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Remotely Sensed Sea Surface Temperature Variations in the Southern Red Sea in Relation to Some Meteorological Variables

Abdullah M. Al-Subhi and **Ahmed M. Taqi**
Faculty of Marine Science, King Abdul-Aziz University
Jeddah – Saudi Arabia
amalsubhi@kau.edu.sa

Abstract. Remote sensing techniques were used to study the sea surface temperature (SST) patterns in the southern Red Sea for the period of January 1993 to December 2007. The results indicated that the surface temperature decreases from the Strait of Bab-al-Mandab towards the north. The temperature is higher on the eastern side of the sea compared to the western side. The changes of SST are associated with air temperature variations and the horizontal wind component especially in Jeddah and Al-Hodeidah. The impact of evaporation is dominant in Jazan region. Multiple regression models for the SST fluctuations were applied to explain the observed SST. The spectrum of SST showed annual and semi-annual components in all sections. The most energetic component is the annual cycle. The semi-annual changes may be due to the effects of surface currents and seasonal changes in wind regime over the Red Sea.

Introduction

Sea surface temperature (SST) plays an important role in the studies of global climate system and upper ocean processes. The SST data are collected by many traditional methods as well as new techniques. Among the later one is the measurements of SST through radiometers onboard of many satellites. The remotely sensed SST data have been verified to be the most useful method because of their wide coverage of the ocean surface. The SST daily and seasonal variations in the Red Sea are affected by many factors including air temperature, evaporation, precipitation, wind regime, currents and topography (Sultan and Ahmad, 1991).

Morcos (1970) summarized many previous works done in the Red Sea. Among these is the SST horizontal pattern shows a decrease of temperature from the north-east to south-west which indicates that high temperature is on the Arabian side and the low temperature is on the African side. Sofianos and Johns (2003) found that temperature pattern is more complicated due to the very weak wind speed observed in the central region of the Red Sea where the wind field is convergent for most of the year. They suggested that the SST maximum is at the center of the basin and decreases toward the two ends of the Red Sea.

Acker *et al*. (2008) showed that winter to summer SST differences is greater in the northern than in the southern Red Sea and SST distribution in the southern Red Sea is remarkably influenced by the wind direction induced by the monsoon. This difference is also linked to changes in air temperature, wind speed and evaporation (Al-Subhi and AL-Aqsum, 2008). Al-Barakati *et al.* (2002) showed that SST increases more regularly from north to south in the southern Red Sea. Sultan and Ahmad (1991) performed spectral analysis on the monthly mean sea surface temperature data near Jeddah (central Red Sea) and showed a dominant annual cycle.

Seasonal pattern of wind stress and thermohaline forces are responsible for the development of the three-layer exchange system during summer observed in the strait of Bab-el-Mandab (Morcos, 1970; Sofianos and Johns (2002). Also, it is believed to be the reason for the wind-induced upwelling in the Gulf of Aden and the southern part of the Red Sea (Patzert 1974; Smeed 1997 and 2000). Morcos (1970) stated that the annual mean evaporation in the Red Sea is 205 cm/year. However, recent estimate for evaporation rate by Matsoukas *et al.* (2007) is 212 cm/yr.

The main objective of the study is to utilize the remotely sensed SST in determining the surface temperature patterns of the southern Red Sea, through the use of AVHRR satellite data. Moreover, the surface temperature will help in understanding the circulation of the surface waters.

Data and Methods of Analysis

The study area which is the southern Red Sea including Bab-el-Mandab lies between latitudes 12° - 21° N and longitudes 37° - 44° E. Figure 1 illustrates the study area and locations of the study regions. The study area consists of three regions for time series analysis. The data were divided to; Jeddah region (A), Jazan region (B), and Al-Hodeidah region (C). Each region is divided into three sections which include; Western (W), Central (C), and Eastern (E) sections. Therefore, all 9 sections are considered for the statistical analysis of SST.

