SEA SURFACE TEMPERATURE CHANGE IN THE MEDITERRANEAN SEA UNDER CLIMATE CHANGE: A LINEAR MODEL FOR SIMULATION OF THE SEA SURFACE TEMPERATURE UP TO 2100

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Abstract. The warming in the inner seas could not be more important and time is certainly running out for it. This study highlights important results about the detectable and predictable warming of the sea surface temperature (SST) in the Mediterranean Sea. The featured analysis of the SST is based on the remote sensed and corrected SST data for the period 1986-2015, and predicted data by using a linear black box model for period 2015-2100. The 30-year (1986-2015) SST analysis shows an increase of about 0.4 ºC per decade. The most fluctuation in the monthly SST was generally detected at the beginning of the summer period. In the last 30 years of this century (2071-2100), the relative increase in average SST is predicted to be about 5.8 ºC in the Mediterranean Sea by the model. The analysis and prediction of the recent studies showed a perceptible warming in the sea surface during the last decades, and the warming will also continue to increase under the present environmental condition.
Keywords: *linear climate model, SST, MODIS, remote sensing, Mediterranean warming*

Introduction

Climate change generally indicates significant changes in the measures of climatic conditions for an extended period. The classical period for defining the climate is about 3 decades, which is determined by the World Meteorological Organization (WMO). In various studies, the climate change is mostly considered as the major changes in precipitation, temperature or wind conditions in a region for at least a 30-year period.

Scientists have been intensively studying the impacts of climate change on the terrestrial and aquatic ecosystems, as the biotic and abiotic basis for life are directly related to the change in the environmental conditions, i.e., climate. The climate change studies particularly feature global warming, which is mainly caused by anthropogenic activities since the beginning of the industrial era. The studies indicate a 0.3-4.8 ºC increase in global average surface temperature up to 2100 (Collins et al., 2013). Not only the terrestrial ecosystem, but also the aquatic ecosystem has been strongly being influenced by climate change since the beginning of the industrial era.

Sea Surface Temperature (SST) is an indicator of the water temperature close to the ocean's surface layer (i.e., from 10 μm to 20 m below the sea surface) in the oceanography. The layer plays an important role for the physical and chemical conditions of the oceans owing to the mixing of atmospheric CO_2 into the seawater (Bricaud et al., 2002). Furthermore, SST has a strong interaction with the carbon biogeochemical cycle between the atmosphere and marine ecosystems. For instance, the increase of the CO_2 in the atmosphere has not only an impact on the temperature but also affects the CO_2 absorption capacity and the aragonite saturation state of the oceans, which has enormous impacts on the marine ecosystems. That mainly leads to a decrease

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in pH, and is directly influenced by water temperature (Feely et al., 1988). Likewise, various studies have intensively presented the dependency of the primary production on the SST in the marine ecosystem in the last century (Greg et al., 2003; Arrigo et al., 2008; Demarcq, 2009).

Hence, the change in surface temperature of the seas under climate change has been analyzed and studied in the ecology and oceanography subjects in the recent decades. The Mediterranean Sea is a semi-enclosed sea that is especially sensitive to astronomically induced climatic variations, which are well documented in its sedimentary record. Emeis et al. (2000) documented in a study about the SST of the Mediterranean Sea that the SST was varying between 12.3 ºC and 24.4 ºC in the sub-basins over the last 16,000 years. Also, Hayes et al. (2005) analyzed the annual average of the SST in the last glacier period, and pointed out a variation in the SST from 9 ºC to 19 ºC in the Mediterranean sub-basins. Marullo et al. (2007) investigated the correlation of remote sensed SST (i.e., AVHRR Pathfinder version 5.0) and measured SST in the Mediterranean Sea for a 21-year time period. The results of the study pointed to a very high correlation (i.e., ca. 99%) between the datasets. On the other hand, Shaltout and Omstedt (2014) specifically analyzed the change and anomalies of the remote sensed SST in the Mediterranean Sea by using 0.25º gridded advanced high-resolution radiometer data from the recent past (1986 to 2015). The study indicated an approximately 0.24º C temperature increase in the Mediterranean Sea per decade. Moreover, they reported that the SST change in the six sub-basins varied from 13.8 ºC to 22 ºC.

