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Research Article

SIGNIFICANT ENVIRONMENTAL CHANGES IN THE NORTHWEST INDIAN OCEAN: WARMING TREND AND REDUCTION OF CHLOROPHYLL

***Karl H. Szekielda**
Research Associate
Earth Engineering Center, Columbia University New York, NY 10027, U.S.A
**Author for Correspondence: karl.szekielda@gmail.com*

ABSTRACT

The NW Indian Ocean undergoes fast increase in temperature and loss in chlorophyll. A satellite-derived data set of seventeen years was analyzed for identifying the nature of those environmental changes in connection with the upwelling region along the Somali coast. The investigated area shows an increase of about 1.3C, and monthly averaged chlorophyll concentrations decreased from 0.69 mg m^{-3} in 2002 to about 0.39 mg m^{-3} in 2012 that corresponds to an average loss of cholorphyll to about 0.03 mg m^{-3} year $^{-1}$. Largest temperature fluctuations are observed at the height of the southwest monsoon period June to August. Increasing wind speed is related to an increase of temperature and seems to be contrary to the common thought that intensifying wind stress on the ocean surface can intensify coastal upwelling. Major temperature fluctuations in the upwelling core are observed for March through May with an estimate of about 1.5C increase over seventeen years and the second largest increase is for the period June through August with about 1.2C increase. Time series of sea surface temperature day-night differences show that the summer monsoon has since 2002 an increasing day-minus-night difference that showed in 2019 about 0.55C warmer surface water at night compared to day temperature. Fluctuations of chlorophyll and temperature may appear with a half-period of about six to nine years whereas wind speed seems to change at larger time scales. The results indicate variability that may be a manifestation of decadal oscillations and the observed variability in temperature and chlorophyll is not an effect of global warming alone, rather a combination of several factors. Warming and building of a deeper mixed layer that reduces nutrient supply to the euphotic zone is deducted from observation of the upwelling core in the Somali Current that has similar thermal progression as the main investigated area.

***Keywords**: Climate change, NW Indian Ocean, Chlorophyll Loss, Temperature Oscillation*

INTRODUCTION

The Indian Ocean 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 biogeochemistry that is especially pronounced along the Somali coast. The inter-annual variations in the western Indian Ocean have an impact on the atmospheric water vapor transport toward India, and therefore, regulate the rate of precipitation over the Indian continent (Izumo *et al.*, 2008). The moisture source for the monsoon rainfall is reduced during summer by upwelling along the Somali coast and along the cost of Oman. The Somali coast has strong upwelling during the southwest monsoon and is considered as the fifth strongest one in the world. In addition to monsoonal changes, the Indian Ocean is exposed to an unusual warming trend over the last decades with the fastest rate of warming among tropical oceans (Beal *et al.,* 2019). An anomalous increase of 1.2°C in summer sea surface temperature was observed in the western basin (Roxy *et al.*, 2019) whereby the Indian Ocean warm pool is defined by sea surface temperature of 28^{o}C. For the period 1951– 2015 sea surface temperature in the tropical Indian Ocean increased by about 0.15 °C per decade and the declining trend in marine phytoplankton over the western Indian Ocean is projected to continue as an outcome of global warming (Behrenfeld *et al.*, 2006; Roxy *et al.*, 2014; Roxy *et al.*, 2015; Roxy and Gnanaseelan, 2020). As emission of anthropogenic greenhouse gases is responsible for heat trapping in the ocean by about 90% (Rhein *et al.,* 2014), it is therefore challenging to identify with long-time observations changes of the marine environment, and in particular, the upwelling development along the Somalia coast in relation to physic-biological interactions. It is assumed that reduced upwelling along the Somali Coast is related to anomalously weak southwesterly winds that build warm sea surface temperature leading to increased precipitation anomalies, whereas seasons with strong upwelling can be attributed to El Niño conditions (Izumo *et al.,* 2008).

The western Indian Ocean undergoes large seasonal and inter-annual variability that gives rise to debatable interpretation of data because decade-long time observations are not always available to recognize climate driven trends. For instance, an increase in productivity by about 350% was attributed to strengthening of the monsoonal winds for the western Arabian Sea and the corresponding decrease in sea surface temperature (Goes *et al.,* 2005). However, no such trend was observed by Prakash and Ramesh (2007). On the other hand, time series of chlorophyll showed a significant decrease from about 1.8 mg m^{-3} in 2003 to about 1.1 mg m^{-3} in 2010 despite change in the wind stress (Prakash *et al.,* 2012). That indicates that other mechanisms may be the cause for changes in temperature and chlorophyll reduction in the northwest part of the Indian Ocean.

Upwelling along the Somali coast is limited to the early phase of the summer monsoon and later, primarily limited to the eddy dominated flows in the northern and to some extent in the southern part of the coast (Chatterjee *et al.,* 2019). The typical response of the Somali Current to the onset of the SW monsoon starts around end of May and develops its strength in relation to the strong winds in June when an atypical current pattern develops containing two anticyclonic gyres that are observed at 5^0N and 9^0N (Bruce, 1973; Duing and Szekielda, 1971; Szekielda, 1976; Brown *et al.,* 1980), and the southern upwelling region migrates north at an approximate speed of 5-75 cm s^{-1} (Evans and Brown, 1981). After July and August, an increasing number of discrete anticyclonic eddies are observed with more than 20 cm sea surface height anomalies (Trott *et al.,* 2017).

