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RESEARCH PAPER

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Upwelling Index Calculations in the Aegean Sea

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Abstract

Different upwelling index calculations used for oceans were tested by applying to the Aegean Sea and compared with each other. The sea surface temperature (SST) and wind data of ECMWF Reanalysis are used for upwelling index calculations. The decrease in SST is a result of upwelling; however, the parameter that lies behind the phenomenon is the wind stress on the sea surface. The results show that SST and wind-driven upwelling indexes could be roughly used to estimate upwelling phenomena in the Aegean Sea, but it is insufficient for the precise determination of upwelling due to the Aegean Sea's unique dynamics. To reach a final formula, the "new upwelling index" shall be improved for Aegean Sea in which current data are considered besides SST & wind data.

Introduction

The surface of the Aegean Sea responds quickly to meteorological changes due to its small size (Georgiou et al., 2015). When geographical features of the Aegean Sea and its response to meteorological events are considered, it is certain that upwelling is a complex event. It is well known that this phenomenon can be identified by seasonally variable salinity, wind, low SST and nutrient-rich water in coastal areas.

The upwelling phenomenon in the Aegean Sea was first described by Unluata (1986). The studies carried out to determine the upwelling in the Aegean Sea have led to the question of "What causes the upwelling in the Aegean Sea". Wilfrid Ekman was the first scientist to reveal the wind-induced upwelling phenomenon mathematically (Ekman, 1905). Moreover, Fridtof Nansen was able to observe the correlation between wind and current by defining the difference in direction between wind and current during his scientific expedition to the north pole (Nansen, 1902). Ekman's theory, which was put forward by his doctoral work and referred to by his own name, is still accepted as basic knowledge in understanding wind-induced circulation.

Ekman's theory and geostrophic balance at the synoptic scale are good tools to explain this phenomenon. The friction force created by the Etesian winds on the sea surface, with the help of the Coriolis force, causes the surface waters to go from east to west in the east of the Aegean Sea. These moving waters cause the middle layer waters to rise from a depth of about 40m to the surface and move west. The surface

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waters are replaced by waters from the intermediate layer (Androulidakis et al., 2017; Mamoutos et al., 2017). That upwelled water is denser and colder than the offshore deflected surface water (Kourafalou & Barbopoulos, 2003; Skliris et al., 2010; Sayın et al., 2011). Cold waters near the coast are indicative of coastal upwelling. Upwelled waters are also seen in the central part of the Aegean Sea due to eddies (Sayın & Beşiktepe, 2010; Sayın et al*.,* 2011). The central region is under the influence of both thin surface waters coming from the north (from the Black Sea) and dense waters from the Eastern Mediterranean waters in the south, as well as upwelling from the winds (Vervatis et al., 2013; Georgiou et al., 2015). The Ionian Sea influences the southwestern part of the Aegean Sea, while the Eastern Mediterranean is active in the southeastern part (Savvidis et al., 2004; Ziv et al., 2004). Black Sea waters could be seen on the Greek coasts in the west (Kourafalou & Barbopoulos, 2003) and upwelling is expected near Cape Baba in the northeast (Sayın et al., 2011; Androulidakis et al., 2017).

In general, high productivity, nutritional value and fish population are expected in upwelling areas (Ryther, 1969; Cushing, 1971; Millan-Numez et al., 1982; Freon et al., 2009); unfortunately, those outputs cannot be observed in the Aegean Sea due to upwelling that flows from shallow depths of ~40 m to the surface (Androulidakis et al., 2017; Mamoutos et al., 2017). For this reason, an output like the studies conducted for Farallones Bay and the southern coastal region of Madagascar on the nutritional value of the sea on the Aegean Sea could not be obtained (Garcia-Reyes et al., 2014; Ramanantsoa et al., 2018).

Currently, a method/formula has not been developed for the detection of upwelling in the Aegean Sea which has unique features such as a narrow & complex coastline and interaction with two different seas. However, studies have been proposed for the detection of upwelling based on SST, nutrients or wind data and applied in Pacific Ocean-California & Atlantic Ocean-Iberian Peninsula coasts. Wind data were used to determine the strength of upwelling on the coasts in the studies conducted by Bakun (1973;1975), Bakun and Nelson (1991), Bakun and Agostini (2001) and Gómez-Gesteira et al. (2006; 2008). In addition to these studies, the efficiency of upwelling was tried to be revealed with the study on Ekman transport and Ekman pumping on the California coast (Pickett & Paduan, 2003). The index obtained from the wind parameter is calculated by changing the direction of Ekman transport due to the shape of the coast. Positive values indicate a movement away from the coast, in other words, upwelling, while negative values indicate a movement towards the coast. In simple terms, UI(wind) is the estimation of Ekman transport due to frictional force on the sea surface (Schwing et al., 1996).

Besides wind data, the definition of upwelling over SST has a wide range of uses (Nykjær & Camp, 1994; Santos et al., 2012; Benazzouz et al., 2014). For each latitude, the analyzes are performed over the reference points. In this method, UI is calculated by taking the differences between the maximum and minimum values of the SST on the axis perpendicular to the coast (Santos et al., 2005; Von Schuckmann et al., 2016). A high UI value indicates strong upwelling. For the Aegean Sea, previous studies have mainly focused on SST variations (Androulidakis et al., 2017); however, the mass transport of water that occurs after the friction force is another needed information for upwelling.