The main purposes of this study are the investigation and illustrative presentation of the sea surface temperature change and anomalies in Mediterranean Sea under climate change by using a very high gridded dataset to develop a linear black box SST model, which simulates the SST up to 2100.

Material and Methods

Near-term SST data

To investigate the change in sea surface temperature, we used the generated/provided SST data by Copernicus Marine Services in ca. 4x4 km very high spatial and temporal (i.e. daily). This data is based on AVHRR Pathfinder Version 5.2 (PFV52) data set obtained from the US National Oceanographic Data Center and GHRSST (http://pathfinder.nodc.noaa.gov) over the period of January 1986 - December 2015. Also, the inter-annual variability of the SST was analyzed for the 30-year period. This was performed with the Climate Data Operators version 1.6.0 (CDO, 2015).

Visualization of the data

Spatial distribution of the data was done for the time average of the 30-year period. The inter-annual variation and seasonal distribution, i.e., DJF, MAM, JJA, SON (capitals presents each capital of the month’s name) were also illustrated in this study.

Average SST were calculated for two 30-year periods (i.e., 2031-2060 and 2071-2100) by using the CDO software to simulate the differences between near past 30-year climate period and near future two 30-year climate periods. Anomalies in SST were also computed by using the following equation:

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$$SST_{Anom(i)} = SST_{mon(i)} - \frac{\sum_{k=1982}^{n=2015} SST_{mon(i,k)}}{n-k+1} \quad \text{(Eq.1)}$$

where i is the number of each grid cell, n and k are start and end of the data collected years, respectively. SST_{mon} is the monthly SST for each grid cell, and SST_{Anom} is the SST anomaly for each grid cell.

Future simulations

To simulate the SST up to 2100, we analyzed the change in each grid cell and defined a linear function for it over the 30-year period of 1986-2015. Afterwards, we run the linear regression model for simulation of the SST in each grid cell from 2016 to 2100. We used the following equations to calculate the linear regression parameter.

$$y = a + bx \quad \text{(Eq.2)}$$

$$a = \frac{\sum y - b \sum x}{N} \quad \text{(Eq.3)}$$

$$b = \frac{N \sum xy - (\sum x \cdot \sum y)}{N \sum x^2 - (\sum x)^2} \quad \text{(Eq.4)}$$

where N is number of the observations, x is a year index, y is the SST for given census years.

Results

Inter annual variability of the remote sensed annual average of SST was conducted using linear regression in the Mediterranean Sea over the period 1986 to 2015. Results of the analysis indicated that the annual average of the SST, since 1986, has been linearly increasing ca. 0.4 ºC per decade in the entire Mediterranean Sea (see *Figure 1*).

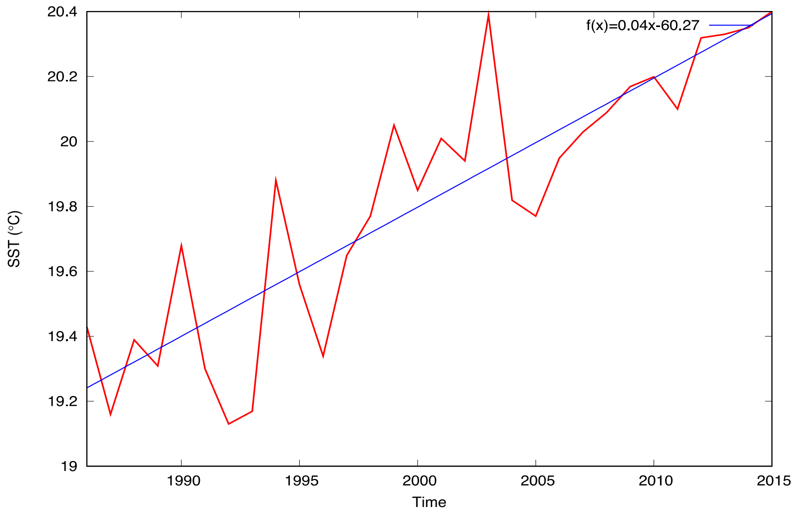

Figure 1. *Annual average sea surface temperature fluctuation in the Mediterranean Sea over the period 1986 to 2015.*

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Spatial distribution of the 30-year average SST was illustrated in a very high resolution, i.e., 4x4 km in the Sea (see *Figure 2*).

