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# RELATIONSHIP BETWEEN SEA SURFACE TEMPERATURE (SST) AND SURFACE AIR TEMPERATURE (SAT) ALONG THE EASTERN ADRIATIC COAST OF CROATIA

Ognjen BONACCI
University of Split, Faculty of Civil Engineering, Architecture and Geodesy, 21000 Split, Matice hrvatske 15, Croatia

## ABSTRACT

The paper analyses the relationship between sea surface temperature (SST) and surface air temperature (SAT) measured at nine climatological stations along the Croatian part of the Adriatic Sea. Climate changes, mostly manifested through the global warming effect, have strongly and seriously influenced the Adriatic Sea and its coastal region in recent decades. The behaviour of the SST and SAT time series are investigated using linear and quadratic regressions, Mann–Kendall test, Rescaled Adjusted Partial Sums method, F-test, and t-test. Analyses are provided in yearly and monthly time scales. Statistically significant increasing trends in the mean annual SST began in 1998. Similar behaviour of SAT time series was observed. Emphasis is placed on analyses of SST and SAT behaviour in the recent period from 1998 to 2022. It is found that the behaviour of SST and SAT differs from station to station, where local climatological, orographic, and other environmental characteristics play a key role. The average SST is higher than the average SAT in the warm part of the year (from May to September). The results of this study could help stakeholders and decision–makers in developing effective measures to mitigate the negative effects of climate change in the different locations of the Adriatic islands and coastal regions.

**Keywords:** Sea surface temperature (SST), Surface air temperature (SAT), Adriatic Sea (Croatia), Climate changes

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Kontakt: obonacci@gradst.hr

## 1 INTRODUCTION

In the recent decades, the Mediterranean basin is definitely recognized as one of the most endangered and vulnerable areas in the Earth to climate change. Because of high concentration of urban and industrial settlements as well as uncontrolled development of tourism it represents one of the most impacted areas of the world in terms of water scarcity (Pumo et al. 2010; Tramblay et al. 2020; Alreeimei et al. 2022). Most of the Mediterranean region has experienced frequent natural disasters, expanding population, increase in temperature, and increase in the surface of the Mediterranean Sea (Noto et al. 2023). The Mediterranean Sea covers an area of about $2.5\times10^6$ km$^2$ and has a volume of about $3.76\times10^6$ km$^3$. It is geographically divided into several regional seas. The Adriatic Sea is among the smaller once. It is located in its northern part and represents the bay that enters the European continent the deepest. The area of the Adriatic Sea is 138,595 km$^2$ representing only 4.6% of the Mediterranean Sea area. The volume of water in the Adriatic Sea is 35,000 km$^3$. It stretches in the NW-SE direction in a length of 870 km. Its average width is about 200 km, with the largest being 216.7 km. It is connected to the rest of the Mediterranean Sea by the 70 km wide Strait of Otranto. Its average depth is about 173 m, with the greatest being 1233 m. The northern part of the Adriatic Sea is shallow (<35 m). The middle part has an average depth of about 140 m, while the southern part is the deepest, with an average depth of over 200 m.

The area of the Adriatic Sea basin is 235,000 km$^2$. The countries on the shores of the Adriatic Sea are Albania, Bosnia and Herzegovina, Montenegro, Croatia, Italy, and Slovenia. Sea currents move in a counter-clockwise direction, entering through the Strait of Otranto along the eastern (Albanian, Montenegrin, Bosnian-Herzegovinian, Croatian, and Slovenian) coast of the sea, and returning along the western (Italian) coast (Orlić et al. 1992; Artegiani et al. et al. 1997). There are more than 1,300 islands, islets, and rocks in the Adriatic Sea, located mostly on the east coast. There are 1,246 of them on the Croatian coast (Duplančić-Leder et al. 2004).

The particularity of the Adriatic, when compared to all other regional seas, lies in the fact that only here there is the so-called positive freshwater balance. Raicich (1996) concluded based on the analysis of the water balance of the Adriatic Sea: „*Nevertheless, on an annual basis, the difference between the freshwater losses by evaporation and the gains by precipitation and runoff is clearly negative, indicating that, unlike the whole Mediterranean, the Adriatic Sea is generally a dilution basin.*“ Although in comparison to the size of the entire Mediterranean, it is a small and marginal sea, its role in the ecological sense is significant not only at the local level.

Pastor (2022) states that the World Meteorological Organization has recognized the sea surface temperature (SST) as one of the essential climate variables which significantly contributes to the characterization of the planetary climate. Zhang et al. (2023) stress importance of SST due to fact that sea surface warming patterns drive hydrological sensitivity uncertainties. Analysing the SST in the Aegean Sea, Vlahakis and Pollatou (1993) determined that it strongly influences, on all time scales, numerous and very different natural and social processes that take place on the islands and in the coastal area. The same is the case with the Adriatic Sea.

The total length of the coast of the Adriatic Sea in Croatia is 5835 km, of which 1777 km refers to the continent (mainland) and 4058 km to the islands. Various aspects related to the water temperatures of the Adriatic Sea have been treated in a series of works (e.g., Zore-Armanda 1969; Grbec 1997; Matić et al. 2011; Yari et al. 2012; Branković et al. 2013; Gačić et al. 2014; Kovač et al. 2014; Grbec et al. 2015; Davolio et al. 2017; Matić et al. 2017; Grbec et al. 2018; Vilibić et al. 2019; Šepić et al. 2022). In a slightly smaller number of papers, analyses of the relationship between SST and surface air temperature (SAT) at individual climatological stations on the islands and coast of the Croatian part of the Adriatic Sea were published (Supić and Orlić 1992; Bonacci et al. 2021a, 2021b; Bonacci and Vrsalović 2022).

Based on measurements in the period from May 2014 to May 2021, Vilibić et al. (2022) quantified sea temperature changes in the shallow (5 m) layer of the north-western part of the Adriatic Sea. They concluded the following: „*As expected for shallow waters, the seasonal influence is prevalent, while diurnal changes are quasi-persistent throughout the year. Marine heat waves and cold spells are the strongest during spring and summer months.*“ They determined that the strong warming of the Adriatic Sea caused by the atmosphere affects the increase in salinity and temperature of the sea in the surface layer.

Tojčić et al. (2023) simulated the trend and variability of the atmosphere-ocean relationship in the Adriatic Sea simulated on a scale of 1 km using the AdriSC (Adriatic Sea and Coast) climate model in the period 1987–2017. They found that „*... stronger temperature trends associated with lower, mostly seasonal, variability over the Adriatic Sea than over the land and positive trends of wind speed and negative trends of relative humidity associated with high, mostly seasonal, variability over the sea and vice versa over the land.*“

Analysing Mediterranean daily SST data in the 1982-2012 period, Shaltout and Omstedt (2014) found significant annual warming (from 0.24 ºC/decade west of the Strait of Gibraltar to 0.51 ºC/decade over the Black Sea) as well as significant spatial variation in annual mean SST (from 15 ºC over the Black Sea to 21 ºC over the Levantine sub-basin). Authors indicate that the observed area SST may experience significant warming, peaking at 2.6 ºC/century.

For a better understanding of the global warming process, it is of particular interest to analyse SST and SAT trends on islands and along the sea coast. The purpose of the analyses carried out in this paper is to study and understand in more detail the interaction between SST and SAT at stations along the Croatian coast of the Adriatic Sea where longer and more reliable measurements of these two parameters are available. Emphasis is placed on the analysis of SST behaviour in recent decades when a more intensive air temperature increase was observed in Croatia and the wider region (Bonacci 2012; Bonacci et al. 2023).