A better understanding of upwelling variability is essential to adequately manage and define ecologically important coastal regions of Aegean Sea. Upwelling of the Aegean Sea remains a topic of active research, but no studies point to an upwelling index. Consequently, there is a strong need to adequately test and create an index for upwelling. The need to reveal upwelling dynamics with a method and to contribute to the studies conducted to fully define the Aegean Sea's thermohaline circulation also motivated us to carry out this study. To our knowledge, no prior studies have applied and tried to display the efficiency of upwelling indexes based on wind and SST in Aegean Sea. That is why the focus of this study lies on UI(SST) and UI(wind) which are most needed for upwelling detection in the Aegean Sea to bring a new perspective. The aim of this study is to test the different upwelling indexes for the Aegean Sea.

In the next section, there is a description of the data and methods used herein while in results and discussion section, temporal and spatial variability of UI (SST) and UI (wind) are presented with discussion. Final conclusions are drawn in last section to conclude a paper.

Materials and Methods

Data

In today's conditions, it is not possible to reveal the ecosystem of a large area with irregular real data on the sea. Instead, the system is defined through the data produced by the numerical models and the deficiency of real data is tried to be eliminated. ECMWF performed the first (reanalysis) data generation process in the early 1980s, especially with the increasing accuracy of data obtained from numerical models in the late 1970s. These data, called reanalyzed data set, can be produced in high resolution with a data assimilation system by means of an advanced numerical model.

In this study, ECMWF Era-Interim data of SST and 10m wind speed-direction with a resolution of 0.75° covering the years 1979-2018 were used at the grid locations shown in Figure 1. With respect to World Meteorological Organization (WMO) report in 2017, at least 30 years of data should be used to obtain reasonable results and understand the climatological structure. In this study, as stated by Weisse and Storch (2010) and the reports of WMO, 40 years of ECMWF Era-

Interim data available monthly from 1979 to 2018 have been used.

Upwelling Index (UI)

UI(SST)

In order to determine the upwelling, the SST difference within the continental shelf is taken into account in the axis perpendicular to the coastline. At this point, the most challenging issue is determining the reference points for the SST (minimum, maximum). While the location where SST is minimum is defined as the upwelling region, the point where the SST is maximum could be expressed as the point where upwelling is not expected. Reference locations for SST can be easily determined for open waters such as the Atlantic & Pacific Oceans; nevertheless, it is hard to determine these reference points for seas due to distance constraint (less than 5° latitude difference). Therefore, it is necessary to act in accordance with the dynamics of each region.

$$U(SST) = SST_w - SST_e \qquad (1)$$

The most easily identifiable SST profile perpendicular to the coast in upwelling areas is that it has a decreasing tendency from coastline to upwelling areas and an ascending tendency from upwelling areas to open seas until it reaches constant value (Demarcq & Faure, 2000). The study of Demarcq and Faure (2000) is applied in this work for the Aegean Sea at seven latitudes as pointed out in Figure 1 and the changes with respect to longitudes are examined. Some studies have taken 400-1000km away from the coast as the maximum SST reference site (Camp et al., 1991; Nykjær & Camp, 1994; Lathuili`ere et al., 2008). However, it is not possible to apply a distance of 400-1000km as in previous studies (Pacific Ocean-California coast, Atlantic Ocean-Iberian peninsula coasts, etc.) for this study; since the average width of the Aegean Sea is less than 400km. Therefore, SSTwest & SSTeast terminology for the Aegean Sea will be used in this study for UI(SST) calculation.

As expected, the determination of upwelling is not a simple task due to not only the divided basins of the Aegean Sea but also its rapid reaction to meteorological events.

UI(Wind)

According to Ekman's theory, the wind blowing parallel to the coast for a certain period of time causes the direction of the wind in the northern hemisphere to change 90° from the coast to the right (Sverdrup, 1938). Ekman-induced convection is calculated by dividing the friction force (τx, τy) created by the effect of the wind on the sea surface by the coriolis parameter (f) and the density of the water (ρw). The UI(wind) method enables the strength of upwelling to be revealed. It is calculated as follows:

$$Q_x = \frac{\tau_y}{\rho_w f} \qquad (2)$$

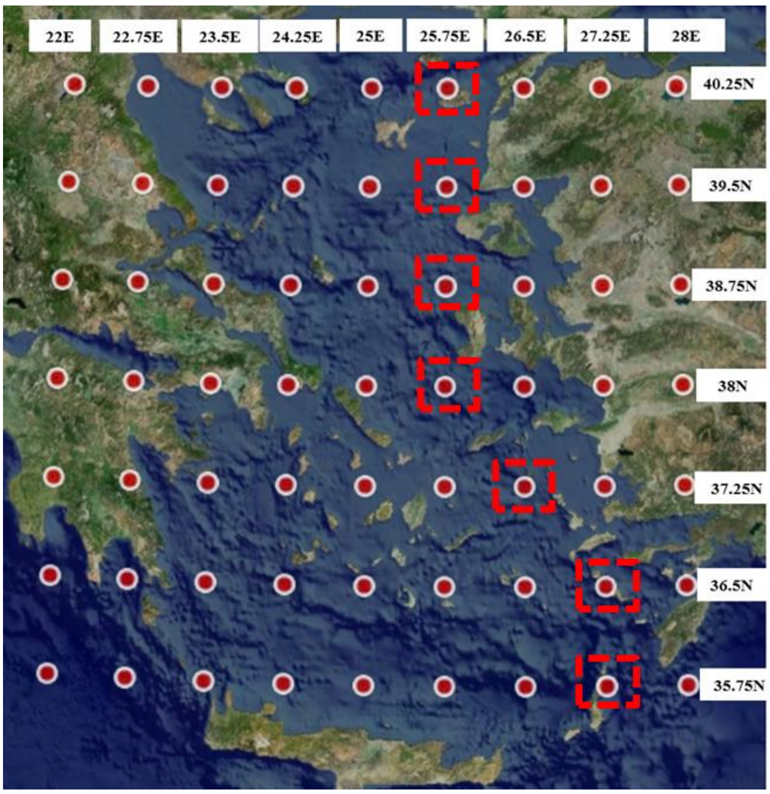


Figure 1. Locations of the ECMWF reanalysis data (0.75° resolution).

$$Q_y = \frac{-\tau_x}{\rho_w f} \qquad (3)$$

$$UI(wind) = -\sin\left(a - \frac{\pi}{2}\right) Q_x + \cos\left(a - \frac{\pi}{2}\right) Q_y$$

(4) (Cropper et al., 2014)

$$UI(wind) = -\left(\sin\left(a - \frac{\pi}{2}\right) Q_y + \cos\left(a - \frac{\pi}{2}\right) Q_x\right)$$

(5) (Kok et al., 2017)

$$UI(wind) = \sin(360 - a)\, Q_y + \cos(360 - a)\, Q_x$$

(6) (Global Upwell. Index-NOAA)

In the equations, east-west/north-south Ekman transport is symbolized by Qx/Qy. Angles are calculated differently for each equation. In the equations of Cropper et al. (2014) and Kok et al. (2017), the angle "a" refers to the angle between the coastline and the equator lines (toward the landward side), for the global upwelling index the angle "a" refers to the angle between the coastline and the vector line pointing north (toward the landward side). The angles used in this study are shown in Figure 2. Due to the structure of the region, a different angle was used for the north part of the city of Izmir (38N) and a different angle for the south. So the angles were calculated by drawing two general coastlines (north-south of the latitude where İzmir is located). A positive UI value indicates strong upwelling, and a negative UI indicates downwelling.

When the coasts of regions such as West Africa, California, Madagascar, Malaysia and the Iberian peninsula are compared with the indented coastline and structure of the Aegean Sea (it includes many islands), it is clear that the Aegean Sea is a more difficult and complex sea to define the angle.

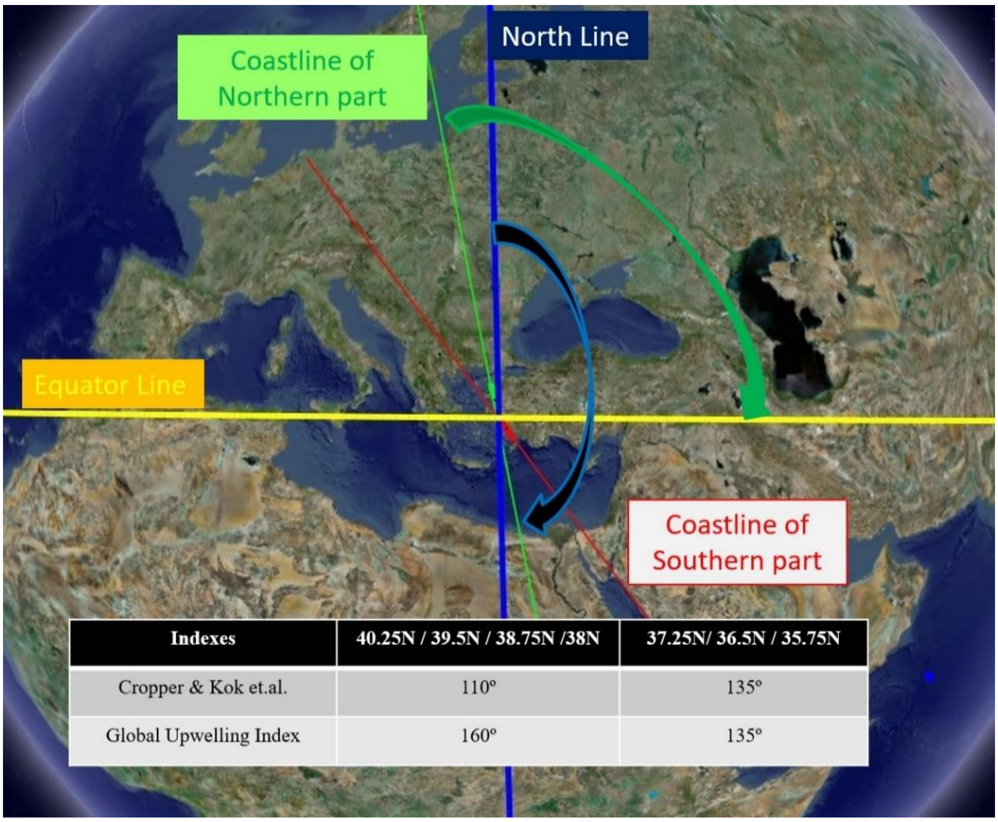
A computer calculation in MATLAB software is employed to analyse and evaluate the data. Then Ocean Data View (ODV) software is used for visualization to make the graphs user friendly.