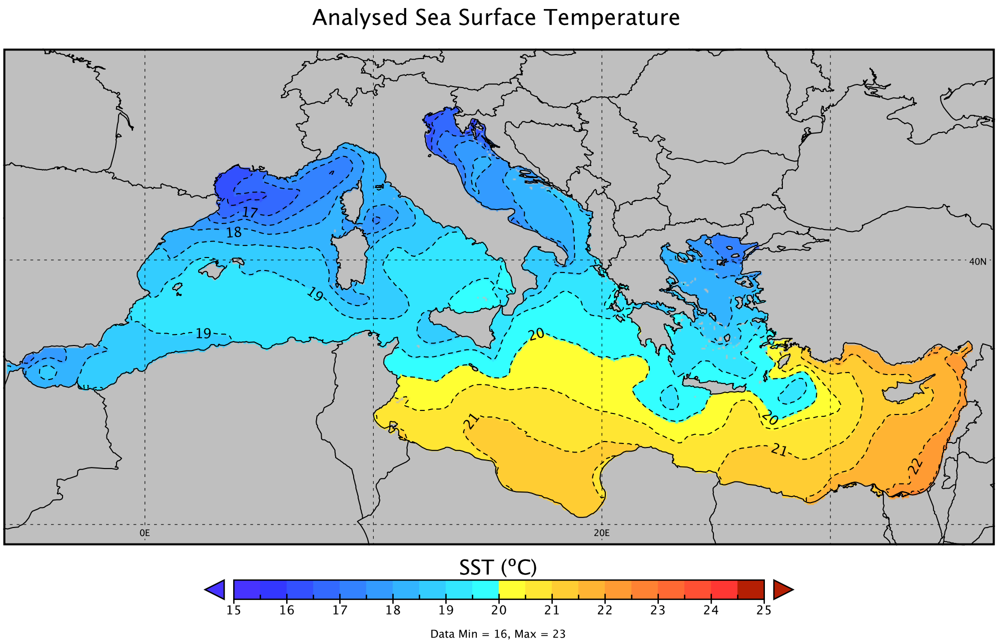

Figure 2. *Spatial distribution of very high resolution (4x4 km) 30-year average sea surface temperature in the Mediterranean Sea.*

The distribution of the SST data showed that south and southeast Mediterranean Sea was approximately 3-5 ºC warmer than other regions in the Sea during the studied period (see Figure 2). Annual cycle of the monthly SST was investigated over the 30-year period, and plotted on Figure 3. On average, lowest (14.1 ºC) and highest (ca. 24.3 ºC) SST were recorded in the Sea in March and August over the 30-year period, respectively (see *Figure 3*).

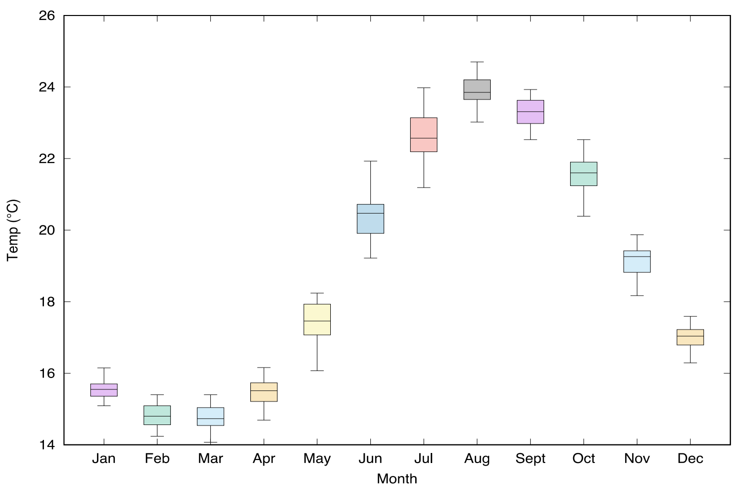

Figure 3. *Inter-annual variation of 30-year average sea surface temperature in the Mediterranean Sea.*

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In the Figure, it can also be seen that the largest amplitude of the SST was found in June and July. Other important points to mention are that the SST in the Mediterranean Sea mainly showed negative amplitude, in other words a cooling, in May, October and November. The SST anomalies were computed by using the Eq. 1. To see the annual anomaly trend for the 30-year study period (1986-2015), results of the annual anomaly analysis were plotted in *Figure 4*.