## 2 DATA AND METHODS

The climate in the entire area of the Adriatic Sea is Mediterranean. The influences of the continental and maritime climate in the northern part are different from those in the central and southern parts of the Adriatic. As a consequence, according to the Köppen-Geiger climate classification, the northern part belongs to Cfa (moderately warm humid climate with hot summers), and the middle and southern part to Csa (Mediterranean climate with hot summer) and to a lesser extent to Csb (Mediterranean climate with hot in summer) area (Köppen 1918; Köppen and Geiger 1936; Geiger and Pohl 1954; Šegota and Filipčić 2003).

For the Croatian part of the Adriatic Sea, SST was or is being measured at about twenty stations. Unfortunately, measurements are no longer performed on some of them, while on other, the series are short, or there are numerous interruptions in their work. In this paper, SST and SAT data measured at nine stations were analysed. A map of the observed area showing the locations of the nine meteorological stations whose data were analysed in this study is given in Fig. 1. Five of them (1. Opatija, 2. Sv. Ivan, 3. Pula, 4. Senj, 5. Rab) are located in the northern Adriatic, while the other four stations are located in the middle Adriatic (6. Šibenik, 7. Split, 8. Hvar, 9 Komiža). Stations that have a series of observations longer than 30 years with an emphasis on the recent period from 1998 to 2022 were selected. Their characteristics are listed in Table 1. The recent period was chosen due to a sudden jump in SAT observed in the wider region, especially in the coastal area belt and islands of the Adriatic (Bonacci 2012; Bonacci et al. 2021a, 2021b). Since there was a sudden increase in SAT in the region at almost the same time, this paper will try to analyse the relationship between the increase in SAT and SST at seven stations where the stations for measuring SAT are located very close to the meteorological stations where SST is measured. All data are official and obtained from the Croatian Meteorological and Hydrological Service.

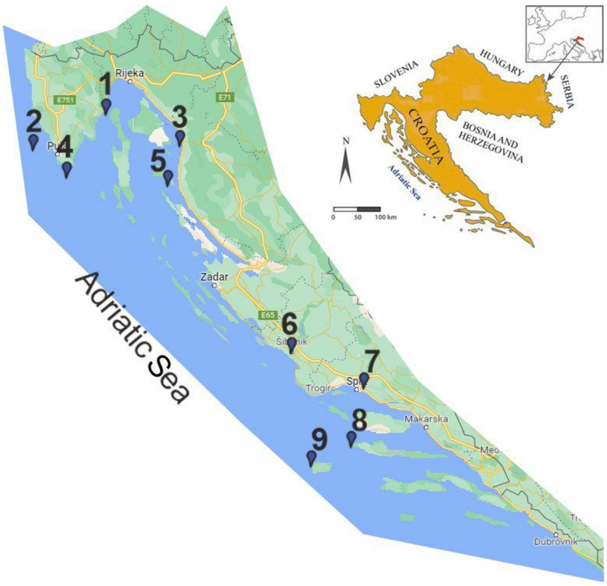


Figure 1. Map of the study area showing the locations of the nine meteorological stations whose data were analysed in this study

Table 1. Characteristics of the investigated meteorological stations

| **STATION** | **SST** | | | **SAT** |
|---|---|---|---|---|
| | **N** | **E** | **year** | **year** |
| 1. Opatija | 45° 20' 03" | 14° 18' 36" | 1976-2020 | 1981-1984 |
| 2. Sv. Ivan | 45° 02' 36" | 13° 36' 52" | 1995-2022 | - |
| 3. Senj | 44° 59' 33" | 14° 54' 12" | 1964-2019 | 1949-2022 |
| 4. Pula | 44° 52' 18' | 13° 50' 32" | 1999-2022 | 1963-2022 |
| 5. Rab | 44° 45' 12" | 14° 46' 02" | 1962-2022 | 1978-2022 |
| 6. Šibenik | 43° 43' 18" | 15° 51' 00" | 1996-2022 | 1948-2022 |
| 7. Split | 43° 29' 59" | 16° 27' 21" | 1959-2022 | 1948-2022 |
| 8. Hvar | 43° 10' 13" | 16° 26' 17" | 1964-2022 | 1946-2022 |
| 9. Komiža | 43° 02' 40" | 16° 05' 09" | 1991-2022 | 1956-2022 |

Linear and nonlinear (second-order curve) trends were calculated for the analysed SST and SAT time series. The equation for a linear trend is:

$$Y = (a \times t) + b \qquad (1)$$

while the nonlinear trend equation is:

$$Y = (c \times t^2) + (d \times t) + e \qquad (2)$$

Where $Y$ is the mean annual STT or SAT in the year $t$, $a$ and $b$ are the linear regression coefficients, $c$, $d$, $e$, are the second-order curve coefficients. For the all-time series, coefficient of determination $R^2$ were calculated.

The coefficient $a$ in Eq. 1 represents the slope of the regression direction whose dimension is expressed in ºC/year.

The statistical significance of the linear trends was determined using the Mann-Kendall (M-K) test (Mann 1945; Kendall 1975) calculated by the pyMannKendall, a python package (Husain Shourov and Mahmud 2019). The null hypothesis was that there is no monotonic trend in the analysed time series, while an alternative hypothesis was that the trend exists. The probability value $p<0.01$ was used as a criterion for accepting the hypothesis for the existence of a statistically significant linear trend.

The Rescaled Adjusted Partial Sums (RAPS) method (Garbrecht and Fernandez 1994) was used in order to detect and quantify the trends and fluctuations in the analysed time series. A visualization approach based on RAPS overcomes small systematic changes in the records and the variability of data values. The equation for calculating RAPS is:

$$RAPS_k = \Sigma_k (Y_t - Y_Y) / S_Y \qquad (3)$$

Where $Y_t$ represents the analysed parameter in a given time interval $t$, $Y_Y$ the average value of the entire analysed time series, $S_Y$ the standard deviation of the entire analysed time series, $n$ the number of data in a series, $k \in (1, 2 \dots, n)$ the counter of sums for the $k$ analysed time unit in a series of the total $n$.

The F-test was used to determine the statistical significance of differences in variance, while the t-test was used to quantitatively assess the statistical significance of mean value differences over two-time periods (McGhee 1985). In both tests, the value of $p<0.01$ was considered the level of significance of differences.

## 3 YEAR AS TIME UNIT OF ANALYSES

### 3.1 Analyses of SST time series

Figure 2 shows the time series of the mean annual SST measured at Opatija (1976-2020, black), Senj (1964-2019, dark blue), Rab (1964-2022, purple), Split (1959-2022, brown) and Hvar (1964-2022, red) stations. Using the M-K test, the linear regressions evidenced increasing trends in the SST at all observed stations with $p<<0.01$. From the graphic representation, it can definitely be concluded that SST at three stations in the north (Senj, Opatija, and Rab) are significantly colder than at two stations in the middle Adriatic (Split and Hvar).

