Spatial and Seasonal Variability of Long-Term Sea Surface Temperature Trends in Aegean and Levantine Basins

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Abstract—This study aims to estimate the spatial variability of the long-term trends of Sea Surface Temperature (SST) in the Eastern Mediterranean Sea including the Aegean Sea for 39 years between 1982 and 2020. Two datasets consisting of in-situ daily mean SSTs provided by the Turkish State Meteorological Service for the 12 stations located along the Aegean and Levantine coasts of Turkey and gridded daily mean Optimum Interpolation Sea Surface Temperature version 2.1 (OISSTv2.1) data obtained from the National Centers for Environmental Information (NCEI) of the United States National Oceanic and Atmospheric Administration (NOAA) are used for this aim. The trend of change in SST is computed using a non-parametric Theil-Sen estimator methodology. The significance of trends is computed using the Mann–Kendall test. As well as the long-term trends of monthly mean SST, the trends of monthly minimum and maximum SSTs are analyzed to reveal the long-term variations of extreme SSTs. It is concluded that there is a statistically significant upward trend within the study area. The annual basin-averaged upward trends of monthly mean, minimum, and maximum SSTs are estimated as 0.039 °C/year, 0.043 °C/year, and 0.037 °C/year, respectively. Coastal in-situ data present different characteristics for the Aegean Sea and the Levantine Basin. Aegean Sea stations show that the annual maximum SST has a higher rate of upward trend than the annual mean and minimum SSTs, while measurements from the Levantine Basin show minimum SST values increasing at a greater rate than both the annual means and maximums. Analysis of in-situ data at 12 stations provides statistically significant trends between 0.024 °C/year and 0.055 °C/year, 0.025 °C/year and 0.093 °C/year, and 0.031 °C/year and 0.071 °C/year for annual mean, annual minimum, and annual maximum SSTs, respectively. Seasonal analysis of the monthly mean SST trends shows that the highest upward trend occurs in August at the Dikili station (Aegean Sea) with a rate of 0.110 °C/year. SST in the study area is significantly affected by the Atlantic Multidecadal Oscillation (AMO), Eastern Atlantic (EA), and East Atlantic/West Russia (EA/WR) indices.

1. Introduction

Sea surface temperature (SST) is a significant parameter used to understand, interpret, and forecast the interactions between oceans, seas, and the atmosphere. For this reason, studying the changes in SST is important to reveal the stages of climate change.

According to the Intergovernmental Panel on Climate Change (IPCC) (Stocker et al., 2013), SSTs began to increase in the early twentieth century. Based on long-term in-situ SST data starting from 1980, the Fifth Assessment Report of the IPCC (Stocker et al., 2013) estimated the global trend to be between 0.042 ± 0.007 °C/decade and 0.054 ± 0.015 °C/decade with a 90% confidence interval. Developments in observational accuracy with emerging technologies such as satellite observations in the last quarter of the twentieth century allowed different estimates of SST trends. Globally increasing SSTs were reported for the period of 1979–2012 with the trend rates of 0.072 ± 0.024 °C/decade based on the HadISST dataset by Rayner et al. (2003), 0.073 ± 0.020 °C/decade based on the COBE-SST dataset by Ishii et al. (2005), 0.105 ± 0.031 °C/decade based on the ERSSTv3b dataset by Smith et al. (2008), and 0.124 ± 0.030 °C/decade based on the HadSST3 dataset by Kennedy et al. (2011) (Stocker et al., 2013). An inspection of trends for different time scales reveals that studies based on shorter time periods tend to give higher trend rates. As well as the time scale, regional studies

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conducted for different parts of the world (Breaker et al., 2016; Kashkooli et al., 2019; Park et al., 2015) also indicate inhomogeneous trends in SST with significant spatial variability, presenting higher or lower trend estimates. Since global estimations are spatially averaged, regional differences may not be reflected. This emphasizes the importance of studies conducted at regional scales with the use of in-situ data from local institutions. In-situ data are used to validate satellite observations, to generate boundary conditions for numerical weather models, to produce reanalysis data, and to reveal site-specific patterns in SST. Improvement of coastal SST data quality was emphasized as one of the priorities for the next decade by O'Carroll et al. (2019), highlighting the importance of high-resolution SST data capable of capturing the meso/sub-mesoscale features, where in-situ observations and regional/local analysis of SST trends will make significant contributions.

The SST data required to determine the directions of trends are obtained through in-situ measurements or the analysis of images provided by satellites.

Remote sensing technologies (e.g., the Advanced Very High-Resolution Radiometer, AVHRR) have been used extensively in order to determine oceanographic parameters such as SST, sedimentation (Pavelsky & Smith, 2009), tides (Shen et al., 2008), upwelling (Pisoni et al., 2014), sea surface salinity (Vinogradova et al., 2019), and circulations (Stocker et al., 2013). In cases where in-situ measurements of SST cannot be obtained, high-resolution SST data provided by institutions such as the National Oceanic and Atmospheric Administration (NOAA) and the European Centre for Medium-Range Weather Forecasts (ECMWF) are used to determine the trends in SST. This way, the impact on biodiversity and climatic events caused by the increase in SST can be better understood and the necessary protection strategies can be developed.

The study area of the present work covers the Eastern Mediterranean, consisting of the Aegean Sea and the Levantine Sea between the coordinates of 30° N and 41° N and 21° E and 37° E (Fig. 1). The study area is important economically for riparian countries,
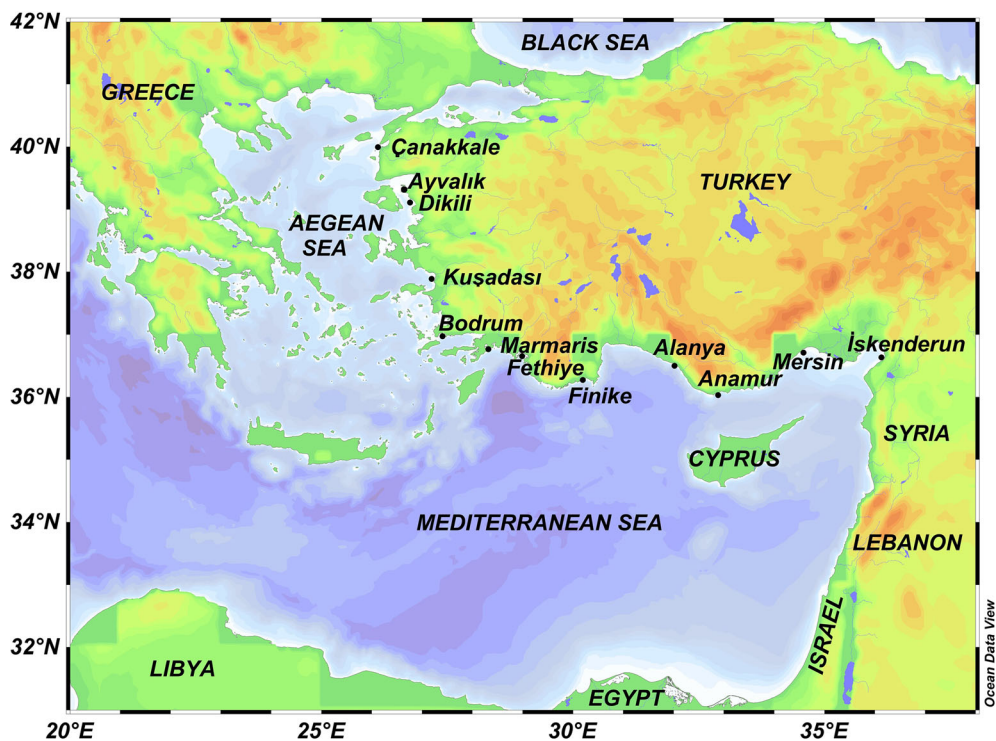

Figure 1
Study area and the locations of the in-situ SST stations

Table 1

Annual SST trends within the Mediterranean Sea according to previous research

Author(s)	Studied time period	Study area	Data	SST trend (°C/year)
D'Ortenzio et al. (2000)	1985–1996	The whole Mediterranean	AVHRR /MEDATLAS	No trend
Criado-Aldeanueva et al. (2008)	1992–2005	The whole Mediterranean	NOAA OI	0.061
Nykjaer (2009)	1985–2006	Eastern Mediterranean	AVHRR	0.050
Skliris et al. (2011)	1985–2008	Aegean	AVHRR/ICOADS	0.045
Skliris et al. (2011)	1992–2008	Aegean	AVHRR/ICOADS	0.055
Skliris et al. (2012)	1985–2008	The whole Mediterranean	AVHRR/NOCS (V.2)	0.037
Skliris et al. (2012)	1985–2008	Eastern Mediterranean	AVHRR/NOCS (V.2)	0.042
Shaltout and Omstedt (2014)	1982–2012	The whole Mediterranean	AVHRR	0.035
Shaltout and Omstedt (2014)	1982–2012	Levantine Basin	AVHRR	0.042
Pastor et al. (2018)	1982–2016	The whole Mediterranean	GHRSST Level 4 AVHRR_OI	0.036
Mohamed et al. (2019)	1993–2017	The whole Mediterranean	AVHRR	0.036

benefiting from tourism, fisheries, mining, and recreation. The Mediterranean Sea is an almost landlocked sea, connected to the Atlantic Ocean via the very narrow Gibraltar Strait. This causes negligible tides within the basin. Generally, evaporation rates are much higher than precipitation and freshwater input. The annual mean precipitation over the basin is 1.12 mm/day and mean evaporation is 2.94 mm/day, almost twice the precipitation (Mariotti, 2010). The annual mean freshwater discharge into the Mediterranean Sea was reported to be 8.1×10^3 m^3/s by Struglia et al. (2004). Hence, the basin suffers from a lack of water due to having evaporation rates that are much higher than the incoming water. This negative water budget creates water of higher salinity, which sinks under the less saline water entering from Gibraltar to even out the water budget. Dense Mediterranean waters also flow into the Atlantic Ocean from Gibraltar via the lower layer.