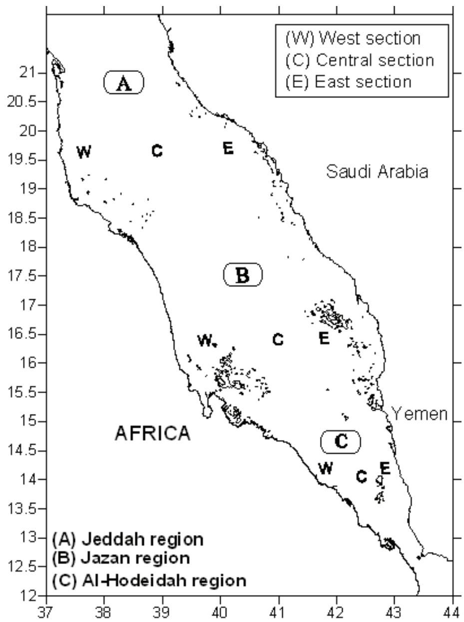


Fig. 1. Map of the study area showing the sections for latitudinal regions of Jeddah, Jazan and Al-Hodeidah.

a. Satellite-Derived SST Data Set

SST data for this study are from January 1993 to December 2007 provided as monthly average data set with a resolution of 0.3°C and high spatial resolution of 4 km. The AVHRR instrument has three infrared (IR) channels, [ch.3, 3.55–3.93 μm; ch.4, 10.3–11.3 μm; ch.5, 11.5–12.5 μm], which are capable of measuring the SST (Robinson, 2004; Reynolds and Smith, 1994; and Walton *et al.*, 1998). The averages of monthly data from satellites are in the gird (0.043945° × 0.043945°), which covers the southern Red Sea (12°N to 22° N and 37° E to 44° E).

All monthly averages (180 months) outline the SST averages for each value of land and sea. The filtered data (grid-points of land are removed) covers the sea in each monthly average data file. Some data set had large missing values at some locations of study area because of clouds, which created a difficulty in investigating the patterns of SST. This problem was solved by averaging all non-cloud pixels array centered on each grid point, constructing a time series at each grid point. Then, data set were reduced to 0.1°×0.1° grids (Fig. 2) to remove errors from data values because of missing numbers. The SST data are in the form of digital numbers (DN). From these DNs the SST in degrees Celsius (°C2) was obtained by using the following equation:

$$SST = 0.075 \times DN - 0.3$$

Where;

SST= Sea Surface Temperature (degrees Celsius).

DN=Digital Number.

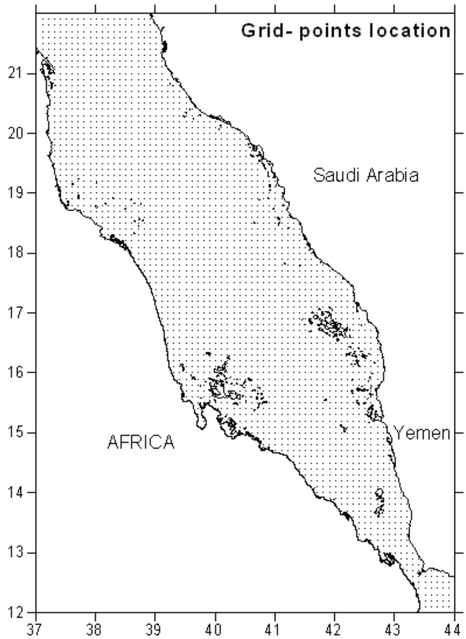


Fig. 2. Map of the study area showing the grid-points locations for the SST values of the reduced data of (0.1°x0.1°) grid-points.

b. Meteorological Parameters and Observed SST (T_{Obs}) Data

Monthly averages of observed SST (T_{Obs}) data were obtained for the period (1993-2007) from the National Center for Oceanographic Data