Results and Discussion

Monthly UI(SST) Distribution

The monthly SST figures are obtained by taking the 40-year average of SST with a resolution of 0.75° at each grid point for all seasons are shown in Figure 3. In April SST starts to ascend and reaches 18-19.5°C after it almost stays constant in the months of December, January, February and March with values ~13 °C in the north and 16°C in the South. During the period from May to August, SST rises by 2 °C every month and the highest SST is observed in August at 24-26°C. In addition, SST decreases by 2°C each month from September to December. SST changes with longitude (east-west axis) in summer and by latitude in winter. The prominent reasons for this difference are summer upwelling, the angle of incidence of sunlight and change in the area covered by sunlight relative to latitude in winter.

Average SST is lower at higher latitudes and higher at lower latitudes, the reason why SST on the world varies with latitudes is solar radiation. The variation in warming is smaller at lower latitudes on Earth; however, it is greater at high- and mid-latitudes. The sea



Indexes	40.25N / 39.5N / 38.75N /38N	37.25N/ 36.5N / 35.75N
Cropper & Kok et.al.	110°	135°
Global Upwelling Index	160°	135°

Figure 2. Angles used for UI(wind) calculations.

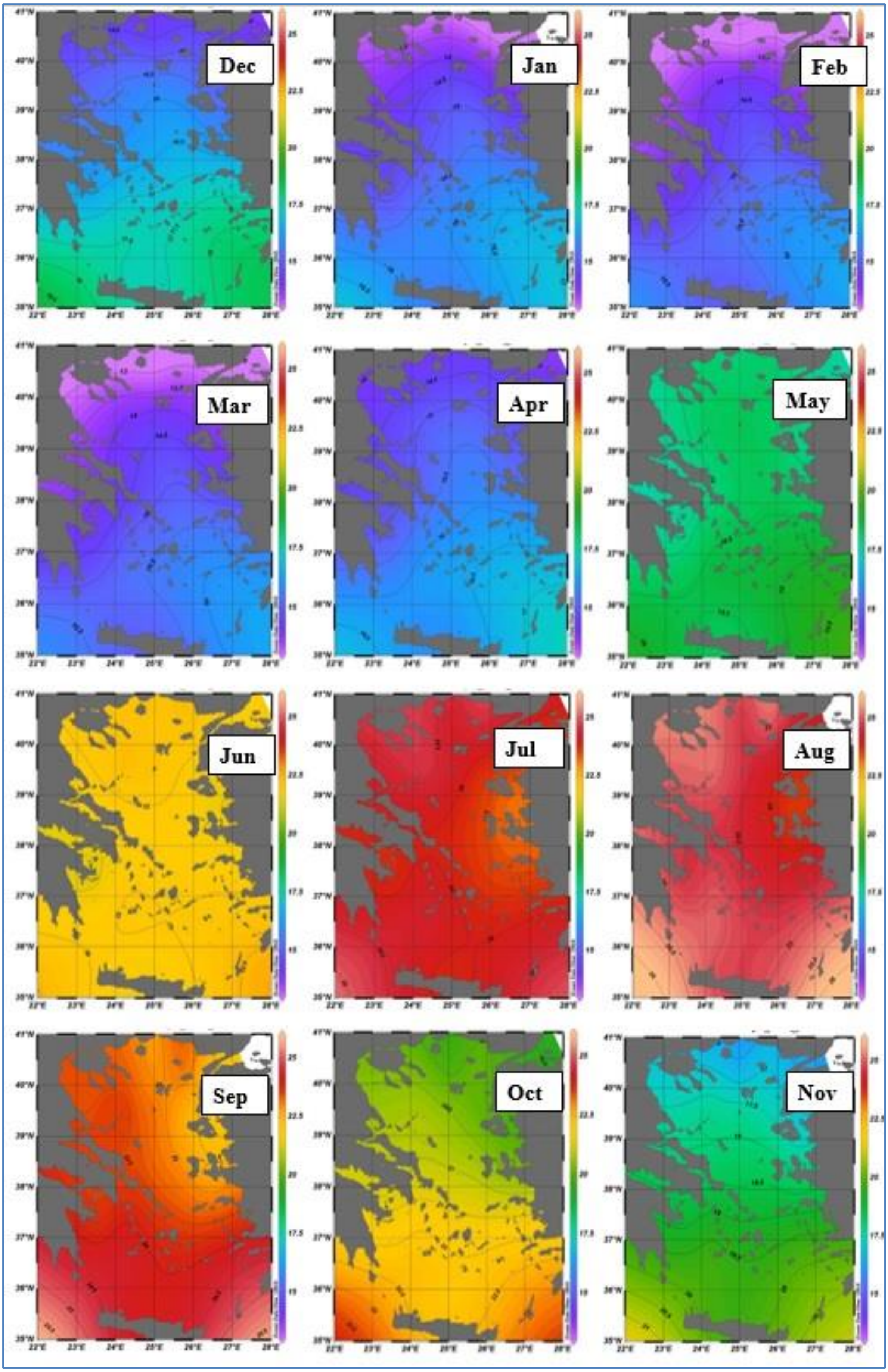


Figure 3. Monthly 40-year average SST distrubition.

temperature decreases with increasing depth and there is no seasonal variation in deep waters. In general, the SST varies with latitudes in the world, contrarily it changes with respect to not only the latitudes but also the longitudes for the Aegean Sea in the summer season due to upwelling as presented in Figure 3. The reason why the difference is evident that waters of the middle layer and surface have similar values due to upwelling in the summer and surface cooling in the winter. Furthermore, the northeastern and the central parts of the Aegean Sea are under the influence of upwelling and have different wind speed, SST and air temperature values (Tukenmez & Altıok, 2022). Although the air temperature and SST differ at the two points for the same latitude in the northeast and northwest, higher values are obtained in the northwest location than in the northeast location (Tukenmez & Altıok, 2022).