Fluctuations in the strength of the Somali Current seem to be related to an asymmetry in the El Niño Southern Oscillation and in the increasing frequency of El Niño events during the last decades (Schott, 1983). Projection on the evolution of the Somali coastal upwelling due to global warming shows an intensification of coastal upwelling and a projected near-shore sea surface temperature warming that will be less intense than in the adjacent ocean (de Castro *et al.,* 2016). In addition, it is assumed that the warming of the western tropical Indian Ocean is responsible for the significant reduction of primary production (Behrenfeld *et al.,* 2006). The largest increase of up to 350% in phytoplankton during the recent decades has been reported for the region. The loss has been attributed to the strengthening of summer monsoon winds in the western Indian Ocean. These findings on the change of biomass in the western Indian Ocean are debatable, because relatively short-time series were used that were not large enough to distinguish noise from real large-scale changes (Beaulieu *et al.,* 2013). Roxy *et al.,* (2016) showed a decrease of up to 20% in phytoplankton in this region over the past six decades that is driven by enhanced ocean stratification due to rapid warming. On a global scale, decline of phytoplankton is observed (Gregg *et al.,* 2005) with inter-annual to decadal fluctuations that seem to be superimposed on long-term trends (Boyce *et al.,* 2010). The discrepancy in previous reporting can be explained by the oscillating nature and large variability of, for instance, the El Niño–Southern Oscillation that generates significant temperature anomalies in the western Indian Ocean (Reason *et al.,* 2000). Furthermore, The Madden–Julian Oscillation modulates the El Niño Southern Oscillation, tropical cyclones and the monsoons (Murtugudde *et al.,* 2000), and climatic variables show responses varying from simultaneous, to about one season's lag.

Fast changes in tropical basins are not uniform (Roxy *et al.,* 2019) and it is of interest to evaluate to what degree changes can be recognized in the northwest Indian Ocean. Sea surface temperature seems to be related also to sea level anomalies along the Somali coast that showed a negative trend 1997-2003 and a positive trend since 2004 (Prakash *et al.,* 2012) that may be based on natural decadal variability. Though some of the observations in this region seem to be contradictory, it appears that several mechanisms coincide but develop on a different time-space scale. Therefore, the long-time observations that are presented in the following are extracted from a large satellite derived data set to identify environmental changes and fluctuations. Continued satellite monitoring over large time spans now allows monitoring environmental events on decadal and inter-annual scale. Thus, the following analysis aims with sea surface temperature, chlorophyll and wind speed observations to search for apparent changes that appear over decadal time frames by applying trend lines for recognition of temporal and spatial changes.

MATERIALS AND METHODS

Remotely sensed data were analyzed over the northwest Indian Ocean that covered the area 48^0 E, 3^0 N to 58^0 E, 12^0 N referred to in the following as the main area of analysis. For comparison, the data includes the upwelling core in the Somali current close to Ras Hafun. The main area covers the upwelling region along the Somali coast and the region where the Somali current turns into a large anticyclonic movement during the summer monsoon. The data were accessed 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 time of observations covered July 2002 to December 31 2019 that resulted in a high number of observations at four-kilometer resolution and allowed to formulate trends that are within the range of global climate changes. Seasonal analysis of the data covered the full years 2003 to 2019 because MODIS started operating in the middle of 2002 and data for 2020 are not complete as of date of this reporting.

RESULTS AND DISCUSSION

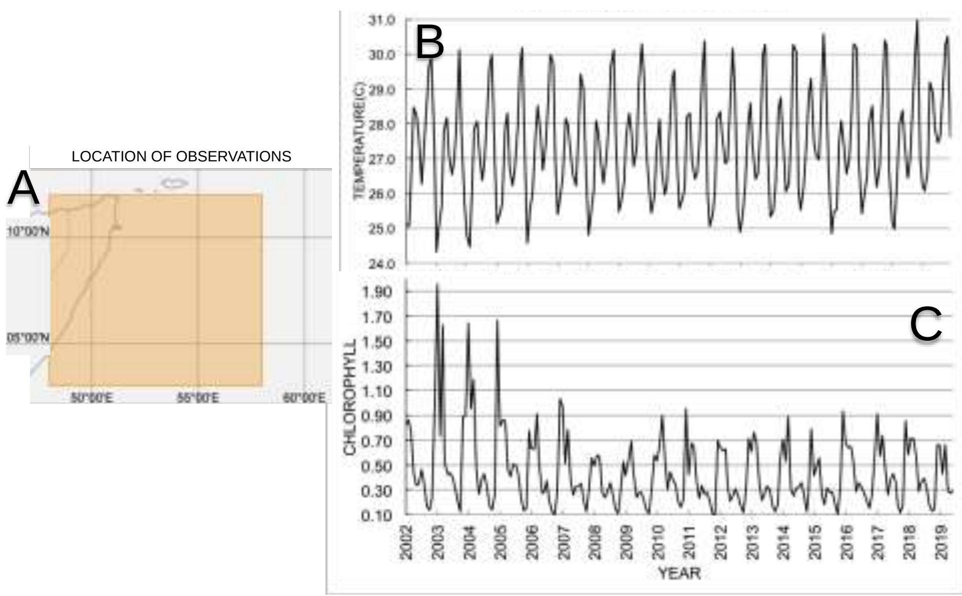

Figure 1: A. Location of observations. B. Monthly averaged sea surface temperature. C. chlorophyll concentration (mg m^{-3}) along the investigated main area.

Figure 1A shows the main area that was analyzed with averaged time series for temperature in 1B and for chlorophyll in 1C over a time frame of seventeen years. The graphs show the yearly monsoonal cycling whereby minimum temperatures and high chlorophyll concentrations coincide during the southwest monsoon when upwelling along the Somali coast is evident. The period 2002 to 2005 shows the highest chlorophyll values with monthly average concentration around 1.9 mg m^{-3} while the corresponding monthly averaged temperature is at a minimum around 24.5C. After that period, the chlorophyll concentrations show a significant reduction while the temperature indicates a steady increase.