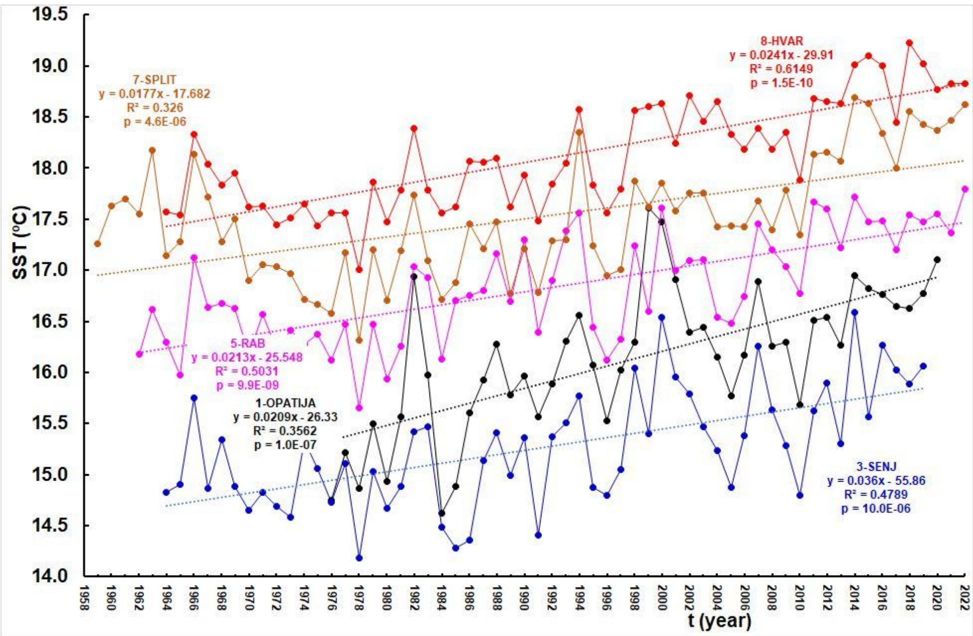


Figure 2. Time series of the mean annual SST measured at the Opatija, Senj, Rab, Split, and Hvar stations. The $R^2$ represents the coefficient of determination, and $p$ represents the Mann–Kendall (M–K) test values

The RAPS method was applied on the time series of the mean annual SST from the previously mentioned five stations. The results are shown in Fig. 3. Based on the graphic presentations in this figure, the all-time series were divided into following time subseries: (1) till 1997; (2) from 1998 onward. A graphic representation of two subsets of mean annual SST and their differences ΔSST measured at Opatija, Senj, Rab, Split, and Hvar stations, determined by the RAPS method, is given in Fig. 4.

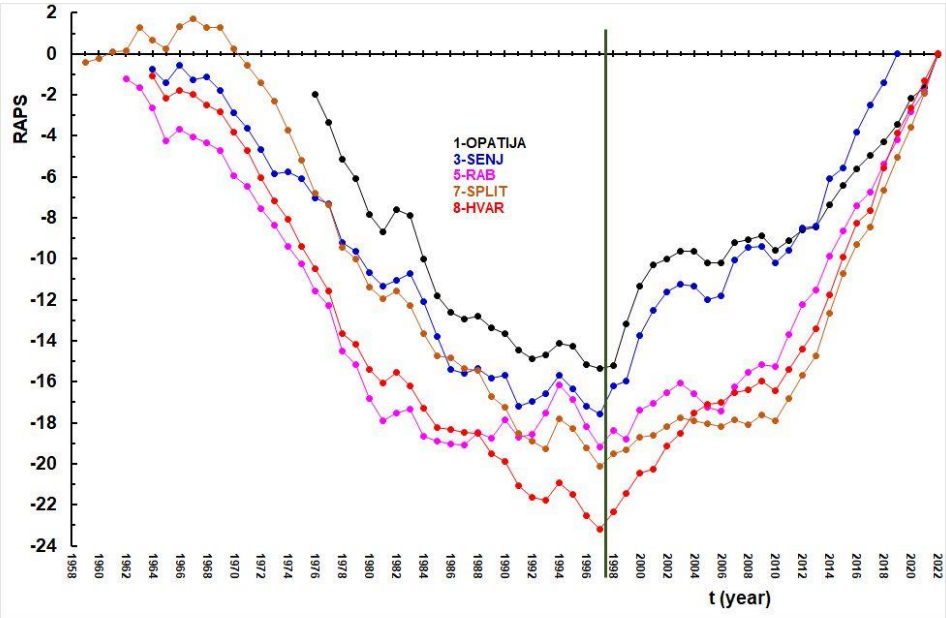


Figure 3. Graphic representation of RAPS for the mean annual SST measured at the Opatija, Senj, Rab, Split, and Hvar stations

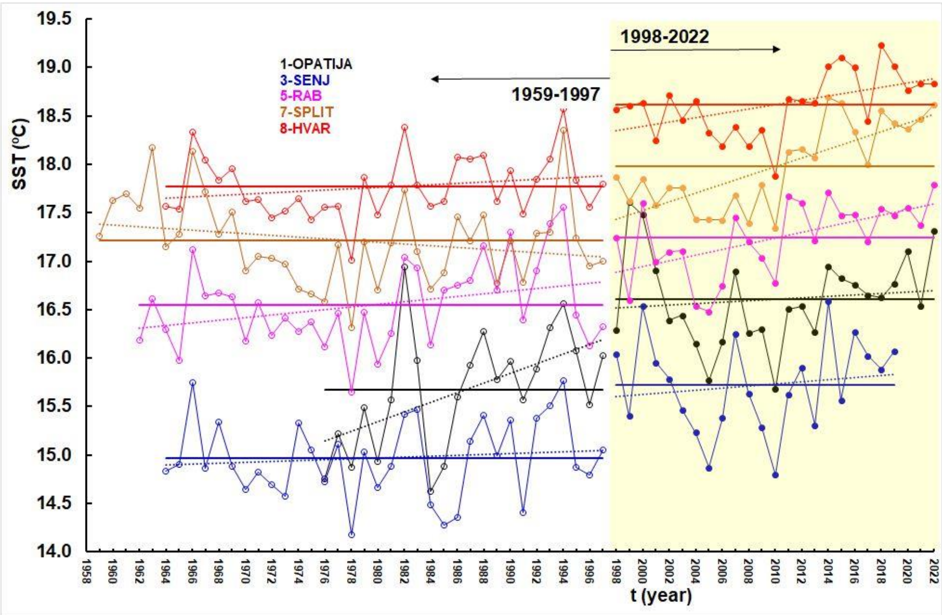


Figure 4. Graphic representation of two subsets of mean annual SST measured at the Opatija, Senj, Rab, Split, and Hvar stations determined by the RAPS method

The average values of the mean annual SST within a subperiod defined by the RAPS method at the observed stations and the results of the F-test and the t-test are given in Table 2. t-test evidenced statistically significant differences between the average values of the mean SST in the two sub-periods at all stations. F-test showed the statistically insignificant differences between their variances. Differences between the average annual SST vary from 0.99 ºC in Opatija to 0.54 ºC in Hvar.

Table 2. The average values of the mean annual SST time series within a sub–period defined by the RAPS method, their differences ΔSST at the analysed stations and the results of the F–test and the t-test

| STATION | Sub-period | SST (ºC) | ΔSST (ºC) | p | |
|---|---|---|---|---|---|
| | | | | F-test | t-test |
| 1. Opatija | 1976-1997 | 15.67 | 0.99 | 0.23 | 1.30E-06 |
| | 1998-2020 | 16.66 | | | |
| 3. Senj | 1964-1997 | 14.97 | 0.75 | 0.33 | 6.75E-08 |
| | 1998-2022 | 15.72 | | | |
| 5. Rab | 1962-1997 | 16.55 | 0.69 | 0.55 | 2.18E-08 |
| | 1998-2022 | 17.24 | | | |
| 7. Split | 1959-1997 | 17.21 | 0.77 | 0.99 | 6.35E-09 |
| | 1998-2022 | 17.98 | | | |
| 8. Hvar | 1964-1997 | 17.77 | 0.54 | 0.87 | 2.22E-14 |

Figure 5 depicts the time series of the mean annual SST measured in the period after 1997 at Opatija, Sv. Ivan, Senj, Pula, Rab, Šibenik, Split, Hvar, and Komiža stations, with *p*, representing the Mann–Kendall (M–K) test values. At all nine observed stations, the mean annual SST trend is upward. It is statistically significant at the level of $p<0.01$ at the stations Sv. Ivan, Pula, Rab, and Split, at the level of $p<0.02$ at the stations Šibenik and Hvar, while at the stations Opatija, Senj, and Komiža, it is statistically insignificant since $p>0.05$. It should also be noted that measuring was not performed at the Opatija station during the last two years (2021 and 2022) and at the Senj station during the last three years (2020-2022). The increasing trend would possibly be more significant at these stations if the measurements for those years were available.