Different researchers have studied the long-term trends of SST in the Mediterranean Sea. Marullo et al. (1999) reported that the seasonal and monthly climatology of the SST was associated with seasonal characteristics and the dynamic structure of the Eastern Mediterranean's upper thermocline circulation. Nykjaer (2009) reported that the maximum change in SST occurs in the Aegean Sea during August. D'Ortenzio et al. (2000) showed evidence of interannual variability but no significant trend for the period between 1985 and 1996. Skliris et al. (2011)

demonstrated that the Aegean Sea started to warm rapidly after a long-term slow cooling period from the late 1960s to the early 1990s. They stated that the SST increased southwards because of the exchange of cold Black Sea water through the Dardanelles Strait and warm Levantine water through the Cretan Arc Straits. Sicre et al. (2016) investigated SST variability in the Northwestern Mediterranean Sea (Gulf of Lion) over the past full 2000 years and reported well-matched trend rates for in-situ and satellite data with rates of 0.22 °C/decade and 0.26 °C/decade, respectively. Annual mean SST trends in the Mediterranean Sea according to different authors are summarized in Table 1. Although D'Ortenzio et al. (2000) found no significant trend in Mediterranean SSTs, other researchers have indicated significant warming ranging between 0.035 °C/year and 0.061 °C/year.

The SST in the Mediterranean Sea is controlled by zonal, meteorological, hydrological, orographic, and oceanographic forcing. The most important oceanographic structures controlling the Mediterranean SST are the Western Cretan and Rhodes gyres in the Eastern Mediterranean Basin and the cyclonic circulation area in the Gulf of Lion with the relatively colder waters in the Western Mediterranean Basin (Pisano et al., 2020; Somot et al., 2018). The specific orography at different parts of the basin and its interaction with specific winds such as mistral or trade winds were also reported to control the SST in previous studies as well as the gyres (Pisano et al., 2020). Skliris et al. (2012) studied the correlations

between SST and net heat flux variations and recorded a negative correlation, indicating that SST warming influences the net heat flux decrease. Another important driver is reported to be teleconnections such as the North Atlantic Oscillation (NAO) and the East Atlantic (EA) oscillation (Skliris et al., 2012). Authors have also reported that the upward SST trends are associated with the sea level rise, as Criado-Aldeanueva et al. (2008) concluded for the Levantine Basin. Criado-Aldeanueva et al. (2008) showed that the maximum sea level rise and the maximum upward trends of SST are observed at the same location in the Levantine Basin. Global warming due to greenhouse effects and the freshwater input are also reported to be main drivers of SST variability in the Mediterranean Sea (Béthoux & Gentili, 1999).

Most of the studies focusing on the Aegean Sea and Mediterranean Sea have analyzed satellite data with different time periods. However, in-situ measurements of SST are also particularly important as they are capable of reflecting the local characteristics, especially in coastal regions. The SST measurement techniques have evolved since the beginning of observations during the mid-nineteenth century. Up until the 1930s, the only available instruments were wooden and canvas buckets, after which the Engine Room-Intake (ERI) technique emerged. During the 1950s, rubber buckets were widely in use, and this continued until the 1980s, when buoys appeared (Kennedy et al., 2011). According to the International Comprehensive Ocean–Atmosphere Data Set (ICOADS) of the US NOAA, more than 60% of SST measurements today are carried out with buoys, 30% with the ERI technique, and only 5% with rubber buckets (https://icoads.noaa.gov/). Different measurement techniques have caused biases in the long-term SST records over time, reaching over 0.5 °C with significant spatial and temporal variability (Carella et al., 2017), especially during the transition from wooden buckets to ERI in the 1940s. Researchers made comparisons and developed different methods to obtain consistency. Their efforts are used to create reanalysis products. Many different data assimilations and checks have increased the quality of long-term SST data, but even after the bias corrections, some uncertainties may still be included

in products, due to the observational and systematic errors of in-situ data (Kennedy, 2013). There are only a few studies where both long-term in-situ and satellite data were used together (Ghanea et al., 2016; Meneghesso et al., 2020; Pisano et al., 2020; Zhang et al., 2019). The present study has been conducted to fill this gap in the literature for the Eastern Mediterranean Basin.

In this study, we extend the study period compared to previous studies by including 12 in-situ SST time series to compare the OISSTv2.1 dataset with in-situ observations. We also analyze long-term trends of monthly minimum and maximum SSTs to enhance the knowledge of extreme SSTs. We analyze the relation between the SST in the study area and various climate indices including the North Atlantic Oscillation (NAO), East Atlantic (EA), East Atlantic/ West Russia (EA/WR), Atlantic Multidecadal Oscillation (AMO), and Indian Summer Monsoon (ISM).

2. Data and Methodology

Two different SST datasets were used in this study to estimate the long-term trends of SST in the study area. The first one is the daily SST dataset, comprising in-situ observations of 12 stations located along the Aegean and Mediterranean coasts of Turkey. The locations of the stations are shown in Fig. 1. The in-situ data were obtained from the Turkish State Meteorological Service (TSMS). SST measurements are conducted daily at 06:00 GMT using sea thermometers by the TSMS for all 12 stations. Stations have water depths of at least 2 m. The TSMS conducts the calibration of the measurement devices and performs quality checks of the data. Daily data were converted into monthly time series of mean, minimum, and maximum SSTs after doing a visual quality check for abrupt changes and unusually steady periods.

The second dataset was retrieved from the OISSTv2.1 database of the NOAA (https://www.ncdc.noaa.gov/oisst/ optimum-interpolation-sea-surface-temperature-oisst-v21). The database was mainly produced using AVHRR infrared satellite SST data; however, it also includes observations taken from cruises, buoys, and Argo floats (Banzon

et al., 2016, 2020; Reynolds et al., 2007) and it does not represent a particular time of day. The OISSTv.2.1 data are an aggregate of data collected over the entire day; therefore, they cannot capture diurnal variability (Banzon & Reynolds, 2021). Daily mean SST values were downloaded with a spatial resolution of $0.25° \times 0.25°$. In this study, the time period between January 1982 and December 2020 was considered to estimate long-term trends in both in-situ and OISSTv2.1 data. Monthly mean SST time series were constructed from the daily data.

Monthly time series of the NAO (Hurrell, 1995), EA (Barnston & Livezey, 1987), and EA/WR (Barnston & Livezey, 1987) indices were obtained from the NOAA National Weather Service Climate Prediction Center (https://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml) for the study period of 1982–2020. The NAO index is defined as the difference between the normalized mean sea level pressure anomalies at Lisbon, Portugal, and Stykkisholmur, Iceland (Hurrell, 1995). The EA pattern is defined as the sea level pressure difference between Greenland and the British Islands in the Baltic Sea. The EA/WR pattern is another remarkable teleconnection pattern characterized by two main large-scale anomalies over Western Europe and the Caspian Sea affecting Eurasia throughout the year.

The monthly time series of the AMO index (Enfield et al., 2001) for the same period was taken from the NOAA Physical Sciences Laboratory (PSL) (https://psl.noaa.gov/data/timeseries/AMO/). The AMO index is produced based on average SST anomalies to describe multidecadal variability in the North Atlantic Basin (Trenberth & Shea, 2006).

The monthly time series of the ISM index (Wang & Fan, 1999; Wang et al., 2001) was obtained from the University of Hawaii Asia–Pacific Data-Research Center of the International Pacific Research Center (http://apdrc.soest.hawaii.edu/projects/monsoon/seasonal-monidx.html) for 1982–2019. The ISM index is calculated for the months of June, July, August, and September (JJAS) based on the difference of zonal mean winds at 850 hPa between southern (5°N–15°N, 40°E–80°E) and northern (20°N–30°N, 70°E–90°E) regions of the Indian

subcontinent, reflecting the magnitude of the ISM (Wang et al., 2001).

In this study, a non-parametric test called the Theil-Sen estimator (Sen, 1968; Theil, 1950) was used to estimate the trends as non-parametric tests are less sensitive to outliers in time series. This test has been widely applied in hydrometeorological and oceanographic studies (Aydoğan & Ayat, 2018; Çarpar et al., 2020). To determine the significance of the trends, we used the non-parametric Mann–Kendall test (Kendall, 1970; Mann, 1945). Correlation coefficients between the in-situ SST and the NAO, EA, EA/WR, AMO, and ISM indices were estimated and a significance level of 95% with a corresponding correlation coefficient of 0.31 was considered.

3. Results and Discussion

3.1. Comparison of In-situ and OISSTv2.1 Data

Statistical properties of the 39-data annual mean time series of mean, maximum, and minimum SST from both in-situ and OISSTv2.1 data in terms of maximum, minimum, average values, Standard Deviation (SD), and skewness were calculated. To compare two datasets, correlation coefficient (R), Root Mean Square Error (RMSE), BIAS, and Scattering Index (SI) values were estimated as presented in Table 2 together with the statistical properties of the two datasets. In the comparisons of both datasets, we used the grid cell ($0.25° \times 0.25°$ in size) from the OISSTv2.1 data in which the corresponding in-situ station coordinates fell.

