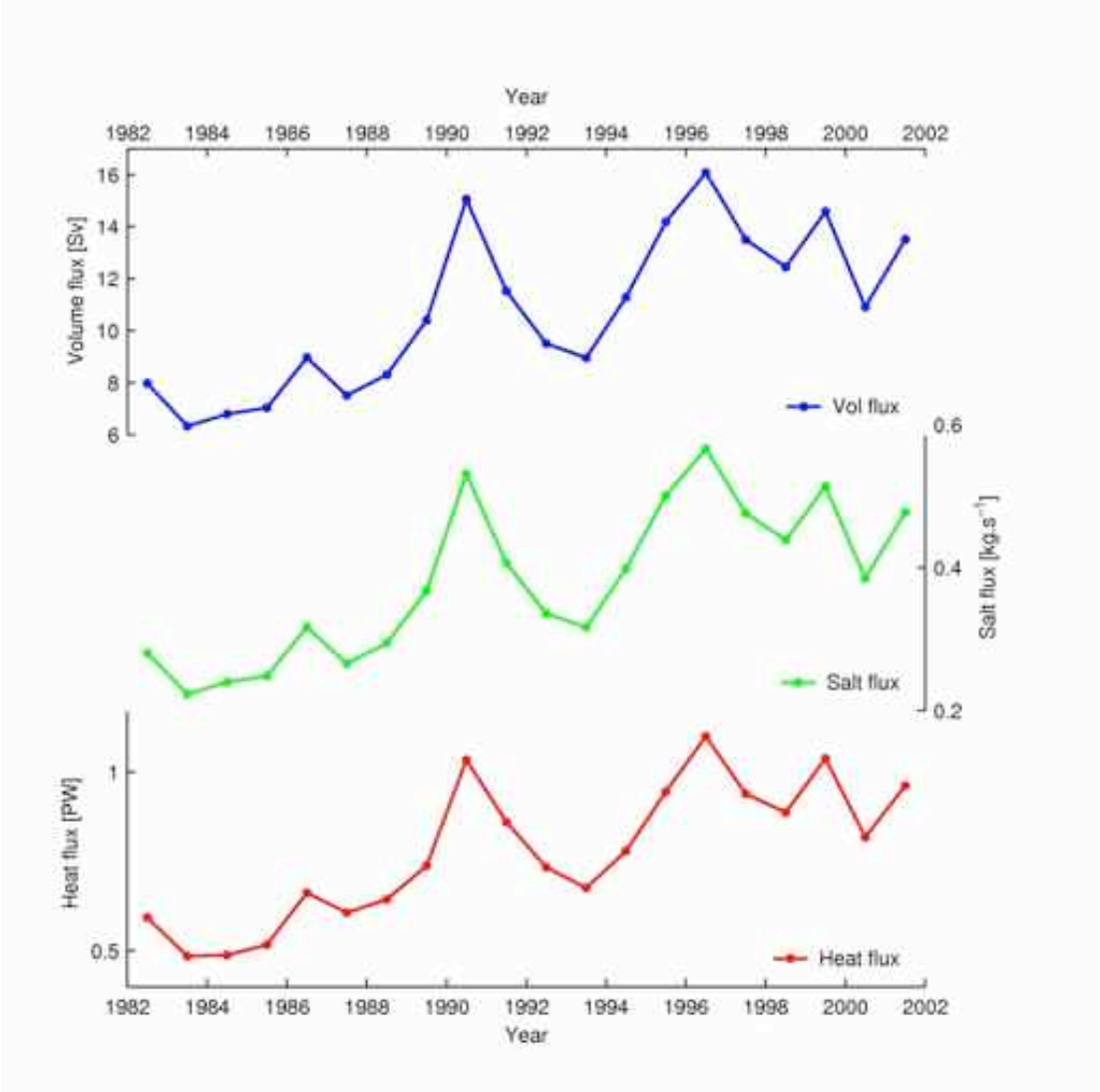
Modeled ocean transport in SV from 1000m to the surface: across a coastal section off South Africa (Port Elizabeth) (blue), South of Madagascar (black) and across a zonal section in the Mozambique Channel at 20 S (yellow). The red line represents the modeled SST over the Retroflection in domain used in Figure 2



