9 Seasonal and Inter-Annual Variation of Chlorophyll and Sea Surface Temperature in Northern and Southern Arabian Sea, India

S. Abhilash, R. Nirmala, and Aravind Sahay

Abstract

Arabian Sea is a dynamic and productive sea due to its long borders and open ocean processes, which evident as upwelling during summer and cooled in winter, especially in the northern regions. The present study aims to discuss the seasonal, inter-annual variations and distinct differences of chlorophyll-a (Chl-a) between Northern Arabian Sea (NAS) and Southern Arabian Sea (SAS) using the MODIS data from 2003 to 2019. The annual mean Chl-a values in NAS are 1.89 mg/m^3 which is large difference compared to 0.44 mg/m^3 in SAS. Seasonal variations in February, March and September, the average Chl-a in the NAS were 3.07 mg/m^3, 2.79 mg/m^3 and 2.51 mg/m^3 and the SAS found average Chl-a value in July, August and September were 1.01 mg/m^3, 1.20 mg/m^3 and 1.20 mg/m^3, respectively. From December to March, which are the cooler months with mean SST of 24.2–25.5 °C in the NSA and 26.7–27.8 °C in the SAS, coincided with the peak months of Chl-a concentration. The SAS recorded the highest monthly SST in May at 29.9 °C and lowest at 26.2 °C in August and 29.3 °C in June and least 23.6 °C in February, NAS showing more complexity than the SAS. The results show that trend of chlorophyll concentration and SST are not consistent for the year and vary greatly with the seasons and that Chl-a concentration shows an inverse relationship with SST. Convection and surface cooling in northern region by increased evaporation and reduced solar radiation makes NAS more productive compared to SAS in the winter and also productive in the summer due to coastal fluctuations.

Keywords

Arabian Sea · Chlorophyll · Sea surface temperature

9.1 Introduction

Plankton is an indicator of climate change (Hays et al. 2005; Taylor et al. 2002; Adrian et al. 2009; Richardson 2008) because their growth and development directly impacts the temperature change of the plankton population during seasonal during seasonal periods of growth (Adrian et al. 2006; Berger et al. 2010; Schulter et al. 2010 and Theckeray et al. 2012). Recent work has shown that in the case of phytoplankton, it

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changes not only in temperature but also in the seasonal cycles that have been shown to contribute to nutrient load (Theckeray et al. 2008; and Theckery 2012). The inherent chlorophyll depth derived from the satellite is associated with the amount of particles present in the water and the coefficient of extinction of the water (Smith 1981; Sergey et al. 2012; Gordon and Mccluney 1975).

The presence of chlorophyll at appropriate concentrations indicates a healthy ecosystem. However, under certain environmental conditions, it tends to overgrow in the short term (Sathyenadranath et al. 1996). High concentration of chlorophyll is visible to naked eye, and water can looks blue, blue-green, green, and red depending on the type of pigments in the particular plankton. Each plankton species has different favourable conditions that promote its growth and reproduction. Also the ocean colour studies are using remote sensing techniques to understand phytoplankton concentration and their impact on climate change (Morel 1980; Sturm 1993; Gordon and Wang 1994). Chlorophyll growth depends on SST and nutrient levels in the sea and is more abundant in cold water. This impact study may help predict the occurrence of oceanographic conditions in the study area for future outbreaks of these events, and may be helpful in implementing fisheries related management measures in this particular study area.

9.2 Materials and Methods

9.2.1 Study Area

The Arabian Sea has an area of 6.225×10^6 km^2. and extends from 0° to 25° N and 50° to 80° E (Qasim 1977). It is bordered by Oman at the west, Iran at the northwest and India in the east (Fig. 9.1). The Arabian Sea is the one of the world's most biologically productive regions and subject to seasonal reverse monsoon wind system, with blooms in the winter monsoon season (December–March) and the summer monsoon (June–September) under strong seasonality. The summer blooming is driven by upwelling process such as lateral advection, wind mixing, mesoscale eddies, filaments and Ekman pumping (Margulis et al., 1990; Deuser et al., 1990 and Lee et al., 2000) which play a key role in supplying nutrients to the euphotic zone during the summer.

