MONITORING CHLOROPHYLL-A AND SEA SURFACE TEMPERATURE VARIATIONS IN SE ARABIAN GULF AND NW SEA OF OMAN FROM MODIS AQUA DATA

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KEY WORDS: Chlorophyll-a, Sea surface temperature, NW Sea of Oman, SE Arabian Gulf, Remote sensing

ABSTRACT: Chlorophyll-a (chl-a) and sea surface temperature (SST) recorded by MODIS-Aqua from 2002-2015 show pronounced monthly, seasonal, interannual and spatial variability and distinct differences between NW Sea of Oman and the adjoining SE Arabian Gulf. The annual average chl-a values in NW Sea of Oman was 1.86 mg m^{-3} compared to 1.78 mg m^{-3} in the SE Arabian Gulf, which showed the lowest variability. Seasonal variations consisted of the highest chl-a concentrations in February and March and the lowest in May, June, and July ranging from 0.85 to 2.92 mg m^{-3} in the SE Arabian Gulf and from 0.37 to 4.96 in mg m^{-3} NW Sea of Oman. During the spring bloom in February and March, the average chl-a in the NW Sea of Oman was 4.96 and 4.69 mg m^{-3} and SE Arabian Gulf was 2.92 and 2.19 mg m^{-3}. In the Arabian Gulf, spring bloom concentrations in the deeper waters were much lower than deeper waters in the Sea of Oman. January to March, which were the coolest months with average SST of 22.6-23.5ºC in the Sea of Oman and 21.3-22.4ºC in the Arabian Gulf, coincided with the peak months of chl-a concentrations. The Sea of Oman area recorded the highest monthly average of 31.4ºC in July and a minimum of 22.6ºC in February whereas the highest of 32.5ºC was recorded in the Arabian Gulf in July and the minimum of 21.3ºC in February. Mean monthly chl-a and SST values were slightly more negatively correlated in the NW Sea of Oman ($r = -0.73$, $p < 0.05$) than the SE Arabian Gulf ($r = -0.56$, $p < 0.05$). The variations in chl-a concentrations in the Sea of Oman showed more complexity than the SE Arabian Gulf. The highest chl-a concentrations were observed in November 2008 and continued to March 2009.

Keywords: Chlorophyll-a, Sea surface temperature, NW Sea of Oman, SE Arabian Gulf, Remote sensing

1. INTRODUCTION

Remote sensing of ocean properties provides a window into the ocean ecosystem on a synoptic scale, and has tremendous potential to deliver essential information on chlorophyll-1 (chl-a) distribution and sea surface temperature (SST) compared to conventional in situ sampling methods from ships or drifting buoys in the sea. Ocean color satellites including Sea-Viewing Wide Field-of-View Sensor (SeaWiFS) and Moderate Resolution Imaging Spectroradiometer (MODIS) have been recording upwelling radiance SST and chl-a concentrations that have been extensively used for the analysis of the seasonal and inter-annual variability of the highly-dynamic characteristics of the marine environment, and also for the determination of spatiotemporal patterns and trends (Werdell et al., 2009; Moses et al., 2009; Waite and Mueter, 2013; Odermatt et al., 2012). It is imperative that with the ever growing satellite data and the application of new and innovative processing techniques several additional information could be generated even for areas that have been studied previously. This study focuses on the inter-annual and inter-monthly variability of chl-a concentrations and SST in the NW Sea of Oman and the adjoining SE Arabian Gulf from MODIS data recorded from 2002 to 2015. Emphasis is on the similarities and differences between the adjoining waterbodies over the years from the chl-a and SST data.