(NODC) available at www.nodc.noaa.gov. These monthly averages (T_{Obs}) are Jeddah, Jazan and Al-Hodeidah regions along the Southern Red Sea located at about 21.57°N, 39.05°E; 16.29°N, 42.28°E; and 14.5°N, 42.98°E, respectively. The monthly averages of SST in the study area given in Fig. 3. In addition, monthly averages of meteorological data including air temperature (T_a), wind speed (W_s) and relative humidity (R_h) were provided by Presidency of Meteorology and Environment (PME) of Saudi Arabia for a period of 15 years (1993-2007) at two coastal stations, Jeddah and Jazan along the southern Red Sea located at about 21.67°N, 39.15°E; 16.89°N, 42.58°E, respectively. The Civil Aviation and Meteorological Authority in Yemen provided meteorological data for a period of 9 years (1999-2007) for Al-Hodeidah (14.5°N, 42.98°E). Using sea surface temperature, air temperature, wind speed, and humidity, the evaporation (E) was estimated using bulk aerodynamic method, according to Osman (1984). In addition, wind speed was analyzed into (u) and (v) components.

Results and Discussion

Figure 3 shows the monthly averages of SST for study area from January 1993 to December 2007. The higher SST is in the years 1995, 1997-1999 and 2001-2002. The lower SST is in 1993-1994, 1996, and 2003-2007. Figure (4) illustrates the monthly average of SST the grid points in the sections at each month and the average for particular month of the 1993-2007, *e.g.* January month is the average of all January from 1993 to 2007. The SST decreases from north-east to south-west.

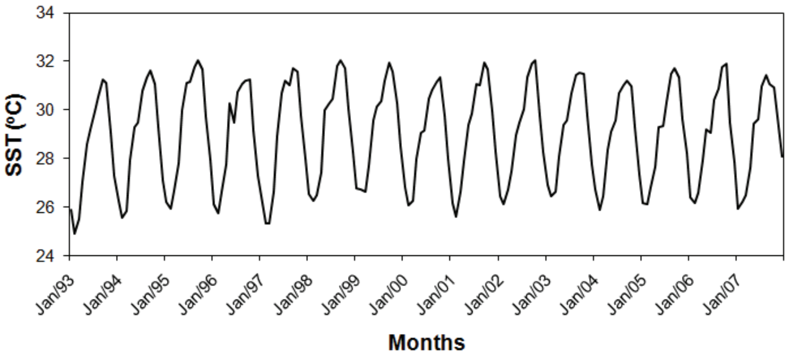


Fig. 3. The monthly average of SST for the period 1993-2007 based on AVHRR data for the study area (12° - 22° N , 37°- 44° E)

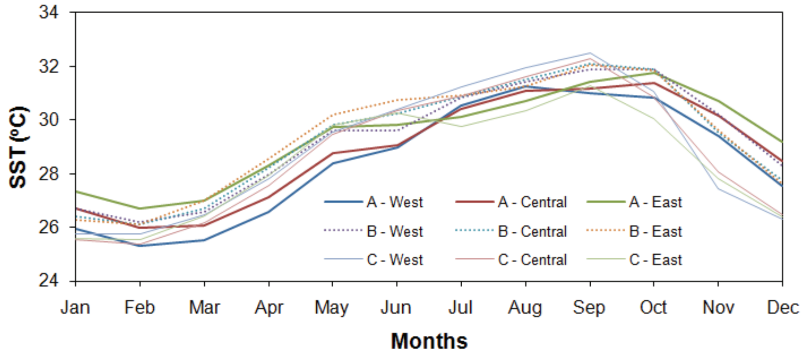


Fig. 4. The monthly of SST for the period 1993-2007 based on AVHRR data for (a) Jeddah, (b) Jazan and (c) Al-Hodeidah regions.

Figure (5) gives the monthly variations of averages of SST for regions of Jeddah, Jazan and Al-Hodeidah.

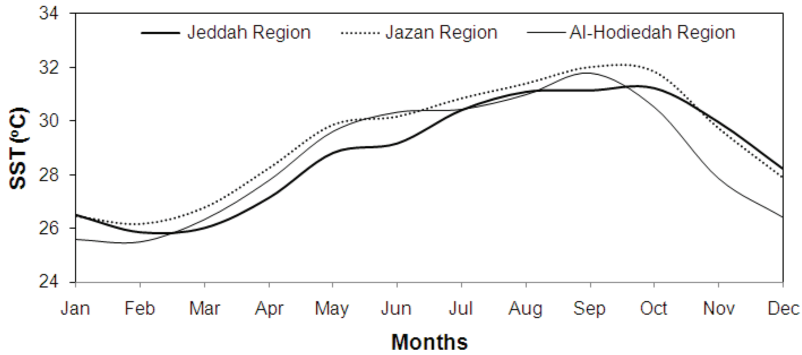


Fig. 5. Monthly variations of SST in southern Red Sea sections (averaged).