In the spring-inter monsoon (April–May), the water is mostly oligotrophic and has low chlorophyll pigment concentration (Madhupratap et al, 2001), but the fall-inter monsoon season (October–November) represents the tipping point of the summer monsoon, with chlorophyll pigment concentration rapidly declining (Banse, 1987; Smith 1998; Wiggert et al. 2005 and Prasanna Kumar et al. 2000). The inter-annual variation of the chlorophyll in the Arabian Sea is poorly explored and understood. The present study mainly focuses on the northern and southern part of Arabian Sea.

9.2.2 Methods

Moderate resolution imaging spectroradiometer (MODIS) on board aqua satellite data from NASA-OPG from 2003 to 2019 was used to obtain monthly chlorophyll-ocx level-3 data with spatial resolution of 4 km (NASA Ocean colour Web) (Table 9.1). MODIS data is useful for tracking changes in the ocean over time (NASA MODIS Web). The SeaWiFS Data Analysis System (SeaDAS) is a software for extracting ocean colour data for chlorophyll and SST analysis. The monthly climatological images are merged in SeaDAS to form seasonal climatological images and statistical analysis is done by Microsoft Excel to find out the values, and then, seasonal variations are plotted. The same analysis pattern applied in case of SST is followed in this case also. The SST values of pre-monsoon, summer monsoon, winter monsoon and post-monsoon seasons of each year and inter-annual variations are plotted to determine differences by season.

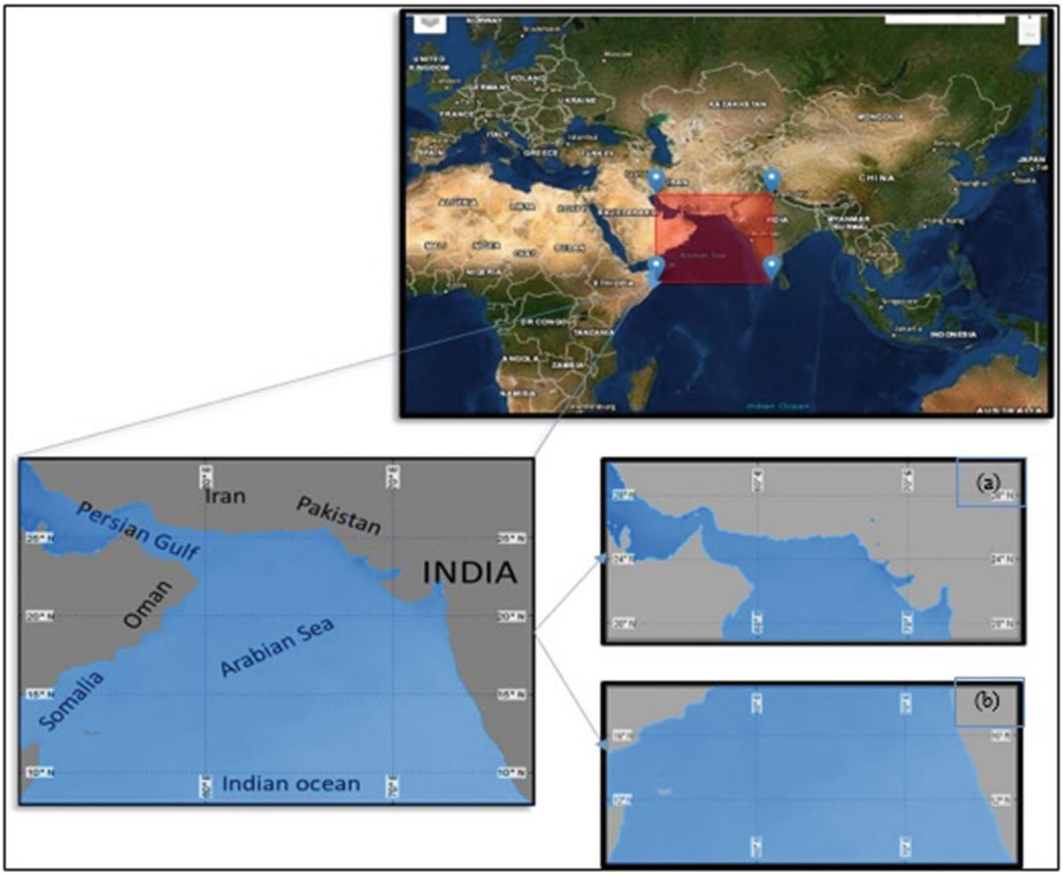

Fig. 9.1 Study area map **a** Northern Arabian Sea and **b** Southern Arabian Sea

