Trends in the Indian Ocean Climatology due to anthropogenic induced global warming.

Prepared by

Alan Aldrin Meyer and Steven Weerts

Coastal Systems Research Group, CSIR, Stellenbosch, South Africa.

e-mail:ameyer@csir.co.za

The global ocean's heat content has increased by 14.5 x 10^{22} J from 1955 to 1998 corresponding to a mean temperature increase of 0.037°C (fig. 1). A trend that will continue into the 21^{st} century.

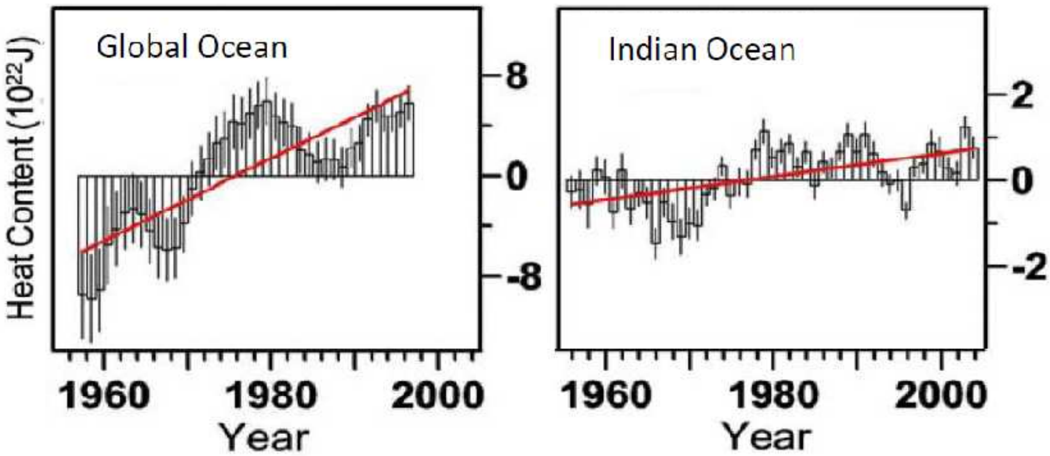

Fig. 1. Time series of 5 year running composites for 1955 to 1998 ocean heat content for the upper 3000 m for the global and Indian Ocean. The linear trend is plotted as a red line.

The Indian Ocean shows the same warming trend (fig. 1). The warming trend for the Indian Ocean is positive south and along 40°S and along 20°S (fig. 2). In contrast, a large negative trend is centred between 5 to 10°S (figs. 2 and 5).

The scientific understanding of these warming and cooling trends in the Indian Ocean is still developing, but observational data and numerical modelling results have allowed for important insights as to the dynamics behind the changing climatology. This changing climatology can only be describe in the context of the anthropogenic induced alterations to the atmosphere of the Southern Hemisphere and its impact on the ocean circulation of the Southern Ocean.

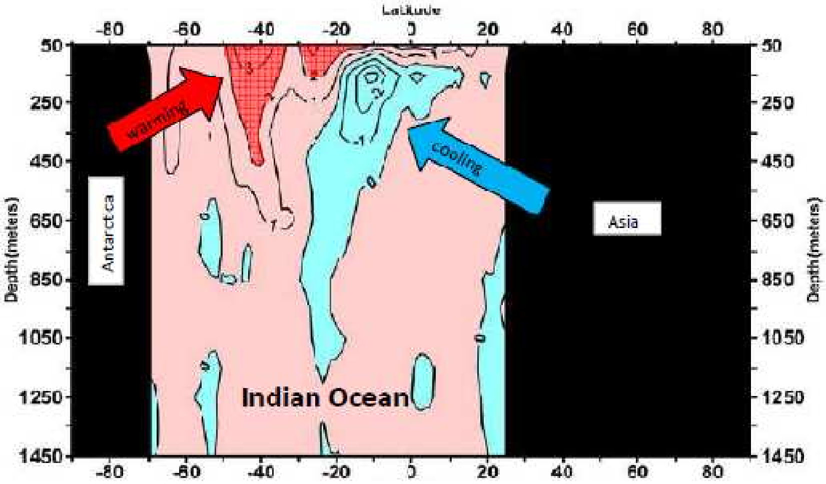

Fig. 2. Linear trend of the zonally integrated heat content of the Indian Ocean for 100 m thick layers. Trend values are plotted at the midpoint of each 100 m layer. Contour intervals is 1 x 10^{18} J/year. (after Levitus et al., 2005).