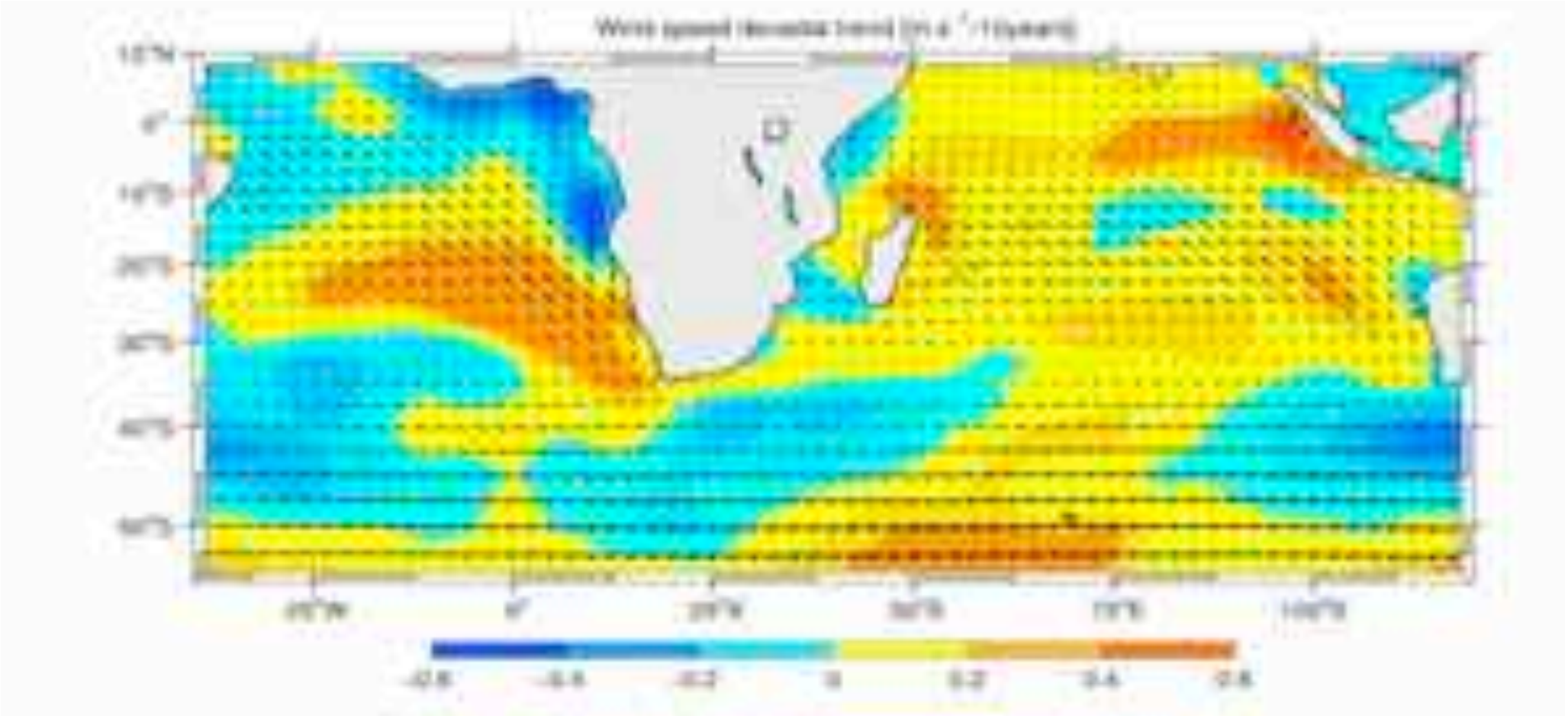
Left: linear trend in modeled temperature from 1982 to 2001 in C/decade along a vertical section going from the Cape of Good Hope to 10 E 42 S.

Right: linear trend in modeled salinity from 1982-2001 in PSU/decade along the same vertical section.