Table 9.1 Channel of MODIS Aqua

Uses	Bands	Band width (nm)
Ocean colour/phytoplankton	8–16	405–877
Surface temperature	31	10.780–11.280
	32	11.770–12.270

9.3 Results and Discussion

The present analysis aims at accessing Chl-a and SST variability in the NAS and SAS from 2003 to 2019 by SeaDAS software (Figs. 9.2 and 9.3). Using ocean colour observations reveals that the Chl-a distribution exerts a controlling influence on seasonal evolution of SST (Kamykowsi 1987; Hood et al. 1990; Sathyendranath et al. 1991; Muller-Karger et al. 1991; Chaturvedi et al. 1998a, b).

9.3.1 Analysis of Northern Arabian Sea (NAS)

Monthly variation of the mean concentration of chlorophyll-a and SST (Fig. 9.4) between 2003 to 2019 is inversely correlated, i.e. sea surface temperature increases but chlorophyll concentration decreases and vice-versa. Chlorophyll concentration variability changes by season due to coastal upwelling and wind mixing affect the chlorophyll concentration (Banse 1987; Prasanna Kumar et al. 2000; Smith 1998 and Wiggert et al.

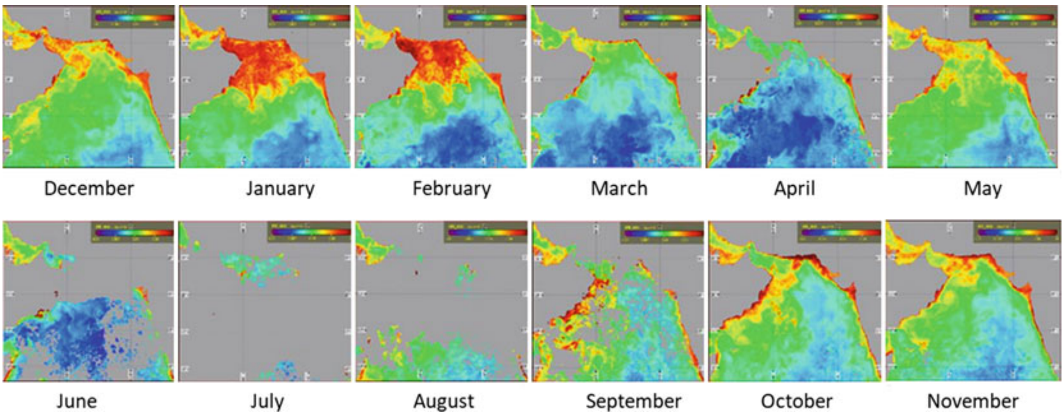

Fig. 9.2 Spatial variation of CHL (mg/m^3) in the NAS and SAS during 2003–2019 with MODIS Aqua data

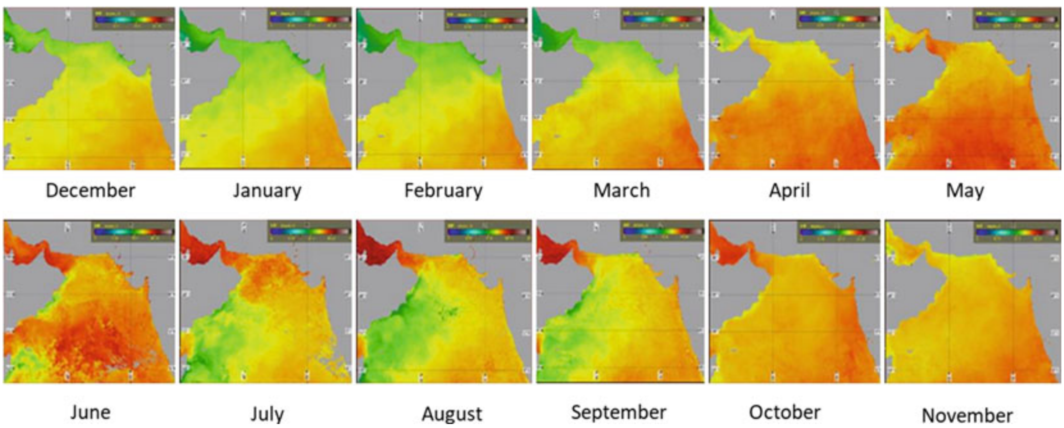

Fig. 9.3 Spatial variation of SST (°C) in the NAS and SAS during 2003–2019 with MODIS Aqua data

2005) and the NAS (the coastal region of Oman and Arabian Gulf) has shown high chlorophyll pigment density.