There is an overall good agreement between the in-situ and OISSTv2.1 data for all stations except Ayvalık. Correlation coefficients between the two types of data are greater than 0.64, 0.54, and 0.56 for annual means of means, maximums, and minimums, respectively. The highest correlations (greater than 0.80) were calculated at Kuşadası, Alanya, and İskenderun stations for all three time series. RMSEs are smaller than 1.16 °C, except for the northernmost stations of Çanakkale (RMSE ≤ 1.60 °C) and Ayvalık (RMSE ≤ 1.83 °C). In general, positive BIAS values are found across the stations, indicating that OISSTv2.1 has greater values than the in-situ SSTs

Table 2

Statistical properties and comparisons of the annual mean time series of mean, maximum, and minimum in-situ SST and OISSTv2.1 data

TS	Stations	Data	Max. value (°C)	Min. value (°C)	Mean value (°C)	SD	Skewness	R	RMSE (°C)	BIAS (°C)	SI (%)
Annual means of mean SST timeseries	Çanakkale	In-situ SST	18.30	15.33	16.33	0.61	1.11	0.66	1.60	1.54	9.82
		OISSTv2.1	18.63	17.16	17.87	0.45	0.14				
	Ayvalık	In-situ SST	18.81	15.87	17.34	0.70	0.17	0.09	1.45	1.20	8.36
		OISSTv2.1	19.36	17.43	18.54	0.50	− 0.10				
	Dikili	In-situ SST	19.55	16.93	18.12	0.79	0.36	0.65	0.81	0.56	4.48
		OISSTv2.1	19.51	17.67	18.68	0.49	− 0.01				
	Kuşadası	In-situ SST	20.79	18.44	19.49	0.70	0.28	0.87	0.37	− 0.12	1.91
		OISSTv2.1	20.35	18.38	19.36	0.52	0.02				
	Bodrum	In-situ SST	21.44	17.73	19.70	0.80	0.15	0.78	0.75	0.56	3.81
		OISSTv2.1	21.31	19.28	20.26	0.54	− 0.02				
	Marmaris	In-situ SST	21.81	19.46	20.38	0.61	0.51	0.67	0.73	0.57	3.58
		OISSTv2.1	22.04	19.97	20.95	0.52	0.05				
	Fethiye	In-situ SST	23.43	21.14	22.06	0.53	0.40	0.82	0.79	− 0.73	3.59
		OISSTv2.1	22.40	20.44	21.33	0.48	0.07				
	Finike	In-situ SST	22.74	20.48	21.81	0.55	− 0.46	0.80	0.34	0.01	1.54
		OISSTv2.1	23.06	20.98	21.82	0.49	0.29				
	Alanya	In-situ SST	23.44	21.00	21.96	0.61	0.22	0.87	0.40	0.26	1.80
		OISSTv2.1	23.34	21.30	22.22	0.49	0.00				
	Anamur	In-situ SST	22.71	20.16	21.54	0.58	− 0.59	0.64	0.64	0.44	2.95
		OISSTv2.1	23.06	21.15	21.98	0.47	0.06				
	Mersin	In-situ SST	22.95	19.54	21.62	0.69	− 0.75	0.67	0.94	0.78	4.34
		OISSTv2.1	23.37	21.46	22.39	0.47	− 0.04				
	İskenderun	In-situ SST	23.54	21.29	22.44	0.60	− 0.30	0.90	0.27	− 0.04	1.18
		OISSTv2.1	23.38	21.46	22.40	0.49	− 0.04				

Table 2 *continued*

TS	Stations	Data	Max. value (°C)	Min. value (°C)	Mean value (°C)	SD	Skewness	R	RMSE (°C)	BIAS (°C)	SI (%)
Annual means of maximum SST	Çanakkale	In-situ SST	19.62	16.73	17.79	0.60	0.90	0.64	1.56	1.48	8.75
		OISSTv2.1	20.33	18.40	19.27	0.49	0.16				
	Ayvalık	In-situ SST	20.15	17.29	18.78	0.67	−0.01	−0.06	1.26	0.94	6.70
		OISSTv2.1	20.56	18.71	19.71	0.48	−0.03				
	Dikili	In-situ SST	20.65	18.17	19.45	0.71	0.30	0.54	0.73	0.41	3.73
		OISSTv2.1	20.71	19.00	19.86	0.46	0.12				
	Kuşadası	In-situ SST	21.82	19.42	20.51	0.69	0.32	0.83	0.39	−0.08	1.91
		OISSTv2.1	21.44	19.31	20.44	0.50	0.01				
	Bodrum	In-situ SST	22.57	18.77	20.72	0.76	0.24	0.75	0.81	0.64	3.91
		OISSTv2.1	22.53	20.21	21.36	0.56	−0.11				
	Marmaris	In-situ SST	23.27	20.56	21.56	0.68	0.53	0.71	0.74	0.56	3.44
		OISSTv2.1	23.31	21.06	22.12	0.55	0.02				
	Fethiye	In-situ SST	24.53	22.39	23.45	0.46	0.19	0.56	1.00	−0.90	4.26
		OISSTv2.1	23.64	21.61	22.55	0.47	0.02				
	Finike	In-situ SST	23.99	21.71	22.93	0.55	−0.15	0.80	0.36	0.13	1.55
		OISSTv2.1	24.25	22.18	23.06	0.49	0.17				
	Alanya	In-situ SST	24.70	22.13	23.19	0.58	0.39	0.83	0.43	0.29	1.87
		OISSTv2.1	24.41	22.61	23.48	0.47	−0.06				
	Anamur	In-situ SST	23.71	21.52	22.68	0.51	−0.15	0.58	0.71	0.56	3.14
		OISSTv2.1	24.18	22.43	23.24	0.46	−0.09				
	Mersin	In-situ SST	24.09	20.94	22.96	0.67	−0.84	0.66	0.86	0.69	3.76
		OISSTv2.1	24.50	22.69	23.65	0.46	−0.03				
	İskenderun	In-situ SST	24.88	23.03	23.97	0.49	−0.24	0.88	0.36	−0.28	1.52
		OISSTv2.1	24.58	22.60	23.69	0.48	−0.22				

Table 2 *continued*

TS	Stations	Data	Max. value (°C)	Min. value (°C)	Mean value (°C)	SD	Skewness	R	RMSE (°C)	BIAS (°C)	SI (%)
Annual means of minimum SST timeseries	Çanakkale	In-situ SST	16.68	14.02	14.87	0.61	0.95	0.61	1.70	1.63	11.46
		OISSTv2.1	17.39	15.66	16.50	0.46	− 0.12				
	Ayvalık	In-situ SST	17.45	14.13	15.82	0.85	− 0.13	0.15	1.83	1.58	11.58
		OISSTv2.1	18.31	16.26	17.40	0.55	− 0.29				
	Dikili	In-situ SST	18.34	15.23	16.72	0.86	0.20	0.64	1.05	0.82	6.27
		OISSTv2.1	18.48	16.29	17.54	0.56	− 0.20				
	Kuşadası	In-situ SST	19.82	17.34	18.43	0.69	0.21	0.86	0.37	− 0.13	2.00
		OISSTv2.1	19.26	17.08	18.30	0.58	− 0.22				
	Bodrum	In-situ SST	20.36	16.83	18.59	0.82	0.24	0.79	0.75	0.56	4.05
		OISSTv2.1	20.27	17.94	19.16	0.60	− 0.15				
	Marmaris	In-situ SST	20.26	18.09	19.15	0.53	0.26	0.56	0.81	0.62	4.22
		OISSTv2.1	21.03	18.82	19.77	0.58	0.09				
	Fethiye	In-situ SST	22.11	19.20	20.60	0.69	0.02	0.84	0.65	− 0.53	3.14
		OISSTv2.1	21.28	19.13	20.07	0.55	0.01				
	Finike	In-situ SST	21.65	19.40	20.69	0.54	− 0.46	0.72	0.43	− 0.16	2.10
		OISSTv2.1	21.89	19.50	20.52	0.55	0.23				
	Alanya	In-situ SST	21.58	19.28	20.67	0.66	− 0.30	0.85	0.44	0.26	2.12
		OISSTv2.1	22.15	19.91	20.93	0.55	− 0.07				
	Anamur	In-situ SST	21.60	18.53	20.31	0.69	− 0.71	0.59	0.70	0.41	3.45
		OISSTv2.1	21.87	19.83	20.72	0.52	0.09				
	Mersin	In-situ SST	21.68	18.18	20.17	0.79	− 0.42	0.65	1.16	0.98	5.77
		OISSTv2.1	22.26	20.19	21.15	0.52	− 0.10				
	İskenderun	In-situ SST	22.45	19.32	20.90	0.79	− 0.21	0.82	0.51	0.21	2.44
		OISSTv2.1	22.29	20.08	21.11	0.54	− 0.01				

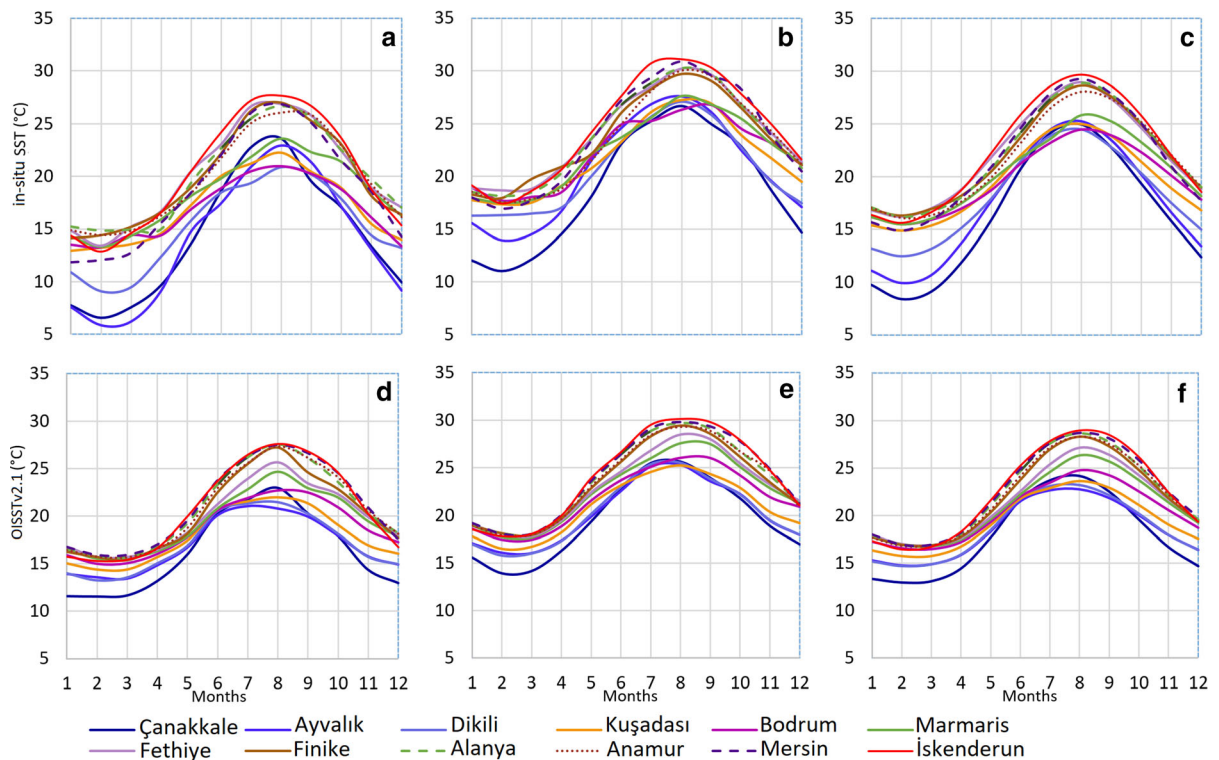Figure 2
Comparisons of **a** the minimum, **b** the maximum, and **c** the mean SST (°C) from the in-situ data and **d** the minimum, **e** the maximum, and **f** the mean SST (°C) from OISSTv2.1 data for 12 stations