Interpretation of the data with linear trend lines suppresses natural fluctuations that exist at different time and space intervals. Therefore, the data were subjected also to polynomial fits of which results are shown together with linear fits as shown in Figure 2.

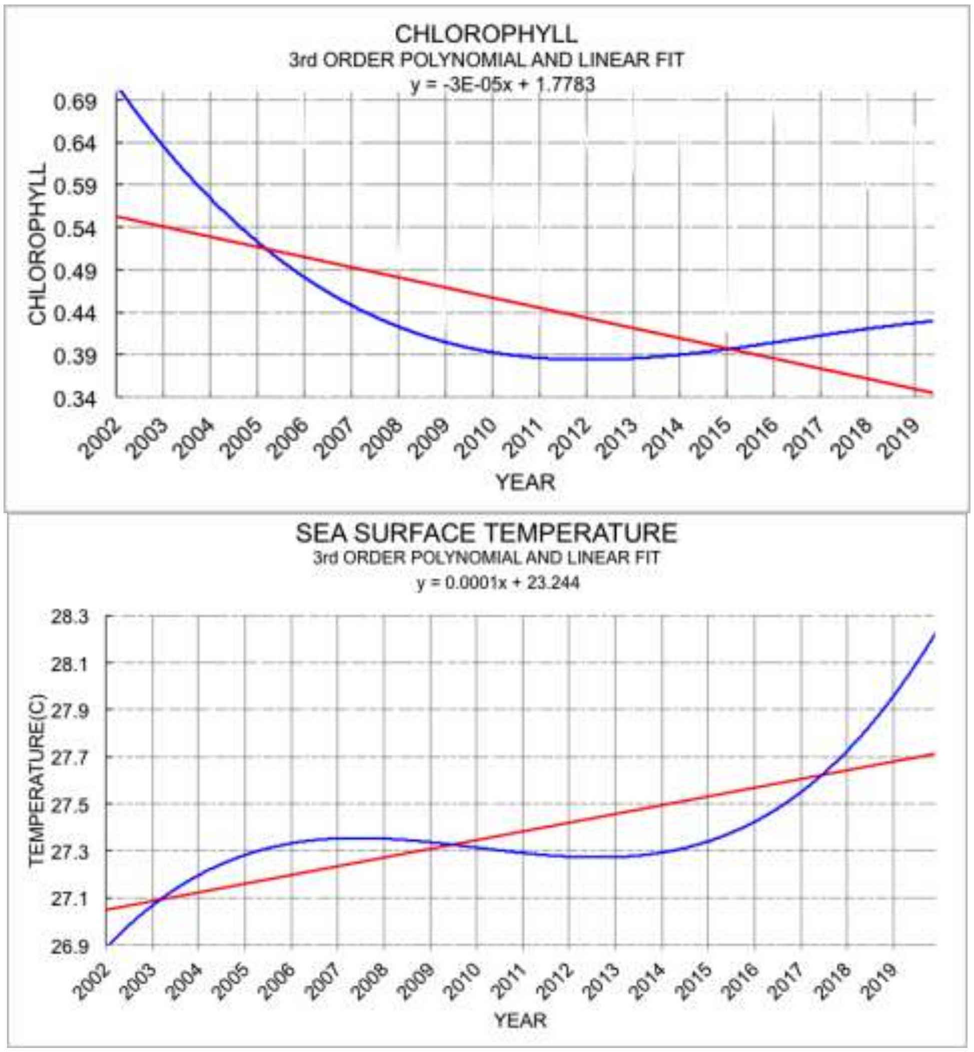

Figure 2: Polynomial fit 3rd order (blue line) and linear fits (red line) for chlorophyll (mg m^{-3}) and daytime temperature at 11µm (^{0}C). The linear regression for temperature increase follows (^{0}C) = 0.0001x + 23.244. The linear regression for chlorophyll change follows (mg m^{-3}) = -3E-05x + 1.7783.

The polynomial fit for chlorophyll discloses highest concentrations in 2002 when monthly temperature was at a minimum of 26.9C. Temperature reached a plateau at around 27.3C between 2008 and 2014 and afterwards continued to increase. Over the time frame of seventeen years the polynomial fit shows an increase of about 1.3C while the chlorophyll concentrations started to decrease from 0.69 mg m^{-3} in 2002 to a concentration of about 0.39 mg m^{-3} in 2012. That corresponds to an average loss of about 0.03 mg m^{-3} year $^{-1}$ or the equivalent of about 44% loss. The following years show a slight increase in concentration but stayed at levels considerably below the concentration found in 2002. For comparison, Prakash *et al.*,

(2012) reported that an increase in chlorophyll and low temperature prior to 2002 are an outcome of the presence of a cold eddy that was responsible for the increase in productivity and bloom formation; however, they observed a decrease from about 1.8 mg m^{-3} in 2003 to about 1.1 mg m^{-3} in 2010. Note that the linear trend lines suppress the extreme values for chlorophyll and temperature as shown in Figure 1.
The change in surface distribution of chlorophyll and temperature is shown with images for selected years in Figure 3. The major upwelling region shows an increase in surface temperature and the offshore region also indicates as well a significant temperature increase in 2019 when compared with the image for 2002. The source of the warm water pool seems to be related to the seasonally northward spreading of water with elevated temperatures from winter to summer (Jaswal *et al.*, 2012). The corresponding chlorophyll images show the degree of reduction in particular in the vicinity of the gyre at five degrees north that in 2013 and in 2019 found to have moved farther south.

