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Detection of upwelling events in the Caspian Sea using thermal satellite image processing

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Abstract

In this article, we studied the upwelling phenomena observed in the surface waters of the Caspian Sea. Studying upwelling is crucial for understanding and managing the complex interactions between the ocean, climate, and marine life, with implications for both environmental conservation and human well-being. To accomplish this, we utilized data from MODIS-Aqua satellite observations in the infrared range of 11 microns. These observations had a spatial resolution of 4 km and covered the period from 2003 to 2021. The data was accessed through the NASA Giovanni online data system databases. Our findings indicate that upwelling phenomena are primarily observed in the eastern part of the Middle and South Caspian from May to September. The most intense upwelling occurs along the eastern coast of the Middle Caspian in July and August. Based on long-term averaged data, the upwelling phenomenon is typically observed between 40-44º latitude during this period. The width of the upwelling zone increases gradually from north to south, extending approximately 60-70 km towards the Kazakh Gulf before decreasing towards the south. In the upwelling zone, the temperature gradient can at times reach 4.0ºC per 100 km. In certain years, the upwelling zone that initially forms along the eastern coasts can extend over long distances and even reach the western coasts. Generally, the upwelling phenomenon occurs alongside the advection of warm waters from the South Caspian towards the Middle Caspian.

1. Introduction

The phenomenon of upwelling is the transfer of water masses from the deep layers to the surface in the world oceans and seas.

The climate of the earth is extremely complex due to interactions between the atmosphere, hydrosphere, geosphere, biosphere and cryosphere. Moreover, the exchange of energy, of matter and moisture between these environmental spheres are the main mechanisms that govern the climate system. The global atmospheric and oceanic circulations are strongly interdependent and the Sea Surface Temperature (SST) is the link between the two [1] Identifying understanding the causes of sea level change is important in global and regional climate change studies [2].

Remote Sensing (RS) technology enables to generate spatial and temporal data of a number of physical attributes about the watershed surface that can be utilized to map the extent of land and water bodies at watershed scale, and to monitor their dynamics at regular and frequent time intervals [3].

The physical mechanism leading to coastal upwelling is related to the Coriolis force, which tends to deflect wind currents to the right in the Northern Hemis phere and to the left in the Southern Hemisphere.

On the one hand, they provide mixing of deep and surface waters, which is important from a climatic point of view. On the other hand, upwelling transports nutrient-rich water masses to the upper photic water layer. As a result, zones of increased primary water production and intensive development of plankton communities are formed in upwelling areas, which is of great importance for fisheries [4]. The upwelling phenomenon also occurs near the eastern and western coasts of the Middle and partly South Caspian.

The phenomenon of upwelling in the Caspian Sea and its causes are the subject of many scientific works. A number of researchers showed in their studies that the rise of deep waters to the surface is due to the water cycle under the influence of wind [5-10].

According to some researchers' easterly winds prevail over the eastern part of the Caspian Sea from mid-July to October [5]. These winds drive relatively warm water from the sea surface into the open sea, and it is replaced by cold water rising to the surface from the deep layers. On the other hand, currents directed from the shore to the open sea create reverse currents of water in the lower layers, i.e., currents of cold water directed towards the shore.

However, it should be noted that according to the results of a number of studies, it has been established that in the eastern part of the Middle Caspian, easterly winds actually prevail in the cold season. However, in the summer-autumn period, when upwelling phenomena are observed, northern and northwestern winds prevail [11-14]. In [6] almost all considered cases with upwelling were observed at the northern wind direction.

There are different explanations for the occurrence of upwelling. So, in the 1960s. it was suggested that groundwater is the cause of temperature anomalies in the eastern part of the Middle Caspian [7]. One of the arguments against this idea is the observed homogeneity of salinity and other hydrochemical properties of the waters of the eastern part of the Middle Caspian.

In 1977 Karimov and Klevtsova put forward a hypothesis about the relationship between tempera-ture anomalies and internal waves [8].

The upwelling phenomenon is observed both on the eastern and western coasts of the Middle and South Caspian. However, it should be noted that if on the east coast in May-September upwelling is systematic, then on the west coast it is relatively episodic. The study of temperature anomalies occurring in the western part of the Middle Caspian showed that they are of a "synoptic" nature [9]. From this point of view, and since the study considered only long-term average monthly, average seasonal and average annual distributions, it is difficult to identify and study the manifestations of upwelling on the west coast based on the corresponding satellite images. Therefore, in this paper, upwelling phenomena observed in the eastern part of the Middle and South Caspian are considered.

