International Journal of Geology, Earth & Environmental Sciences ISSN: 2277-2081
An Open Access, Online International Journal Available at http://www.cibtech.org/jgee.htm
2021 Vol. 11, pp. 1-6/Szekielda

Research Article

EXTREME CHANGES IN THE NW INDIAN OCEAN 2002-2020

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ABSTRACT
The NW Indian Ocean witnesses a fast temperature increase in the world's ocean and a loss of chlorophyll at an alarming rate. Satellite observations along the Somali Coast that includes the upwelling region of the Somali Current allowed for identifying trends that are within the range of global climate changes. The anticyclonic movement of the Somali current is well established although the upwelling intensity seems to be reduced and the center of the anticyclonic gyre showed a warming trend compared to 2003 temperature data. The investigated region of the NW Indian Ocean, with a temperature average of 25.3°C in 2002, shows a trend of increasing temperatures that, should this trend persist, could reach around 27.7^{0}C in 2050.

Keywords: *NW Indian Ocean, Chlorophyll Loss, Sea Surface Warming, Prediction*

INTRODUCTION
Anthropogenic forcing is now believed to have made a substantial contribution to the increase of temperature in the upper layer of the ocean covering the layer from the surface to a depth of about 700 meters. It is estimated that more than 90 percent of the heat accumulated between 1971 and 2010 is stored in the oceans warming especially at near surface waters. As a consequence, the upper 75 m warmed by about 0.11°C per decade over the period 1971 to 2010 (IPPC, 2014). The Indian Ocean is a particular ocean basin because it undergoes seasonal changes in response to the monsoon cycle that results in the reversing of oceanic circulation, sea surface temperature fluctuations and changes in the biosphere.

Aside from the monsoonal reversal, the NW Indian Ocean witnesses the fastest temperature increase in the world's ocean and loss in chlorophyll is observed at an alarming rate (Roxy *et al.*, 2014; Reason *et al.*, 2000; Behrenfeld *et al.*, 2006; Prakash and Ramesh, 2007; Prakash *et al.*, 2012; Roxy *et al.*, 2016; Roxy *et al.*, 2020). The data indicate that these anomalies are projected to continue as an outcome of global warming and accelerated warming has been recorded in several parts of the ocean. From 2002 to 2020, the NW region of the Indian Ocean showed a temperature increase of about 1.3°C and monthly averaged chlorophyll concentrations started to decrease from 0.69 mg m^{-3} in 2002 to about 0.39 mg m^{-3} in 2012 (Szekielda, 2020).

A negative temperature trend was found along the Somali coast during 1997 to 2003 and a positive trend was observed since 2004 that may be based on natural variability (Prakash *et al.*, 2012; Trott *et al.*, 2017)). There is, however, also strong evidence that the region has undergone a decrease of up to 20 percent in phytoplankton over the past six decades, driven by enhanced ocean stratification due to rapid warming and reduced upwelling.

The upwelling along the Somali coast is in response of the Somali Current at the onset of the southwest monsoon that starts to develop around end of May. The upwelling has its maximum strength in July when two anticyclonic gyres develop at 5^{0}N and 9^{0}N, respectively (Bruce, 1973; Duing and Szekielda, 1971; Szekielda, 1976; Brown *et al.*, 1980, Szekielda, 1987). For this reason, the latest satellite observations on temperature and chlorophyll were accessed for July monthly averaged data for the period 2002 to 2020 with the objective of identifying trends in temperature distribution and in determining if the previous observed loss of biomass, expressed in terms of chlorophyll, is undergoing a recovery.

MATERIALS AND METHODS

The data in this study are derived from the System for Multidisciplinary Research and Applications (NASA Giovanni) that is developed for application in the analysis of Earth remote sensing for weather, climate, atmospheric composition, oceanography and hydrological processes (Acker *et al.*, 2006). The observations are at a four-kilometer resolution and allows for identifying trends that are within the range of global climate changes. The area of observations is located at 48^0E, 3^0N, 58^0E and 16^0N and includes the upwelling region of the Somali Current, part of the Gulf of Aden and a portion of the Oman coast.