with the exceptions of the Kuşadası, Fethiye, and İskenderun stations. While the maximum SST values from in-situ data were slightly greater than those of the OISSTv2.1 data, the minimum SSTs from in-situ data were much smaller than those of the OISSTv2.1 data at the northern Aegean stations of Çanakkale, Ayvalık, and Dikili. In general, the OISSTv2.1 data give higher SST values than the in-situ data in the Aegean Sea. Higher discrepancies with greater RMSE and BIAS values were found at the stations located along the northern Aegean shoreline (Çanak-kale, Ayvalık, and Dikili). The two datasets were better matched at the Levantine Basin stations than the Aegean Sea stations, where relatively higher RMSE, BIAS, and SI values were estimated.

A similar analysis was performed on a seasonal basis (Fig. 2) to reflect seasonality. In this analysis, the minimum, maximum, and mean SST values were estimated from 39-value time series (one data point for each year) for each month.

According to the in-situ data, the lowest minimum SST values were recorded in the northernmost stations (5.9 °C at Ayvalık and 6.5 °C at Çanakkale) (Fig. 2a). The highest maximum SST values were recorded in the northeastern part of the Levantine Basin (31.2 °C at İskenderun and 30.9 °C at Mersin) (Fig. 2b). There is a clear increasing SST gradient in the Aegean Sea from north to south captured by both OISSTv2.1 and in-situ data for the winter season. This winter SST gradient was also reported by Pastor et al. (2018), who performed cluster analysis and linked the SST patterns to the atmospheric and oceanographic properties of the basin. A milder increasing SST gradient is found in the OISSTv2.1 data along the Eastern Mediterranean stations from west to east for the summer season. The lowest SST values occur from February to March, and the maximum SST values are seen between July and September. Although these findings are consistent with the OISSTv2.1 data in general, significant
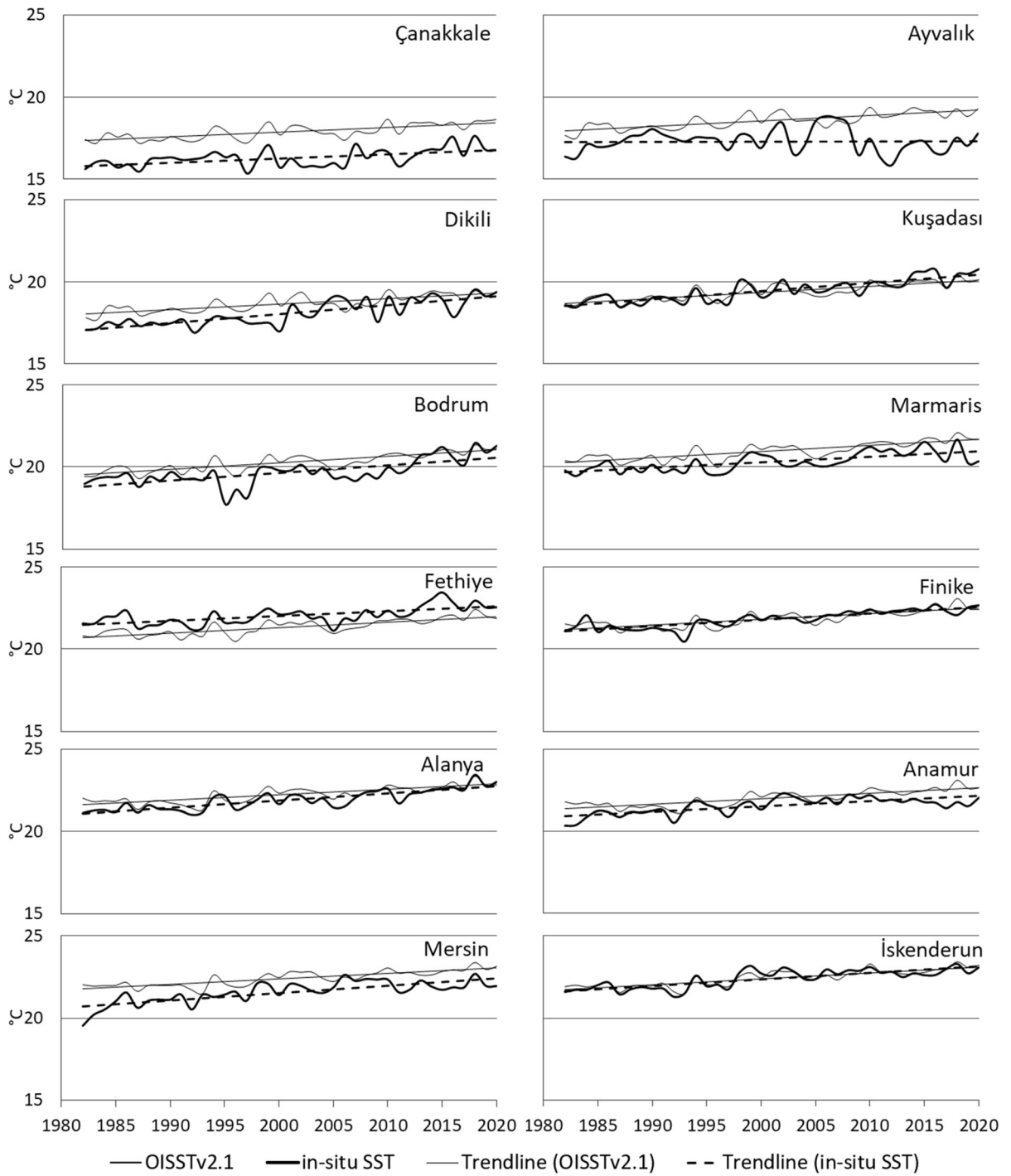
Figure 3
Temporal evolution of annual mean SST from both in-situ and OISSTv2.1 data for 12 stations

inconsistency between the two datasets occurs for the SST minimums during winter and spring months at the Northern Aegean Sea stations. The lowest minimum SST values were estimated at the northernmost stations on the Aegean coast (11.57 °C at Çanakkale, 13.44 °C at Ayvalık, and 13.23 °C at Dikili) (Fig. 2d) according to OISSTv2.1 data.

The annual mean SST derived from the in-situ and OISSTv2.1 datasets presented a good match in terms of trends at almost all stations, except Ayvalık and Dikili (Fig. 3). The temporal evolution of the in-situ annual mean SST is captured well by the OISSTv2.1 data, especially for the Finike, Kuşadası, Alanya, and İskenderun stations. Although positive
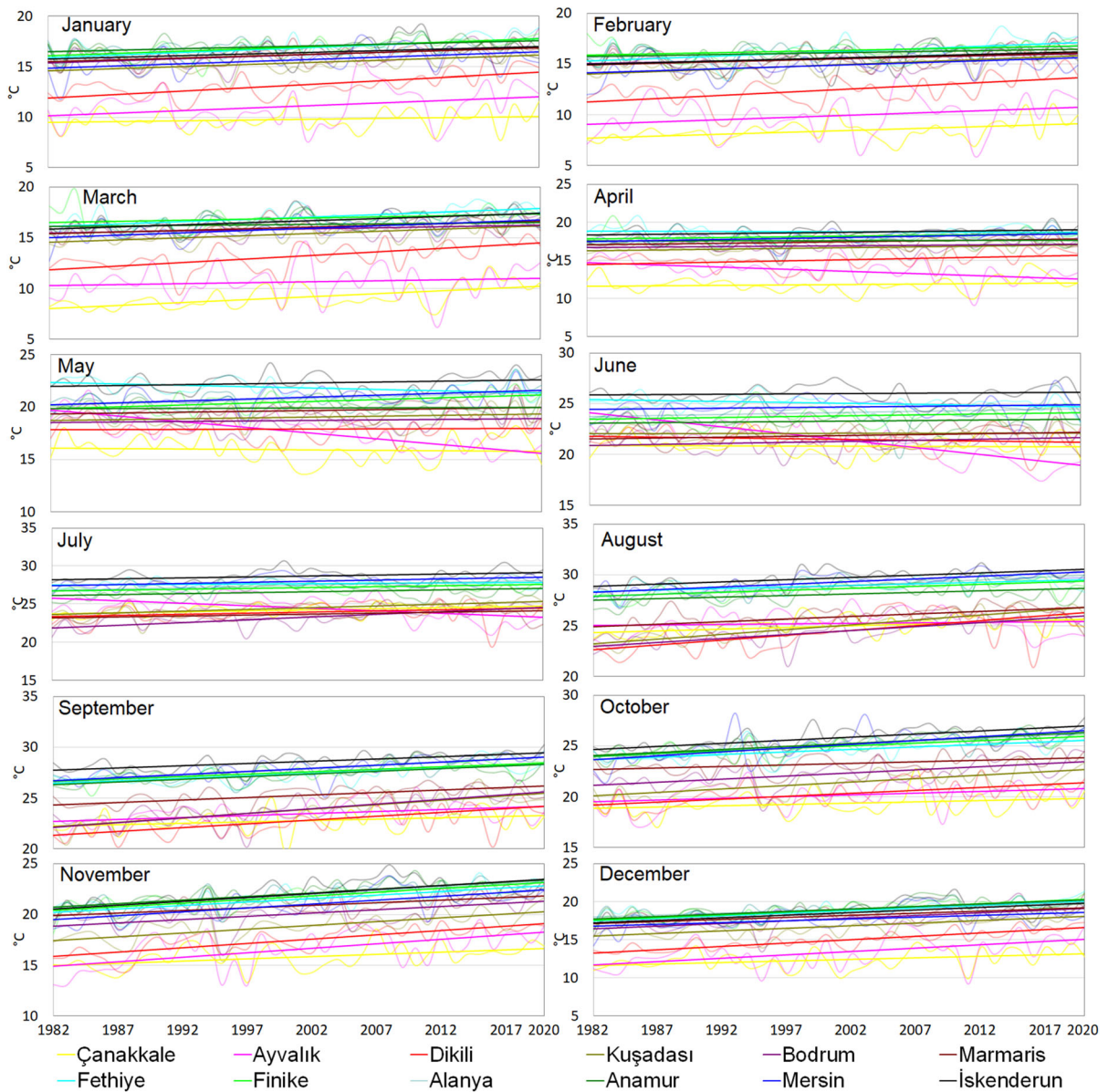
Figure 4
Temporal evaluation of in-situ monthly mean SSTs for all 12 stations during the period of 1982–2020