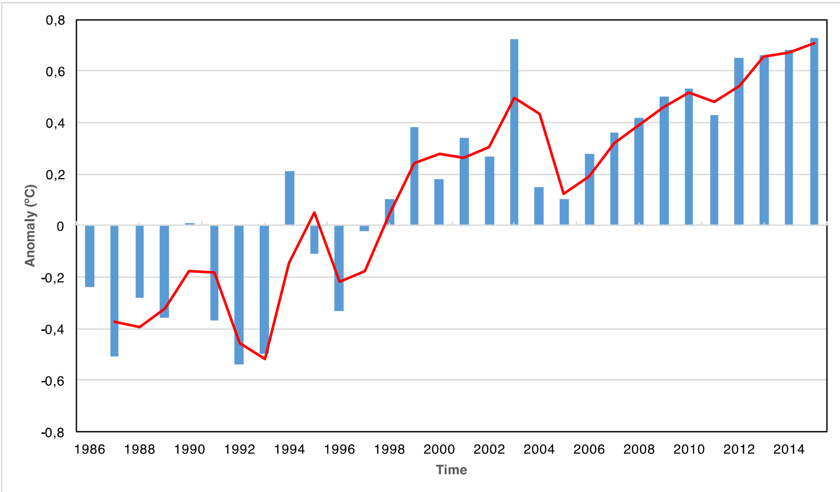

Figure 4. *Anomalies for 30 year and running mean (red solid line).*

It can be seen that the annual average SST generally recorded below the 30-year average SST between 1986 and 1997. The largest annual anomaly was found in 2003. The figure also illustrates that the annual anomaly increased almost continually from 2005 to 2015, except in 2011.

The annual and seasonal cycle of anomaly in monthly mean SST is presented in *Figure 5 and Figure 6* over the 30-year period.

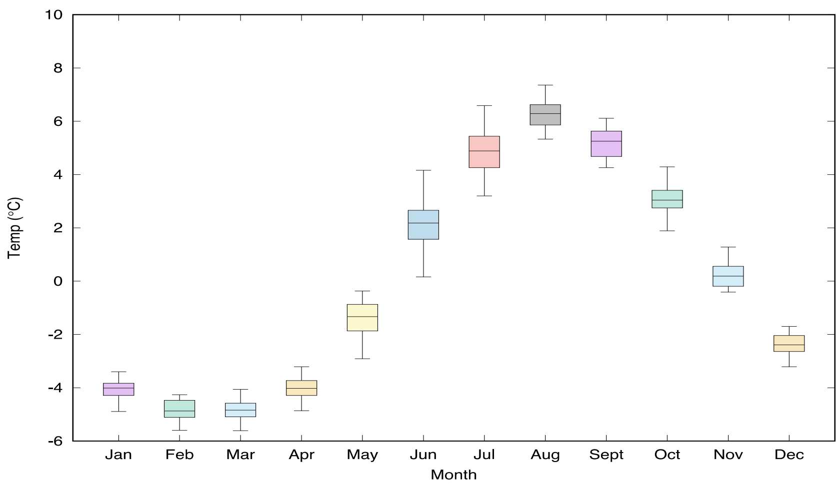

Figure 5. *Inter-annual variation of the 30-year sea surface temperature anomalies in the Mediterranean Sea.*

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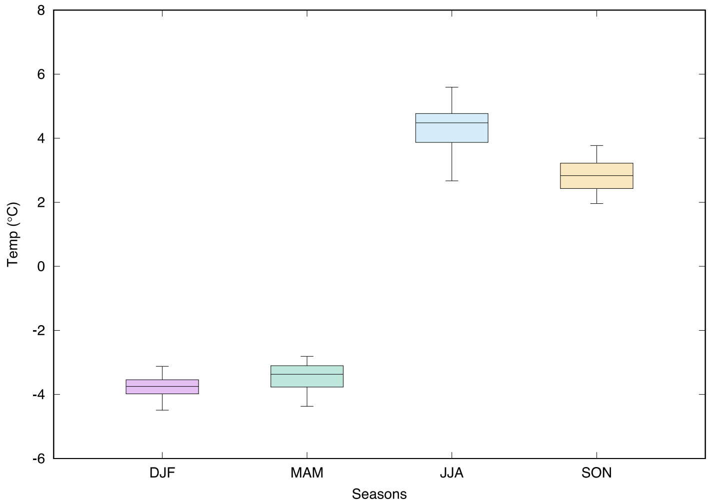