Mean condition superimposed in black

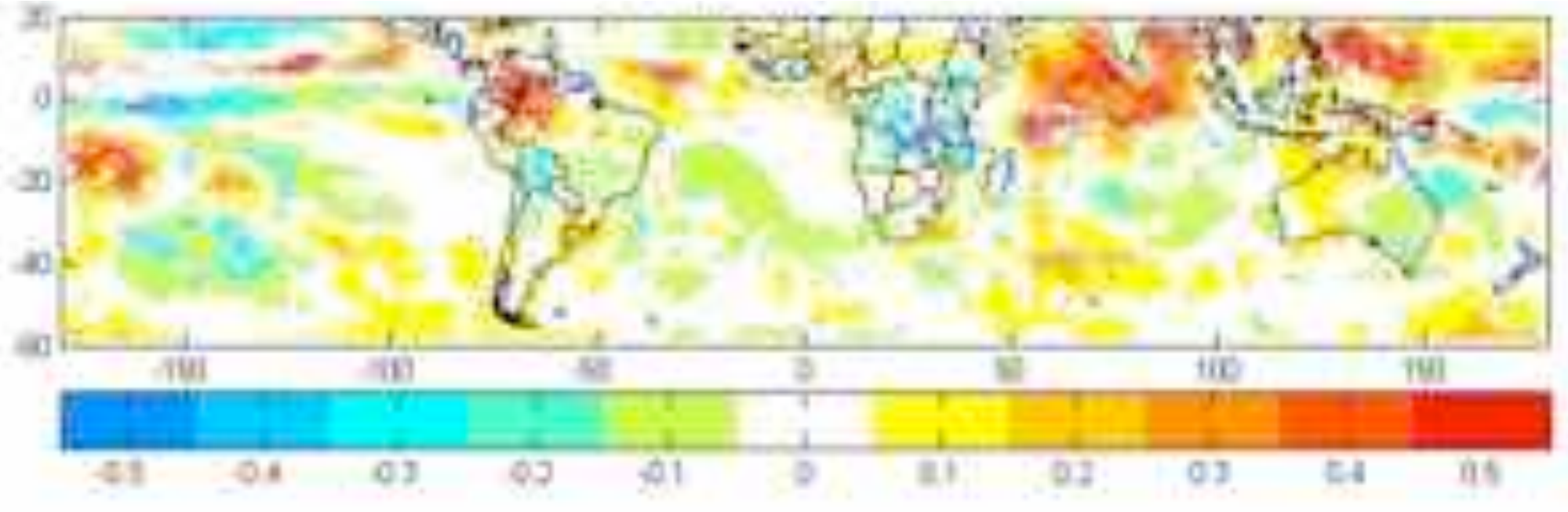


Consequences of an increase of the Agulhas current. Net westward transport for water with temperature above 5 C and salinity above 34.8 PSU across a meridional section at 18 E (blue), net salt flux in kg.s-1 (green) and net heat flux in PW for the same water across the same section (red).



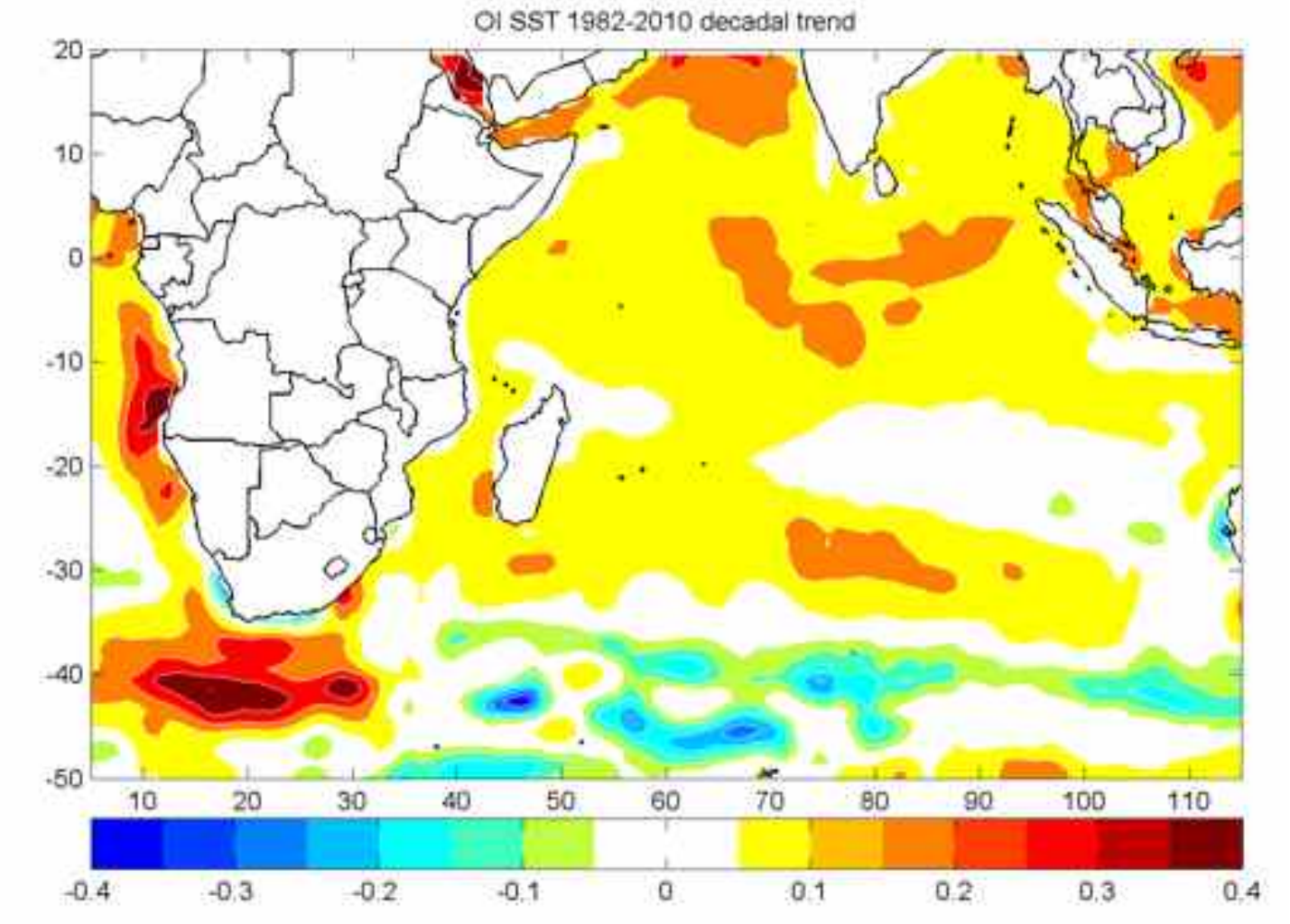
Linear trend in surface wind speed from 1979 to 2001 in m.s-1/decade using ERA 40. Climatological wind direction is represented with black arrows. (Rouault, Penven, Pohl, 2009, supplementary material)