The Arabian Gulf and NW Sea of Oman are located in a harsh arid environment with extreme hot temperatures but are known to be one of the most productive benthic waterbodies in the world (Price, 1991). The area is one of the most economically important waterbodies as approximately 60% of the world's marine oil transport passes through every year. The Sea of Oman forms the NW arm of the Arabian Sea which is interconnected to the Arabian Gulf through the Strait of Hormuz (Figure 1). The Arabian Gulf has an average depth of 36 m and a maximum depth of 120 m near to the Strait of Hormuz. The asymmetric floor of the Arabian Gulf slopes from the shallow deltaic northern waters to the deeper southern waters and from the shallow west to deeper waters to the east along the coast of Iran. The bathymetry of NW Sea Oman increases gradually from the Strait of Hormuz southeastwards to depths exceeding 3500 m. The northwesterly *Shamal* which is the most predominant wind in the area occurs throughout the year. The winds are slightly stronger from November-February (~5 ms^{-1}) than from June-September (~3 ms^{-1}). However, the winds can reach 15-20 ms^{-1} during a typical *Shamal* (Perrone, 1979). The Sea of Oman is affected by the overall tropical weather systems in the Arabian Sea and Indian Ocean. Summers are characterized by southerly winds and the winters strong northerly winds. The tidal response in the Arabian Gulf is controlled by forcing through the Strait of Hormuz and consists of semi-diurnal and diurnal signals. Tidal elevations range from 0.5-1.5 m and tidal velocities between 0.2-0.5 ms^{-1} (Blain, 1998). The western Arabian Sea, which includes the Sea of Oman is characterized by strong eddies with intraseasonal variation which is dominated by monsoonal forcing (Kim et al., 2001). The currents are dominated by the eddy field. The region is well known for its biological productivity (Madhupratap et al., 1966). The Gulf is characterized by high salinity water and the Strait of Hormuz serves as the link between the hypersaline Arabian Gulf and the low salinity of the Sea of Oman.

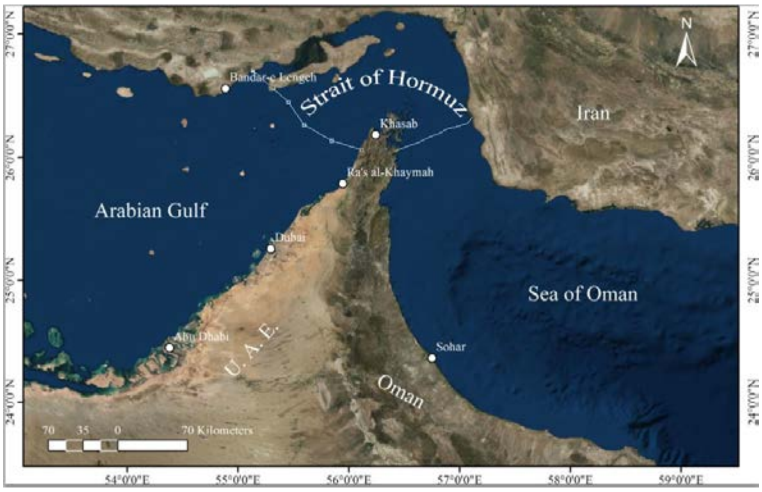

Figure 1. Location map of SE Arabian Gulf, Strait of Hormuz and NW Sea of Oman. The white lines show the approximate boundaries used for NW Sea of Oman, Strait of Hormuz and SE Arabian Gulf used in this study.

Moradi and Kabari (2015) used wavelet transforms to analyze the spatiotemporal variability of MODIS chl-a and SST data in the Arabian Gulf recorded from 2002 to 2013. They observed seasonal variability in chl-a and SST and related them to input from rivers, circulations patterns and potential climate change. Other studies using the combination of satellite derived chl-a and SST have been used to characterize the variability of short-term phytoplankton blooms, long-term changes in temperature and coastal upwelling and mesoscale eddies in the NW Arabian Sea and Sea of Oman (Tang et al., 2002; Piontkovski and Chiffings, 2014; Piontkovski and Al-Jufaili, 2013; Piontkovski and Nezlin, 2012).

2. METHODOLOGY

In this study, we utilized the concurrent daily daytime MODIS Aqua Level 2 chl-a and SST data that were retrieved from NASA's OceanColor website (http://oceancolor.gsfc.nasa.gov). The data which have been processed by NASA's Ocean Biology Processing Group (OBPC) to incorporate the latest algorithms and instrument calibrations were extracted to produce the longest available continuous time series for the study area from September 2002 to April 2015. Standard Level-2 flags were used to mask land and cloud areas which were subsequently excluded from further processing. All processing were conducted using SeaDas 7.1 ocean color image analysis software (http://seadas.gsfc.nasa.gov/). The spatiotemporal variability of chl-a concentrations and SST and their relationship was examined based on (1) analysis and examination of monthly and yearly climatologies, (2) statistical analysis of monthly chl-a and SST, and (3) empirical orthogonal function (EOF) analysis of the 13 years monthly anomaly time series. Monthly chl-a climatologies were created by averaging each individual month over the entire 13 year period. Yearly climatologies were generated by averaging the 12 months within each year for which chl-a data were available.