9.3.2 Seasonal Variation of Chlorophyll and SST (NAS)

Monthly and seasonal mean are calculated for the spring, winter, summer and fall-inter monsoon (Fig. 9.4). Their monthly mean chlorophyll pigment concentration in the NAS from 2003 to 2019 shows second peak with the highest chlorophyll concentration in September after a strong season with a primary peak in February. The summer monsoon season ranges from 0.47 mg/m^3 to 3.4 mg/ m^3 (Sept. 2004), then from 0.59 mg/m^3 to 2.93 mg/m^3 (April, 2019) in the spring-inter monsoon, from 1.04 mg/m^3 to 5.79 mg/m^3 (Mar 2017) in winter season and from 0.97 to 2.87 mg/ m^3 (Nov. 2006) during fall-inter monsoon season.

Analysing all the averages of chlorophyll concentrations in NAS from 2003 to 2019, the highest concentration were found in February (3.07 mg/m^3) and March (2.79 mg/m^3) with SST minimum values and the lowest Chl-a values in May (0.78 mg/m^3) with highest values in the case of SST. The maximum SST value is found in the year 2019 (29.5 °C) to least 2013 (27.8 °C). The months of October and November fall in

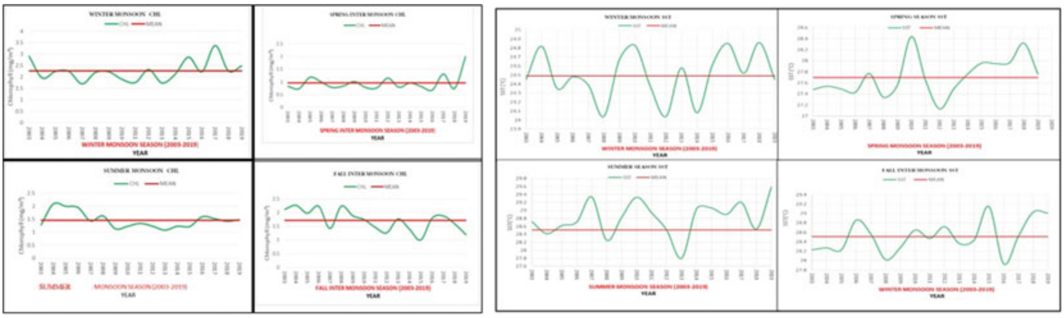

Fig. 9.4 Variation in Chl-a and SST during four different seasons from 2003 to 2019 of NAS

the post-monsoon season period (Fall-inter) and this shows the mean value (28.51 °C), which is higher than the winter monsoon and lower than the summer monsoon and depicts the high and low values for 2015 (29.15 °C) and 2008 (28.02 °C), respectively (Fig. 9.5).

9.3.3 Inter-Annual Variation of Chlorophyll (NAS)

The inter-annual variation of chlorophyll over the year 2003–2019 shows a slightly decrease with a negative slope of − 0.0042 (R^2 = 0.0075), with some notable positive and negative anomalies in some years (Fig. 9.6). The highest peak found in 2008 shifted from the grand mean (mean of 2003–2009) with the chlorophyll value in 2017, of which 2017 has the most positive anomaly (i.e. + 2.37 mg/m^3). The 2007 maximum value is depicted negative anomaly during the study period (i.e. −1.49 mg/m^3) and from 2009 to 2014 show a negative anomaly. The inter-annual variation of SST over the year 2003–2019 shows an increasing trend with positive slope of 0.0248 with some significant positive and negative anomalies over the years. The years 2015, 2016, 2017, 2018 and 2019 showed an increase in SST from the grand mean (mean of 2003–2019), of which 2015 had the highest positive anomaly (i.e. + 0.52 °C). The 2008 depicts a peak negative anomaly of − 0.64 °C.