a. *Time Series Analysis*

The SST analysis statistically using time series methods, described by Chatfield (1989) which include: (a) calculating linear trend by fitting the least square method to the chosen data set, (b) calculating seasonal variation in the sea surface temperature and then remove it from data, (c) applying spectral power techniques to examine the annual and semi-annual cycles in the SST time series, and (d) applying the polynomial method to the detrended, deseasonalized SST time series to discover longer cycles. Figure 6 shows variation in computed anomalies of SST at Jeddah, Jazan, and Al-Hodeidah after removing the trend and seasonal variations. The inter-annual cycle of the residual SST at all sections show that the phase and amplitude of each are roughly the same. The polynomial trend shows that the SST has a clear cycle about 3-4 years for all sections. Positive and negative SST anomalies values show lower temperatures during years (1996-1997), (2000-2001) and (2005-2007), while higher temperatures are found during the summers of (1995, 1996 and 1997) in Jeddah region, summers of (1995 and 1997) in Jazan region (1998, 2001 and 2003) in Al-Hodeidah region. The warm period may be due to the El Niño effect and the period (2000-2003) may be associated with La Niña cycle. However, there is a probability that these periods were associated with the 11-year cycle of sunspot activities (Al-Subhi and Al-Aqsum, 2008).

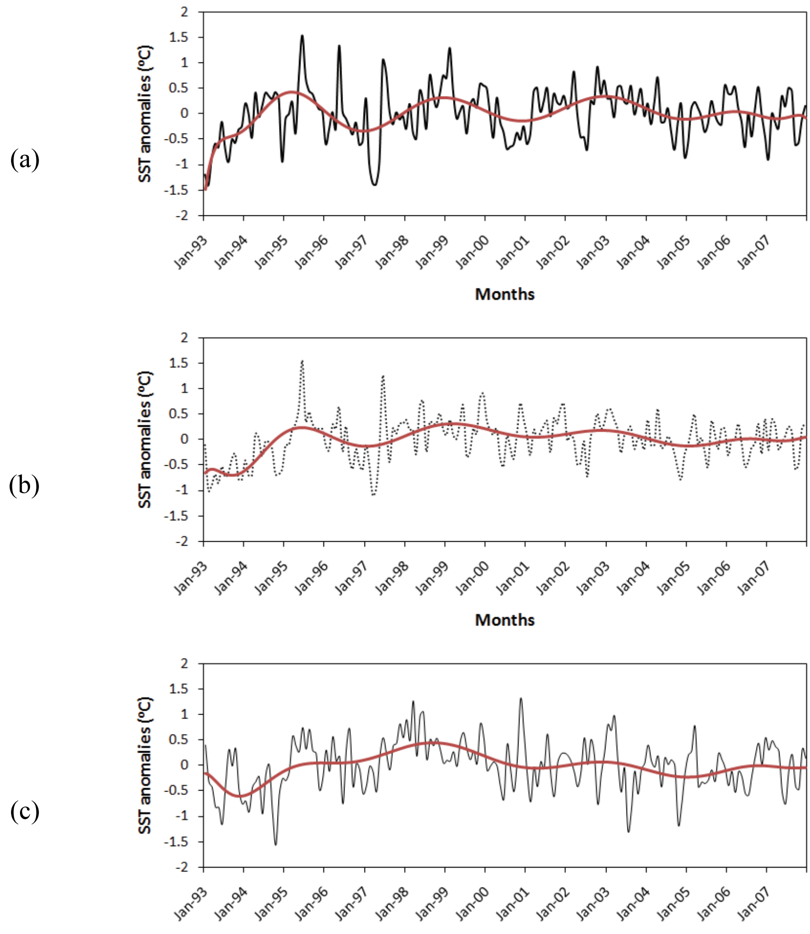


Fig. 6. Monthly variations of SST (1993-2007) at the central sections after removing trend and seasonality for (a) Jeddah, (b) Jazan and (c) Al-Hodeidah regions. Bold red lines indicate SST cycles in all regions.