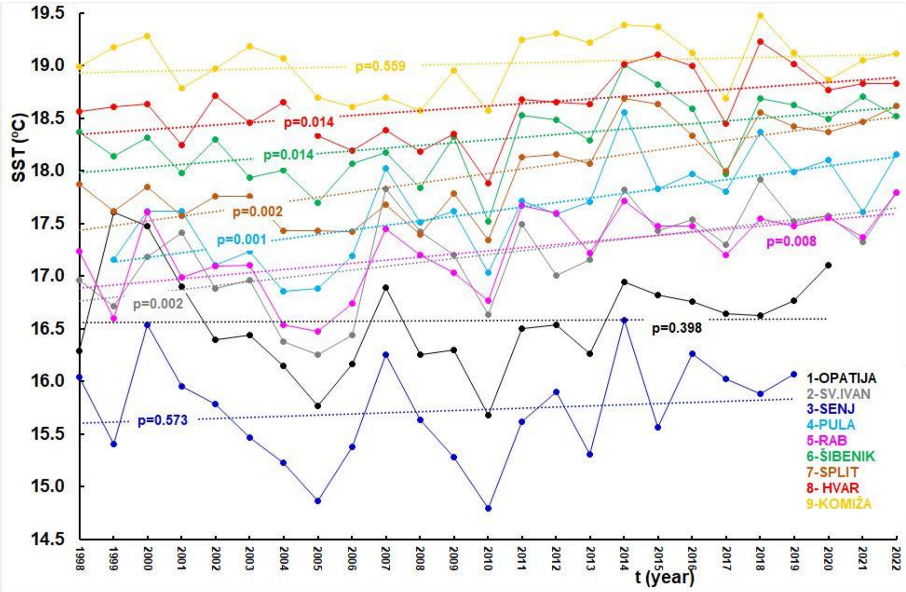


Figure 5. Time series of the mean annual SST measured in period after the 1997 year at the Opatija, Sv. Ivan, Senj, Pula, Rab, Šibenik, Split, Hvar, and Komiža stations with *p*, representing the Mann–Kendall (M–K) test values

### 3.2 Analyses of SAT time series

At the stations measuring SAT, significantly longer time series were available. At two stations (Opatija and Sv. Ivan) the SAT measurement was performed with interruptions, so these data could not be used in this analysis. The presentation of seven SAT sequences is given in Fig. 6, where the probability values *p* calculated by the M-K test are written along with the name of the station. It can be seen that in all analysed time series, SAT shows a statistically significant trend of increase at the p<<0.01 level. Even in the case of SAT temperatures at the northern stations, the temperatures are lower than those in the middle part of the Adriatic.

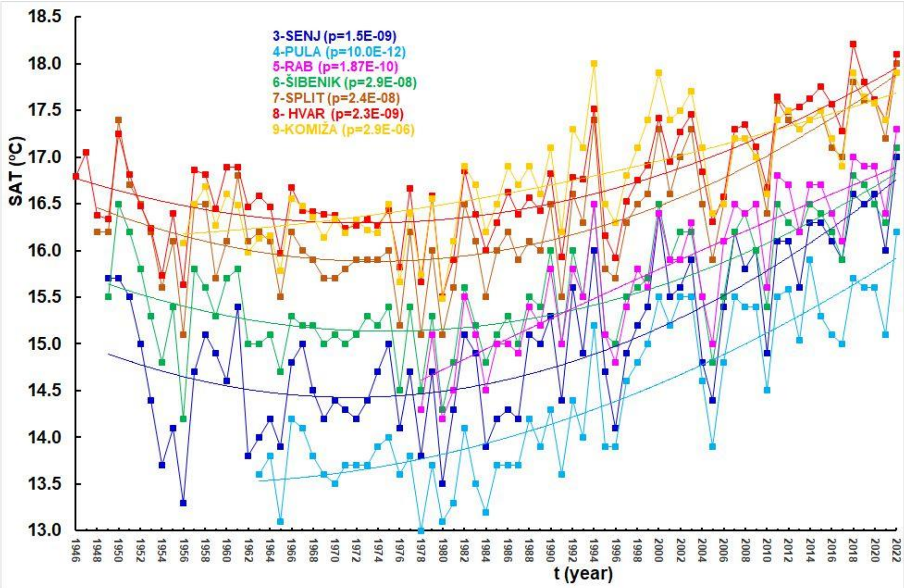


Figure 6. Time series of the mean annual SAT measured at the Senj, Pula, Rab, Šibenik, Split, Hvar, and Komiža stations, with *p*, representing the Mann–Kendall (M–K) test values

Using the RAPS method, it was determined that the sudden increase in SAT started in 1998 at five stations: Senj, Pula, Šibenik, Split, and Hvar. At the Rab station, it appeared a little later in 2000, while at the Komiža station, a sudden increase appeared a little earlier in 1992. The average values of the mean annual SAT time series within a sub-period defined by the RAPS method at the analysed stations and the results of the F-test and the t-test are given in Table 3. At all stations, the t-test shows a statistically significant difference between the average values at the p<<0.01 level. No statistically significant difference in variance between sub-periods was observed. At all stations, the probability defined by the F-test was p>>0.1. Time series of the mean annual SAT measured in the recent period 1998-2022 at Senj, Pula, Rab, Šibenik, Split, Hvar, and Komiža stations, with *p*, representing the Mann–Kendall (M–K) test values are shown in Fig. 7. At all observed stations there are increasing trends. Only at station Komiža, it is not statistically significant.

Table 3. The average values of the mean annual SAT time series within a sub–period defined by the RAPS method at the analysed stations and the results of the F–test and the t-test

| STATION | Sub-period | SAT (°C) | *p* | |
|---|---|---|---|---|
| | | | F-test | t-test |
| 3. Senj | 1949-1997 | 14.60 | 0.87 | 1.87E-12 |
| | 1998-2022 | 15.86 | | |
| 4. Pula | 1963-1997 | 13.80 | 0.55 | 1.86E-17 |
| | 1998-2022 | 15.25 | | |
| 5. Rab | 1978-1999 | 15.18 | 0.87 | 1.87E-12 |
| | 2000-2022 | 16.36 | | |
| 6. Šibenik | 1949-1997 | 15.28 | 0.79 | 1.10E-09 |
| | 1998-2022 | 16.13 | | |
| 7. Split | 1948-1997 | 16.04 | 0.84 | 5.59E-13 |
| | 1998-2022 | 17.10 | | |
| 8. Hvar | 1946-1997 | 16.43 | 0.43 | 4.30E-12 |
| | 1998-2022 | 17.32 | | |
| 9. Komiža | 1956-1991 | 16.35 | 0.19 | 5.71E-13 |
| | 1992-2022 | 17.25 | | |