Table 3

Long-term SST trends for annual mean, annual maximum, and annual minimum for in-situ monthly mean SST data (°C/year)

Stations	Annual mean	Annual maximum	Annual minimum
Çanakkale	**0.024******	**0.044******	**0.025*****
Ayvalık	0.002	− 0.022	0.045
Dikili	**0.055******	**0.068******	0.030
Kuşadası	**0.051******	**0.071******	**0.040*****
Bodrum	**0.045******	**0.067******	0.025
Marmaris	**0.032******	**0.057******	0.025
Fethiye	**0.031******	0.009	**0.093******
Finike	**0.041******	**0.044******	**0.040******
Alanya	**0.044******	**0.047******	**0.050******
Anamur	**0.032******	0.027	0.037
Mersin	**0.042******	**0.038******	**0.050****
İskenderun	**0.039******	**0.031*****	**0.048****

Bold font indicates statistical significance. Significances are as follows: *95%; **97%; ***99%; ****99.9%

BIAS between the in-situ SST and OISSTv2.1 data is clear for the Çanakkale, Ayvalık, Dikili, Anamur, Bodrum, Mersin, and Marmaris stations, the trend rates were found to be almost the same. The only notable negative BIAS was observed for the Fethiye station, where the trends were again almost the same.

Discrepancies between in-situ and OISSTv2.1 SST data can be attributed to the spatial resolution of the OISSTv2.1 data. The OISSTv2.1 data are based on grids with a surface area of about 625 km^2. Although this may be sufficient to give the general impression of temperatures in deep-water regions governed by the main circulation patterns of the Mediterranean Sea, considering coastal circulation patterns and nearshore dynamics of coastal waters this resolution is not sufficient to capture the local effects that may influence the temperature of coastal waters such as freshwater discharges, rivers, or coastal springs. The existence of submarine springs throughout the Aegean Sea coasts was reported by Meriç et al. (2017). The in-situ measurements were conducted in the near-shore region at depths of about 2–3 m, where coastal circulation patterns govern the physical parameters (i.e., flow velocity, temperature, and salinity). Hence, the selection of data sources for specific purposes should be done based on the intended usage scenario, where the points of interest may be either coastal waters or the offshore region.

3.2. Seasonality of SST Trends Based on In-situ Data

The temporal variation of the in-situ monthly mean SST was analyzed to reveal the changes in the last 39 years as well as the seasonal variations. Results for the 12 stations are presented in Fig. 4.

Most of the stations show similar warming trends, except the stations located along the northern Aegean Sea (Çanakkale, Ayvalık, and Dikili). SSTs are clearly increasing in January, February, March, August, September, October, November, and December and seem to be stable in April, May, June, and July. Upward trends are more evident from August to December. The only exception for these steadily warming trends occurs at the Ayvalık station during April, May, June, July, and August, where an obvious cooling seems to occur. The annual warmest SSTs occurred in July between 1982 and 1998 and shifted to August after 1999 at the Ayvalık, Dikili, and Kuşadası stations. Monthly mean SSTs vary within a relatively wider range for the Ayvalık station, especially in January, February, and March.

To estimate the trend values and their significances, analysis was carried out using the Theil-Sen and Mann–Kendall tests for the annual mean, annual maximum, and annual minimum SST time series obtained from the in-situ measurements. For this aim, monthly mean SST time series (39 × 12 data) were constructed based on daily in-situ data. Evaluating the annual maximums and annual minimums is important for estimating the trends of extremes,

Table 4

Long-term trends for each month separately based on the monthly mean SST from in-situ data (°C/year)

Stations	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Çanakkale	0.017	0.033***	0.056****	0.010	− 0.011	− 0.004	0.029***	0.036***	0.033*	0.026	0.043***	0.047**
Ayvalık	0.050	0.054	0.026	− 0.050****	− 0.108****	− 0.135****	− 0.067***	0.014	0.039**	0.025	0.092****	0.090****
Dikili	0.063****	0.050****	0.067****	0.027*	0.000	− 0.009	0.042**	0.110****	0.078****	0.062***	0.082****	0.089****
Kuşadası	0.038****	0.048****	0.044****	0.019	0.014	0.000	0.043****	0.100****	0.085****	0.070****	0.071****	0.065****
Bodrum	0.037***	0.030	0.022	0.012	0.000	0.014	0.071****	0.076****	0.086****	0.067****	0.060***	0.064****
Marmaris	0.044***	0.033**	0.038***	0.023*	0.018	0.025	0.027*	0.055****	0.050****	0.032*	0.050****	0.050****
Fethiye	0.050****	0.052***	0.050****	0.000	− 0.026**	− 0.016	0.013	0.030***	0.046****	0.050****	0.058***	0.072***
Finike	0.043****	0.033***	0.033***	0.025***	0.036***	0.021	0.023**	0.043****	0.050****	0.051****	0.065****	0.067****
Alanya	0.036***	0.030***	0.042****	0.037****	0.033**	0.025**	0.029***	0.055****	0.065****	0.064****	0.078****	0.057****
Anamur	0.029**	0.019	0.009	0.003	0.000	0.010	0.031*	0.033**	0.052****	0.065****	0.069****	0.068****
Mersin	0.035*	0.040*	0.037***	0.025**	0.031**	0.007	0.029**	0.048****	0.061****	0.071****	0.081****	0.042**
İskenderun	0.032	0.030**	0.041****	0.019	0.022	0.013	0.026*	0.043****	0.044****	0.067****	0.086****	0.067****

Bold font indicates statistical significance. Significances are as follows: *95%; **97%; ***99%; ****99.9%.

which are assumed to be indicators of climate change. The Theil-Sen slopes and their significances are given in Table 3 for all 12 stations. Since different significances were observed among the stations, four significance levels (95%, 97%, 99%, and 99.9%) were considered.

In terms of annual mean SST, 11 stations show an upward trend with a confidence level higher than 99.9% with trend rates between 0.024 °C/year and 0.055 °C/year. The highest upward trends of annual mean SST were estimated at the Dikili and Kuşadası stations with rates of 0.055 °C/year and 0.051 °C/year, respectively. The lowest statistically significant upward trend was calculated at the northernmost station of Çanakkale with a rate of 0.024 °C/year. Statistically significant upward trends with a confidence level greater than 99.9% were found for annual maximum SST values for eight stations and a confidence level of 99% at the İskenderun station with trend rates between 0.031 °C/year and 0.071 °C/year. Statistically significant trends of annual maximum SSTs have greater values than the trends of annual mean SSTs for all stations except Mersin and İskenderun. Annual minimums are increasing with statistically significant trend rates between 0.025 °C/year and 0.093 °C/year at Çanakkale, Kuşadası, Fethiye, Finike, Alanya, Mersin, and İskenderun. Trends of annual minimum SSTs are evident only at seven stations with confidence levels greater than 97%. Although the trends of annual mean and maximum SSTs have remarkably high confidence levels, the trends of annual minimum SSTs have relatively low confidence levels for half of the investigated stations. No significant downward trend was observed based on the analysis of in-situ data. Positive trend values reached up to 0.071 °C/year at Kuşadası for the annual maximum SST. According to the annual minimum SST, the statistically significant lowest and highest trends were found to be 0.025 °C/year at Çanakkale and 0.093 °C/year at Fethiye, respectively.