2. Method

Until recently between 2002 to 2020, to study upwelling in the Caspian Sea, mainly data from hydrological stations located mainly on the coasts and islands were used [4,5,9,10]. Such contact data make it possible to identify the upwelling phenomenon and its development quite clearly over time, but do not allow us to assess its spatial scales [10].

It is known that data from a number of NOAA series satellites have recently been used to remotely determine hydrometeorological parameters, including land and water basin surface temperatures. Practically all meteorological satellites of this series are equipped with infrared radiometers, which allow estimating land, ocean and sea surface temperatures on a global scale.

A number of scientific articles are devoted to the study of the surface temperature of the Caspian Sea using satellite data [15-18] which studied various aspects of the problem under consideration. The present study used monthly average sea surface temperature (SST) data (2003-2021) from the NASA Giovanni online information system database based on nighttime measurements of the MODIS radio spectrometer installed on the Aqua satellite. The MODIS spectroradiometer with a wavelength of 11 μm has a horizontal spatial resolution of 4 km, which makes it possible to detect mesoscale anomalies in the distribution of the SST of the Caspian Sea, especially upwelling zones, and their characteristic features.

One of the disadvantages of the MODIS Aqua spectroradiometer is the inability to measure temperature on ice-covered water surfaces in the cold season, but this problem applies only to the North Caspian Sea, since the water surface in other parts of the sea is almost never frozen. On the other hand, upwelling phenomena are observed in warm seasons.

In order to verify the degree of correspondence of the satellite data to the real data, they were compared with the data of contact observations.

Maps of SST distribution over the sea area for every month and season were obtained using the procedures provided at [19].

Remote sensing data of SST by the MODIS Aqua radio spectrometer has a relatively high resolution (4 km). This factor allows comparing the corresponding satellite data with real contact data (calibration) and revealing the statistical relation between them. For individual observation points of the Middle and South Caspian Sea such comparison shows that there is quite a high correlation between them (R = 0.91-0.98). Moreover, the degree of coincidence of satellite and actual data was about 0,5 °C (Figure 1), which is close to the results obtained by other researchers (10). A similar pattern is observed when comparing SST for the May-September period (Table 1).

Table 1. Correlation coefficients (r) between the actual SST and the corresponding MODIS Aqua data in different months of the year for the Neft Dashlari (Oil Stones) observation point.

Month	May	June	July	August	September	Year
r	0,91	0,98	0,96	0,94	0,92	0,94

3. Results and discussion

As it was mentioned above in the Caspian Sea water area, the upwelling phenomenon occurs mainly during the period May-September.

The continued increase in air temperature in May creates a peculiar distribution of water surface temperature in the Caspian Sea.

As SST in the North Caspian increases rapidly (due to shallow water), the north-south temperature gradient at the border with the Middle Caspian continues to be high (-2,7 °C/100 km). The lowest water surface temperatures in the North Caspian are observed at the boundary with the Middle Caspian (16.0 °C) and in the Ural Basin (17,0 °C), and the highest - in coastal areas (20,0 °C) (Figure 2).