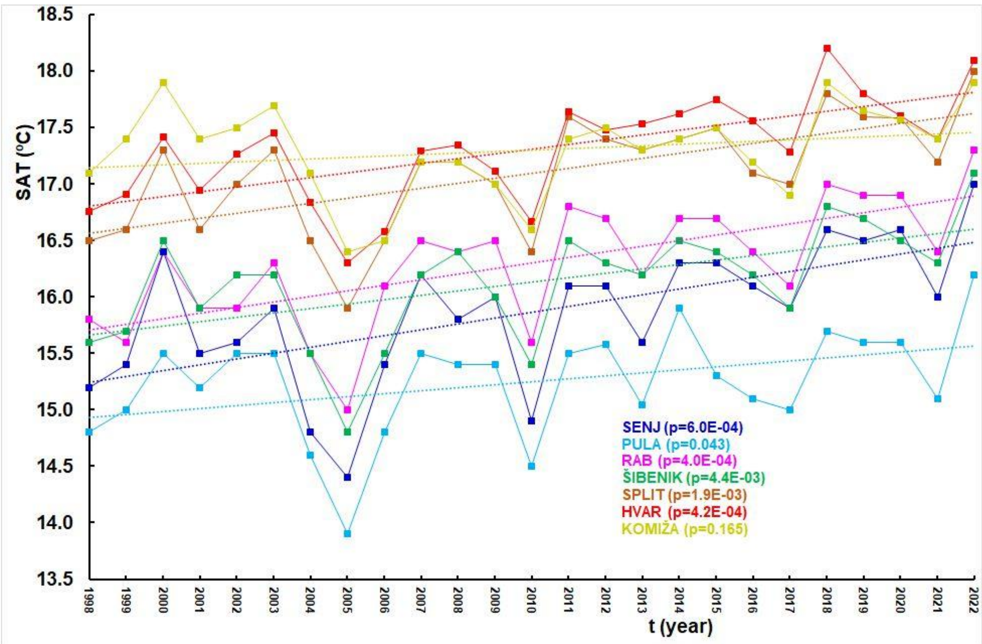


Figure 7. Time series of the mean annual SAT measured in the period 1998-2022 at the Senj, Pula, Rab, Šibenik, Split, Hvar, and Komiža stations, with *p*, representing the Mann–Kendall (M–K) test values

### 3.3 Relationship between SST and SAT

Table 4 shows the squared values of the coefficients of determination $R^2$ between mean annual SST and SAT. At all seven stations, the values are very high and range from $R^2$=0.541 in Pula to $R^2$=0.808 on the island of Rab. Based on these indicators, it is possible to conclude about a high interdependence between air and sea temperatures on an annual time scale. Table 5 includes the values of the coefficient of linear regression *a*, $R^2$, and *p* of the mean annual SST and SAT time series in the recent period, from 1998 onward at analysed stations.

Table 4. Coefficient of determination $R^2$, calculated from the time series of the mean annual SST and SAT at the analysed stations

| STATION | period | $R^2$ |
|---|---|---|
| 3. Senj | 1964-2019 | 0.716 |
| 4. Pula | 1999-2022 | 0.541 |
| 5. Rab | 1978-2022 | 0.808 |
| 6. Šibenik | 1996-2022 | 0.576 |
| 7. Split | 1959-2022 | 0.727 |
| 8. Hvar | 1964-2022 | 0.805 |
| 9. Komiža | 1991-2022 | 0.598 |

It is of particular importance to establish how this interdependence developed over time. For this purpose, Fig. 8 shows a series of mean annual differences (SAT-SST). At five stations, the differences have a decreasing trend. The trend is statistically significant at the Senj, Rab, and Split stations while statistically insignificant at the Hvar and Šibenik stations. The series of differences (SAT-SST) at the Pula and Komiža stations show a statistically insignificant increasing trend. It is obvious that the relationship between SAT and SST is influenced significantly at each station by local conditions. In this sense, Senj represents a specific case. It is a locality where strong wind, bora, blows very often. Bora is strong, usually dry temporally and spatially transient wind, common on the eastern Adriatic coast, especially in the Senj region (Yoshino 1976; Lepri et al. 2017). These are regional downslope winds, where cold air is pushed over a coastal mountain range due to the presence of a high-pressure gradient or by the passage of a cold front over the mountain range (Alpers et al. 2009). It is characterized by intense air–sea interactions and produce important meteorological effects not only over the eastern Adriatic basin, where bora originates and attains its maximum intensity, but also downstream over the Italian peninsula where heavy rainfall and snowfall can occur (Davolio et al. 2017).

Table 5. The values of the coefficient of linear regression *a*, coefficient of determination $R^2$, and *p* of the mean annual SST and SAT time series in recent period, from 1998 onward

| STATION | period | parameter | a (°C/year) | $R^2$ | p (M-K test) |
|---|---|---|---|---|---|
| 1. Opatija | 1998-2020 | SST | 0.0014 | 0.0004 | 0.398 |
| | | SAT | - | - | - |
| 2. Sv. Ivan | 1998-2022 | SST | 0.0369 | 0.3402 | 2.21E-03 |
| | | SAT | - | - | - |
| 3. Senj | 1998-2019 | SST | 0.0110 | 0.0216 | 0.573 |
| | | SAT | 0.0469 | 0.2746 | 5.11E-03 |
| | 1998-2022 | SST | - | - | - |
| | | SAT | 0.0515 | 0.3787 | 6.29E-04 |
| 4. Pula | 1999-2022 | SST | 0.0433 | 0.4527 | 6.78E-04 |
| | | SAT | 0.0248 | 0.1291 | 0.085 |
| | 1998-2022 | SST | - | - | - |
| | | SAT | 0.0262 | 0.1576 | 0.043 |
| 5. Rab | 1998-2022 | SST | 0.0295 | 0.3250 | 8.31E-03 |
| | | SAT | 0.0496 | 0.4552 | 3.95E-04 |
| 6. Šibenik | 1998-2022 | SST | 0.0259 | 0.2752 | 0.014 |
| | | SAT | 0.0392 | 0.3240 | 4.39E-03 |
| 7. Split | 1998-2022 | SST | 0.0451 | 0.5693 | 1.89E-03 |
| | | SAT | 0.0441 | 0.4161 | 1.95E-03 |
| 8. Hvar | 1998-2022 | SST | 0.0224 | 0.2614 | 0.014 |
| | | SAT | 0.0420 | 0.4444 | 4.21E-04 |
| 9. Komiža | 1998-2022 | SST | 0.0074 | 0.0409 | 0.559 |
| | | SAT | 0.0132 | 0.0579 | 0.165 |