Figure 6. *Seasonal distribution of the 30-year sea surface temperature anomalies in the Mediterranean Sea.*

The largest amplitude of anomaly in monthly mean SST can be seen in June, July, 0 ºC to 4.2 ºC, and 3.1 ºC to 6.9 ºC, respectively. On the other hand, the anomaly in seasonal mean SST indicates a relatively smaller range (from -3.2 ºC to -4.4 ºC ca. 1.2 ºC) in winter time, compared to other seasons (see *Figure 6*). Also, distribution of the seasonal mean SST was computed and plotted in this study (see *Figure 7*).

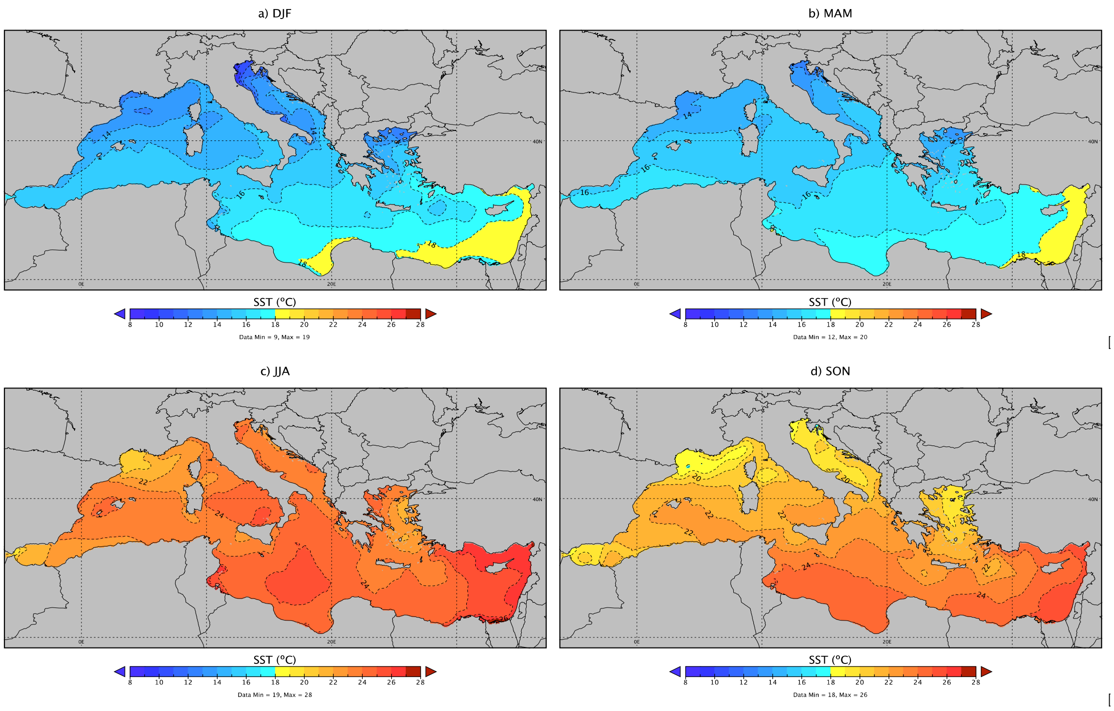

Figure 7. *Distribution of the 30-year (1986-2015) seasonal average sea surface temperature in the Mediterranean Sea. a) DJF (December-January-February) season, b) MAM (March-April-May) season, c) JJA (June-July-August) season, d) SON (September-October-November) season.*

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The Figure shows that the north and west Mediterranean Sea is generally 5 ºC to 10 ºC colder than the south and east of the Sea during the same seasons, and the maximum temperature (ca. 28 ºC) is observed during the summer period.

The annual cycle of the SST from 2016 to 2100 was computed by using the functions Eq. 2-4. In *Figure 8-a and 8-c*, spatial distribution of the annual average SSTs of the future simulation are shown in the Mediterranean Sea for 2031-2060 (i.e., 1st future period) and 2071-2100 (i.e., 2nd future period) periods, respectively.