1979-2009 linear trend (mm/day per decade) in rain rate using 2.5x 2.5 degree resolution GPCPV2.1 rainfall data estimated from satellite remote sensing



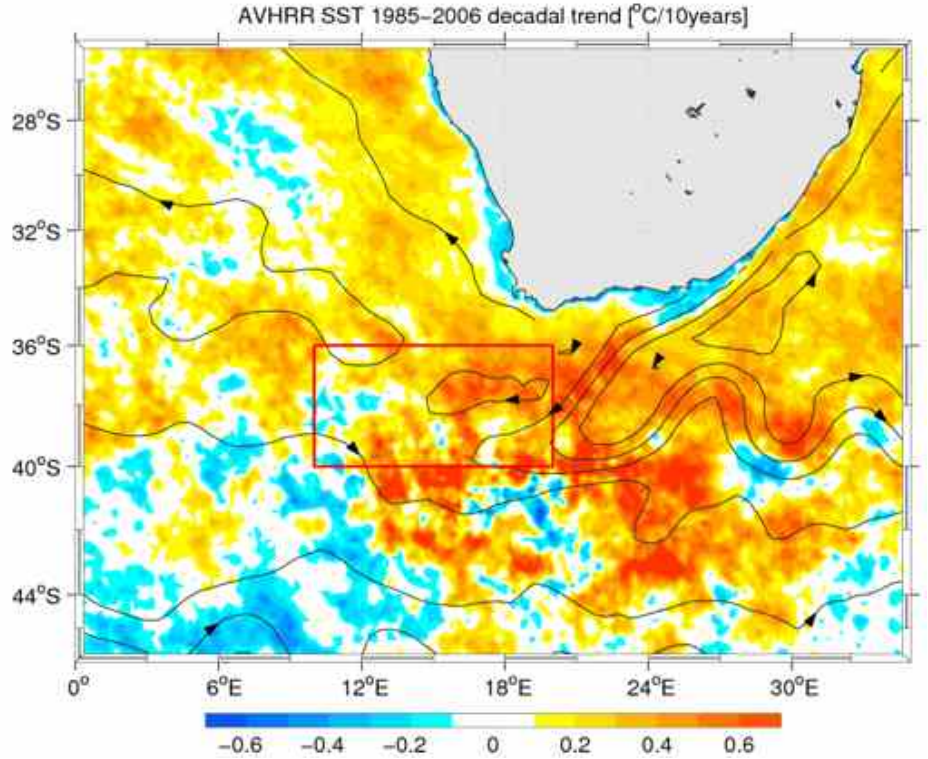
A substantial increase in rainfall has occurred above the Indian Ocean between 15 N and 15 S concomitant with the increase in sea surface temperature previously described. According to William and Funk, 2010 this is the cause of the observed decrease in rainfall over East Africa via modification of the Walker circulation. This also could be the caused of a intensification of the Hadley circulation in the Indian Ocean.