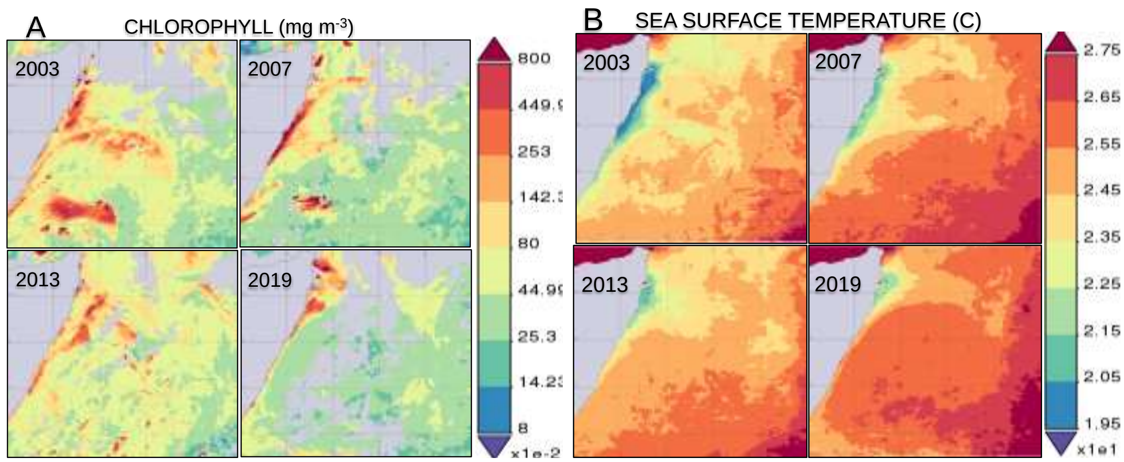

Figure 3: Comparison of monthly averages of chlorophyll and temperature for July to August in different years A. Chlorophyll averages and B. sea surface temperature averages. The image display for chlorophyll was in the range of 0.08 to 8 mg m^{-3} with a log annotation of the color scale and smoothing was applied. The color annotation for the temperature scale was linear and smoothing of the data was applied.

Grouping of chlorophyll observations by seasons is shown in Figure 4. It is evident that the loss of chlorophyll follows different trend lines according to the seasons. December to February season shows decreasing concentrations of chlorophyll but after 2013, an increase is observed. The concentration for March through May decreased until 2016, slightly increased until 2015 but then continued to decrease. The June to August season is normally the season when upwelling is strongest along the Somali coast but chlorophyll decreased and recovered only slightly with an intermittent maximum in 2017. September through November showed a similar trend line although the absolute values are significantly lower when compared to the values for June to August.
Trend lines for seasonal temperature changes are shown in Figure 5 revealing that the slopes for the seasons are not uniform. Based on the linear trend lines, all seasons show temperature changes not exceeding more than one degree, but the December to February season indicates slight cooling whereas the other seasons witness increasing temperature. The polynomial fits demonstrate for December to February the oscillating nature of temperature changes with an intermediate temperature minimum occurring around 2009 that is followed by an increase in temperature. During the upwelling season June to August the polynomial fit shows the oscillating temperature that starts in 2002 at a temperature around 25.2C, goes through a maximum in 2008, with another minimum in 2015, and afterwards continued to increase again. By comparing the different seasons it becomes evident that the temperature during the

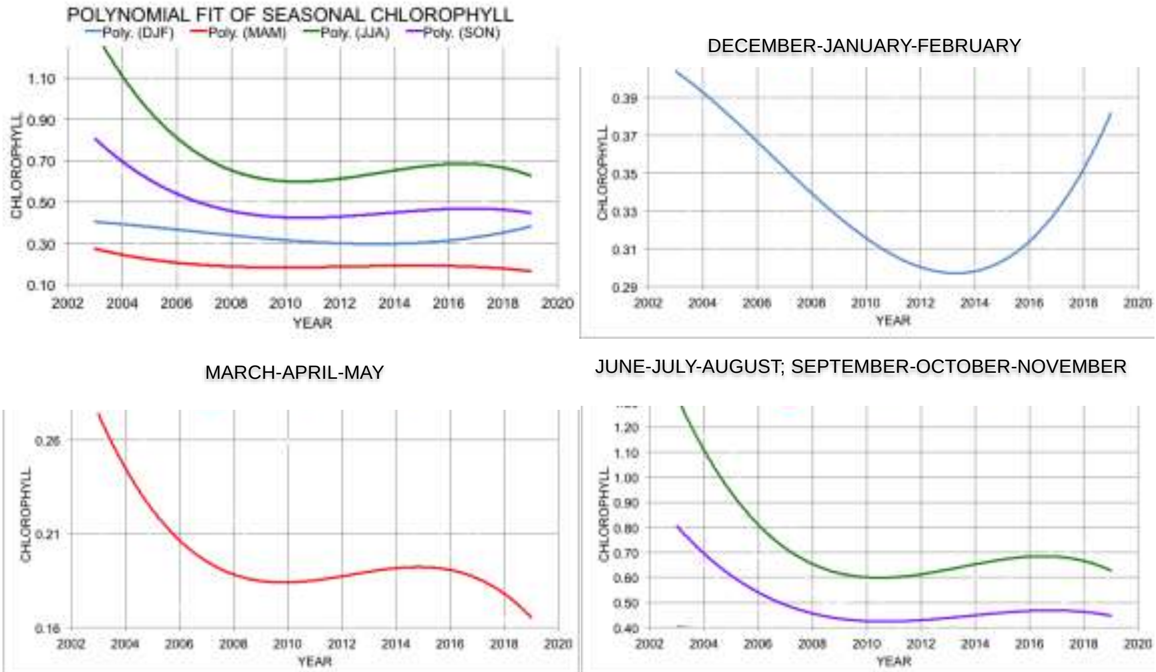

Figure 4: Polynomial fits for seasonal changes of chlorophyll (mg m^{-3}) from 2003 to 2019. Colors of the curves correspond to the color code on top of the graph for the seasons (DJF, MAM, JJA and SON). Note the different scale at the vertical axis for each season in order to emphasize the change.