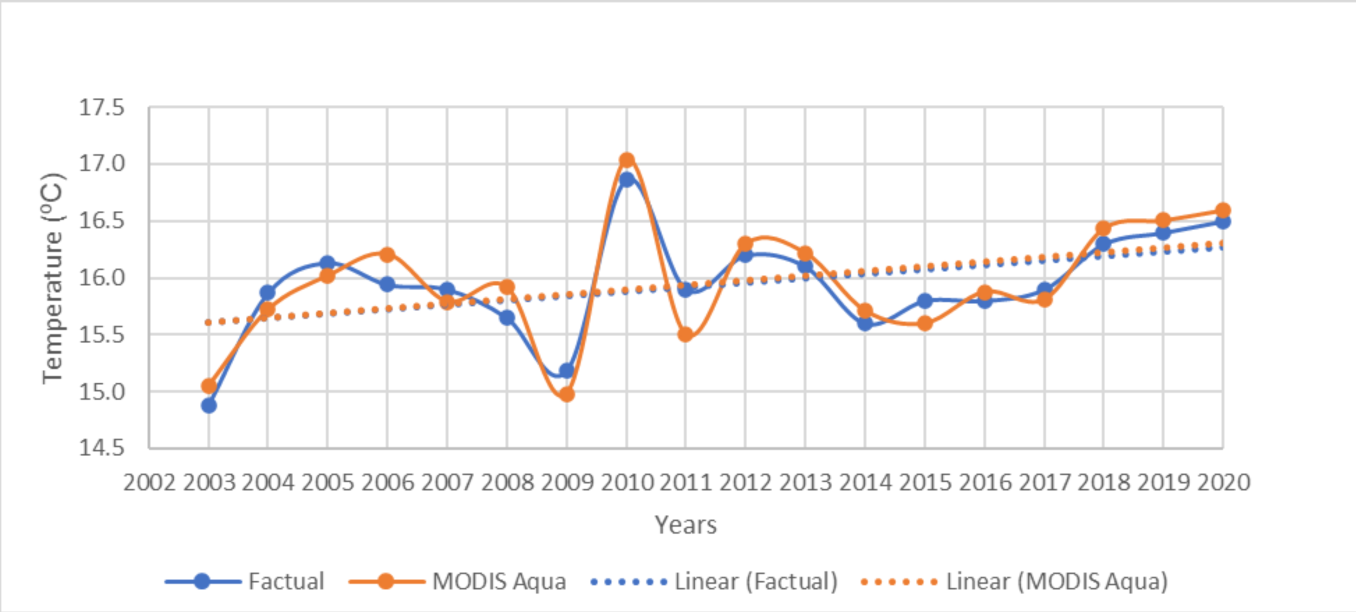

Figure 1. Dynamics of mean annual SST from the observation point data and corresponding MODIS Aqua data.

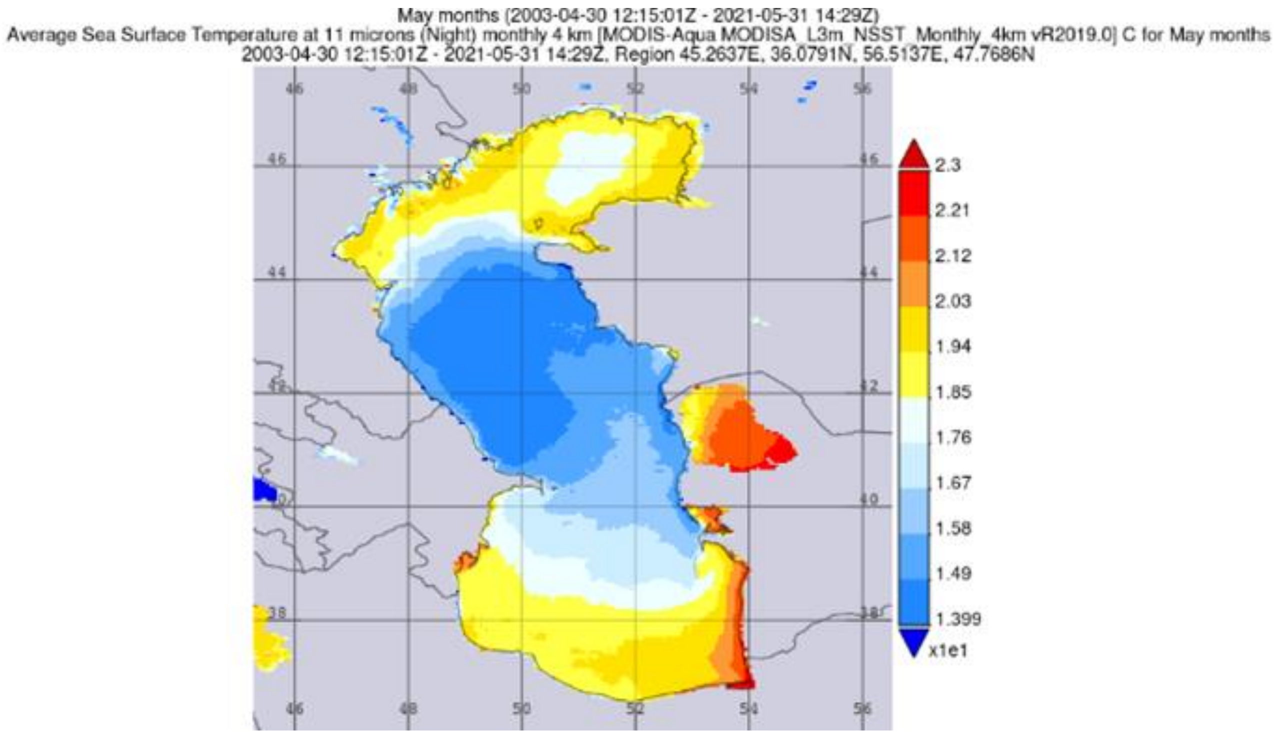

Figure 2. Distribution of SST in the Caspian Sea in May for 2003-2021.