The main climate mode of the Southern Hemisphere is known as the Southern Annular Mode (SAM) an index of the pressure gradient measured between 40^{o}S and 56^{o}S. A high (positive) SAM index indicates an intensification of the mid-latitude westerlies and a lower (negative) SAM to a relaxation of the westerlies. SAM has been steadily increasing over the last 40 years due to anthropogenic induced global warming and ozone hole depletion over Antarctica. Observational data and contemporary climate models show that the positive trend in SAM has lead to an intensification and southwards shift of the SH westerlies, with a consequential acceleration of the planet's largest ocean current, the Antarctic Circumpolar Current (ACC) (Fig. 3).

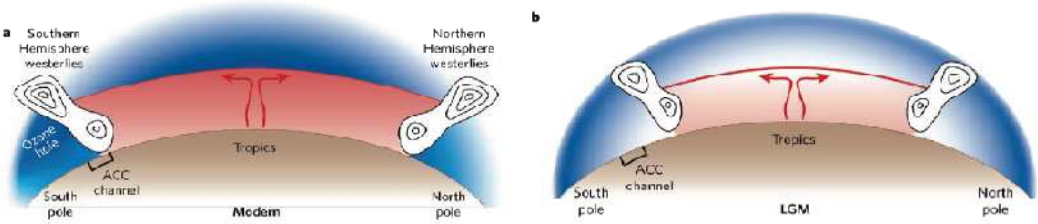

Fig. 3. Changes in the westerlies and atmospheric structure in response to different CO2 concentrations. Bands of westerly winds in the Northern Hemisphere (NH) and Southern Hemisphere (SH) separate the warm air (red shades) in the tropics from the cold air (blue shades) over the poles. a) Atmospheric structure today. Over recent decades, higher CO2 concentrations have made the warm air warmer and the surrounding envelope of cold air cooler, especially near the top of the troposphere. The thermal contrast across the zones of strong westerlies in the NH and SH is therefore greater, and the westerlies have become stronger and have shifted polewards in response. b) Proposed atmospheric structure at the last glacial minimum (LGM). With less CO2 in the atmosphere, the thermal contrast in the middle of the atmosphere was decreased, and the westerlies aloft therefore relatively weak. The strongest westerlies were also significantly north of the ACC, where they would have had much less impact on the ocean.

Furthermore, satellite, *in-situ* observations and climate model simulations all reveal an amalgamation of the subtropical gyres of the Pacific, Indian and Atlantic Oceans (called the Southern Hemisphere Super Gyre) linked via inter-ocean outflows south of Australia and Africa (fig. 4).

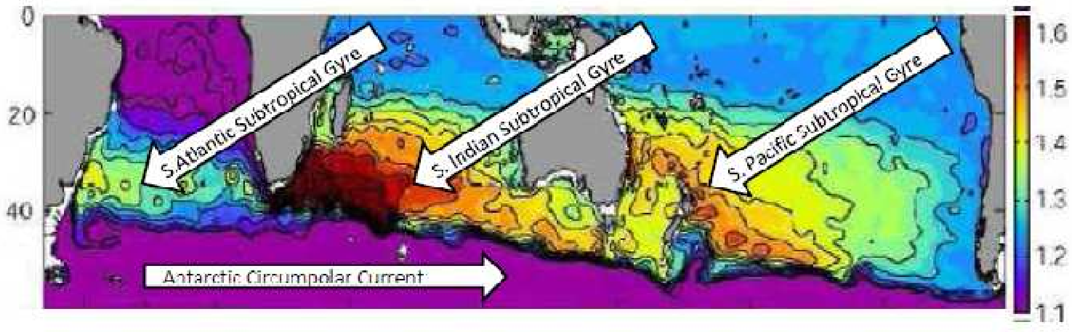

Fig. 4. The mean steric height for the 0 to 400 m layer (contour interval 0.02 m), showing the Super Gyre connections between the subtropical gyres of the Atlantic, Indian and the Pacific Oceans. Connections are via the Agulhas Retroflection and Tasman outflow, south of Africa and Australia, respectively. The southern boundary of the Super Gyre is in contact with the eastward flowing Antarctic Circumpolar Current of the Southern Ocean.