Linear trend in SST 1982-2010 in C per decade using 1x1 degree Reynolds SST

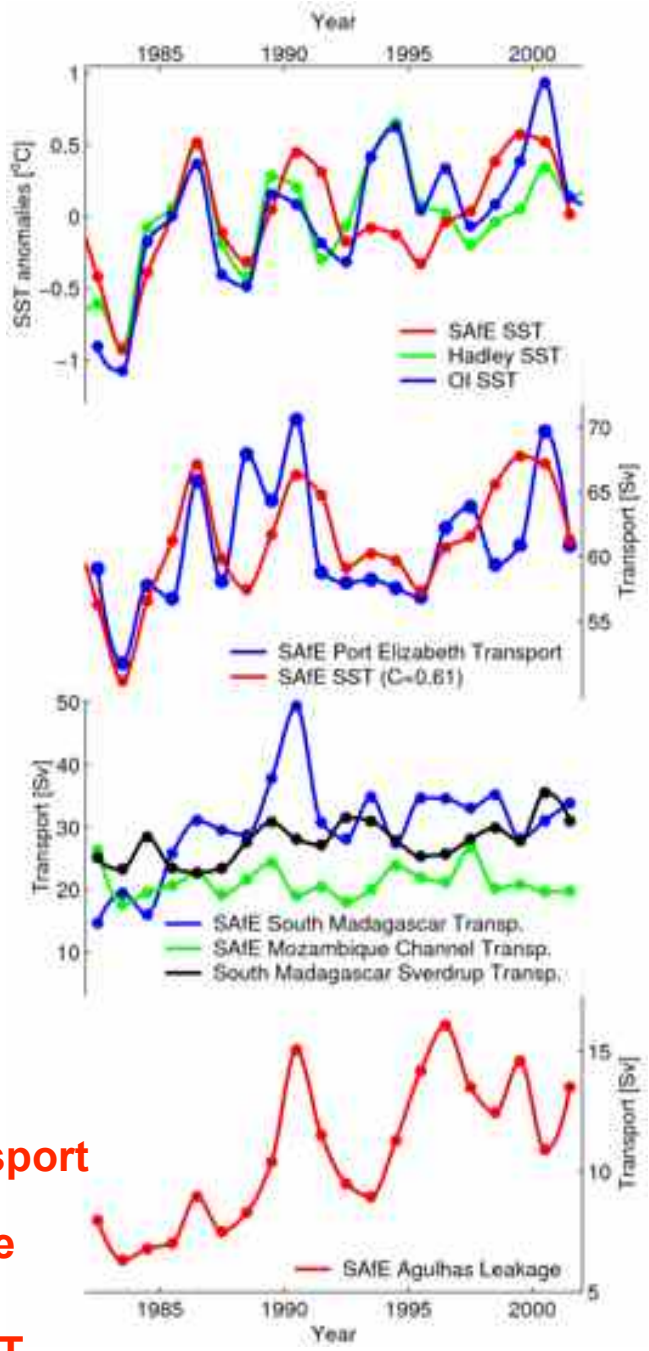


The Agulhas Current system and South Angola have significantly warmed up by up to 1.5 °C since the 1980's.

Observation: recent warming in the Agulhas Retroflection region.



- Signal in a regional ocean model (SAfE): possibility for diagnostics.



Increased wind stress curl → **Increased Agulhas Current transport**

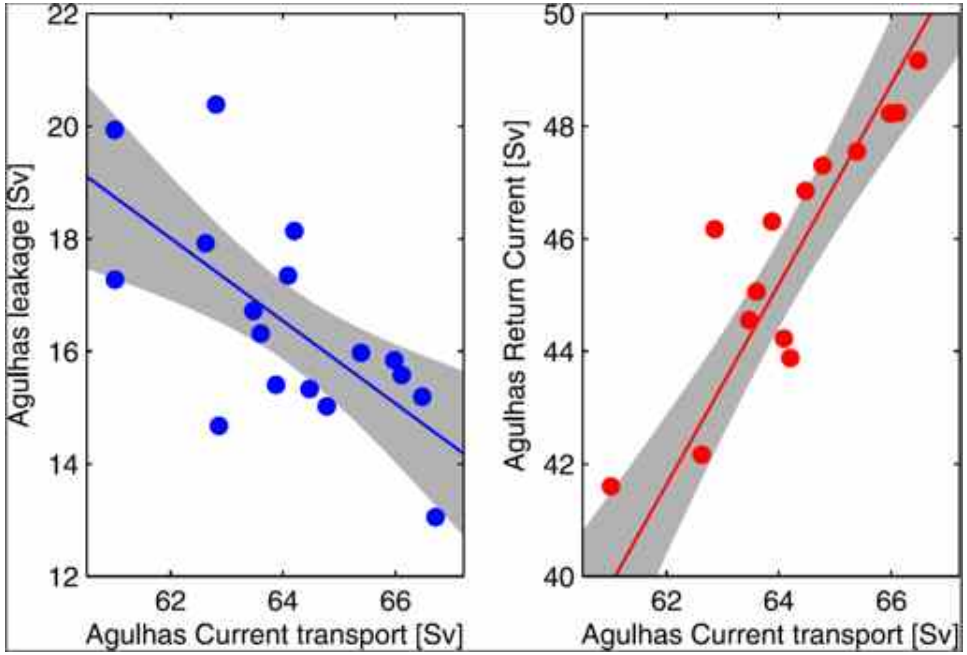
Increased Agulhas Current → **Increased Agulhas Leakage**

Increased Agulhas Current → **Increased Retroflection SST**

Rouault, M., P. Penven and B. Pohl, Warming in the Agulhas Current system since the 1980's, 2009, *Geophys. Res. Lett.*, **36**, L12602.

BUT... **A weaker Agulhas Current leads to more Agulhas leakage**
van Sebille et al. (2009).

Virtual Lagrangian floats in a nested ocean model.



"smaller (larger) Agulhas Current transport leads to larger (smaller) Indian-Atlantic inter-ocean exchange"