SST of the Middle Caspian Sea varies between 14-17 °C and increases mainly from north to south. The influence of the relatively warm waters of the South Caspian Sea is felt in the southern part of the area (Figure 1). In May, the highest SST is recorded in Kara-Bogaz-Gol Bay (19-22 °C).

SST of the South Caspian Sea in the meridional direction from north to south increases from 15.5 °C to 22 °C. There is a noticeable increase in SST from west to east, especially in the southern part of the area. The highest temperatures are observed in the eastern coastal waters and especially in bays (Figure 2).

As can be seen from Figure 2, the upwelling in May in average is not very intense, but the size and intensity of the upwelling zone in May in different years can be different [20,21]. Upwelling, which began mainly in the eastern part of the Middle Caspian in May, relatively weakens the advection of warm water mass from the South Caspian to the Middle Caspian.

In June, the air temperature rises even more. This increase, in combination with other meteorological factors, complex geomorphological conditions and sea bathymetry, creates unique features of SST distribution in the Caspian Sea (Figure 3).

As can be seen from Figure 1 and Figure 2, in June compared to May, the increase in surface temperature of the North Caspian is 5,0-6,0 °C, the Middle Caspian 5 ºC, the South Caspian 3,0-3,5 °C.

As in May, in June the lowest SST observed in the Middle Caspian Sea, while to the north and south of it there is a gradual increase in temperature (Figure 3).

SST in the North Caspian varies between 22-25 °C. The average SST gradient at the boundary between the Middle Caspian and the North Caspian is -1.6 °C (Figure 3). Except for the eastern coastal areas, SST varies between 20-22 °C throughout the Middle Caspian. In the eastern coastal areas, the surface temperature is close to 19 °C. SST of the South Caspian varies from north to south within the range of 19-25 °C. Higher temperatures are noted in the southeastern regions and bays.

In most parts of the Kara-Bogaz-Gol Bay SST is above 25 °C.

In June, the upwelling phenomenon, which began from the eastern coast of the sea, begins to manifest itself more clearly (Figure 3). Thus, the upwelling zone extends along the eastern part of the sea along the 20,2 ^{0}C isotherm from latitude 44,2^0 to 39,5^0 and covers large areas to the west. It can spread to the western coast of Ogurchink Island [6]. As can be seen from Figure 2, the minimum SST in the upwelling zone is 18 ^{0}C, but in some years it can drop to 14 ^{0}C.

In June, the intensification of the upwelling phenomenon in the eastern part of the Middle and partly the South Caspian is accompanied by a noticeable weakening of the advection of warm water masses from the east of the South Caspian and its deviation to the west (Figure 3).