3. RESULTS
3.1 Chl-a Variation

Monthly climatologies depicted in Figure 2 show pronounced spatiotemporal changes in chl-a concentrations recorded in the 13 year period in the SE Arabian Gulf and NW Sea of Oman. The annual average of chl-a concentrations for the whole study area was 1.79 mg m^{-3}; however, the averages for the SW Arabian Gulf and NW Sea of Oman regions were 1.78 and 1.86 mg m^{-3}, respectively. The maximum single day chl-a value of 99.65 mg m^{-3} was recorded in the Arabian Gulf in February 2008. On the other hand, the maximum single day chl-a value in the Sea of Oman was 93.14 mg m^{-3} and was recorded in January 2012. The minimum single day concentrations of 0.07 and 0.13 mg m^{-3} were recorded in June 2003 and 2012 in the Sea of Oman and Arabian Gulf, respectively. February and March produced the overall highest average chl-a concentrations of 3.88 and 3.02 mg $m^{-3,}$ respectively—the so-called spring bloom— in the entire study area, 2.92 and 2.19 mg m^{-3} in the Arabian Gulf and 4.96 and 4.69 mg m^{-3} in the Sea of Oman.

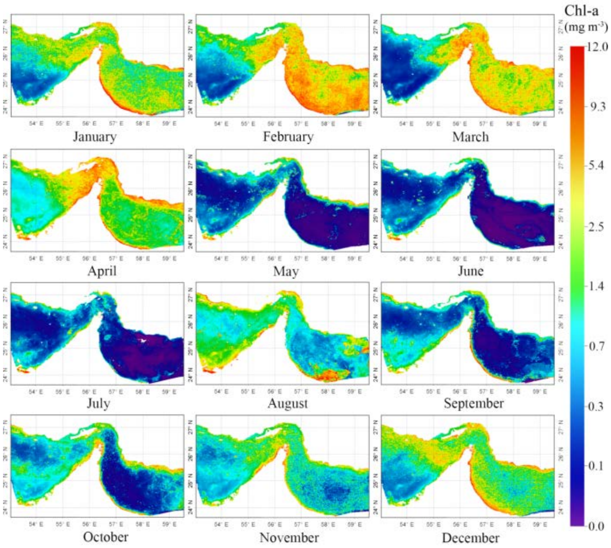

Figure 2. Monthly mean chl-a climatologies for SE Arabian Gulf and NW Sea of Oman recorded from 2002-2015.

The spatial distribution chl-a concentrations in February and March were similar but completely different in the two regions. In the Sea of Oman, higher concentrations were observed in shallow waters along the coastline. In the Arabian Gulf, spring bloom concentrations in the deeper waters were much lower than in deeper waters in the Sea of Oman. The month of April showed a drastic decrease in the average chl-a concentrations from the previous two months with an average of 1.21 mg m^{-3} in the entire region, 1.67 mg m^{-3} in the Arabian Gulf and 1.42 mg m^{-3} in the Sea of Oman. In addition, there were decreases in the maximum and minimum daily values in the two regions. The decrease was most evident in the offshore. However, the chl-a concentration remained high and in some areas increased in the area centered on the Strait of Hormuz and the adjoining two water bodies, and also in shallow waters. The months of May-July ushered in the peak season of low summer chl-a concentration in the whole study area. The average lows ranged from 0.67 to 0.74 mg m^{-3} in the whole region, 0.85 to 0.96 mg m^{-3} in the Arabian Gulf and 0.37 to 0.57 mg m^{-3} in the Sea of Oman area. The months also recorded the lowest single day highs as well the minimum single day lows chl-a concentration in both regions. Relatively high chl-a concentrations were recorded along the coastal waters in the two regions; however the deeper water, especially in the Sea of Oman remained the lowest. During the summer period, some blooms were recorded along the coastline and shallow waters. A systematic increase in chl-a concentrations was recorded from August to January, prior to the spring bloom. During those months the average chl-a concentrations ranged from 0.93 to 2.21mg m^{-3} in the whole study area, 0.92 to 2.63mg m^{-3} in the Arabian Gulf, and 0.66 to 2.46 mg m^{-3} in the Sea of Oman. Additionally, there were increases in the daily maximum and minimum chl-a concentrations in the two water bodies. During the period the bloom in coastal shallow waters was relatively high. The chl-a concentrations and times series for the whole study area shows the gradual increase from November till the peak in February and March (Figure 3). The highest chl-a concentrations which occurred during the spring bloom were recorded in the Sea of Oman in 2003, 2004, 2006, 2008, 2009, 2010 and 2013. In the Arabian Gulf area, the most prominent spring bloom was recorded in 2009. The magnitude of the highest blooms in the Sea of Oman was far higher than the Arabian Gulf except in 2009.