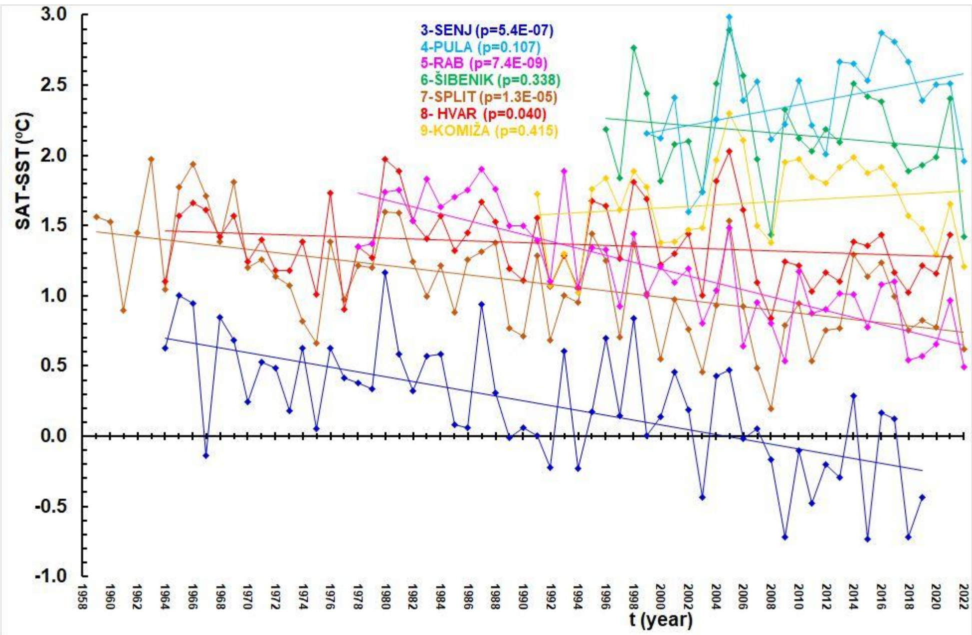


Figure 8. Time series of the differences between the mean annual SST and SAT measured at the Senj, Pula, Rab, Šibenik, Split, Hvar, and Komiža stations, with *p*, representing the Mann–Kendall (M–K) test values

## 4 MONTH AS TIME UNIT OF ANALYSES

Table 6 presents the average values of the mean annual SST time series measured at five stations within two sub–periods: (1) till 1997; (2) from 1998 onward. The probability values of the t-test *p*. During certain months of the year, there are different intensities of SST increase. The biggest differences occur in the summer months. Figure 9 shows histograms of average monthly SST in the recent period 1998-2022. It is possible to clearly see from the picture that during the winter period, SST at the stations in the northern Adriatic is significantly lower than in the middle Adriatic. This difference begins to decrease from May and lasts until September inclusive. A particular case is Senj, where the average monthly SST is always significantly lower than in all other locations in the period from May to October. During the cold period of the year, from November to April, the average monthly SSTs in Senj are almost identical to those at other stations in the northern Adriatic. This phenomenon can be explained by the influence of bora occurring throughout the whole year.

Table 6. The average values of the mean annual SST time series within two sub–periods at the analysed stations and the results *p* of the t-test

| month | 1. Opatija | | | 3. Senj | | | 5. Rab | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Sub-period** | **$SST_{av}$ (°C)** | ***p*** | **Sub-period** | ***$SST_{av}$ (°C)*** | ***p*** | **Sub-period** | ***$SST_{av}$ (°C)*** | ***p*** |
| Jan. | 76-97 | 10.72 | 0,206 | 64-97 | 10.89 | 0.012 | 62-97 | 10.82 | 0,228 |
| | 98-20 | 11.07 | | 98-19 | 11.40 | | 98-22 | 11.12 | |
| Feb. | 76-97 | 9.93 | 0.195 | 64-97 | 10.24 | 0.085 | 62-97 | 10.42 | 0,115 |
| | 98-20 | 10.34 | | 98-19 | 10.61 | | 98-22 | 10.80 | |
| Mar. | 76-97 | 10.28 | 0.215 | 64-97 | 10.30 | 0.039 | 62-97 | 10.94 | 1.2E-3 |
| | 98-20 | 10.69 | | 98-19 | 10.78 | | 98-22 | 11.71 | |
| Apr. | 76-97 | 11.84 | 5.0E-4 | 64-97 | 11.60 | 1.5E-4 | 62-97 | 13.10 | 4.1E-4 |
| | 98-20 | 12.91 | | 98-19 | 12.48 | | 98-22 | 13.92 | |
| May | 76-97 | 15.02 | 2.5E-5 | 64-97 | 14.81 | 2.0E-3 | 62-97 | 17.07 | 0.033 |
| | 98-20 | 16.78 | | 98-19 | 15.90 | | 98-22 | 17.84 | |
| Jun. | 76-97 | 19.64 | 4.1E-6 | 64-97 | 18.53 | 3.4E-4 | 62-97 | 21.22 | 3.3E-5 |
| | 98-20 | 21.38 | | 98-19 | 19.74 | | 98-22 | 22.40 | |
| Jul. | 76-97 | 22.62 | 3.9E-4 | 64-97 | 20.03 | 2.2E-4 | 62-97 | 23.45 | 6.7E-6 |
| | 98-20 | 23.82 | | 98-19 | 21.46 | | 98-22 | 24.59 | |
| Aug. | 76-97 | 23.06 | 0.021 | 64-97 | 20.27 | 0.028 | 62-97 | 23.70 | 2.7E-3 |
| | 98-20 | 23.86 | | 98-19 | 20.98 | | 98-22 | 24.48 | |
| Sep. | 76-97 | 20.55 | 0.097 | 64-97 | 18.95 | 0.465 | 62-97 | 21.41 | 0.176 |
| | 98-20 | 21.09 | | 98-19 | 19.19 | | 98-22 | 21.78 | |
| Oct. | 76-97 | 17.60 | 0.072 | 64-97 | 17.00 | 0.024 | 62-97 | 18.50 | 0.068 |
| | 98-20 | 18.28 | | 98-19 | 17.67 | | 98-22 | 18.94 | |
| Nov. | 76-97 | 14.53 | 2.4E-3 | 64-97 | 14.49 | 2.2E-3 | 62-97 | 15.15 | 5.5E-5 |
| | 98-20 | 15.60 | | 98-19 | 15.29 | | 98-22 | 16.03 | |
| Dec. | 76-97 | 12.30 | 0.068 | 64-97 | 12.27 | 5.2E-3 | 62-97 | 12.38 | 0.065 |
| | 98-20 | 12.83 | | 98-19 | 12.84 | | 98-22 | 12.86 | |

Table 6 (continue). The average values of the mean annual SST time series within two sub–periods at the analysed stations and the results *p* of the t-test

| month | 7. Split | | | 8. Hvar | | |
|---|---|---|---|---|---|---|
| | **Sub-period** | $SST_{av}$ (ºC) | ***p*** | **Sub-period** | $SST_{av}$ (ºC) | ***p*** |
| Jan. | 59-97 | 12.21 | 0.017 | 64-97 | 13.38 | 1.7E-4 |
| | 98-22 | 12.71 | | 98-22 | 14.03 | |
| Feb. | 59-97 | 11.51 | 2.0E-3 | 64-97 | 12.51 | 2.3E-4 |
| | 98-22 | 12.08 | | 98-22 | 13.09 | |
| Mar. | 59-97 | 11.97 | 3.6E-3 | 64-97 | 12.68 | 5.7E-5 |
| | 98-22 | 12.60 | | 98-22 | 13.40 | |
| Apr. | 59-97 | 13.88 | 1.4E-4 | 64-97 | 14.21 | 6.3E-7 |
| | 98-22 | 14.60 | | 98-22 | 15.04 | |
| May | 59-97 | 17.24 | 8.6E-4 | 64-97 | 17.16 | 1.2E-5 |
| | 98-22 | 18.22 | | 98-22 | 18.23 | |
| Jun. | 59-97 | 21.05 | 3.2E-5 | 64-97 | 20.66 | 9.3E-8 |
| | 98-22 | 22.1 | | 98-22 | 22.00 | |
| Jul. | 59-97 | 23.12 | 3.7E.5 | 64-97 | 22.75 | 1.7E-6 |
| | 98-22 | 24.07 | | 98-22 | 23.84 | |
| Aug. | 59-97 | 23.53 | 1.8E-3 | 64-97 | 23.34 | 6.8E-6 |
| | 98-22 | 24.39 | | 98-22 | 24.42 | |
| Sep. | 59-97 | 21.7 | 0.015 | 64-97 | 22.36 | 5.6E-3 |
| | 98-22 | 22.42 | | 98-22 | 23.09 | |
| Oct. | 59-97 | 19.37 | 0.018 | 64-97 | 20.52 | 0.019 |
| | 98-22 | 20.00 | | 98-22 | 21.08 | |
| Nov. | 59-97 | 16.59 | 1.9E-3 | 64-97 | 17.99 | 1.7E-3 |
| | 98-22 | 17.42 | | 98-22 | 18.73 | |
| Dec. | 59-97 | 13.98 | 3.9E-3 | 64-97 | 15.32 | 2.2E-4 |
| | 98-22 | 14.68 | | 98-22 | 16.12 | |