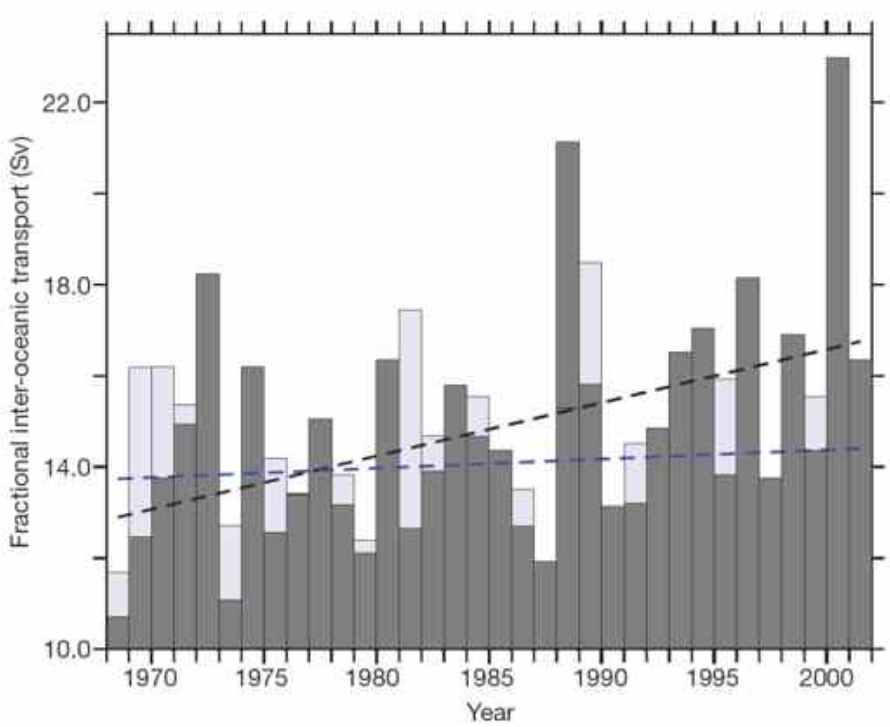
Increased Agulhas Current → **Earlier Retroflection (Ou and de Ruijter, 1986)** → **Reduced Agulhas Leakage**

van Sebille, E., A. Biastoch, P. J. van Leeuwen, and W. P. M. de Ruijter (2009), A weaker Agulhas Current leads to more Agulhas leakage, *Geophys. Res. Lett.*, **36**, L03601.

Ou H.W. and W.P.M. de Ruijter (1986), Separation of an Inertial Boundary Current from a Curved Coastline, *J. Phys. Oceanogr.*, **16**, 280-289.

AND...

Increase in Agulhas leakage due to poleward shift of Southern Hemisphere westerlies Biastoch et al. (2009), Beal et al (2011).