9.3.4 Analysis of Southern Arabian Sea (SAS)

The Southern Arabian Sea is affected by the south West Monsoon (SWM), with a lower chlorophyll concentration compared to northern part and higher chlorophyll found in winter and summer season (Khole 2005) while the

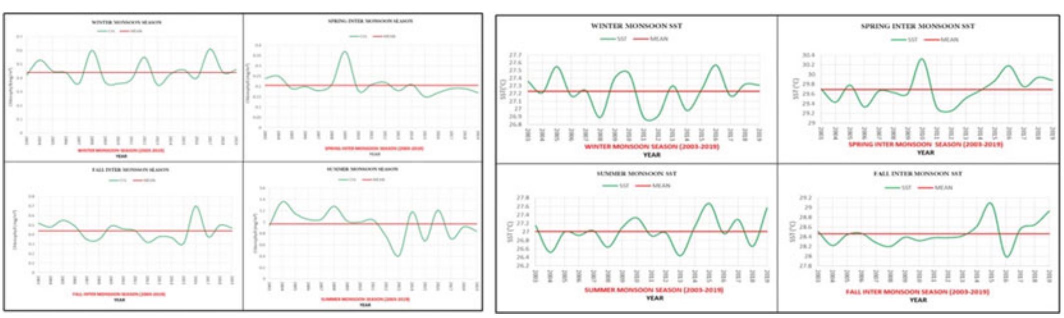

Fig. 9.5 Variation in Chl-a and SST during four different seasons from 2003 to 2019 of SAS

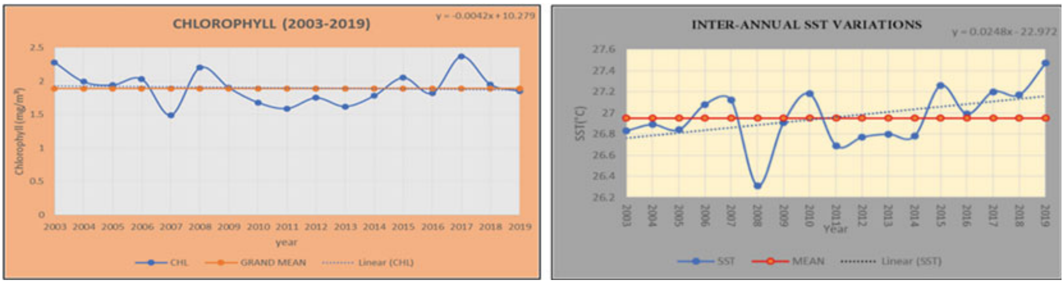

Fig. 9.6 Inter-annual chlorophyll and SST variability for the period 2003 to 2019 of NAS

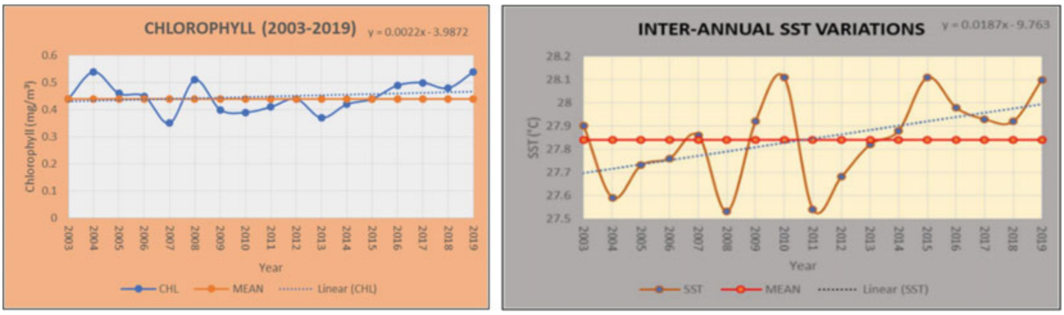

Fig. 9.7 Inter-annual chlorophyll and SST variability for the period 2003 to 2019 of SAS

chlorophyll concentration during the summer monsoon is higher than in winter. The highest value of chlorophyll concentration was recorded in February 2008 (0.91 mg/m^3), showing normal chlorophyll concentration in winter, with no significant differences this season. The same chlorophyll value was 0.41 mg/m^3 Jan and Feb 2007 but there were changes in SST (26.3 °C and 27.2 °C), respectively. The highest SST observed in March 2004 (27.9 °C) with a chlorophyll concentration of 0.31 mg/m^3 was due to the end of winter season, and the lowest SST was 0.48 mg/m^3 in Jan 2011.