To analyze the seasonality of the data, trend values and their significance levels were computed on a monthly basis for the in-situ data and results are given in Table 4. The significant trends with confidence levels higher than 95% are shown in bold and different significance levels are depicted by asterisks.
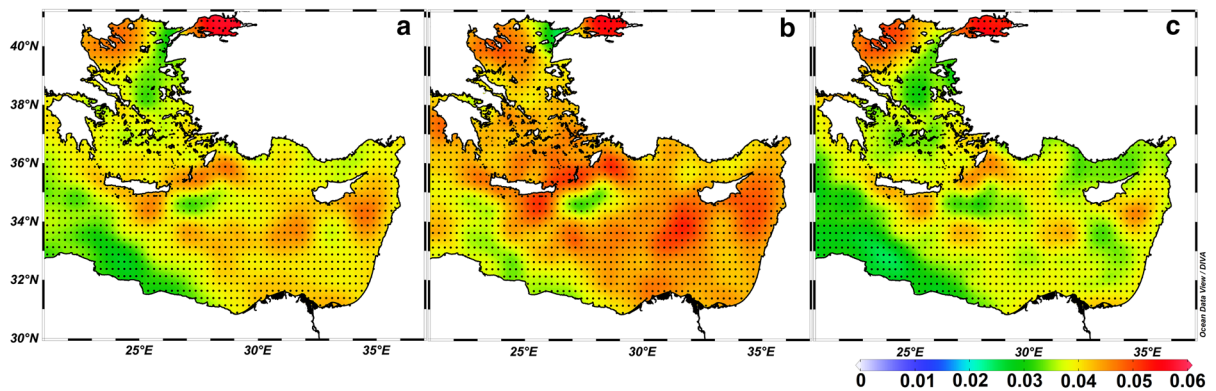
Figure 5
Annual long-term SST trends of **a** monthly mean, **b** monthly minimum, and **c** monthly maximum SST (°C/year)

Table 4 reveals that the SSTs are significantly increasing for most of the stations, especially for the months from July to December. Despite the annual trends, analysis on a monthly basis indicated downward trends with confidence levels greater than 99%. June seems to be the most stable month with only two statistically significant trend values: one downward at the Ayvalık station and the other upward at the Alanya station. Statistically significant downward trends were observed at the Ayvalık station in April, May, June, and July and at the Fethiye station in May. The highest positive trend values occur in August at the Dikili station with a rate of 0.11 °C/year. The lowest statistically significant upward trend was calculated at the Marmaris station in April with a rate of 0.023 °C/year. The part of the annual cycle between July and December has higher upward trend rates with higher confidence levels in general. In particular, November and December present statistically significant trend rates with confidence levels higher than 99%. Trend rates are relatively higher for the second half of the annual cycle than the first half.

3.3. Spatial Distribution and Seasonal Variability of the Long-Term Trends Based on OISSTv2.1 Data

To study spatial variability of the long-term SST trends in the study area, we used the daily mean OISSTv2.1 dataset for the period between January 1982 and December 2020. The monthly mean, monthly maximum, and monthly minimum SST time series (12 × 39 data) at each grid point were determined for this aim. Trends for each series were estimated and mapped using the Ocean Data Viewer (Schlitzer, 2020) (Fig. 5). Statistically significant trends at confidence levels of 95% or higher are depicted by black dots.

Spatial distributions of the trends indicated that the statistically significant positive SST trend is evident within the whole study area. No downward trend is observed. An inhomogeneous distribution is clear for the trends of all three variables (monthly mean, minimum, and maximum SSTs) within the basin. The northernmost part of the study area presents the highest trend rates for all three variables. In particular, the Sea of Marmara and the Thermaic Gulf have the highest positive trend rates of up to 0.057/0.056/0.055 °C/year for mean/min/max SST. The lowest trends were found to be down to 0.027/0.025/0.025 °C/year for mean/min/max SST along the western and southwestern boundaries of the study area. Basin-averaged annual trends were estimated as 0.039 °C/year, 0.043 °C/year, and 0.037 °C/year for monthly mean, minimum, and maximum SST, respectively. The upward SST trends are milder for the maximum SST and steeper for the minimum SST with respect to the mean SST.

Long-term trend analysis was performed in the same manner for each month separately to reveal the seasonal variations in the spatial distributions of the trends of monthly mean, monthly minimum, and
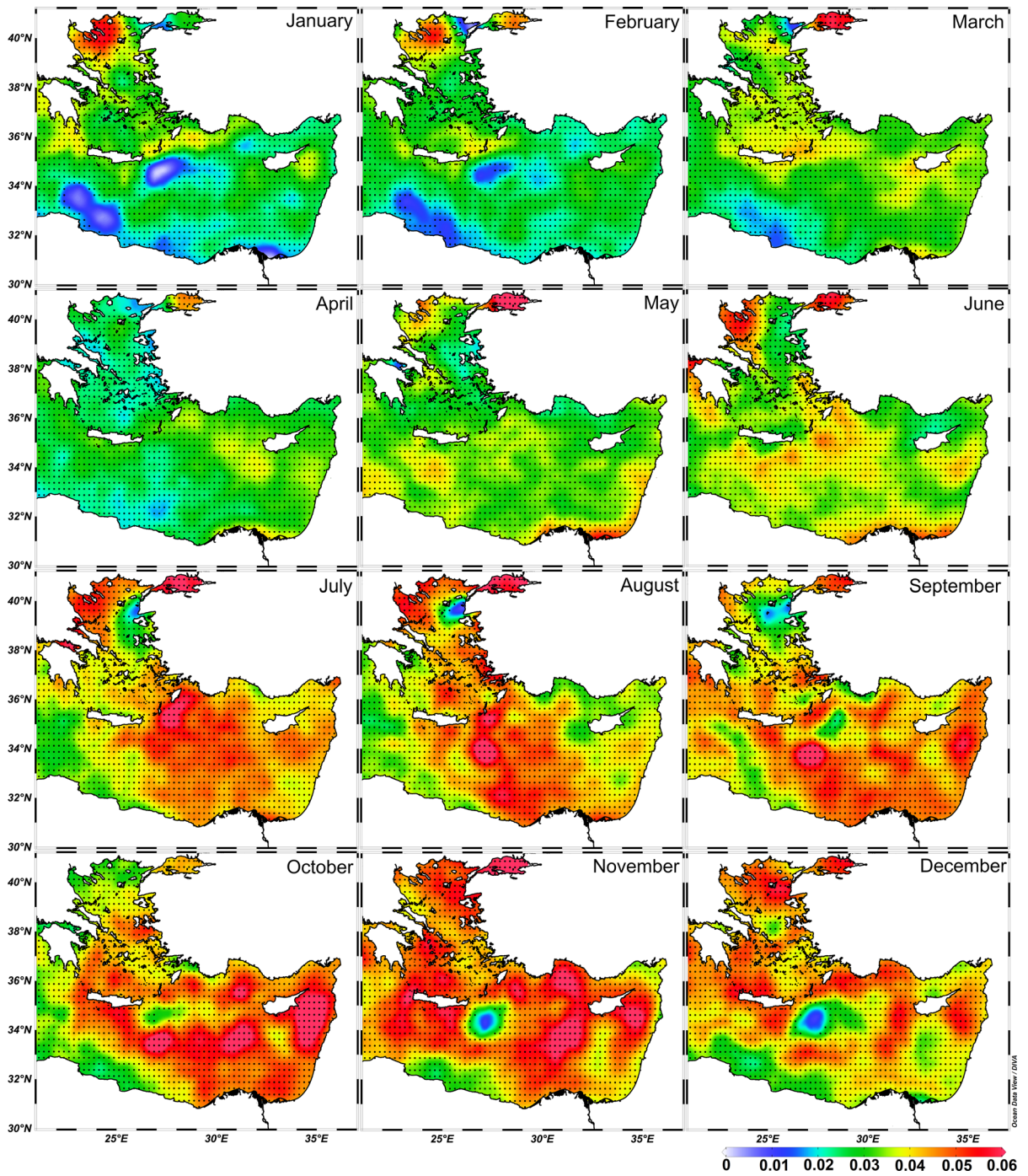
Figure 6
Seasonality in the long-term trends of monthly mean SST (°C/year) and their spatial variability
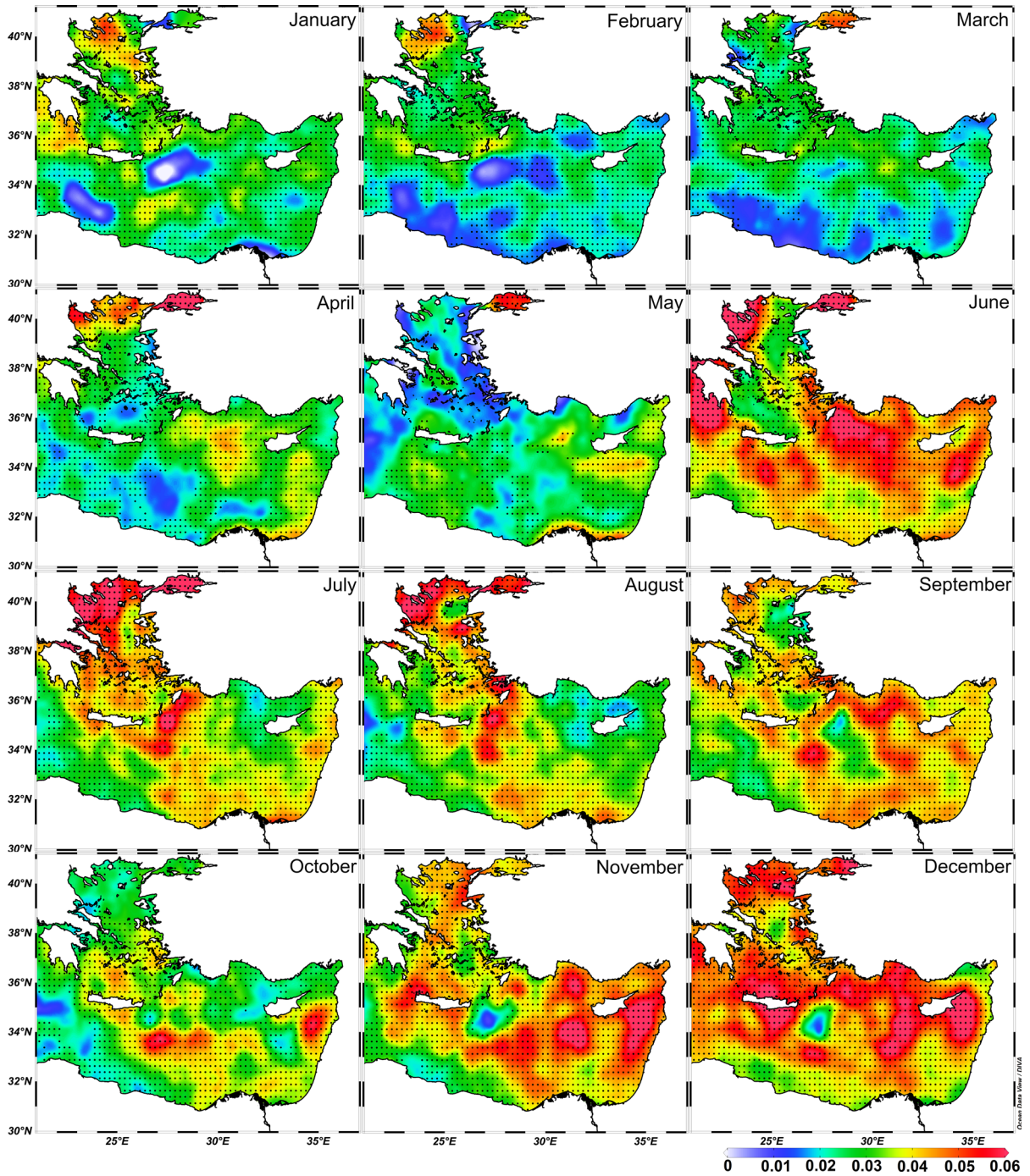
Figure 7
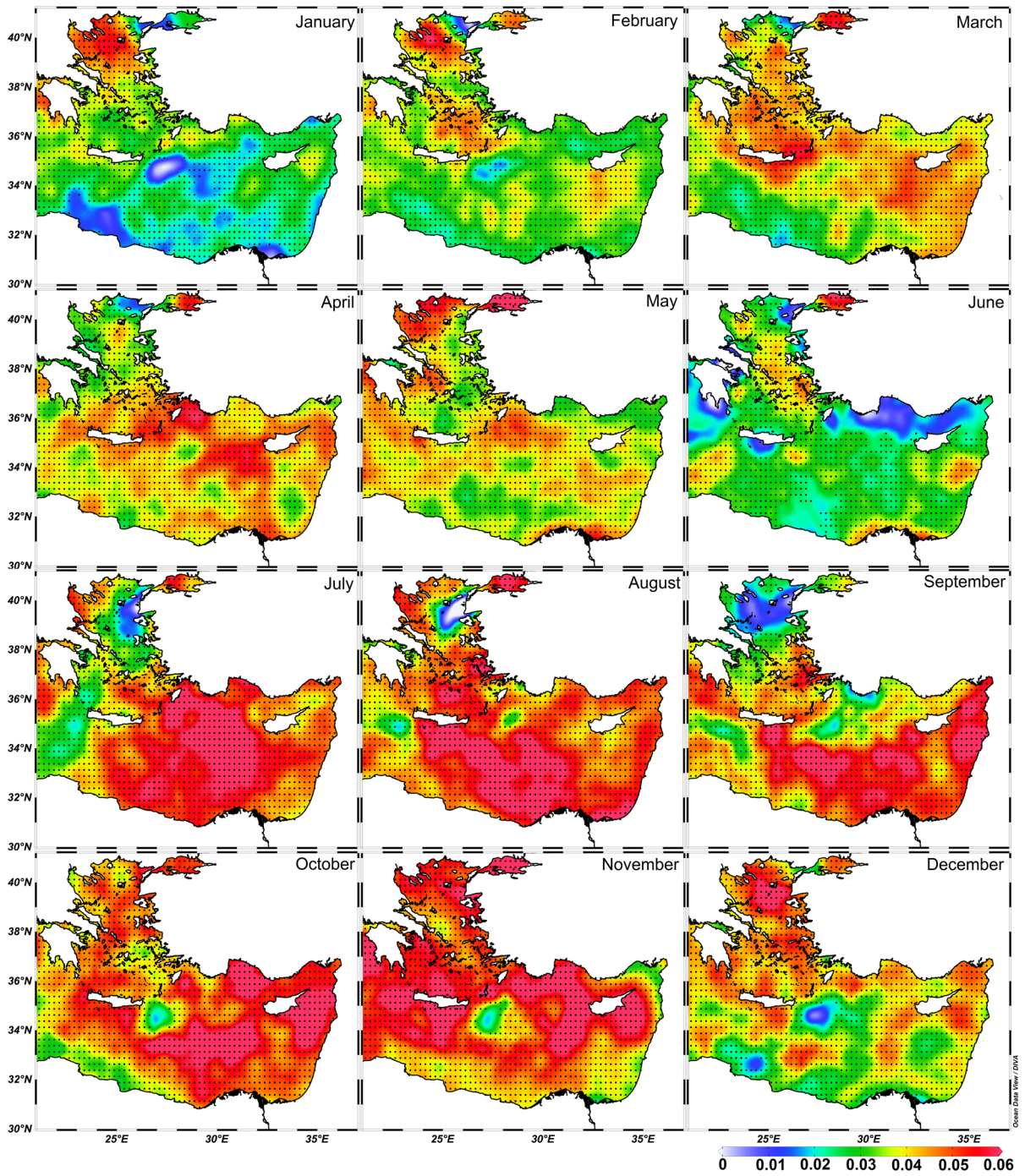Seasonality in long-term trends of monthly maximum SST (°C/year) and their spatial variability