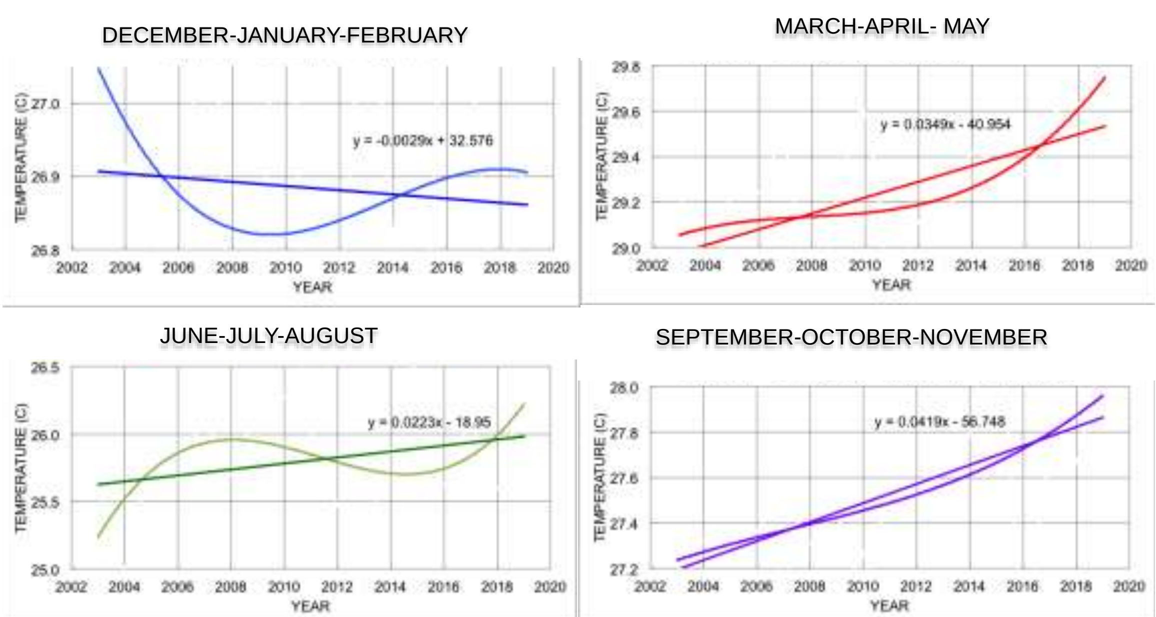

Figure 5: Linear and polynomial fits for seasonal changes in temperature along the Somali coast for 2003 to 2019. Note that the temperature scale is different for each season in order to emphasize the changes. The equations are included for the linear trend lines.

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2020 Vol. 10(3) September-December, pp. 56-68/Szekielda
Research Article

southwest monsoon seasons undergoes the widest changes although it is not conclusive whether the observed oscillation for the period July to August is directly related to the upwelling along the coast.
For comparison, data in the core of upwelling at around 10^0N were analyzed to indicate if the upwelled water has similar characteristics as the main field. The location of the investigated site and results are shown Figure 6 where 6A represents the area for which temperature data were analyzed and the corresponding results are shown in Figures 6B and 6C. The monsoonal cycle is well documented and inter-annual fluctuations are recognized. The linear regression and polynomial fit for the data in Figure 6B are shown in Figure 6C with an enlarged vertical scale. The region where upwelling occurs during the southwest monsoon shows also the increase of temperature when data for all seasons are averaged. When subjected to linear and polynomial fits the data show an increase of about 0.5C from 2002 to 2019.