3.2 SST Variations

The 13-year monthly SST from MODIS showed an annual average of 27.5^{o}C for the whole area, 27.4^{o}C in the Arabian Gulf, and 27.5^{o}C in the Sea of Oman. The maximum and maximum daily temperature of 36.6^{o}C and 14.7^{o}C, respectively, were recorded in the Arabian Gulf Figure. 4 shows that January-March were the coolest months with the average temperatures of 22.5-23.5^{o}C in the entire study area, 21.3-22.4^{o}C in the Arabian Gulf and 22.6-23.5^{o}C in the Sea of Oman. The minimum monthly SST in the entire study area, Arabian Gulf and Sea of Oman were recorded in the month of February. The Arabian Gulf showed relatively lower SST compared to the Sea of Oman. The adjoining Sea of the Strait of Hormuz displayed SST that were more similar to others part of the Arabian Gulf. The month of April was the transition from the relatively mild winter SST to warm summer SST. During that month the Arabian Gulf was about 1.3^{o}C cooler than the Sea of Oman. May to October were the long and hot summer months with the peak SST of 32.46^{o}C in the Arabian Gulf in August and a peak of 31.4^{o}C in the July in the Sea of Oman. From August to October the waters in the Arabian Gulf were 1-1.5^{o}C warmer that the Sea of Oman. The hot summer SST gradually dropped off to milder SST in November and December. In December the Arabian Gulf SST was lower compared to the Sea of Oman. The monthly variation of SST in the Arabian Gulf and Sea of Oman is presented in Figure 5 which shows that the two water bodies behaved differently. SST showed moderate inter-annual variability of around 2^{o}C.

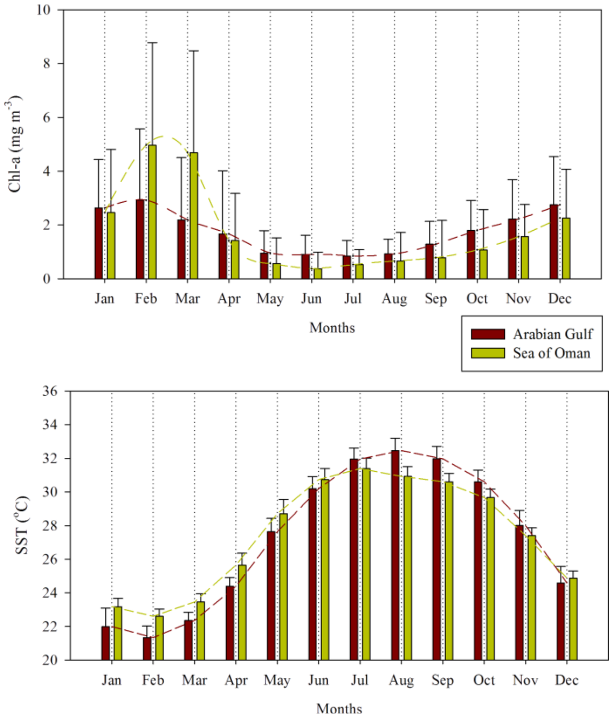

Figure 3. Monthly variations of chl-a concentrations and SST in the SE Arabian Gulf and NW Sea of Oman.