Figure 10 shows histograms of the average monthly SAT in the recent period 1998-2022. The SAT differences between the stations in the northern Adriatic and those in the middle during the year are somewhat smaller than in the case of SST. Differences between monthly averages (SAT-SST) are shown in Fig. 11. In the warm part of the year from May to August, SST is lower than SAT at most stations. This is particularly evident at the Senj station, where SST is lower than SAT in April and September. At Pula station, SST and SAT are almost equal from April to August. At the Šibenik station, the difference values (SST-SAT) are the highest of all analysed locations in the cold part of the year from November to April. The individual behaviour of the relationship between SST as a dependent variable and SAT as an independent variable for the period from 1998 to 2022 (for Pula until 2019) is shown in Fig. 12 on the example of four stations: Senj, Rab, Split, and Hvar. The loops for three stations (Rab, Split, Hvar) show similar behaviour, while the loop for Senj differs significantly.

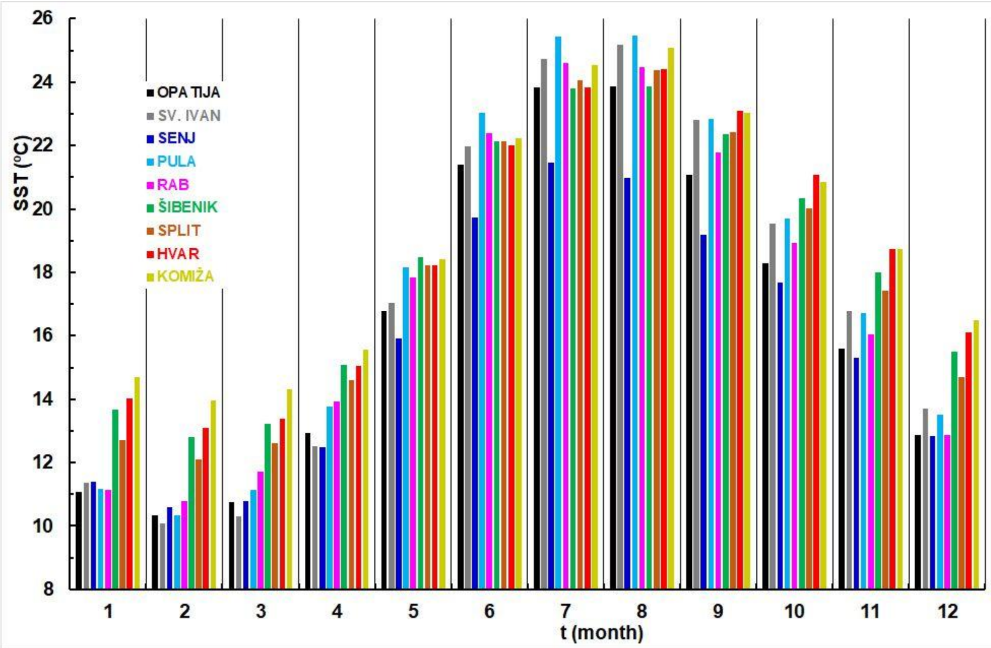


Figure 9. The average values of the monthly mean SST measured at the Opatija, Sv. Ivan, Senj, Pula, Rab, Šibenik, Split, Hvar, and Komiža stations in the 1998-2022 period

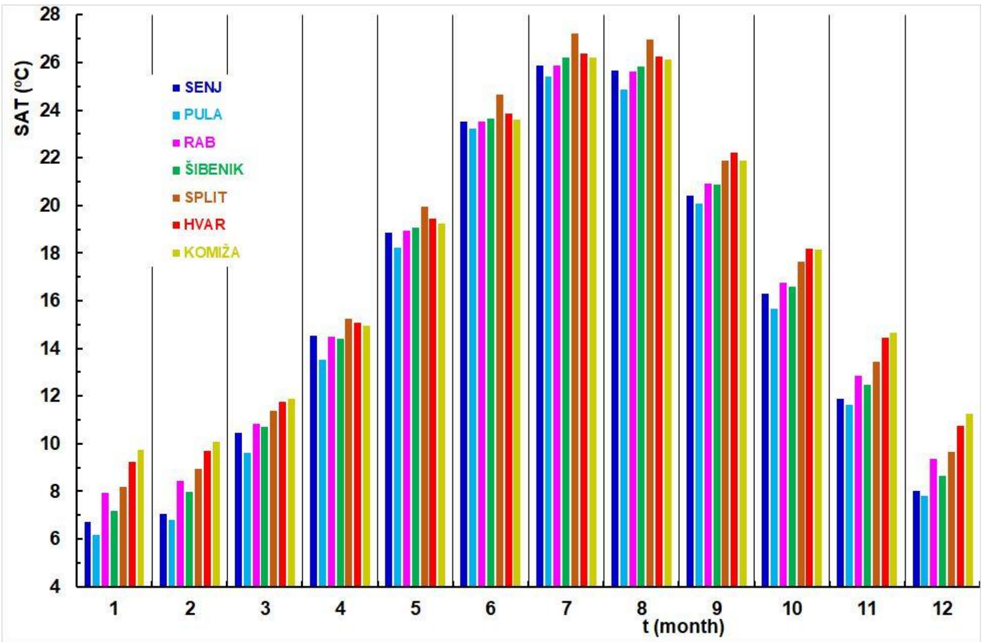


Figure 10. The average values of the monthly mean SAT measured at the Senj, Pula, Rab, Šibenik, Split, Hvar, and Komiža stations in the 1998-2022 period

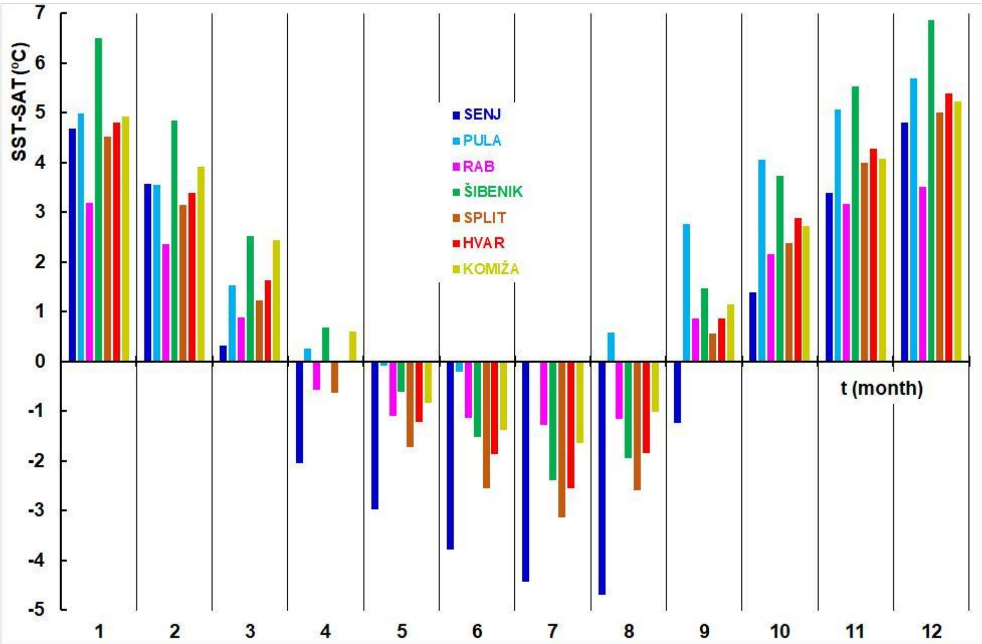


Figure 11. The differences between the average monthly SST and SAT measured at the Senj, Pula, Rab, Šibenik, Split, Hvar, and Komiža stations in the 1998-2022 period