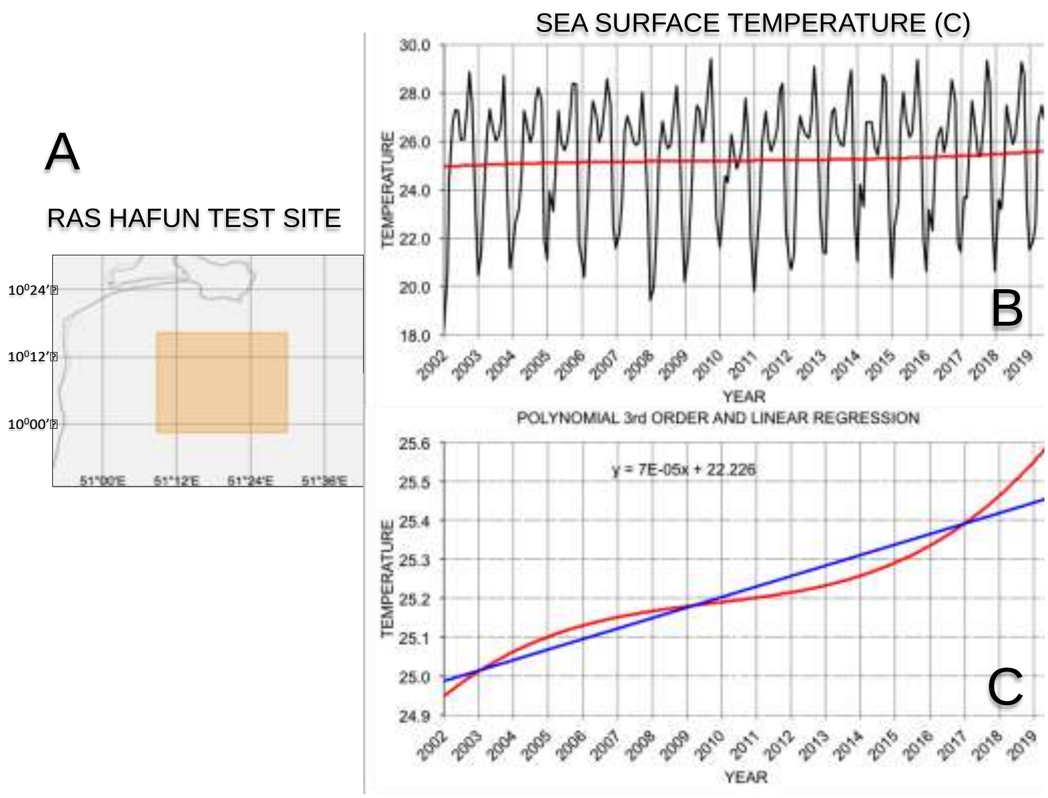

Figure 6: Temperature recordings at Ras Hafun. A: Location of investigated area. B: Time series area monthly averaged 11µm temperature (^{0}C) at four-kilometer resolution with polynomial fit in red. C: Enlarged temperature range with polynomial fit and linear regression based on temperature recordings in B.

When separated by seasons, the temperature fluctuations display individual characteristics as shown in Figure 7. During December to February and March through May, the polynomial trend lines follow those shown for the main site although the amplitude of temperature fluctuation is reduced. During the upwelling season, June through August, the temperature shows a continuous increase while the season September to November show an oscillation that differs from the main site. Major fluctuations in temperature are observed for March through May with an estimate of about 1.5C increase over seventeen years and the second largest increase is for the period June through August with about 1.2C increase.

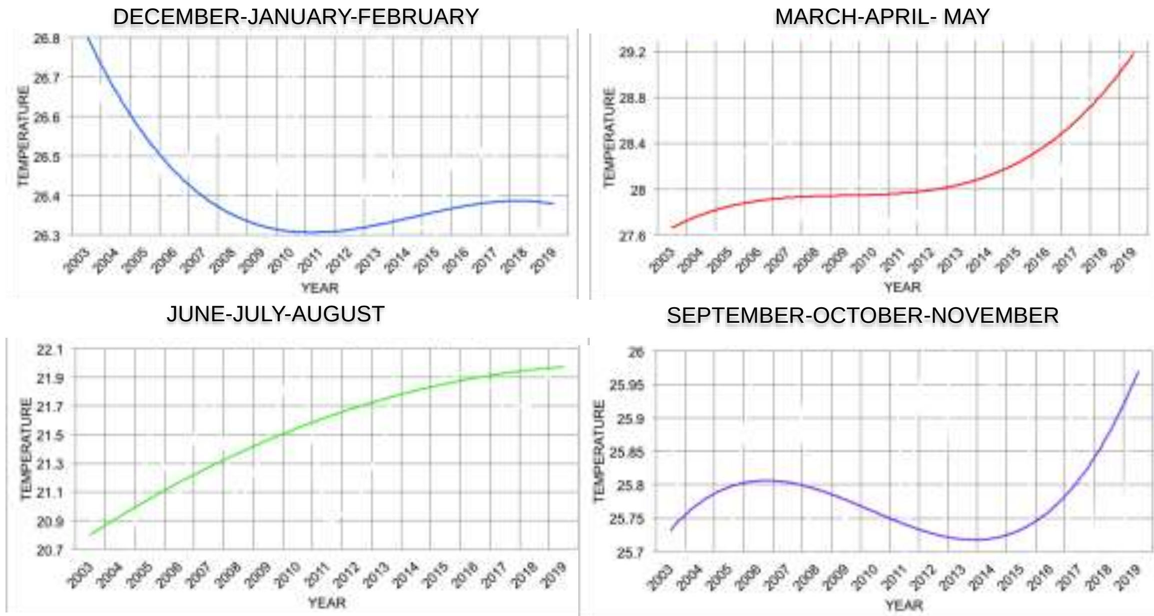

Figure 7: Temperature fluctuations at Ras Hafun polynomial fit. Note the different scale at the vertical axis for each season in order to emphasize the change.

Normally, intensity of upwelling is linked to wind stress and the observed increase in temperature may therefore be a result of diminishing wind speed. Consequently, the wind speed was analyzed and the results are shown in Figure 8 that shows fluctuations in wind speed are in response to the monsoon seasons. Grouping wind speed by seasons as shown in Figure 8B, the trend lines show season-specific characteristics as seen in Figures 8C through 8F. Except for June through August, the data display fluctuations with a periodicity of about twenty years, whereas the wind speed for the southwest monsoon period showed continuous increase. The findings that increasing wind speed parallels increase of temperature in the upwelling region, seems to be contrary to the common thought that coastal upwelling can be accelerated by intensifying wind stress on the ocean surface, in particular, as a result of global greenhouse warming (Bakun, 1990). However, the increase of temperature is not necessarily related to a reduction in the strength of upwelling, rather, the deepening of the mixed-layer as an outcome of warming is sufficient to reduce turbulent transport of nutrients to the euphotic zone.

Global warming can be considered as a continuous contribution to sea surface temperature therefore, the summer anomaly must have an additional heat transfer either through the oceanic or atmospheric circulation. The major contribution of heat can be attributed to the westward extent of the Indian Ocean warm pool during summer (Izumo *et al.*, 2008).