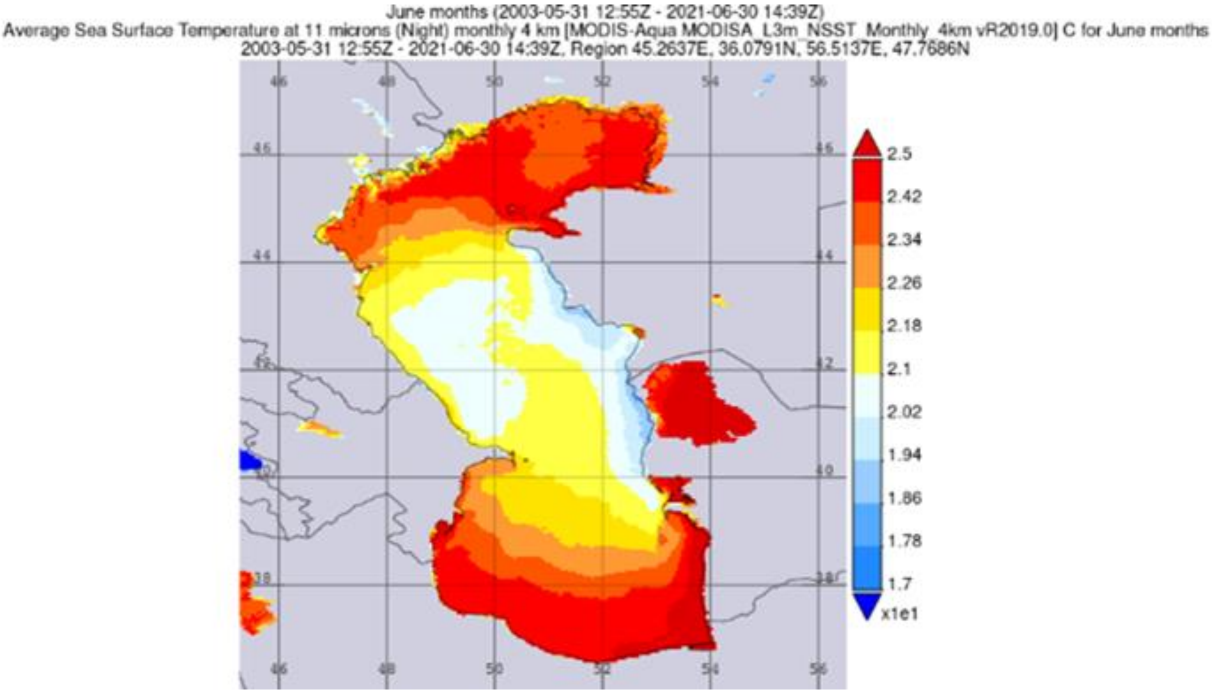

Figure 3. Distribution of SST in the Caspian Sea in June for 2003-2021.

In July, SST distribution in the Caspian Sea area is generally similar to that in June. In addition, as in May and June, the lowest temperatures are observed in the Middle Caspian and gradually increase towards the North and South Caspian. In July, compared to June, the mean multiyear SST increases by 2,0-3,5 ºC in the North Caspian, by 2,5-3,5 °C in the Middle Caspian and by 5,0-5,5 °C in the South Caspian (Figure 4).

SST distribution in the North Caspian is rather homogeneous and varies only within 25,5-27 °C. SST gradient at the boundary between the Middle Caspian and the North Caspian is much lower compared to June and amounts to -0,9 °C and is directed from north to south (Figure 4).

SST in the western areas of the Middle Caspian is almost unchanged (24,5-25,5 °C), but sharply decreases to the east, due to the upwelling phenomenon, and approaches 21,5 °C in the coastal zone. SST of the South Caspian Sea varies from north to south within the range of 24,5-28,0 °C. Higher temperatures (30 °C) are observed in the southeastern regions, as well as in the Kara-Bogaz-Gol area and bays located to the south of it (Figure 4).

In July, a pronounced upwelling was recorded on the eastern coast of the Middle and partly Southern Caspian (Figure 4). As can be seen from the figure, the width of the upwelling zone increases from north to south, and in some places even reaches 60 km. In the east of the Middle Caspian, SST drops from 25 °C to 21 °C from west to east. The temperature gradient is 4,2 °C/100 km.

Figure 4 shows that the upwelling zone extends from the 40th parallel to the 44,5th parallel, expands to the south from Cape Peschany and even penetrates the South Caspian. Intense upwelling partially extinguishes the advection of warm water mass from the South Caspian to the Middle Caspian, and even the reverse process occurs, i.e., advection of the upwelling mass of cold water from the Middle Caspian to the South Caspian.

It should be noted that the distribution of mean SST in July and the shape and size of the upwelling zone may differ in individual years [22,23].

In August, the positive heat balance reaches its maximum in the Caspian Sea [2]. As can be seen from Figure 3 and Figure 5, in most areas of the North Caspian Sea, compared to July, the mean multiyear SST in August is almost unchanged, and even in some places slightly decreases by 0,5 °C. In the Middle Caspian there is an increase in SST by 1,0 °C, and in the South Caspian - by 0-1,5 °C.