Strong winds of the SWM are generally present at the centre of Arabian Sea from mid-June to late-September (Banse et al. 2000), affecting the southwestern Arabian Sea more than south-eastern region. The SAS from 2003 to 2019, most of the chlorophyll is found in the year of July 2008 (2.54 mg/m^3) and the remaining years was less than 1 mg/m^3. From June to July, the chlorophyll concentration increased rapidly with an increase of 2.19.

9.3.5 Seasonal Variation of Chlorophyll and SST (SAS)

The winter monsoon season shows the least values of chlorophyll (i.e. values range from 0.35 to 0.61 mg/m^3) compared to the summer season and greater than the other seasons. Year 2009 shows the maximum chlorophyll concentration, which then depicts a negative anomaly. The value of the summer monsoon season ranges from 0.4 mg /m^3 to 1.36 mg /m^3 slightly greater compared to the other season. From 2003 to 2011, the values are slightly higher, later it shows a declining trend when compared to their mean values.

9.3.6 Inter-Annual Variation Chlorophyll and SST (SAS)

The inter-annual variation of chlorophyll from 2003 to 2019 shows a slightly increasing trend with a positive slope of + 0.0022 (R^2 = 0.0396) and depicts positive and negative anomalies in few years and from 2009 to 2015, chlorophyll has been shown to decrease from the grand mean (Fig. 9.7). Both 2004 and 2019 showed a very high peak in chlorophyll values (both 0.54 mg/m^3) with positive anomaly from the grand mean (i.e.0.1 mg/m^3). But in 2007 shows maximum negative anomaly during the study period (i.e. − 0.09 mg/m^3).

The inter-annual variability of SST in SAS shows a large difference in some years with great negative and positive anomalies. From 2003 to 2019, the linear trend curve shows an increasing trend with a positive slope of 0.0187. The 2010, 2015 and 2019 show same maximum values of SST (i.e. 28.1 °C). In 2008 and 2011, it showed maximum negative anomaly from the grand mean (2003–2019), with a negative anomaly of − 0.31 °C in 2008 and a positive anomaly of + 0.27 °C in 2010.

9.3.7 Chlorophyll and SST Variation

The spatial distribution of chlorophyll-a concentrations is completely different in the two regions; the northern region has high chlorophyll-a concentrations in February–March and low in August–September, but is completely opposite in the case of SAS. Additionally, there was a decrease in maximum and minimum monthly values in the two regions offshore. The highest chlorophyll-a concentration was recorded in the Northern Arabian Sea, was far higher than the Southern Arabian Sea.

The 16-year monthly SST from MODIS data showed an annual average of 27.5 °C for the entire region, 29.65° C in the NAS, and 27.84 °C in the SAS (Fig. 9.5). The minimum monthly SST in the NAS was recorded in February and SAS have found in August. The NAS showed relatively lower SST compared to the SAS and April is the transition from a relatively mild winter SST to warm summer SST. The monthly variation of SST in the NAS and SAS behaves differently. Remote sensing-to-ocean communication is the most effective tool for analysing global oceanic physical and biological changes with coastal zone colour scanner (CZCS). This is the only option to study the expected changes in future (Chaturvedi. 2005).

9.4 Conclusions

The behaviour of the Arabian Sea is differs from what is traditionally understood as a tropical basin due to its high salinity, reverse of monsoons, fluctuations of the coastal and open sea, and the effects of winter season cooling with a variety physical processes in summer and winter. The annual mean chlorophyll-a values in NAS showed a better contrast with higher average chlorophyll-a compared to SAS concentrations in February, March and September along the coast. The SAS showed higher average chlorophyll-a concentration in December–February and decreased in April and May. In NAS, the maximum single month chlorophyll-a value was recorded at 5.76 mg/m^3 in March 2017 and at least 0.53 mg/m^3 in July 2003, while the SAS in July 2008 recorded a maximum of 2.54 mg/m^3 and a minimum of 0.15 mg/m^3 in June 2015. The monthly variation of SST in NAS and SAS behaves differently, with the least monthly SST in the NAS recorded in February and SAS in August. The NAS showed relatively low SST compared to SAS, and April transitioned from a relatively mild winter SST to a warm summer SST. In the winter, the NAS becomes a biologically highly productive area due to winter cooling and enhanced evaporation from dry continental air under low incoming solar radiation. Since the ambient salinity of the NAS is high and sufficient cooling to increase the density and initiate convection. In south central waters, high productivity is caused by nutrient rich and high water advection from Somalia.

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