b. Fast Fourier Transform (FFT)

Power spectra are shown in Fig. 7 for Jeddah, Jazan and Al-Hodeidah respectively. The SST presents high coherence over almost the whole range of frequencies in the spectrum. The two significant component which complete their cycles are the annual and semi-annual in the 15 year respectively in the southern half of Red Sea. In Al-Hodeidah region, seasonal cycle reflects more power spectrum than the other two regions. However, the annual component is much stronger than the semi-annual component.

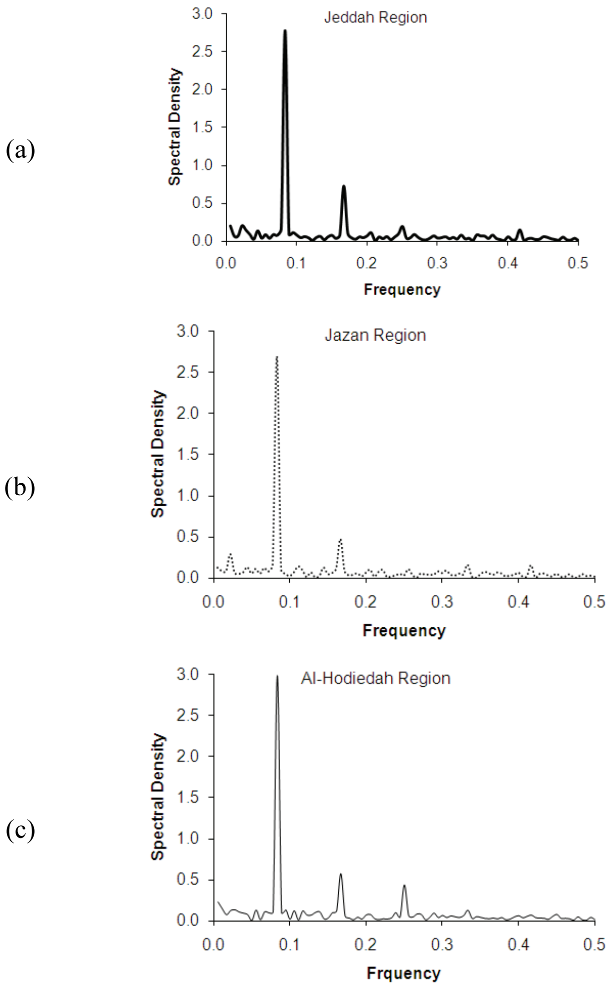
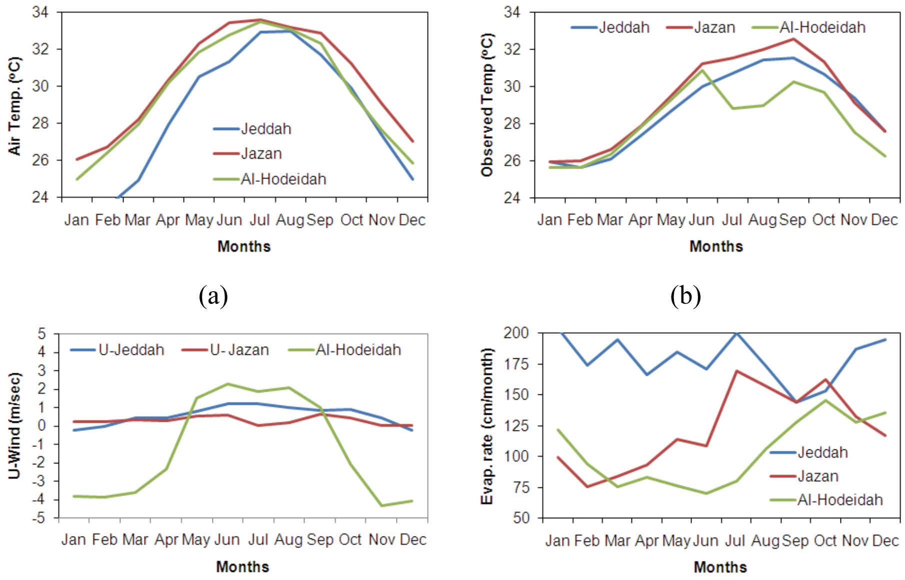