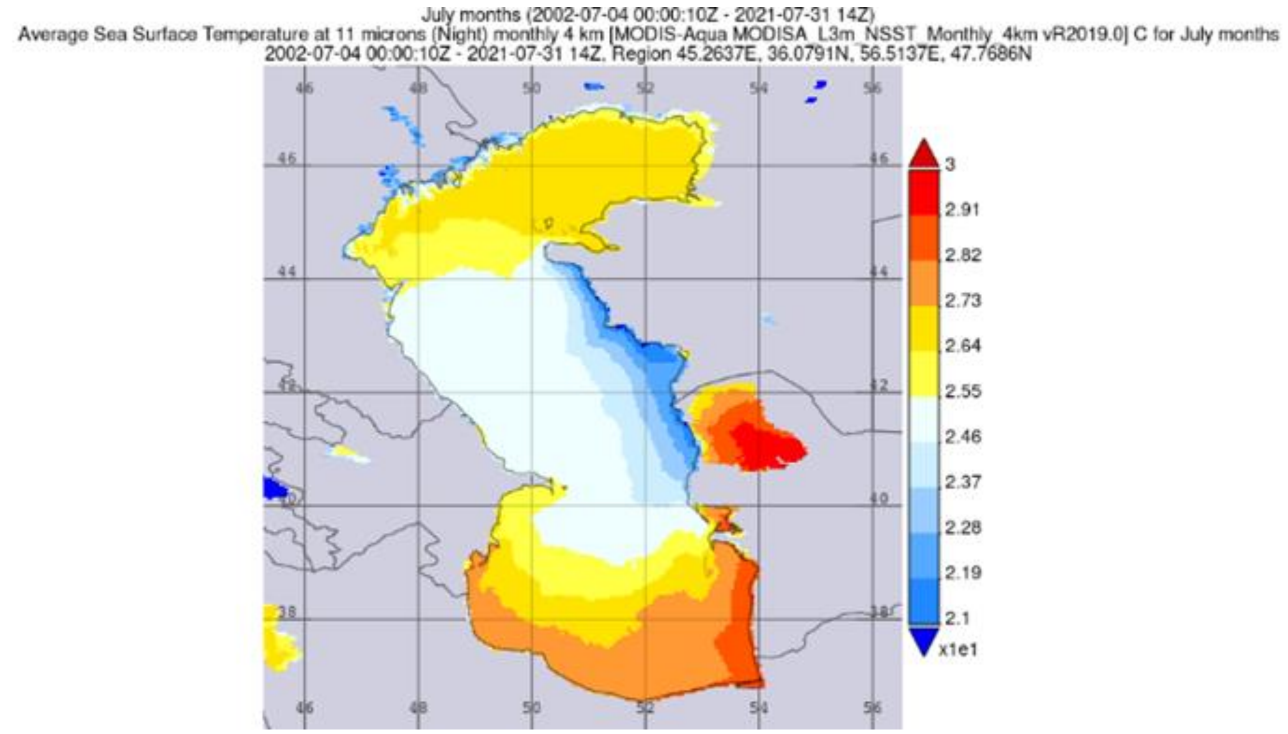

Figure 4. Distribution of SST in the Caspian Sea in July for 2003-2021.