Poleward shift of 0 wind stress curl

Increased Agulhas Leakage

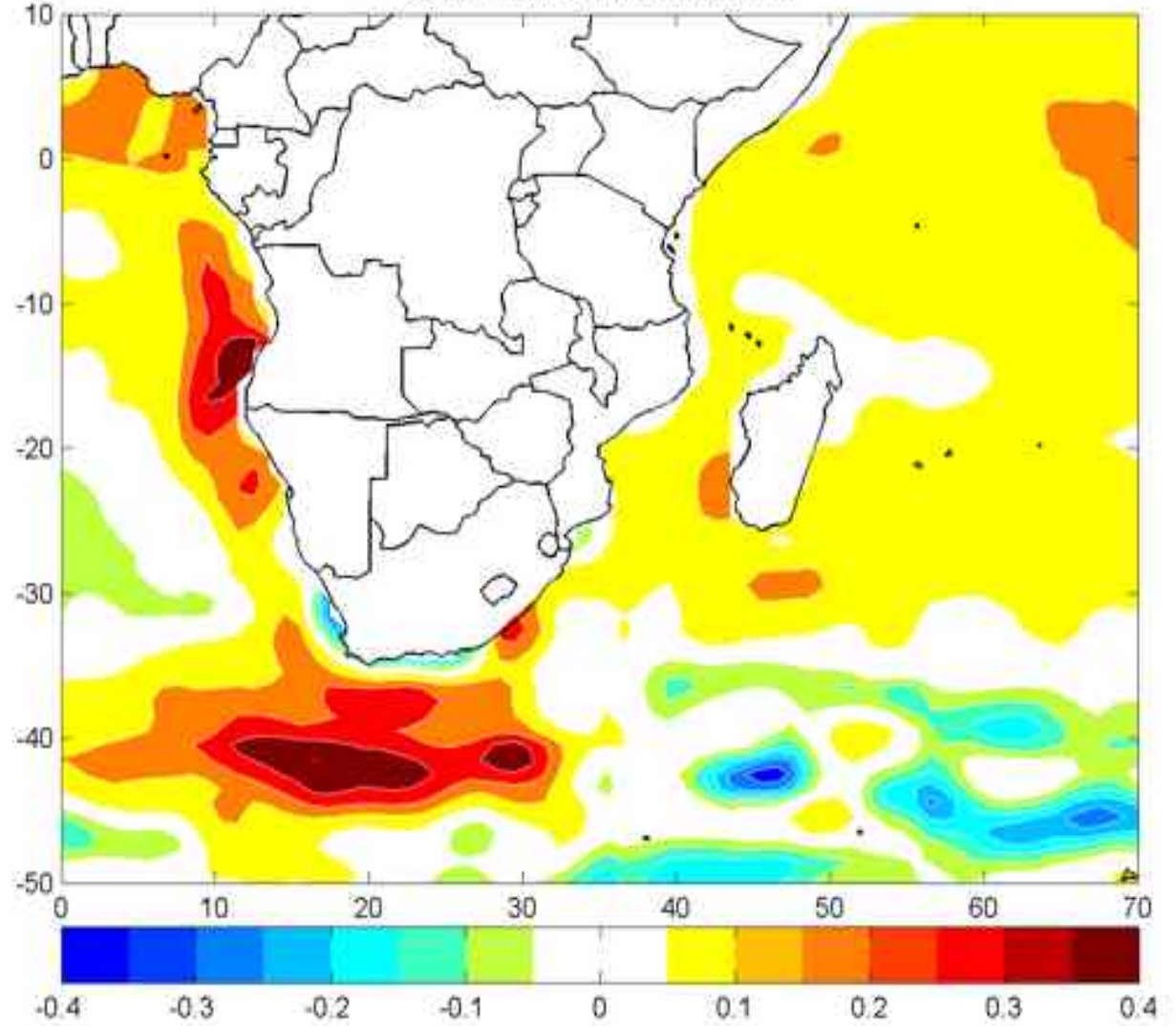
Reduced Agulhas Current

Decreased transport in the Mozambique Channel + Reduced South west Indian Subgyre

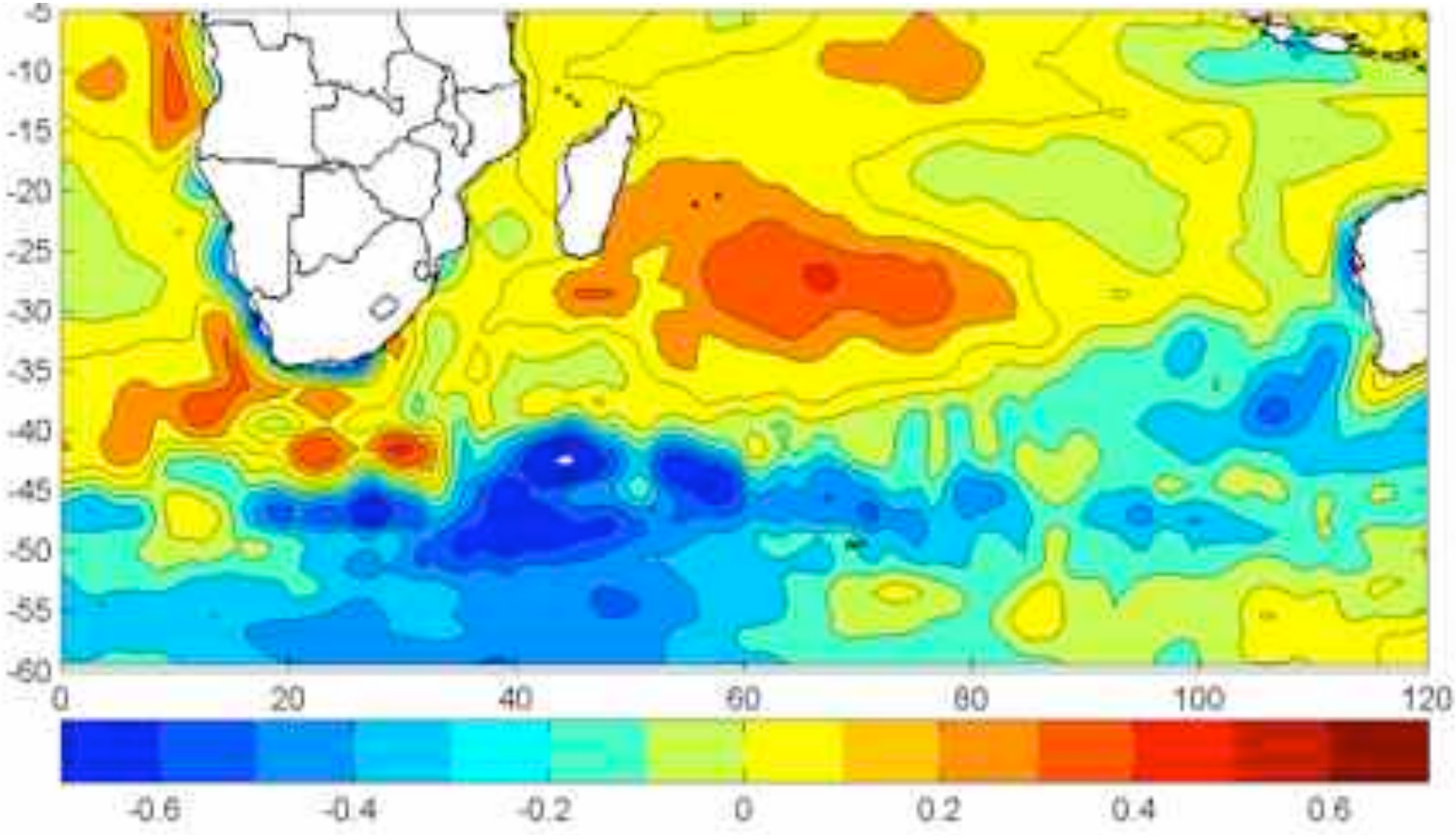
Agulhas Current do not follow sverdrup transport relationship

A. Biastoch, C. W. Boning, F. U. Schwarzkopf and J.R.E. Lutjeharms, Increase in Agulhas leakage due to poleward shift of Southern Hemisphere westerlies, *Nature*, **462**, 495-499.