Figure 8
Seasonality in long-term trends of monthly minimum SST (°C/year) and their spatial variability

monthly maximum SST (39-data time series) by using the OISSTv2.1 dataset. The spatial distributions of trends of monthly mean SST for each month separately are shown in Fig. 6.

A clear increase in SST was found in the whole study area throughout the whole year. Higher trend rates were observed between July and December. The easternmost part of the study area has the highest trend rates, reaching up to 0.080 °C/year in October. Basin-averaged trends were estimated as 0.028 °C/year, 0.027 °C/year, 0.032 °C/year, 0.028 °C/year, 0.033 °C/year, 0.036 °C/year, 0.042 °C/year, 0.042 °C/year, 0.043 °C/year, 0.045 °C/year, 0.047 °C/year, and 0.042 °C/year for each month, respectively. The highest basin-averaged trend was calculated in November. Spatial distribution and the seasonality of trends of monthly maximum SST are mapped in Fig. 7.

Long-term trends of both monthly mean and monthly maximum SST data present similar patterns in the means of spatial distribution, the magnitude of trends, and the seasonal characteristics. Trends are significant in almost the whole basin for all months except May. The highest trend rates of up to 0.083 °C/year were calculated for the Sea of Marmara in July. Downward trends were depicted at Aegean Sea and central Levantine Basin in January and May; however, they were not statistically significant. Basin-averaged trends for monthly maximum

SST were found to be 0.028 °C/year, 0.024 °C/year, 0.024 °C/year, 0.029 °C/year, 0.025 °C/year, 0.044 °C/year, 0.039 °C/year, 0.036 °C/year, 0.040 °C/year, 0.032 °C/year, 0.042 °C/year, and 0.046 °C/year for each month, respectively. The highest basin-averaged trend was calculated in December. The spatial distribution and seasonality of trends of monthly minimum SST are mapped in Fig. 8.

The long-term trends of the monthly minimum SSTs were found to be higher between July and November. The trends are statistically insignificant in June along the northern coasts of the Levantine Basin and the northwestern boundary of the study area. The highest upward trend was computed in the Levantine Basin between July and November. Basin-averaged trends were estimated as 0.029 °C/year, 0.034 °C/year, 0.040 °C/year, 0.041 °C/year, 0.040 °C/year, 0.029 °C/year, 0.047 °C/year, 0.049 °C/year, 0.044 °C/year, 0.049 °C/year, 0.051 °C/year, and 0.040 °C/year for each month, respectively. The highest basin-averaged trend was calculated in November.

3.4. Comparison of SST Trends Derived From In-Situ and OISSTv2.1 Datasets

Table 5 is given for a comparison of OISSTv2.1 and in-situ SST trends for the same period (January

Table 5

Comparison of trends of monthly mean, maximum, and minimum SSTs based on OISSTv2.1 and in-situ data

Stations	Monthly Mean (°C/year)		Monthly Maximum (°C/year)		Monthly Minimum (°C/year)	
	In-situ	OISSTv2.1	In-situ	OISSTv2.1	In-situ	OISSTv2.1
Çanakkale	0.034	**0.030****	0.036	**0.034****	0.031	**0.029****
Ayvalık	0.010	**0.035*****	− 0.009	**0.033*****	0.018	**0.040*****
Dikili	**0.060*****	**0.035****	**0.044****	**0.031****	**0.066*****	**0.041*****
Kuşadası	**0.054*****	**0.038*****	**0.057*****	**0.037****	**0.051*****	**0.042*****
Bodrum	**0.051*****	**0.041*****	**0.046*****	**0.042*****	**0.052*****	**0.046*****
Marmaris	**0.036****	**0.039*****	**0.040****	**0.041****	0.025	**0.043*****
Fethiye	**0.038****	**0.035****	0.019	**0.034****	**0.059*****	**0.042****
Finike	**0.045****	**0.037****	**0.044****	**0.036****	**0.041****	**0.041****
Alanya	**0.048****	**0.037****	**0.044****	**0.033****	**0.051*****	**0.042****
Anamur	**0.037****	**0.038****	0.030	**0.034****	**0.040****	**0.042****
Mersin	**0.049****	**0.037****	**0.048****	**0.035****	**0.048****	**0.041****
İskenderun	**0.046****	**0.040****	**0.036****	**0.038****	**0.058****	**0.042****