Since, the southern boundary of the Super Gyre is in contact with the eastward flowing ACC, the acceleration of the ACC has been shown to have lead to an intensification and southwards shift of the SH sub-tropical gyres over the last 40 years, with a concomitant intensification of the sub-tropical gyres' western boundary currents, e. g., Agulhas, Brazil and East Australian Currents.

The southward shift in the South Indian subtropical gyre is thus in part responsible for, 1) the warming along 40^{o}S (as warm water transport to these region increases via a stronger Agulhas Current), and 2) for the off-equatorial upwelling (intensification of the tropical gyre, with concurrent shoaling of the thermocline ridge between Seychelles and Madagascar). Model studies show clearly the correlation of an increasing SAM and the warming and cooling trends over the Indian Ocean (fig. 5).

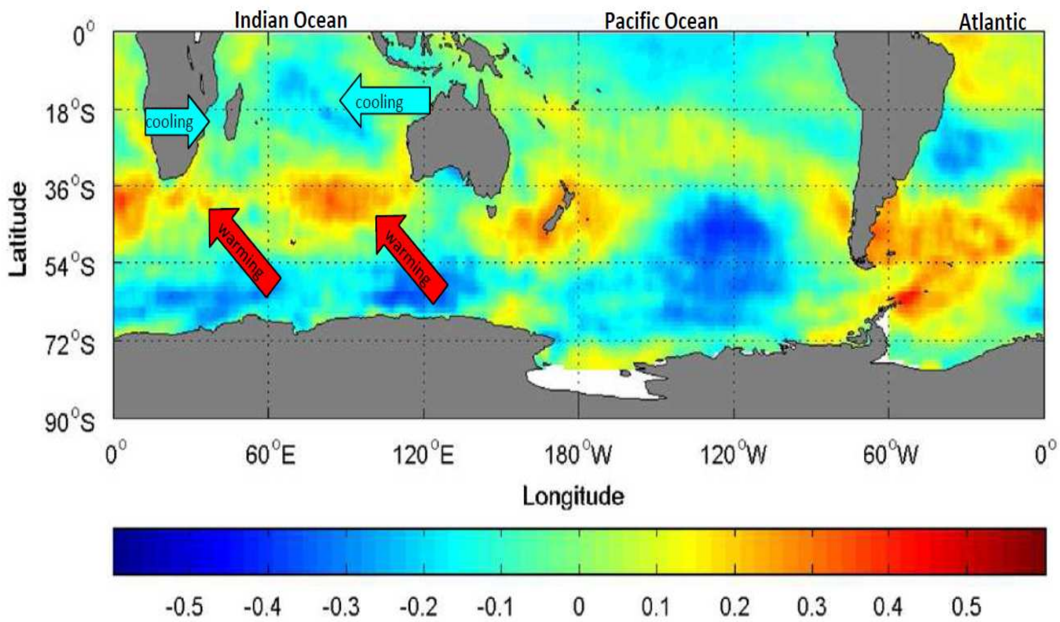

Fig. 5. Spatial pattern of the correlation of monthly Southern Hemisphere sea surface temperatures with the Southern Annular Mode (SAM) index. Red colours denote an increase in surface temperature in response to a positive change in SAM, blue colours the reverse. Correlations are shown for a 1 month lag, which give the clearest ocean temperature response to the SAM.

Modern global climate models based on present day atmospheric CO_2 levels and projected levels of increasing CO_2 levels, motivated by the IPCCs estimates of a 1% increase in CO_2 per year up to the year 2100, show that the above trend in the S. H. ocean circulation will continue. The climate models elucidate the following;

1) A further intensification and southward shift of the mid-latitude westerlies with an affiliated increase in the Antarctic Circumpolar Current transport,
2) A southwards migration and intensification of the Southern Hemisphere Sub-tropical gyre circulations;
3) A further intensification of the western boundary currents – e. g., the Agulhas Current, East Australian Current and the Brazil Current, and
4) Further warming of the Southern Hemisphere oceans between 40 to 50^{o}S, with increased off-equatorial subsurface upwelling and cooling between 5 to 10^{o}S.