RESULTS AND DISCUSSION

Figure 1A gives the location of the area where temperature and chlorophyll concentrations were analyzed. Figure 1B shows the average monthly daytime sea surface temperature for July 2002 to July 2020, and the corresponding chlorophyll concentrations are shown in Figure 1C. It is evident that the surface temperature oscillates with a periodicity of 2 to 4 years and shows an increase from 25.3°C in 2002 to a temperature of 27°C in 2020. The linear fit gives a range from 25°C to 26°C while the polynomial fit provides a range from 24.8°C to 26.5°C whereby the polynomial fit indicates an accelerated increase during the last six years. The chlorophyll data confirm the previously reported trend of decreasing concentrations (Szekielda, 2020) and only a small increase can be recognized with the polynomial fit in 2014 that is mainly due to the slightly elevated values in 2017. Both temperature and chlorophyll concentrations confirm that the environmentlal conditions in the upwelling system continue to be modified at a rate of change for temperature at 0.09°C year^{-1} for the polynomial fit and at 0.06°C year^{-1} for the linear fit.

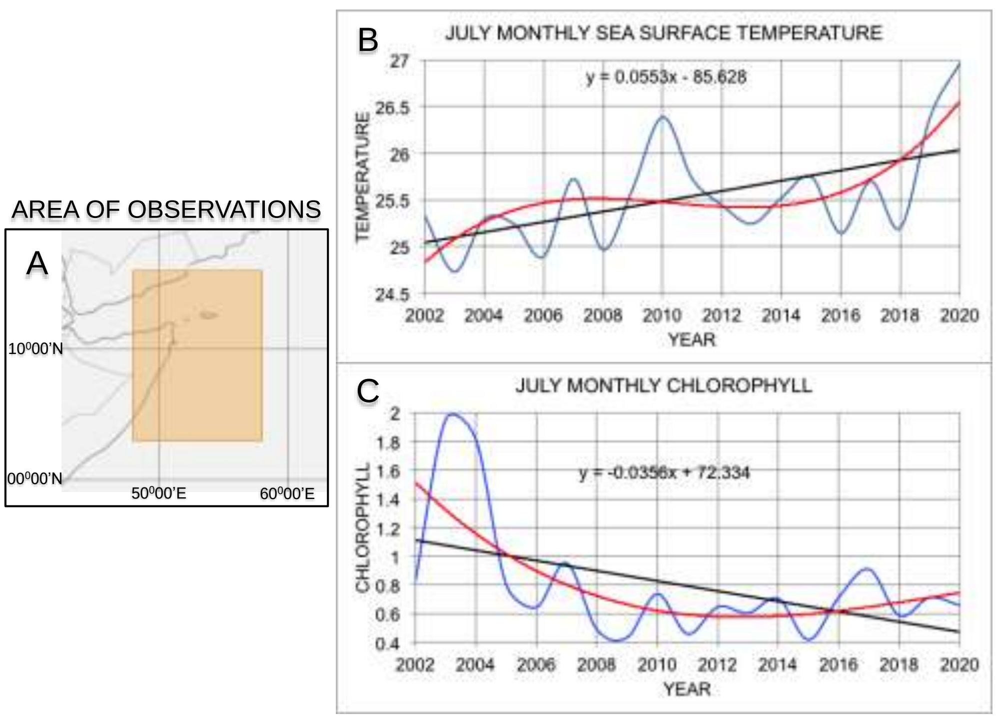

Figure 1: Average monthly daytime sea surface temperature at 11µm and four kilometer resolution for July 2002 to July 2020. A: Area of observations located at 48^0E, 3^0N, 58^0E, 16^0N; B: Temperature changes; C: chlorophyll concentrations (mg m^{-3}). Included in the graphs are linear fits in black and polynomial 3rd order fits in red. The linear fit for temperature follows y= 0.0553x – 85.628.

The year-to-year changes in the investigated region show the development of upwelling for three selected years as shown in Figure 2 with eight–day averaged sea surface temperature. The coverage for 2003, when the highest chlorophyll concentrations were recognized, lowest average temperatures were also observed. The anticyclonic movement of the Somali current is well established during the years of the studied period although the upwelling intensity seems to be reduced. The center of the anticyclonic gyre shows a warming trend compared to the 2003 temperatures, and in 2020 the temperature increase is recognized throughout the whole region.