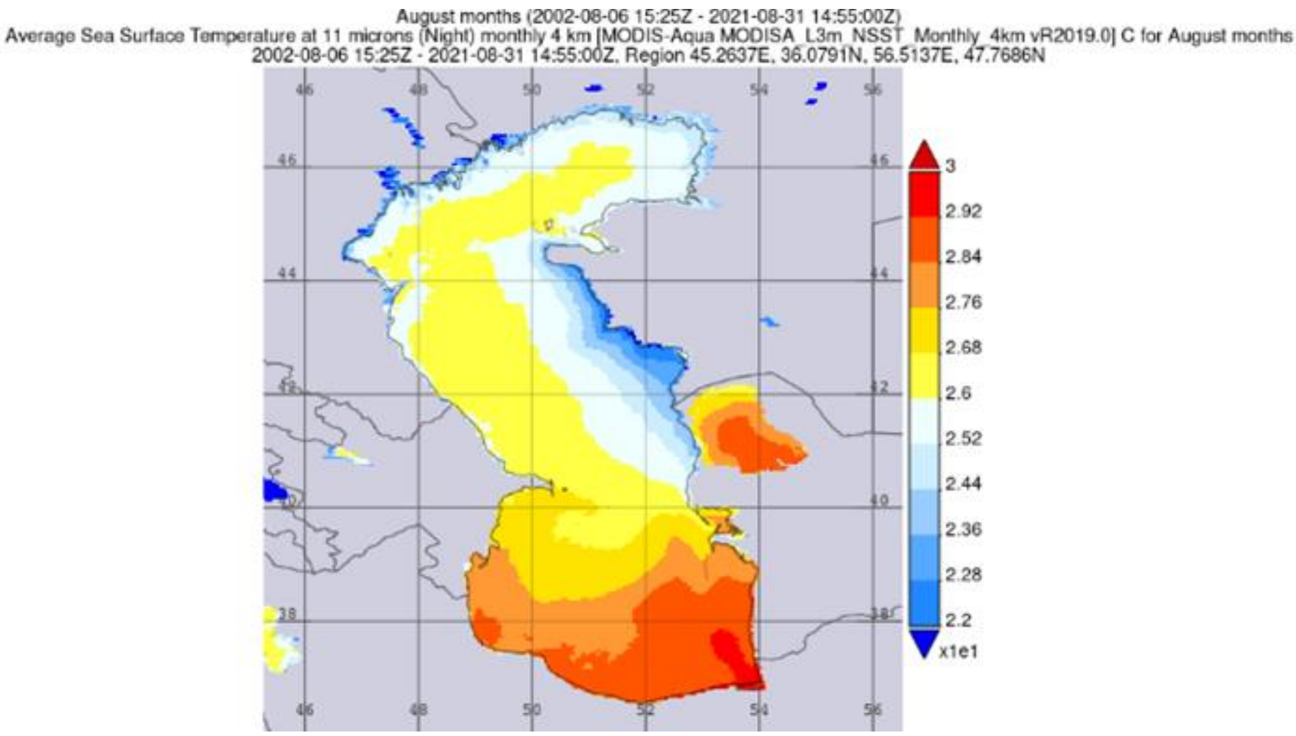

Figure 5. Distribution of average SST in the Caspian Sea in August for 2003-2021.

This month, except for the eastern regions, the surface temperature distribution in the Middle Caspian is almost the same as in the North Caspian (25 -27 °C). In the North Caspian, higher temperatures are noted in the central parts and gradually decrease towards the coasts, which is most likely due to cooler waters brought by the Volga and Ural rivers (Figure 5). On average over the multiyear period, no significant temperature gradient is observed at the boundary between the North Caspian and the Middle Caspian. However, in some years, high gradients may occur at the boundary due to the intensification of the upwelling phenomenon in the eastern regions (Figure 7).

In the Middle Caspian Sea, SST does not change from north to south. The temperature change is characterized by its decrease from west to east. As can be seen from Figure 4, the zone of warm waters is directed towards the western part of the sea, while towards the east, due to the upwelling process, the SST drops with a large gradient (up to 3,2 °C /100 km). Outside the zones of anomalous upwelling, the SST of the Middle Caspian Sea is 26-27 ºC, which is about 1 °C higher than indicated in [9]) and characterizes the temperature increase over the last 20 years compared to the previous period.

In the northern part of the South Caspian Sea, SST is close to 26 °C and rises to 30 °C towards the southeast. SST in Kara-Bogaz-Gol Bay increases from 26 °C to 29,5 °C from north to southeast.

As can be seen from Figure 5, the upwelling process in August remains intense, but compared to July, its southern border shifts by about 0,5-0,7° to the north, and the process cannot penetrate the South Caspian. As can be seen from Figure 4, the reason for this is the advection of warm waters from the South Caspian to the Middle Caspian more often than in July. In the western part of the South Caspian, on the contrary, advection of relatively cold waters from the Middle Caspian prevails. Lower upwelling temperatures (22 °C) are observed in the area from the southern coast of Cape Peschanyi to the northern part of the Kazakh Bay.

It should be noted that in some years the nature of the distribution of the average SST in August may undergo certain changes. Figure 6 shows the distribution of the average SST for August 2009 over the sea area. As can be seen, there is a strong advection of warm water masses from the eastern part of the South Caspian to the Middle Caspian, as evidenced by the convexity of the corresponding isotherms to the north. This process prevents the upwelling zone from spreading to the south. Instead, the rising cold-water mass extends to the west in a strip about 200 km long and about 100 km wide from the direction of Cape Peschany, and even individual jets of cold water reach the western coast.