In order to define upwelling, firstly revealing the change of SST in the longitudinal axis perpendicular to the coast is needed. The variation of the typical SST is shown in the study of Demarcq and Faure (2000). It is not possible to obtain a similar graph for the Aegean Sea due to reasons such as the dynamics of the Aegean Sea. In order to better understand the variation and characteristics of the SST in the axis perpendicular to the coast, the SST-based UI formula was used. The method in this study is the application of the work applied for the Iberian peninsula to the Aegean Sea (Von Schuckmann et al., 2016). While calculating this index, Figure 4 was produced by using the 40-year average SST for each month. Calculations made by considering the monthly averages of SST values of the eastern and western locations display that strong upwelling exists especially at the eastern sides of latitudes of 38.75N, 39.5N, 38N, 40.25N. The upwelling areas indicated by UI(SST) calculations are compatible with previous studies and catch the right locations of upwelling expected areas. According to Figure 4, upwelling starts to increase in May, reaches its highest level in August (>1 °C difference) and starts to decline in September. It is also obvious that the upwelling could be clearly determined in July and it continues until October.

SST fluctuates seasonaly and average SST varies from 13 to 26 °C. The climatological minimum SST occurs during February and maximum values are observed in August. During winter colder waters spread and dominate the northern part while lower values are observed in the eastern Aegean Sea during summer. Autumn and spring are transitional periods. Those findings and seasonal averages are consistent with modeling, obsevations and satellite studies of upwelling variability of Aegean Sea (Poulos et.al.1997, Skliris et al 2010, Androulidakis et al., 2017; Ciappa, 2019). The maximum mean value obtained in this study is similar to Poulos et.al.(1997)'s result but minimum mean is 5 °C greater than Poulos et.al.(1997)'s study.

Monthly UI(wind) Variations

As mentioned in the materials and method section, different UI(wind) formulas exist. Before applying them to the Aegean Sea they should be tested and compared with UI(SST) which gives accurate results in summer for upwelling expected locations. Results of the comparison of UI methods are displayed in Figure 5. The existence of upwelling is presented with roughly 0.75° gridded data.

Comparison of UI(SST) and three different UI(wind) formulas puts forward that the formula of Kok et al. (2017) and the Global Upwelling Index are favourable formulas since UI(wind) values have high values in upwelling regions (39.5K, 38.75K, 38K) with respect to SST (Figure 5). Considering the two methods give similar results, one of them (Kok et al., 2017) is chosen in order to see the performance of the method. UI(wind) values

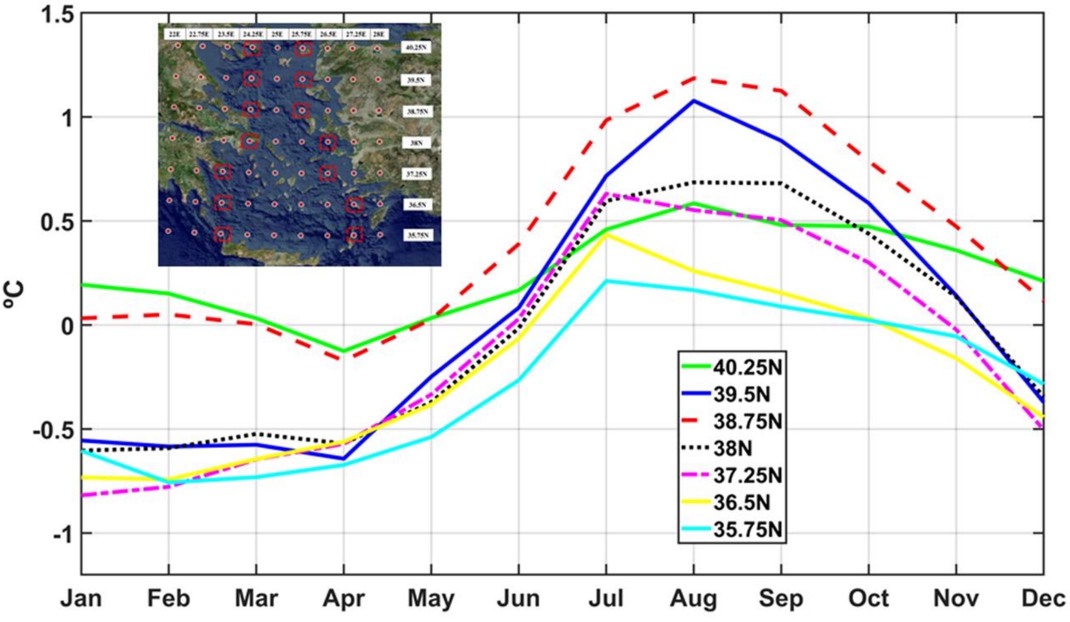


Figure 4. The 40-year mean of UI(SST) at each latitude.

of Cropper et al.(2014) present low values in areas where upwelling is expected. All UI(wind) calculations are performed with 40 years of mean data for Kok et al. (2017)'s formula at all grid points (Figures 6 & 7).