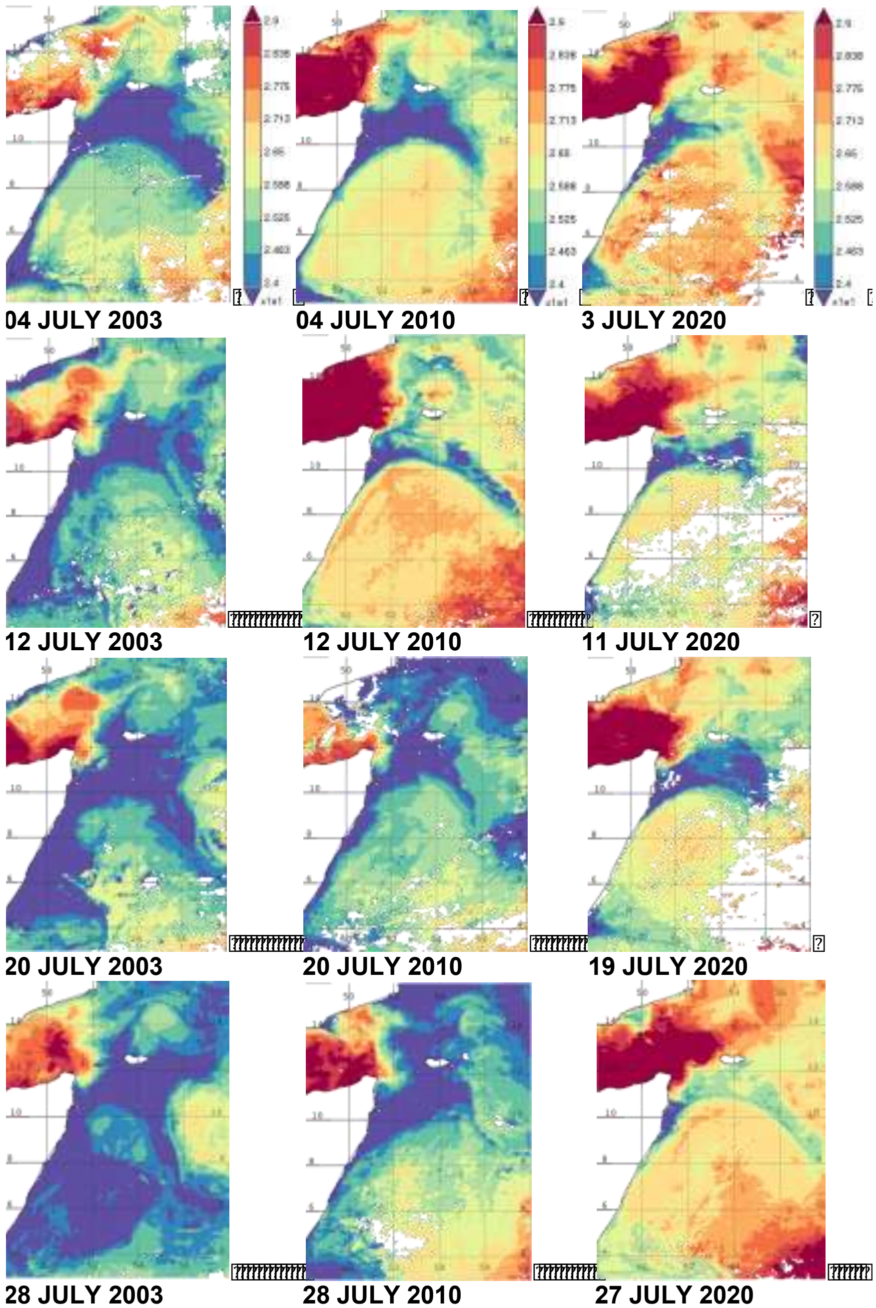

Figure 2: Eight–day averaged sea surface temperature at four-kilometer resolution for July at selected years. The color annotations are based on the same scale and a temperature range of 24°C to 29°C with smoothing of the data.

Analysis of terrestrial wind speed data along the Somali coast indicated an increase in speed while the water temperature in the offshore region increased (Szekielda, 2020). This particular issue may be an indication that the terrestrial wind speed, although close to the coast, might not necessarily be related to the strength of the Somali Current and the intensity of coastal upwelling. Still the anomalous temperature increase and the loss of chlorophyll are most probably related to a deeper mixed layer and reduced nutrient supply to the euphotic zone (Behrenfeld *et al.*, 2006; Boyce *et al.*, 2010). However, the oscillatory nature of warming is an indication that various cycles in wind stress and the ocean surface topography are decoupled and may be the cause for the observed decline in chlorophyll concentration. That would indicate that the observed variability in temperature and chlorophyll is not necessarily an effect of global warming alone.