Furthermore, an anomaly in heat transfer from the atmosphere to the ocean can be expected from an anomalous behavior in the diurnal warming cycle of the ocean's surface. Normally, during daytime the bulk temperature is elevated when solar radiance is strong and turbulent heat transfer takes place from the air-sea interface to the atmosphere and at night, heat transfer continues from the ocean interface to the atmosphere. However, when wind stress is reduced at night, and the atmosphere having a warmer temperature than the ocean surface, the heat transfer can go in the opposite direction (Kawai and Wada 2007). This is documented with temperature differences of day and night observations that are shown in Figure 9.

The time series of sea surface temperature differences (day minus night) in Figure 9A show that the summer monsoon period June through August is characterized by an anomalous trend because the negative values indicate that the night temperature was warmer than the day temperature. Furthermore,

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2020 Vol. 10(3) September-December, pp. 56-68/Szekielda
Research Article

the linear trend lines for the seasons in Figure 9B demonstrate an increasing difference between day and nighttime temperatures that was about 0.15C warmer in 2019 compared to the corresponding season in 2003. The other seasons show temperature differences with minimal changes except for the period March to May that reveals even a slighter cooling.

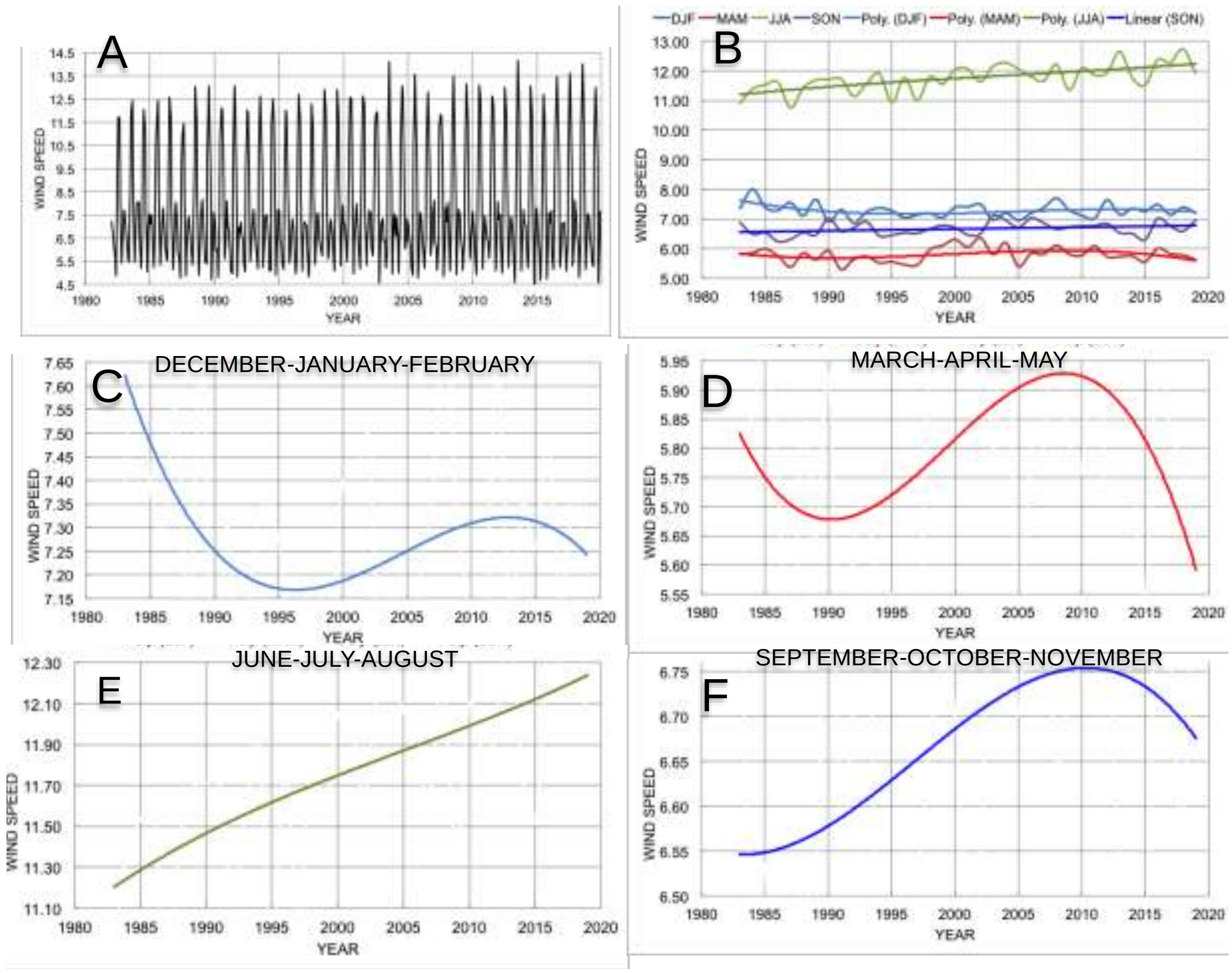

Figure 8: Time series of area-averaged monthly 0.1 degree near surface wind speed (m s^{-1}) for 1982 to 2019. A. Representation of wind data for all seasons. B. Seasonal changes of wind with polynomial fit 3rd order. C through F shows polynomial fits 3rd order for the four seasons with color-coding that corresponds to the graphs in B. Note the different scale at the vertical axis for each season in order to emphasize the change.