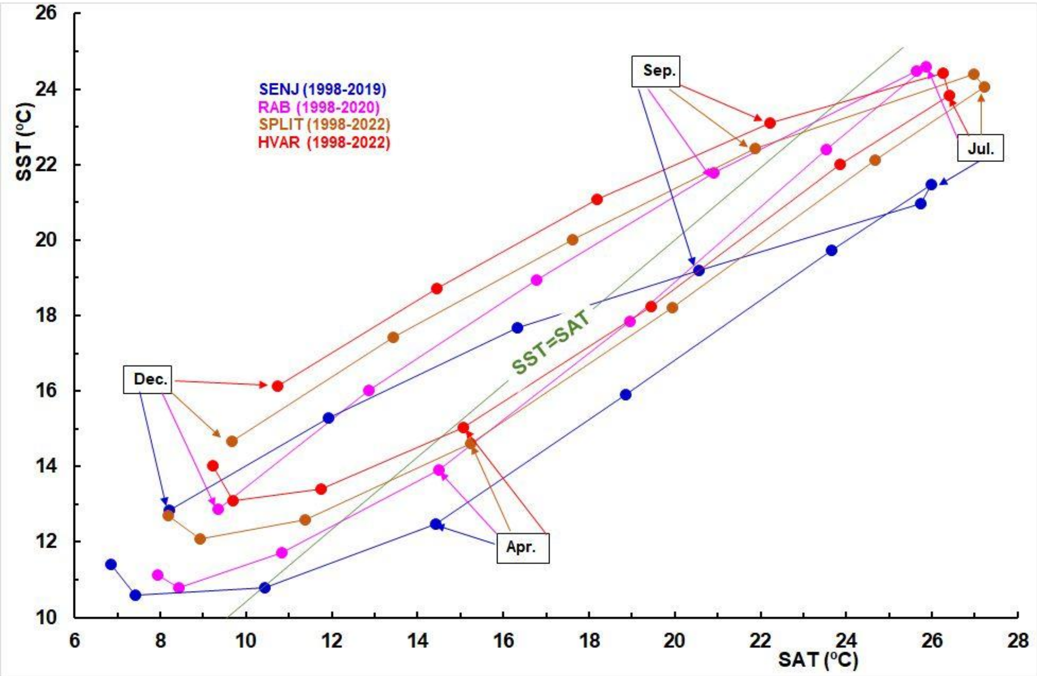


Figure 12. The ratio of the mean monthly SST and SAT from the period of contemporaneous measurements at the Senj, Rab, Split, and Hvar station**s** during the 1998-2022 period

**5 CONCLUSIONS**

In the second half of the 20th century, SST measured on the islands and on the Adriatic coast showed a significant increase, with the fact that it particularly intensified from 1998 to the present day. SATs measured at the same locations showed similar behaviour. Bonacci and Vrsalović (2022) showed that global warming has a greater impact on the northern Adriatic island of Krk than on the southern Adriatic island of Lastovo which is 160 km further south. At all stations analysed in this paper, it is detected a positive trend for both SST and SAT but with a lag between them. The long-term SST warming trend in the Adriatic has already had in marine fauna and the implications of climate change in the Adriatic islands' population and development. However, it should be noted that the trend in SSTs, as well as SATs in the analysing stations, depends strongly on the local environment and anthropogenic characteristics, which can be very different in neighbouring locations.

The variability is mostly controlled by the autumn/winter cooling process. The exceptionally low summer SSTs occur at Senj. At the Sv. Ivan station the spring/summer heating is significantly faster than the autumn/winter cooling which can be ascribed to the influence of the water from the Po River, which spread over the open Adriatic in spring/summer and mostly confines to the western coasts in autumn/winter (Supić and Orlić 1992).

Analyses of SST variations must be linked to establish changes in salinity (Lipizer et al. 2017; Llasses et al. 2018; Pastor et al. 2018; Mihanović et al. 2021) and sea level rise (Raichic 2003). For example, from 1960 to 2015, the mean Adriatic Sea level along the Slovenian coast rose by 10 cm. It means that the level of the Adriatic Sea has been rising faster than the level of any other sea in the last two decades. This dangerous phenomenon is attributable to both global sea-level rise and weather conditions in the region (https://www.adriatic-ionian.eu/2021/04/20/the-level-of-the-adriatic-sea-has-been-rising-faster-than-the-level-of-any-other-sea-in-the-last-two-decades/).

Analyses of the relationship between SSTs and SATs at individual locations can be useful for planning effective measures related to the local tourism industry, which is extremely strong along the entire Croatian Adriatic coast. They can play an important role in bringing effective measures related to local agricultural production.

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# ODNOS IZMEĐU TEMPERATURE POVRŠINE MORA (TPM) I TEMPERATURE VAZDUHA (TV) DUŽ ISTOČNOG DELA JADRANSKE OBALE HRVATSKE

Ognjen BONACCI
Sveučilište u Splitu, Fakultet građevinarstva, arhitekture i geodezije,

Rezime

U radu se analizira odnos između temperature površine mora (TPM) i temperature vazduha (TV) merenih na devet klimatoloških stanica duž hrvatskog dela Jadranskog mora. Klimatske promene, uglavnom manifestovane kroz efekat globalnog zagrevanja, snažno i ozbiljno su uticale na Jadransko more i njegov obalni region tokom poslednjih decenija. Ponašanje vremenskih nizova TPM i TV analizirano je korišćenjem linearnih i kvadratnih regresija, Mann-Kendall testa, metode Rescaled Adjusted Partial Sums, F-testa i t-testa. Analize su urađene na godišnjem i mesečnom nivou. Statistički značajni trendovi porasta srednje godišnje TPM počeli su 1998. godine, a osmotreno je slično ponašanje i vremenskih nizova TV. Posebna pažnja posvećena je analizi ponašanja TPM i TV u skorijoj prošlosti od 1998. do 2022. godine. Utvrđeno je da se ponašanje TPM i TV razlikuje od stanice do stanice, gde lokalne klimatološke, orografske i druge ekološke karakteristike igraju ključnu ulogu. Prosečna TPM je viša od prosečne TV u toplijem delu godine (od maja do septembra). Rezultati ovog istraživanja mogu pomoći donosiocima odluka u razvoju efikasnih mera za ublažavanje negativnih efekata klimatskih promena na različitim lokacijama jadranskih ostrva i obalnih regiona.

Ključne reči: temperatura površine mora (TPM), temperatura vazduha na kopnu (TV), Jadransko more (Hrvatska), klimatske promene