Linear trend in SST since 1982 in C per decade using 1x1 degree Reynolds SST



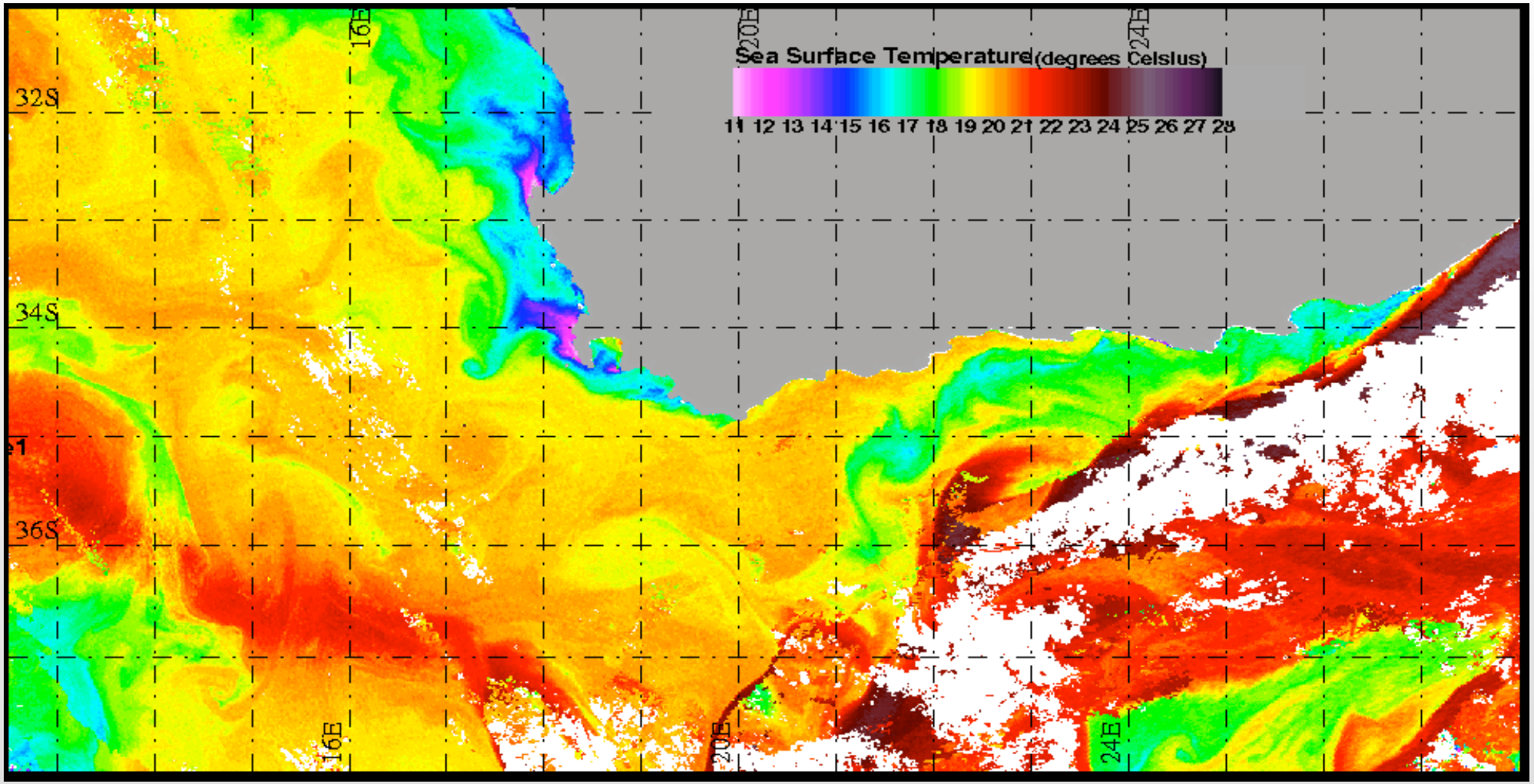
A zoom of the former graph shows that closer to Africa the Agulhas Current system has significantly warmed up by up to 1.5 °C since the 1980's.



Sea surface temperature (SST) trends in ºC / 10 years from OI SST from 1992 to 2010

Thanks, please visit us in Cape Town

Contributions from Pierrick Penven(IRD), Benjamin Pohl(CRC Dijon), Bjorn Backeberg



Sea surface temperature estimated by AVHRR aboard NOAA (1x1 km resolution)

Funding from WRC, ACCESS, Nansen-Tutu Center