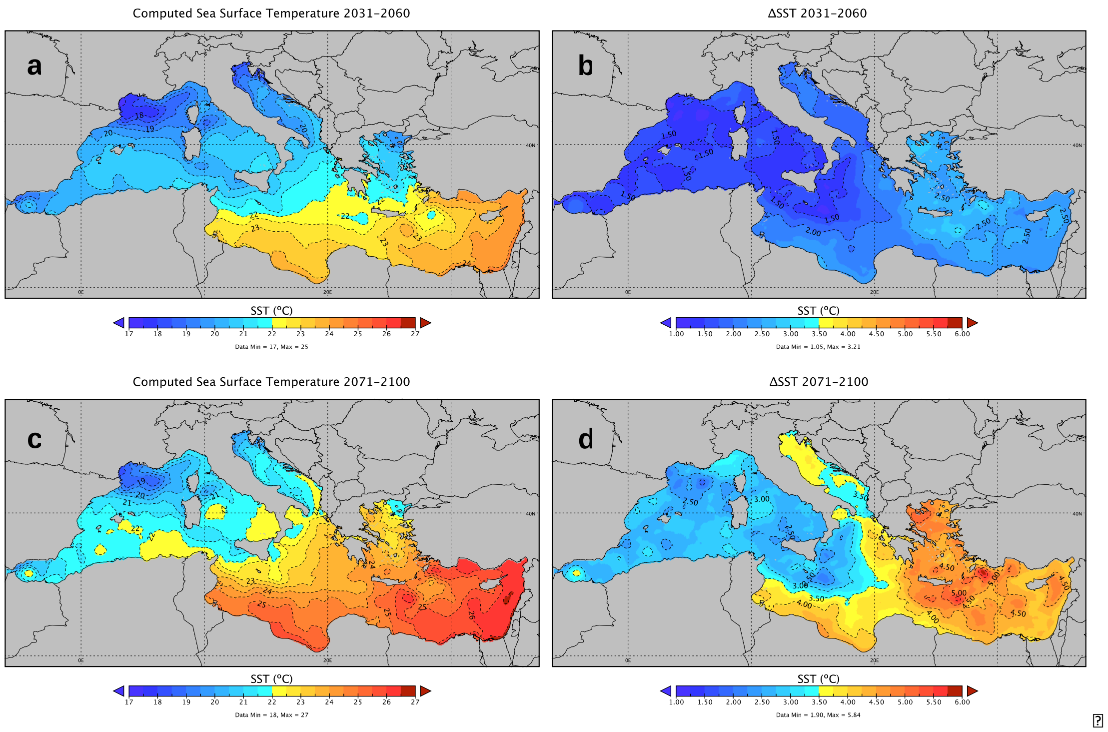

Figure 8. *Distribution of the predicted 30-year, i.e. a) 2031-2060 and b) 2071-2100 average sea surface temperature in the Mediterranean Sea, and the relative differences (c and d) to the 30-year study time period (1986-2015), respectively.*

In the 1st future period, the 30-year mean SST generally has a range of 22 ºC to 25 ºC from Gulf of Gabes to Gulf of Iskenderun toward southeast, and from Aegean Sea toward the south (see *Figure 8-a*). Compared with near past period, warming of the Mediterranean Sea reaches up to +2.5 ºC in the 1st future period (see *Figure 8-b*). In the Sea, South and southeast regions also become warmer than west and north (including Aegean Sea) regions during this period. In the 2nd future period, the warming of the Mediterranean Sea continuously increases towards the west (see *Figure 8-c*). In this period, the mean SST reaches up to 27 ºC, and the relative difference to the near past period gets nearly up to 6 ºC (see *Figure 8-d*).

Discussion

Remote sensed surface temperature of the Mediterranean Sea is detailed analyzed in the last decades. Marullo et al. (2007) validated the remote sensed SST from AVHRR (Advanced Very High Resolution Radiometer) with more than 21 000 matchups (in-situ data) for 21

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years, and found out that the remote sensed SST has quite a good correlation (ca. r^2 = 0.99) with the in-situ dataset. This is a concrete proof for the quality of the remote sensed data, which is often used for determining the climate change in the near past.