Fig. 7. The power spectrum density of SST at the central sections for (a) Jeddah, (b) Jazan and (c) Al-Hodeidah regions.

c. Meteorological Parameters and Observed Sea Surface Temperature Data

Air temperature (T_a), observed sea surface temperature (T_{Obs}), *u*-wind component, and evaporation (E) for Jeddah, Jazan, and Al-Hodeidah regions are given in Fig. 8.



(a) (b)

(c) (d)

Fig. 8. Monthly variations of (a) air temperature (Ta) in °C, (b) observed sea surface temperature (TObs) in °C, (c) u-wind component in m/s and (d) evaporation rate (E).

d. Forecasting Model

SST fluctuations are explained mostly by the air temperature (T_a) in all regions, evaporative (E) in Jazan region and *u*-wind component (U) in Al-Hodeidah region. The *v*-wind component is not significant in the SST fluctuation. A multiple regression model with 95% level of confidence was used to compute the SST for the three sections of the regions. Results give the following fitted model for the monthly averages of the SST for the three regions;

$$Y_{Jed} = 15.5 + 0.480\, T_a - 0.00189\, E - 0.122\, U$$

$$Y_{Giz} = 11.5 + 0.504\, T_a + 0.0198\, E + 0.250\, U$$

$$Y_{Hod} = 7.81 + 0.640\, T_a + 0.0182\, E + 0.0852\, U$$

Where;

Y_{Jed} , Y_{Giz} , Y_{Hod} are the calculated SST (SST_{cal}) in °C for three regions Jeddah, Jazan, and Al-Hodeidah respectively; air temperature (T_a), evaporation (E) and wind component (U) . The coefficients of Pearson correlation estimate with 95% level of confidence are shown in Table 1. Comparison of the T_{obr}, SST and SST_{cal} are given in Fig. 9.

(a)

(b)

(c)

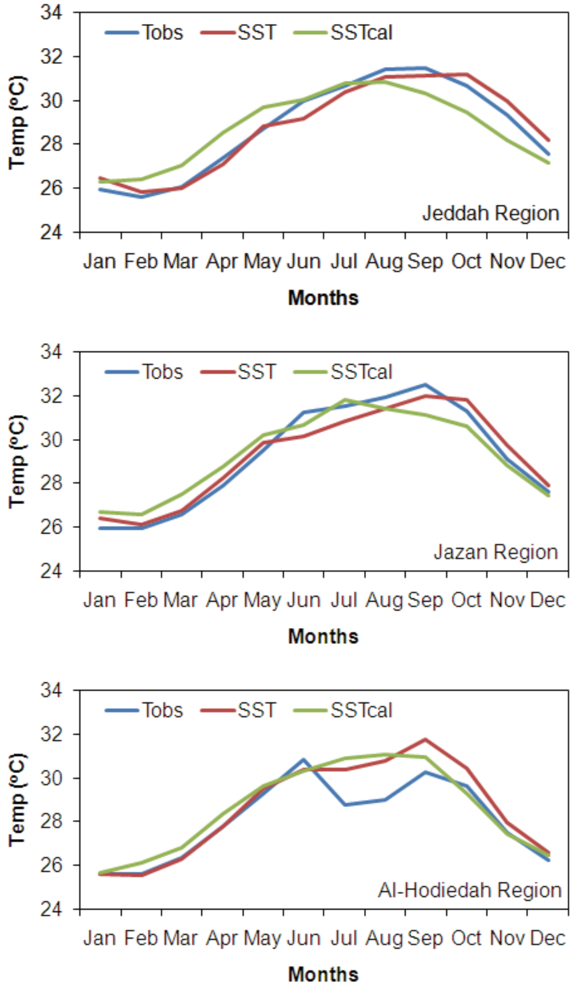


Fig. 9. Monthly averages of SST from AVHRR, Tobs from NODC and computed mean SSTcal based on the multiple-regression model for (a) Jeddah,(b) Jazan and (c) Al-Hodeidah regions.