The changes to the climate of the SWIO is complicated since the changes induced by global warming, may be masked by other shorter -climate variability, i. e. ENSO and the Indian Ocean Dipole modes. For example an additional and important forcing of the off-equatorial south Indian Ocean thermocline is the transmission of ENSO induced thermocline anomalies from the Pacific into the Indian Ocean through the Indonesian passages. Moreover, It was shown that during La Nina and/or negative Indian Ocean Dipole, a southward migration of the South Equatorial Current (the northern boundary of the south Indian Ocean sub-tropical gyre), with most of its transport diverted south of Madagascar. This in turn induces the intensification of the tropical gyre (thus the shoaling of the thermocline ridge), and a reduction of Mozambique Channel Through-flow. The transport southwards through the Mozambique Channel is mainly in the form of large anti-cyclonic eddies containing equatorial warm water. A reduction in this warm transport will lead to a cooling of the waters of the Mozambique Channel. Satellite derived sea surface height for the La Nina/negative IOD event of 2007/8 (Fig. 6), show the intensification of the tropical gyre, as well as large cyclonic eddies in the Mozambique Channel (unpublished data, 2009). The latter two phenomena will lead to a cooling of the water column in the two SWIO regions.

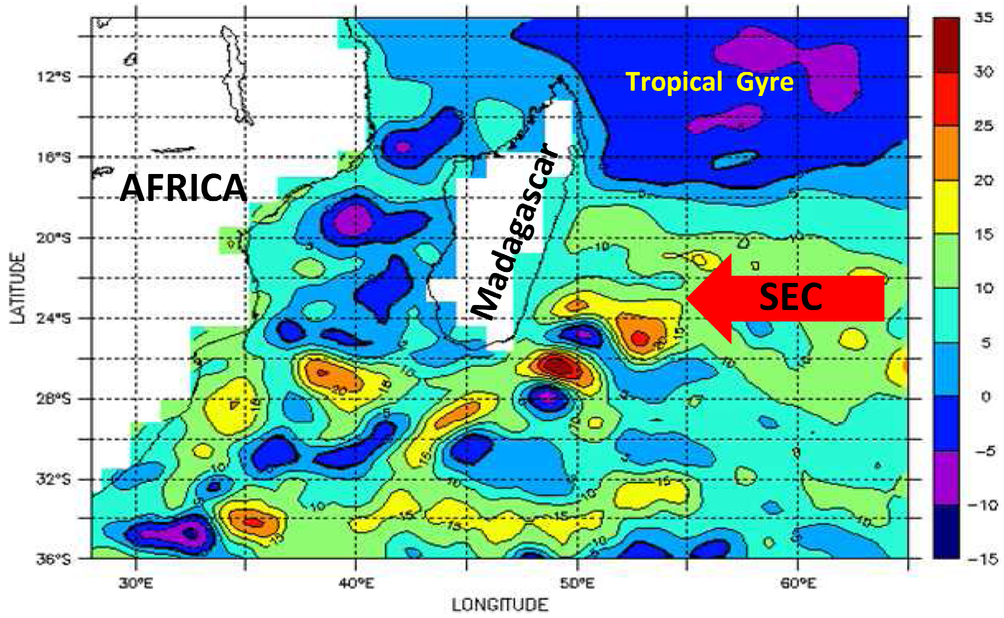

Fig. 6. Sea Surface Height anomalies (cm) for the South Western Indian Ocean integrated for the period January 2008 to June 2008. The South Equatorial Current (SEC) is forced southwards around the island of Madagascar, the tropical gyre is intensified, and the southward transport of warm water through the Mozambique channel via anti-cyclonic eddies is reduced.