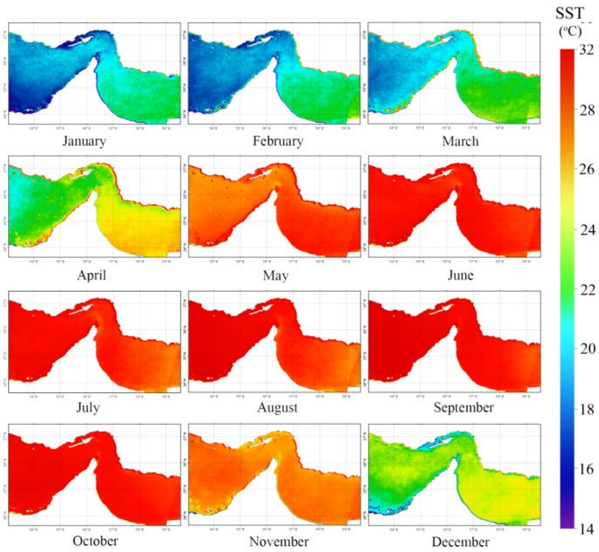

Figure. 4. Monthly mean SST climatologies for SE Arabian Gulf and NW Sea of Oman recorded from 2002-2015.

3.3 Chl-a and SST Anomalies

The most noticeable blooms with highest positive anomalies in the Sea of Oman were recorded in 2003 and 2009, whereas the most prominent blooms in the Arabian Gulf were in 2004, 2007 and 2009 with the later coinciding with similar bloom in the Sea of Oman. In the Sea of Oman prominent negative anomalies were recorded in 2004, 2005, 2007, 2011 and 2014. Several negative anomalies were also observed in the Arabian Gulf with the significant ones occurring in 2003, 2007, 2010, 2012, 2013 and 2014. SST varied between 20-33^{o}C during the study period. The months of May to October were consistently high whereas November to April were relatively mild (Figure 5). Inter-annual SST variation was minimal. In general the SST variation in the Arabian Gulf was relatively higher in the summer and lower in the winter months compared to the Sea of Oman. In the Arabian Gulf prominent positive

SST occurred in 2004, 2005, 2006 and 2010. On the other hand strong negative SST anomalies were recorded in 2006, 2008, 2009, 2012 and 2013. The Sea of Oman region recorded several positive and negative anomalies. The significant positive anomalies occurred in 2004, 2005-2006, 2009-2010 and 2013. Prominent negative anomalies occurred in 2003, 2004, 2007, 2008, 2009, 2012 and 2013.

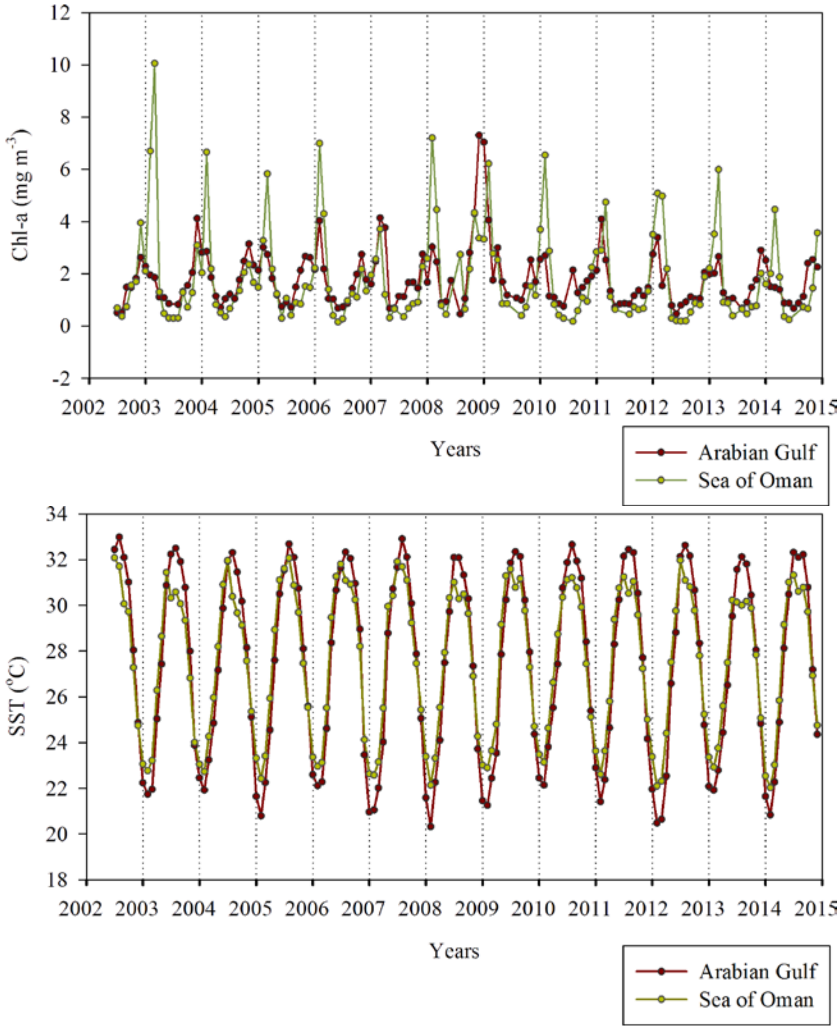

Figure 5. A time series of chl-a concentrations and SST in SW Arabian Gulf and NW Sea of Oman.