Upwelling varies by season and displays the horizontal climatic UI(wind) variation as presented in Figure 6. It can be stated that there is a significant increase in winter although not as much as in summer. Figure 7 indicates that upwelling covers a wide area from Saros Bay to the south of the Central Aegean Sea (towards the Turkish coast), especially in July, August, and September (UI>6 m^2/s). It is also understood that UI(wind) values decrease in October and reach very low values in November. Although there are no high UI(wind) values in winter as in summer, there are still high UI(wind) values, especially in the area from Saros Bay to the central Aegean Sea. For spring, UI(wind) values decrease in March, there is no upwelling in April (1.5 m^2/s) and May (2.2 m^2/s), and it offers much lower values than the summer and winter seasons.

The wind is strong and northerly for both summer and winter seasons, for instance, while the wind force is 4.17 m/s and direction is 030° in January, it blows from 000° with the speed of 3.76 m/s in July at the location of 38.75 °N and 28.75 °E. The Aegean Sea is more open to northerly winds due to its coastline and the synoptic scale weather events.

With the influence of the combination of Etesian winds and the TSS, an east-west gradient and a north-south gradient in salinity are both seen in the Aegean Sea, unlike the Sea of Marmara. The northeastern and central parts of the Aegean Sea are under the influence

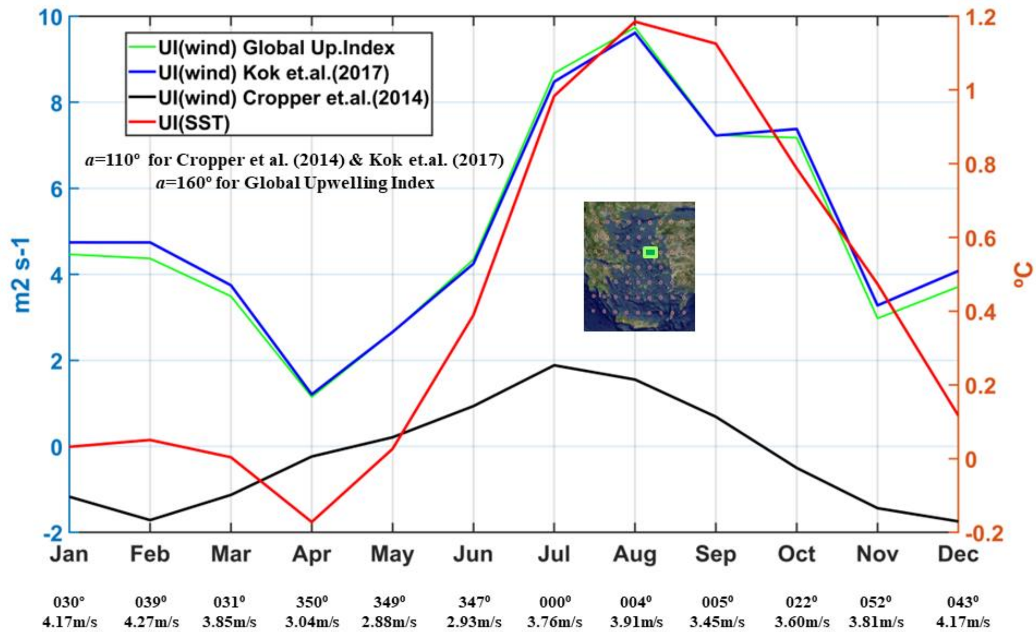


Figure 5. Comparisons of the 40-year average of UI calculations at 38.75 °N & 28.75 °E with mean wind speed & direction data.

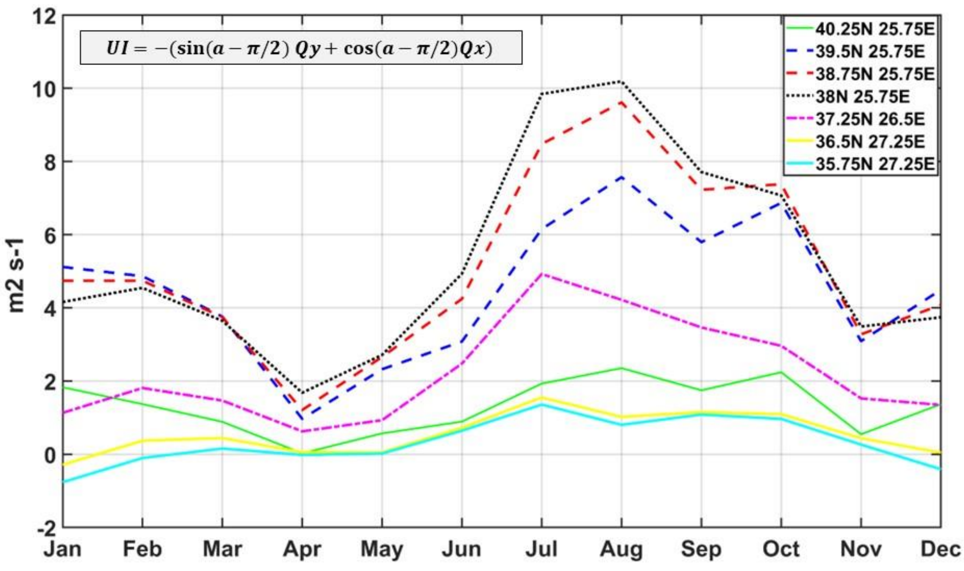


Figure 6. The 40-year mean of UI(wind) at certain locations.