The effect of night heat transfer from the atmosphere to the ocean is shown with the horizontal distribution in Figure 10. Figure 10A shows the long-term changes of the June to August season with linear and polynomial fits. The distribution of difference temperature (day minus night) in 10B to 10D shows that night warming in July 2020 is in the range of less than one degree but the changes over sixteen years are from about minus 0.39C in 2003 to about minus 0.54C in 2019 showing an increase in the difference temperature of about 0.15C. It is apparent that night heat transfer from the atmosphere to the ocean is a supplemental contribution to the continuous increase of global sea surface temperature.

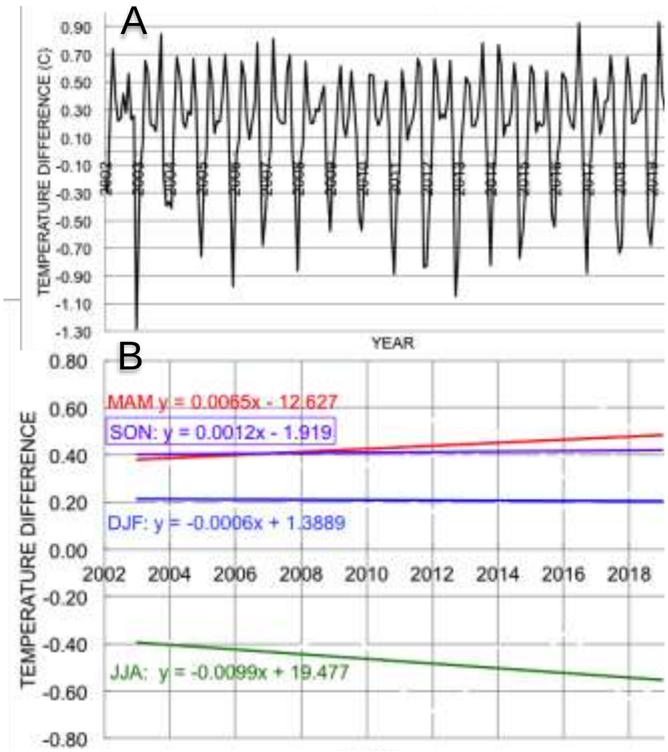

Figure 9: A: Time series of monthly area-averaged sea surface temperature differences at 11µm (^{0}C), daytime minus nighttime for 2002-07 to 2020-07. B: Linear fits of seasonal temperature differences from the data shown in Figure A. Note that negative values indicate warmer nighttime temperatures and that day-night difference is significantly higher in the original data as shown in figure A.

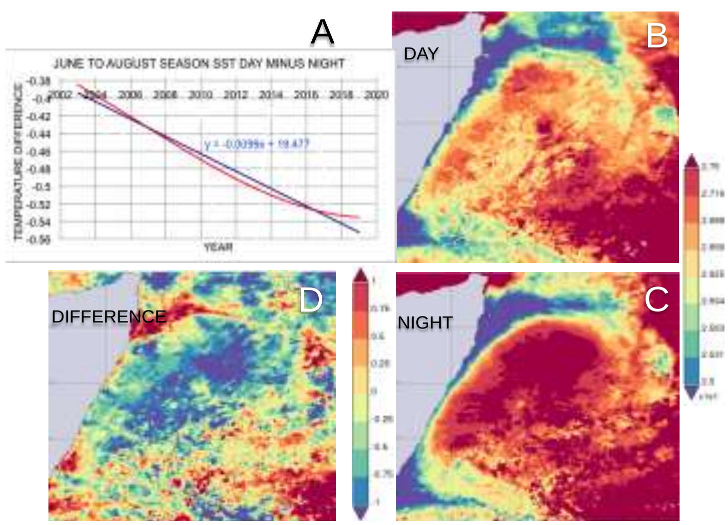

Figure 10: A: Difference daytime sea surface temperature minus nighttime sea surface temperature at 11µm (^{o}C) based on monthly averaged measurements as in Figure 9B but with expanded y-axis and linear and polynomial fits. B: Monthly averaged daytime sea surface temperature for July 2020. C: Same as B but for nighttime sea surface temperature measurements. D: Temperature differences, day minus night, for July 2020.

CONCLUSIONS

This study gives evidence of the dramatic changes in the northwest Indian Ocean and oscillatory nature in temperature, chlorophyll and wind velocity that appear at different time scales with possible period changes that are given in the summary in Table 1.

Table 1: Estimated half periodic changes in sea surface temperature and chlorophyll concentrations according to seasons for the main region of observations and temperature measurements at Ras Hafun. Numbers in parenthesis give the years.

SEASON	SST MAIN	SST RAS HAFUN	CHLOROPHYLL	WIND SPEED
DJF	2009-2017 (8)	2011-2018 (7)	Not recognized	1996-2013 (17)
MAM	Not recognized	2007-2014 (7)	2010-2015 (5)	1990-2009 (19)
JJA	10	Not recognized	2011-2017 (6)	Not recognized
SON	Not recognized	2006-2014 (8)	2011-2017 (6)	1980-2015 (25)
AVERAGE YEARS	9	7.1	5.7	20.3

Based on Table 1, fluctuations show that chlorophyll and temperature may appear with a half-period of about six to nine years whereas wind speed changes seem to change at larger time scales. The results indicate variability that may be a manifestation of decadal oscillations and that the observed variability in temperature and chlorophyll is not an effect of global warming alone, rather a combination of several factors. The opposite trend in chlorophyll compared to temperature is an effect of surface warming and building of a deeper mixed layer that reduces nutrient supply to the euphotic zone. This is deducted from the observation of the upwelling core that has similar increase in temperature as the main area. In addition, the decadal fluctuations and inter-annual phenomena may overlap, added to each other or subtracted from their amplitudes that would add further to an already complicated interpretation of observation.

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