The temperature gradients between the east and west Mediterranean basins are mainly caused owing to diffusing of the Atlantic water into the sea through the strait of Gibraltar (Millot, 1999). On the other hand, the north-south sea surface temperature gradients are among others caused owing to the effects of the North African hot winds (e.g., Sirocco winds), and flowing warm pacific water through Suez Canal into the sea (Russo and Artegiani, 1996; Ferrarese et al., 2009; Schicker et al., 2010; Galil et al., 2015).

Warming of the Mediterranean Sea is reported as 0.24 ºC per decade from 1986 to 2015 (Shaltout and Omsted, 2014), and 0.03 ºC per year (ca. 0.3 ºC per decade) in the study from Nykjaer (2009); however, a linear 0.4ºC warming per decade was detected in this study from 1986 to 2015 (see *Figure 1*). The difference between SST of the studies could be caused from the differences in spatial resolution and origin of the datasets. It is important to mention that this study has ca. 36 and 16 times higher spatial resolution than the two studies, respectively.

Within the analysis, annual SST mostly shows high negative anomalies before 1998, and high positive anomalies after 1998. That clearly points to a warming of the sea surface in the Mediterranean, and it is related–with a high probability–to the El Niño (warm)-South Oscillation (ENSO) periods over the Pacific Ocean (Brönniman, 2007; Brönnimann et al., 2007; Marti, 2007). Moreover, inter annual fluctuations of SST anomalies presents the highest variability in monthly SST during the summer periods of the last 30 years. Chronis et al. (2011) reported similar impacts of Summer North Atlantic Oscillation (SNAO) on surface temperature (i.e., sea and terrestrial surface temperature) in East Mediterranean region during summer periods from 1979 and 2008. It is still not clearly known which oscillation may have impacts on the increase in surface temperature over the entire Mediterranean Sea.

Recent studies about the rapid increase in sea surface temperature during last centuries shows that it will drastically continue to rise in the future (Meissner et al., 2012; Collins et al., 2013; Mizuta et al., 2014). Within the World Climate Research Program, a large number of comprehensive climate and Earth system models have been used in studying the interaction between climate and biosphere recent years (Collins et al., 2013). Analysis of the results from Coupled Model Intercomparison Project Phase 5 (CMIP5) shows an up to 4 ºC increase in SST under consideration of the Representative Concentration Pathway Scenario 8.8 (RCP8.5) on global average at 2100 (Collins et al., 2013). In this study, the predicted SST of the Mediterranean Sea by using the linear black box model suggests that there will be a 3.5 ºC increase at the middle of the century (see Figure 8-a) and 5.8 ºC increase at the end of the century (see *Figure 8-b*). This means that the SST of inner Seas like the Mediterranean will be more influenced by the climate change in the future. Shaltout and Omsted (2014) also predicted an increase in SST between 0.5 ºC (RCP2.6) and 2.6 ºC (RCP8.5) by analyzing the CMIP5 SST data with various RCP scenarios (i.e., RCP2.6, RCP4.5, RCP6.0 and RCP8.5) and 1.25ºx1.25º spatial resolution for the Mediterranean Sea. The linear black box model in this study predicts the sea surface warming–approximately–being two (RCP8.5) to ten times (RCP2.6) higher than the CMIP5 analysis estimates. By comparing SST results with different spatial resolutions, it can be seen that the change in predicted SST can vary enormously, and impacts of the sea surface warming can lose their meaning in the future period.

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Conclusion

Not only the oceans' surface temperature, but also inner seas' surface temperature is strongly influenced by climate change. Recent study shows that the increase of the SST is about 0.4 ºC per decade in the Mediterranean Sea. During the continual increase in the SST, the analyses show that the fluctuation in inter-annual SST and anomaly particularly appear in the sea during June, July and October. The warming in the Sea will definitely continue in the future, and will rise about 5.8 ºC (i.e., relative change to the average SST for the period 1986-2015) on average at 2100. A large part of the warming will be presumably irreversible in the Mediterranean Sea. Regarding the previous studies, a question about "which oscillation has stronger impacts on the surface temperature in Mediterranean region?" is still open, and has a high priority for investigation and clarification in the future.

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