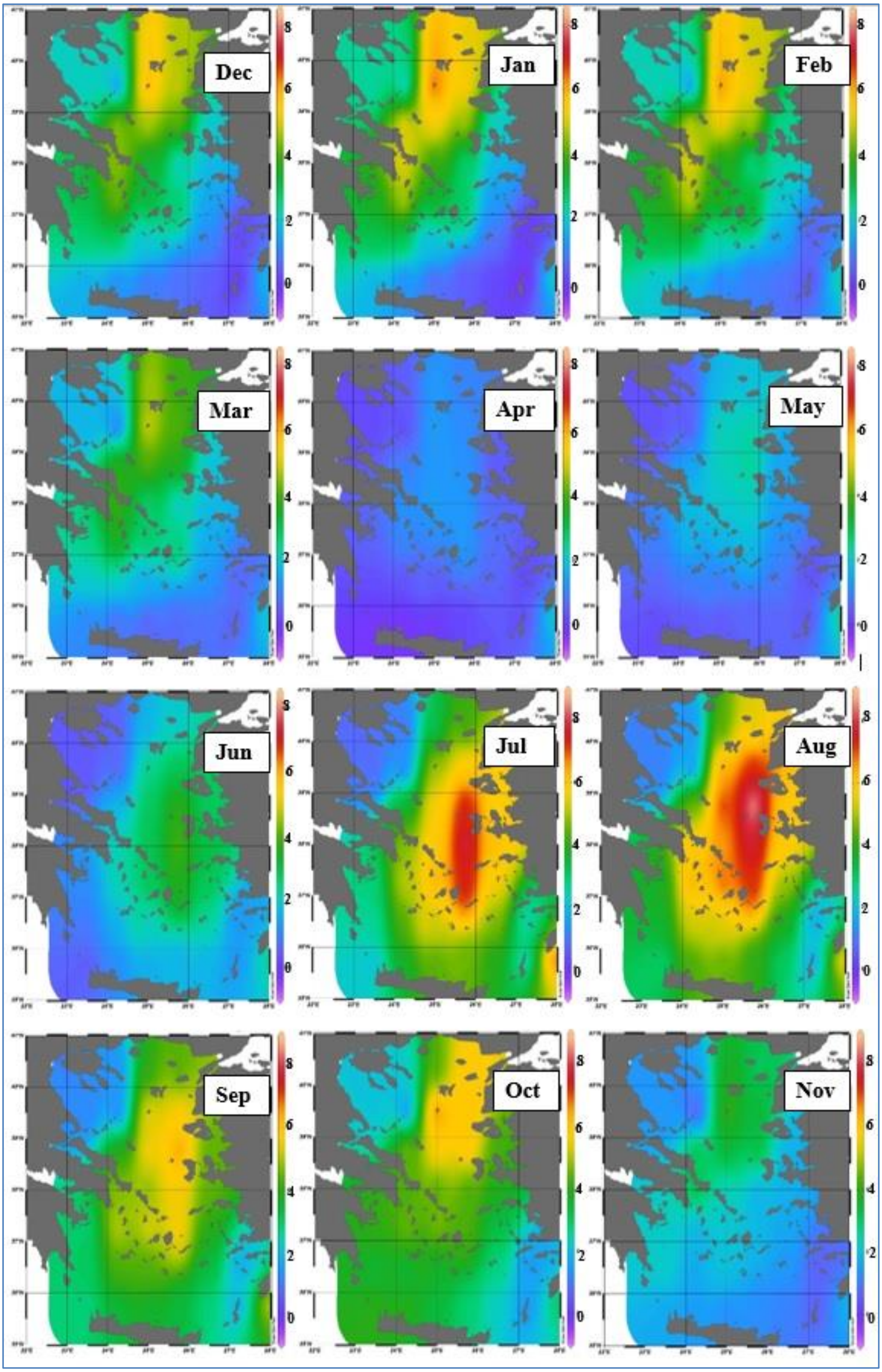


Figure 7. Monthly 40-year average of UI(wind).

of upwelling and have different wind speed, SST, and air temperature data. The Black Sea waters could be seen on the coasts of Greek mainland (Kourafalou & Barbopoulos, 2003) and upwelling is expected near Cape Baba, Saros Bay and eastern Aegean Sea (Savvidis et al., 2004, Sayın et al., 2011; Androulidakis et al., 2017). The water masses developing in both Black Sea and Mediterranean Sea can reach the Aegean Sea and the currents of those adjacent seas govern the dynamics in the Aegean Sea, independent from the wind driven circulation. This means that the explanation of the upwelling phenomena in the Aegean Sea without considering complex dynamics of Aegean Sea is suspect.