One of the most prominent oceanic feature of the SWIO circulation is the Agulhas Current. The Agulhas Current transports about 70 Sv (Sv ≡ 10^6 m^3 s^{-1}) from the equatorial regions south-westwards along the continental margin of southeast Africa. South of Africa the Agulhas Current bifurcates, with most of its transport returning to the South Indian Ocean as the Agulhas Return Current, north of 40°S. The second branch of the bifurcated Agulhas is leaked into the south east Atlantic Ocean as large scale (up to 400 km in diameter) Agulhas Rings (Agulhas Leakage). A stronger Agulhas Current transport has been predicted and observed due to global warming. Certain model studies indicate that the increase of Agulhas Current transport will lead to an associated stronger Agulhas Leakage, while others clearly show the opposite - that an increase in Agulhas Current transport will lead to a higher frequency Upstream Retroflections, with a concomitant decrease in Agulhas Leakage. Either way, the impact of a stronger Agulhas Current will have definite effects on the climate of the SWIO.

The scientific review and analysis presented here are derived from very recent scientific observations, and scientific papers concerning the warming and cooling trends and their implications to the biology of the SWIO are not yet available. The impact of the intensification of the south Pacific sub-tropical gyre has, however, been documented. For example, contemporary research results for the south western Pacific Ocean have already revealed that the alteration in the East Australian Current's physical behaviour is correlated to a southward displacement of marine species boundaries, invasion of foreign marine fauna and a widespread decrease in coastal primary production along the south-eastern coast of Australia. Similar, biological and ecosystem impact may be expected for the coastal region bordering the Agulhas and East Madagascar Currents. Moreover, if you consider the spatial distribution of ecosystems for the SWIO (fig. 7) and overlay the predicted changes due to climate change, e. g., the shoaling of the thermocline ridge (cooling trend), one would expect these coastal ecosystems to change accordingly. The shoaling of the thermocline ridge has been positively correlated to the sea surface temperature, thus with a thinning of the mixed upper layer to shallower than the present average of 80m, you may expect a significant decrease in surface and sub-surface temperatures for the regions between Seychelles and Madagascar and the Mozambique Channel. Similarly, other areas will be affected by increases in temperature.

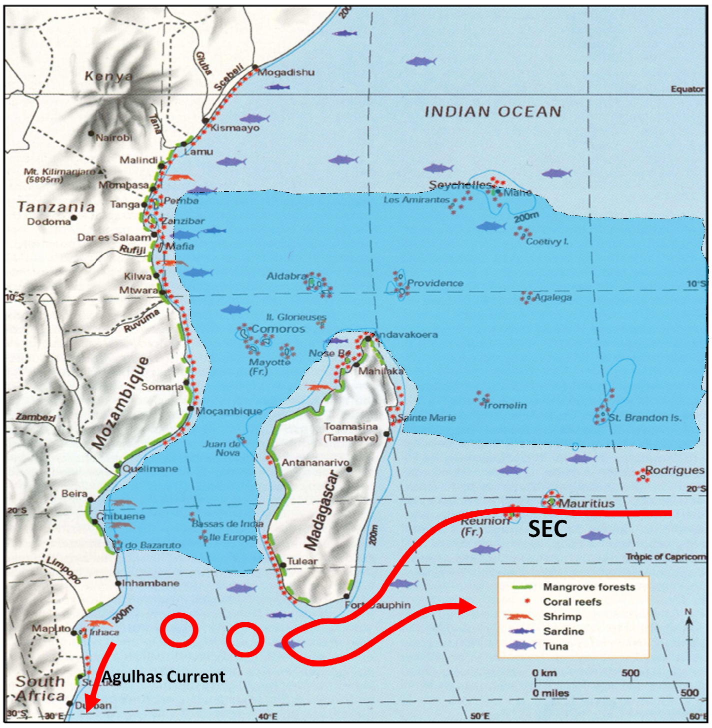

Fig. 7. Spatial distribution of mangrove forest, coral reefs, shrimp, sardines and tuna for the South Western Indian Ocean (after Richmond, 2002). Overlay (blue stippled region) show area of predicted shoaling of the thermocline due to changes to the climate of the SWIO as predicted.