Table 1. Correlation coefficients for all central sections between SST and the main significant factors for Jeddah, Jazan and Al-Hodeidah regions.

Significant Meteorological Factors	Person Correlations					
	Jeddah		Jazan		Al-Hodeidah	
	Correlation	*P-Value*	*Correlation*	*P-Value*	*Correlation*	*P-Value*
Air temperature (T_a)	0.824	0.000	0.849	0.000	0.867	0.000
Evaporation rate (E)	-0.270	0.000	0.671	0.000	0.052	0.618
U-wind (u)	0.409	0.000	0.146	0.051	0.675	0.000
V-wind (v)	-0.157	0.035	-0.285	0.000	0.042	0.683

Conclusion

Remote sensing techniques were used to study the sea surface temperature (SST) patterns in the southern Red Sea for the period January 1993 to December 2007. The results indicated that the SST and air temperature were higher in Jazan region and lower temperature in the Jeddah region. The lower monthly values of SST were found in winter with a minimum in February. From March onwards the SST rises steeply to reach a maximum in August for two sections Jeddah and Jazan. Air temperature differences play an important role in the changes in sea surface temperature, increasing the temperature of the Red Sea from north to south. There is a strong correlation between air temperature and sea surface temperature in all the regions and is about 0.9 throughout the year. The temperatures during the month of May to September are the largest in Jeddah and Hodeidah. Sultan and Ahmad (1991) reported that changes in SST almost follow those of air temperature. Al-Subhi and Al-Aqsum (2008) stated that SST has a positive correlation with the air temperature in northern part of the Red Sea. The effect of the wind component (east-west) on the SST variability has been examined and shows a correlation of about 0.675 in Al-Hodeidah region only. It can be seen that the general pattern of the wind field is the important component of the seasonal variability of SST. Generally, the wind is one of the important elements in the seasonal changes of SST (Al-Subhi and Al-Aqsum, 2008). It is clear that the monthly evaporation rates are higher in the Jeddah region and lower in Al-Hodeidah region. The relationship between SST and evaporation rate differs at each section. The close correlation between the SST and evaporation rate are noticeable in the Jazan region where correlation coefficient is strong (about 0.7).

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تغيرات درجة حرارة المياه السطحية المستشعرة عن بعد في جنوب البحر الأحمر وعلاقتها ببعض العوامل الجوية

عبدالله محمد الصبحي، و أحمد محمد تقي

كلية علوم البحار، جامعة الملك عبد العزيز

جدة – المملكة العربية السعودية

amalsubhi@kau.edu.sa

المستخلص. استخدمت تقنية الاستشعار عن بعد لمعرفة أنماط تغيرات درجة الحرارة السطحية في النصف الجنوبي للبحر الأحمر للفترة بين يناير ١٩٩٣ إلى ديسمبر ٢٠٠٧م. أظهرت النتائج تناقصًا في درجة الحرارة السطحية كلما اتجهنا شمالاً من مضيق باب المندب. درجة الحرارة السطحية كانت أعلى في الجانب الشرقي مقارنة بالجانب الغربي للبحر. التغيرات في درجة الحرارة السطحية كانت مرتبطة بتغيرات درجة حرارة الهواء والمركبة الأفقية لإجهاد الرياح خاصة في منطقتي جده والحديده بينما كان تأثير البخر واضحاً في منطقة جازان. تم تطبيق نماذج الانحدار المتعدد لتذبذبات درجة الحرارة السطحية لإيضاح سلوك درجة الحرارة المقاسه. أوضح التحليل الطيفي وجود المركبتين السنوية ونصف السنوية في كل القطاعات ، لكن المركبة الأكثر نشاطًا كانت هي المركبة السنوية. التغيرات نصف السنوية ربما كانت بتأثير التيارات السطحية والتغيرات الموسمية في نظام الرياح في جنوب البحر الأحمر.