Even though many previous studies focused on summer upwelling due to the advantage of cooler surface waters and points out that Aegean Sea has a summer coastal upwelling because of Etesian winds (Skliris et al 2010, Androulidakis et al.2017; Ciappa, 2019), the main focus of Bakun and Agostini (2001)'s research was wind induced upwelling/ downwelling in the Mediterranean Sea covering the zone of Aegean Sea. In accordance with Bakun and Agostini (2001)'s study strong upwelling is expected in Eastern Aegean Sea throughout the year and weakest upwelling is observed in spring. Additionaly they also found that coastal transport increases in late spring. Our findings are strongly correlated and in line with Bakun and Agostini (2001)'s work except for western and soutwestern parts. With respect to point analysis UI calculations give good results for upwelling expected areas.

Unfortunately UI(wind) does not give an accurate result for the west side of the Central Aegean where upwelling is not expected with respect to Ekman's theory in the months of December, January, February, March, September, and October. In addition, UI(wind), which can reveal upwelling in July, August, September and October for the eastern part, indicates the presence of upwelling in the south of the Aegean Sea where upwelling is not expected. The reason why UI(wind) gives incorrect results in some areas is that UI(wind) could be adjusted according to the coasts where upwelling is expected or the formula has been created according to the open seas for long distances (400-1000km).

Calculations based on wind data reveal the existence of upwelling not only in summer but also in winter. However, due to the fact that SST generally decreases in the whole area during the winter season, the values of the intermediate and the surface waters have similar numbers. In other words, there is an increase in the UI(wind) values in winter, but this change does not look reasonable for UI(SST) due to the decrease in the SST in winter (no vertical change-isothermal). Additionally, the presence of the cyclonic cycle in the Central Aegean Sea makes demonstrating the upwelling over the SST hard for the summer season. Therefore UI(wind) is indispensable method in the determination of upwelling.

In the light of all the information, UI(wind) draws a general picture and can roughly indicate the areas where upwelling occurs, but gives erroneous results in some areas due to the dynamics of the region. Even though 100% accurate calculations could not be obtained for the Aegean Sea, it is still a viable method in the determination of the upwelling. The UI(wind) calculation provides results just for a certain time which is a shortcoming of the index. The wind persistence is important since an upwelling occurs only as a result of sustained winds of more than about 12 hours. It is crucial to point out that wind creates an influence on the sea surface with friction force after it blows for a certain period of time. The short distances of the east-west points in the Aegean Sea with the indented coastline and the inability to make a precise evaluation for the angle value which is the most important parameter of the UI(wind) are other reasons behind the imprecise values.

The work presented here does not attempt to come to a final & convincing answer to automatically upwelling detection, but to contribute elaborating the factors influencing upwelling with a new approach in the Aegean Sea.

Conclusion

To our knowledge UI calculations previously used for the Pacific, Indian and Atlantic oceans were applied to the Aegean Sea for the first time and comparisons were made to test their accuracy. In our work, the compatability of UI(SST) and UI(wind) is investigated with SST data based on latitudinal and wind calculated for grid points (by calculating Ekman transport).

Calculations with UI(SST) indicate that strong upwelling exists at latitudes of 38.75N, 39.5N, 38N and upwelling starts to increase in May and reaches its highest level in August and decreases in September. UI(wind) and UI(SST) values were compared to determine which UI(wind) formula is accurate. It has been determined that the formula of Kok et al. (2017) and the Global Upwelling Index are useful formulas that can be used to explain the upwelling phenomenon in the Aegean Sea.

The monthly climatic UI(wind) map reveals that upwelling varies significantly seasonally. Upwelling is present not only in summer but also in winter, and minimum UI value is detected in spring and maximum UI is observed in summer. Although the UI(wind) calculations reveal the presence of upwelling in winter, the UI(SST) results cannot show the presence of upwelling for the winter season. The reason for that is the temperature difference between the surface and intermediate layers decreases in the winter season and an isothermal profile emerges. Moreover, UI(wind) presents the existence of upwelling in the areas (western side) where upwelling is not expected. Thus the upwelling in the Aegean Sea, which is an important part of the global climate, should be revealed by the vertical current change in further studies. Although the previous upwelling index studies conducted on the Pacific, Indian and the Atlantic Oceans for detecting upwelling give positive results in terms of showing the existence of upwelling areas on the Aegean Sea, current measurements and *in-situ* CTD measurements should be conducted to come to a final decision on an index.

The results show that SST and wind-driven upwelling indexes could be roughly used to estimate upwelling phenomena in the Aegean Sea, but it is not sufficient for the precise determination of upwelling due to the Aegean Sea's unique dynamics. In this context, the development and use of the "new upwelling index", in which current data are taken into account in addition to SST and wind data calculations will give better results for the Aegean Sea. The existence of many small cyclonic/anticyclonic cycles, interaction with different seas, and the coastal structure of the region necessitate the examination of the vertical current variations related to the depth. Our UI calculations also display that model data could give a reasonable result for upwelling detection.

Ethical Statement

Not applicable.

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Author Contribution

E.T.: Methodology; Investigation; Analysis; Original Draft; Writing. H.A.: Conceptualization; Supervision; Review & editing.

Conflict of Interest

The author(s) declare that they have no known competing financial or non-financial, professional, or personal conflicts that could have appeared to influence the work reported in this paper.

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