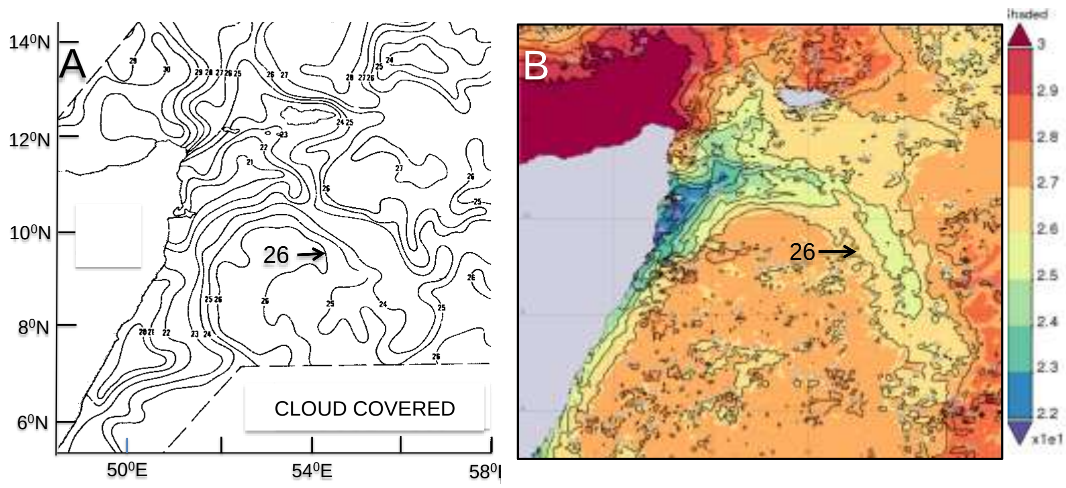

Figure 3: Comparison of satellite-derived temperature for 1966 and 2020. 3A: Observation with the Nimbus II satellite High Resolution Infrared Radiometer (HRIR) on 3 July 1966 along the Somali Coast (Szekielda, 1971, 1976). The spatial resolution of the HRIR was around 8.5 kilometer. B: Sea surface temperature distribution of time averaged at 11µm daytime measurements at 4-kilometer resolution from 1-8 July 2020. In both figures the center of the anticyclonic gyre is indicated by the 26-degree isoline.

The unusual fast temperature changes may date back decades because a comparison with one the first thermal infrared satellite image that was recorded along the Somali coast in 1966 showed a wider upwelling with lower temperatures than in 2020 as shown in Figure 3. The comparison shows that the decreasing surface extent of cold upwelling water is a long-time process, as well as the increasing extent of the warm central region of the anticyclonic gyre that is characterized by the 26-degree isoline in Figures 3A and 3B. The latest data set from 2020 shows that the increase of temperature coincides with the decrease of chlorophyll and the areal decrease of cold surface water. The trend of temperature changes in the investigated region can be described through estimates with the linear regression that is derived from the dataset shown in Figure 1. Should this trend persist, the forecasting for the year 2050 would give a temperature at around 27.7^{0}C and for 2100 a temperature of 30.5^{0}C. As limited as such forecasting may be, it provides at least the range of anticipated changes that may have a dramatic impact on the marine environment, in particular on the marine ecosystem. The temperature increase by 0.9°C per decade for the polynomial fit and 0.6°C per decade for the linear fit, shows the seriousness of heating in this particular part of the ocean. By comparison, the global warming of the upper ocean layer is about 0.11°C per decade (IPPC, 2014). Although at present, the risks resulting from such dramatic temperature change remain uncertain, the rising sea surface temperature documented may trigger abrupt and irreversible change because with increasing temperature, the capability to mitigate the risk of severe and irreversible detrimental impacts is reduced.

ACKNOWLEDGEMENT
Analyses and visualizations used in this study were produced with the Giovanni online data system, developed and maintained by the NASA GES DISC.

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