Mean monthly chl-a and SST values were negatively correlated for the whole study area ($r = -0.69$, $p < 0.00$). The Sea of Oman ($r = -0.73$, $p < 0.05$) was more negatively correlated than the Arabian Gulf ($r = -0.56$, $p < 0.05$). Enhanced chl-a values were more associated with relatively cooler SST. The Sea of Oman showed high positive correlation and statistically significant values from February to May with the highest positive correlation ($r = 0.959$, $r = 0.000$) recorded in March. During those months the Arabian Gulf showed some relatively lower positive and insignificant correlation. The chl-a and SST correlation in the Sea of Oman during the months of June, July and August were relatively lower than the previous months and statistically insignificant. From February to August, the correlation in the whole study area remained negative and statistically insignificant.

4. CONCLUSIONS

Chl-a concentration and SST data from MODIS-Aqua acquired between 2002 and 2015 were analyzed and used to map the difference between NW Sea of Oman and SE Arabian Gulf which are interconnected through the Strait of Hormuz. Spatiotemporal distribution of the satellite-derived data showed distinct monthly, seasonal and interannual differences between the two adjoining waterbodies. The annual average chl-a values in NW Sea of Oman was 1.86 mg m^{-3} compared to 1.78 mg m^{-3} in the SE Arabian Gulf which showed the lowest variability. The Sea of Oman area experienced higher average chl-a concentrations in February and March than the Arabian Gulf. However, for the rest of the months the chl-a values in the Arabian Gulf were much higher. The peak chl-a concentrations were recorded in February and March and dropped to lows in May, June and July. During the spring bloom in February and March the average chl-a in the Sea of Oman was 4.96 and 4.69 mg m^{-3} and SE Arabian Gulf was 2.92 and

2.19mg m^{-3}. The spatial distribution of chl-a concentrations in February and March were similar but completely different in the two waterbodies.

In the Sea of Oman, higher concentrations were observed in shallow waters along the coastline. In the Arabian Gulf, spring bloom concentrations in the deeper waters were much lower than deeper waters in the Sea of Oman. From August the chl-a concentration increased systematically till another spring bloom the following year. In SE Arabian Gulf the maximum single day chl-a value of 99.65 mg m^{-3} was recorded in February 2008 and the minimum single day value of 0.13 mg m^{-3} in June 2012. The Sea of Oman recorded the maximum single day chl-a concentration of was 93.14 mg m^{-3} in January 2012 and the single day minimum of 0.07 mg m^{-3} in June 2003.

January to March, which were the coolest months with average SST of 22.6-23.5ºC in the Sea of Oman and 21.3-22.4ºC in the Arabian Gulf, coincided with the peak months of chl-a concentration. The Sea of Oman area recorded the highest monthly average of 31.4ºC in July and a minimum of 22.6ºC in February. The highest average monthly SST of 32.5ºC was recorded in the Arabian Gulf in July and the minimum of 21.3ºC in February. From December to June the average SST in the Sea of Oman was higher that the Arabian Gulf. However SST in the Arabian Gulf from July to November was about 1-1.5ºC higher than in the Sea of Oman. Mean monthly chl-a and SST values were more negatively correlated in the Sea of Oman ($r = -0.73$, $p < 0.05$) than the Arabian Gulf ($r = -0.56$, $p < 0.05$). Enhanced chl-a values were more associated with relatively cooler SST. From February to May the Sea of Oman showed high positive correlation and statistically significant values with the highest positive correlation ($r = 0.959$, $r = 0.000$) recorded in March. During those months the Arabian Gulf showed some relatively lower positive and insignificant correlation. The chl-a and SST correlation in the Sea of Oman during the months of June, July and August were relatively lower than the previous months and statistically insignificant.

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