Bold font indicates statistical significance. Significances are as follows: *95%; **97%; ***99%; ****99.9%
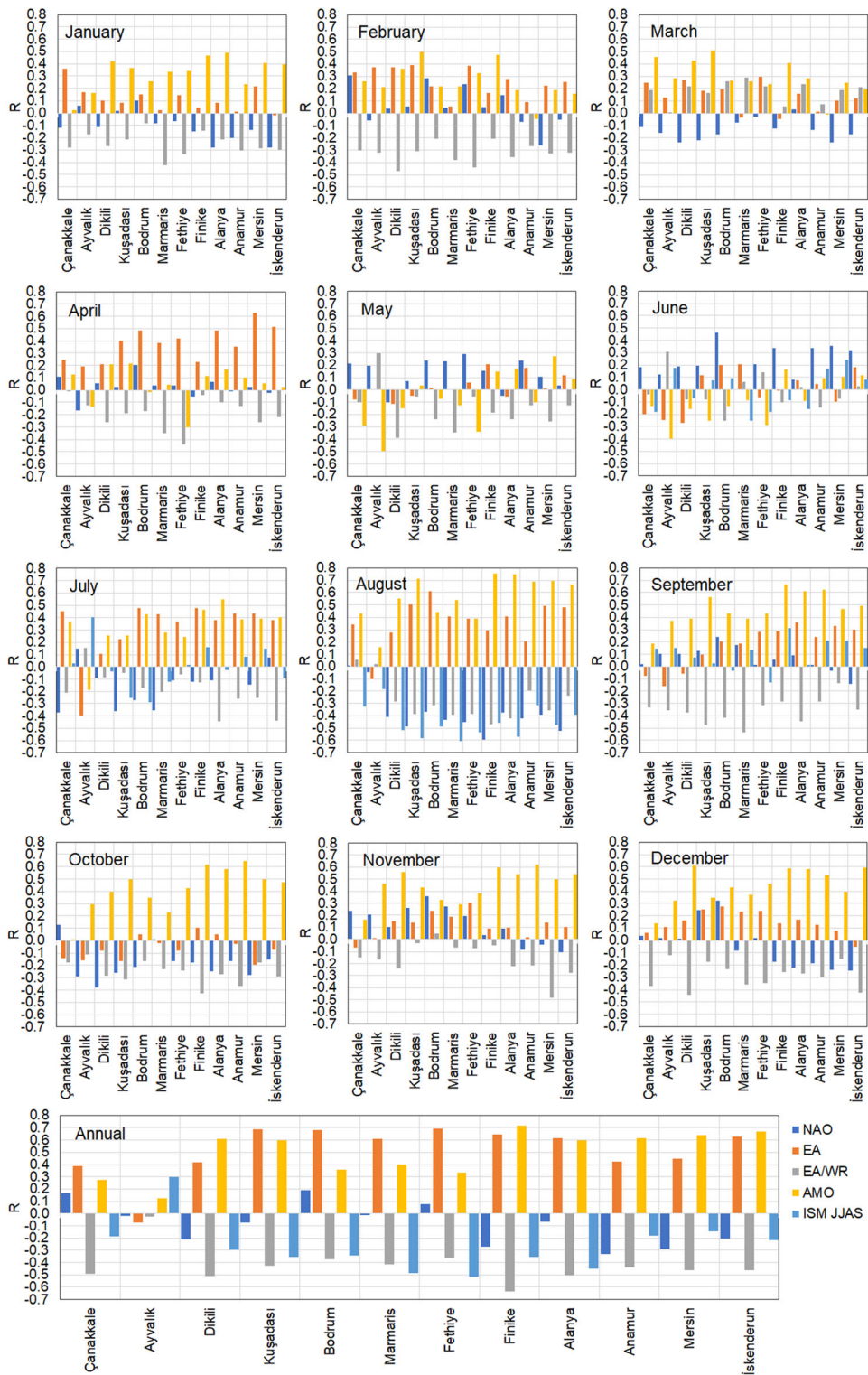
Figure 9
Correlations between different climate indices and the in-situ SST at 12 stations

1982–December 2020). The long-term trends were compared for monthly mean, maximum, and minimum SSTs at 12 coastal stations along the coasts of the Aegean Sea and the Levantine Sea.

Table 5 indicates that the in-situ SST data give higher trend rates than the OISSTv2.1 data in general. A significant upward trend for almost all stations is evident for both datasets at a confidence level higher than 97%. Exceptions are the Çanakkale and Ayvalık stations, which have the only insignificant trends with lower rates in comparison to the other stations' data. The OISSTv2.1 data provided statistically significant upward trends at these two stations. Monthly mean SST trends along the coasts of the Levantine Basin are relatively homogeneous with a rate of around 0.030–0.040 °C/year according to OISSTv2.1 data, while they vary between 0.036 and 0.060 °C/year based on the in-situ data. The same pattern with relatively homogeneous trend rates for OISSTv2.1 is observed for both monthly minimum and maximum SSTs.

3.5. Relation of SST Variability to Climate Indices

Relations of the NAO, AMO, EA, EA/WR, and ISM indices with SSTs in the study area were evaluated based on the correlation coefficients (R) for all in-situ stations. We aimed to provide information about the teleconnection patterns associated with SST variability in the study area. Analysis was done on a monthly basis as well as an annual basis. Hence, 39-data time series of both the considered index and the SST at each in-situ station were compared (Fig. 9).

The Mediterranean SST presented a statistically significant positive correlation (≥ 0.31) at the 95% level with the EA index and a negative correlation (≤ -0.31) with the EA/WR index for all the stations except Ayvalık based on the annual evaluation. The AMO index also presented a significant positive correlation with the SSTs at almost all stations except Çanakkale and Ayvalık. The AMO index was associated with the SSTs throughout the whole year, except for April, May, and June. The highest R was estimated as 0.72 between the AMO index and the SST measured at the Finike station. The ISM index averaged over JJAS also presented a significant

negative correlation with the SSTs at the Kuşadası, Bodrum, Marmaris, Fethiye, Finike, and Alanya stations. Analysis of the results on a monthly basis indicated that all studied teleconnection patterns are highly correlated with August SSTs at almost all stations. Correlation coefficients reached up to 0.76 at the Finike station in August, followed by 0.75 at Alanya. While the EA and AMO indices present positive correlations, the NAO, EA/WR, and ISM indices present negative correlations in general. The NAO index shows significant positive correlations at the Levantine Basin stations in June, negative correlations in the Aegean Sea stations in July, and negative correlations for almost all stations in August. The ISM index was associated with the SSTs at all stations except Ayvalık, revealing negative correlation coefficients varying between -0.33 and -0.61 in August.

4. Conclusions

In this study, the long-term SST trends for the Aegean Sea and Eastern Mediterranean Sea have been determined using both OISSTv2.1 and in-situ data covering the period between 1982 and 2020. Spatial and seasonal variability of the long-term trends of annual and monthly mean, minimum, and maximum SSTs have been revealed.

The main findings from the present study are summarized below:

1. Annual basin-averaged (the whole study area, including the Levantine Basin and the Aegean Sea) upward trends of monthly mean, minimum, and maximum SSTs are estimated as 0.039 °C/year, 0.043 °C/year, and 0.037 °C/year, respectively, being almost four times greater compared to the global SST trends. Long-term positive trends of monthly mean, minimum, and maximum SSTs are significant at confidence levels of 95% or higher within almost the whole study area. This finding is supported by both in-situ and OISSTv2.1 data.

2. According to in-situ data, long-term trends of annual maximum and minimum SSTs are higher than the trend rates of annual mean SST. The ecosystem may be impacted more severely due to the steeper

rate of change in the extreme SSTs than the changes in the annual mean SSTs.

3. Comparison of annual trends from in-situ SST data and OISSTv2.1 data revealed some discrepancies. These differences may be related to the coarse spatial resolution and the interpolation of the point data to a spatial map for the OISSTv2.1 dataset. Local upwelling structures, freshwater inflows, or circulation patterns may not be captured by the OISSTv2.1 data. Hence, the selection of the data source for analysis should be done based on the intended usage scenario, where the points of interest can be either on the coastal waters or in the offshore region. In-situ observations and comparative studies of different interpolated SST data are needed to improve the quality of interpolated SST data.

4. Evaluation of the seasonality of the long-term trends of monthly mean SSTs for all three variables (monthly mean, minimum, and maximum SST) revealed that a higher upward trend exists between July and December in general. This finding is supported by both in-situ and OISSTv2.1 data.

5. Spatial variation of the long-term SST trends within the study area indicated more significant trends and a more homogeneous pattern within the Levantine Basin. The Aegean Basin has less significant trends and a more inhomogeneous distribution of trends. This most probably occurs due to the complex circulation pattern and the upwelling structure within the Aegean Sea (Meriç et al., 2017). Another important reason is the less saline water being discharged from the Black Sea via the Turkish Straits System (TSS) towards the Aegean Sea (Öztürk et al., 2012). Hence the insignificant trends over the northern Aegean Sea may occur due to the dynamics of the TSS, driven by a complex combination of barotropic and baroclinic forcing. Further studies are needed to better understand the impact of the dynamics of the TSS on the SST trends in the northern Aegean Sea.

6. The upward trends with confidence levels of 95% or higher were found to be greater than 0.024 °C/year in all studied SST data and time series. The estimated basin-averaged upward trend rate of 0.039 °C/year is generally found to be comparable to the results of previous research. Skliris et al. (2012) and Shaltout and Omstedt (2014) reported upward trends between 0.038 °C/year and 0.042 °C/year,

which are in line with our results, while Nykjaer (2009) reported a higher trend rate of 0.050 °C/year. The slight differences may arise from the distinct temporal and spatial coverages as well as the data and methods used in different studies.

7. Seasonal analysis of trends indicated that the trends of the monthly minimum SST between July and November are higher than the trends of the monthly maximum SST, especially in the Levantine Basin.

8. Statistically significant correlations were found between teleconnection indices (EA, AMO, EA/WR, NAO, and ISM) and in-situ SSTs. The AMO index is associated with the SSTs at almost all stations with the highest positive correlation coefficients especially for the period between July and December. Our results indicated that the EA index with positive correlations and the EA/WR index with negative correlations are the second most effective teleconnection indices in the study area.

9. The diurnal variability of SSTs could not be evaluated in this study. Future studies based on datasets available for evaluating daily variability are needed to better quantify the uncertainties in the gridded datasets.

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