While little has been published on the biological effects of climate induced circulation and physico-chemical changes in the SWIO, widespread changes can be expected. These are likely to affect many of the region’s fisheries. Many fishery species have small dispersive larvae that are heavily reliant on ocean currents. Changes circulation patterns could result in changes recruitment patterns, with larvae being moved into different areas, and consequent shifts in the location of some fisheries. Alternatively reproductive effort may be completely lost, with larvae not able to locate suitable settlement habitat. Changes in primary production as a result of changes circulation will also have a marked affect on trophic chains with likely consequences for fisheries species. Changes in river discharges as a result of changed rainfall regimes could have similar affects, with reduced nutrient and detrital loads delivered into coastal waters.

The likely effect of water temperature on biogeographic distributions has already been noted for some marine fish species in the WIO. Climate changes effects on key habitats within the WIO region are likely to play a major role in shaping fisheries. In this regard, discussion of three major ecotones is pertinent. Coral reefs, mangroves and seagrass beds are common across the WIO region. All are important in artisanal, subsistence and commercial fisheries, as areas of high productivity and in providing structural habitat for many species. All are presently threatened by direct exploitation, ongoing coastal development and degradation, destructive fishing practises and pollution. Climate change is now an additional threat.

The effect of global warming on corals is well understood. Coral bleaching events in the WIO have had devastating effects on local species and reefs. Global patterns show that these events have increased in frequency and severity. Ocean acidification as a result of CO_2 levels increasing also threatens corals. Thus coral coverage is expected to decline over many parts of the world and in areas of the WIO. At face value, increases in temperature and CO_2 levels might result in increases in coverage and spatial extent of mangroves and seagrasses. Sea level rise, increased severity of sea storms, coastal erosion, increased sedimentation due to land erosion and increased turbidity are likely to have the opposite effect however, and threaten to reduce mangrove and seagrasses (as well as contribute to the loss of corals).

Thus, climate change effects threaten to change fundamentally the nature of WIO fisheries as we know them today. In some cases fisheries will be reduced or lost, while in others fisheries are likely to move as species distributions change. Clearly this will have impacts to national economies as well as local communities, their use of coastal resources and human population distribution in coastal areas. In this document we are only speculating on potential impacts to fisheries from climate and oceanographic changes predicted and observed for the SWIO. It is our responsibility as scientists and marine system managers to monitor if any concomitant changes to the ecosystems are observed in response to the predicted variations in the SWIO climatology.

Summary:

Both observational data and global climate models show that the Indian Ocean is warming up due to global warming. The warming is however geographically specific, with most of the warming concentrated along 40^{o}S. Affiliated with the warming is an off-equatorial subsurface cooling. Observation and model results show that these climatological changes are due to many intertwined factors, of which the intensification of the subtropical gyre systems and their southward displacement were identified as the main factors. Observations also suggest that during La Nina and/or negative IOD a southward migration of the SEC induces an intensification of the tropical gyre and a reduction in warm water transport through the Mozambique Channel, causing a shoaling of the thermocline. Uncertainty still remains concerning the feedback of an observed stronger Agulhas Current on the SWIO climatology.

The lack of observational data and downscaled climate models for the SWIO, and especially the Agulhas Current Region are unfortunate drawbacks and will impact on our ability to assess the consequences of global warming on regional coastal ecosystem regimes and climate more robustly. It is, however, believed that with the various new initiatives in monitoring and modelling of the region a more comprehensive understanding of global warming impacts on the SWIO will be forthcoming.

There are well documented links between circulation and physico-chemical conditions in oceans and the fisheries that they support. There is therefore every reason to expect climate change impacts to reflect in changes in SWIO fisheries. Effects will manifest due to changes in biogeography of target species and the distribution of their larval stages. Ecosystem effects will result even if non-fisheries species are impacted. Productivity of offshore and coastal waters will be impacted by changes in circulation as well as fluvial runoff patterns, and thus the trophic basis for some fisheries is likely to be effected. Ecotones in the WIO that play major roles in fisheries are coral reefs, mangroves and seagrass beds. Climate change impacts on these systems will result in major changes to fisheries. Clearly this will have impacts to the regions economy and its people.

Note: This scientific review was produced using a total of 20 scientific publications, of which 13 were published after 2005. You are welcome to request the referenced version of this scientific review by contacting ameyer@csir.co.za (Alan Meyer).