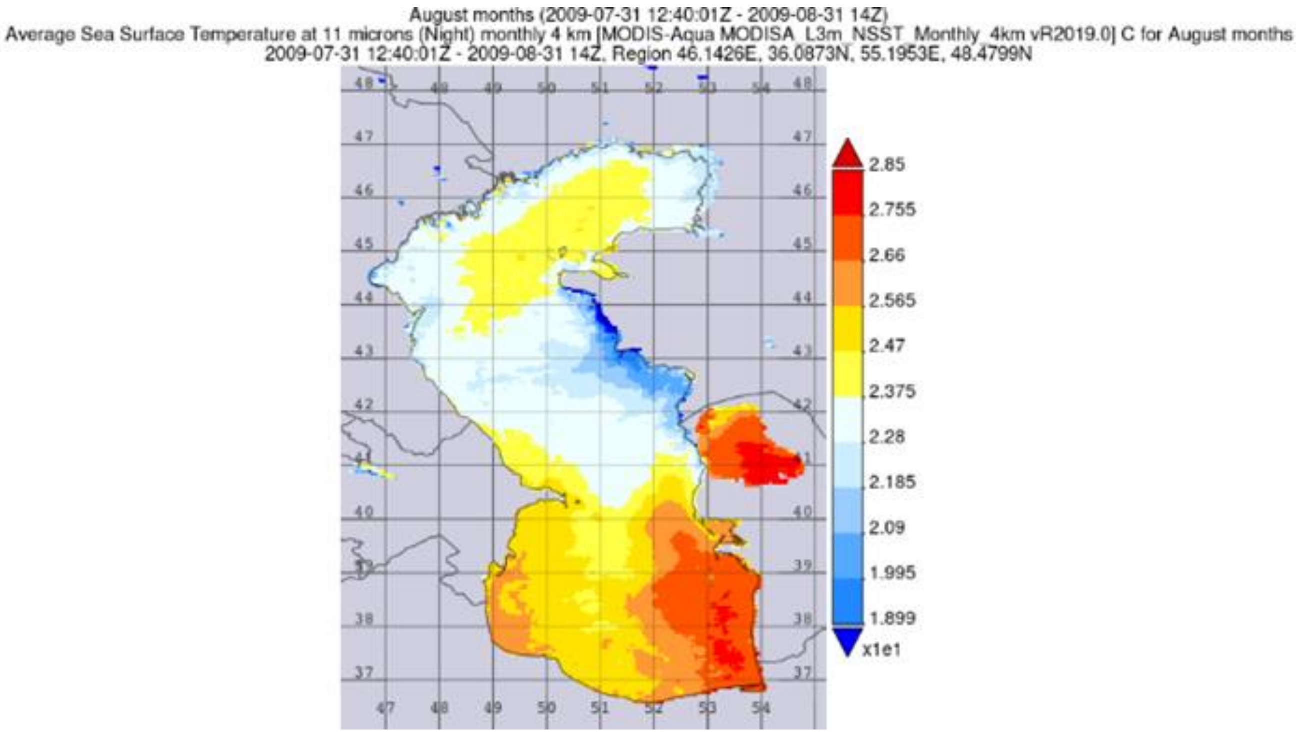

Figure 6. Distribution of the average SST in the Caspian Sea area in August 2009

The upwelling event, which took place in August 2014, is of greater interest due to its uniqueness. The distribution of the average surface temperature for August 2014 is shown in Figure 7. As can be seen from the figure, the upwelling phenomenon here occurs under conditions of strong temperature advection, which originates in the eastern part of the South Caspian and is directed to the north, which prevents upwelling from spreading to the south. Temperature advection from the eastern part of the South Caspian to the north extends along the eastern coast of the Middle Caspian to the Kazakh Gulf, and therefore the southern border of the upwelling zone begins only from the northern coastal waters of this bay. From the north, the upwelling zone is limited by the southern coastal waters of the Tyube-Karagan peninsula.

As can be seen from Figure 6, the upwelling waters, which could not penetrate south from the Kazakh Gulf due to strong temperature advection from the southeast, spread to the west and south, reaching a very significant part of the Middle Caspian and even the northeastern coastal waters of the South Caspian, or rather the Azerbaijani sector of the sea. From this point of view, this effect can explain the sometimes-sharp cooling of the waters of the western coast of the sea during hot periods of the year. On the other hand, the penetration of upwelling waters into the South Caspian leads to anomalous changes in the distribution of surface waters here (Figure 7).

In September, the character of the average SST distribution over the Caspian Sea area is influenced, especially in the northern areas, by the relative air temperature decrease and continuation of the upwelling process in the eastern coastal waters. As a result, the positive heat balance turns into a negative one. In this connection, the mean multiyear SST in September decreases by 4,5-7,0 °C in the Northern Caspian, by 2,5-3,5 °C in the Middle Caspian and by 1,5-2,0 °C in the Southern Caspian (Figure 5 and Figure 8). As can be seen, the decrease in the heat balance has the greatest impact on the North Caspian, which is shallower.

The mean annual SST of the North Caspian decreases from 22,5 °C in the south to 18 °C to the north and especially to the east. The temperature gradient at the North Caspian-Middle Caspian boundary is 1,5 °C/100 km (Figure 8). SST of the Middle Caspian Sea increases from 22,5 °C to 24,5 °C from north to south and decreases from 24,0 °C to 19,0 °C from west to east due to the upwelling phenomenon. A slight decrease in surface temperature in the western coastal zone of the Middle Caspian is associated with the arrival of cyclonic cold surface currents from the north. The surface temperature of the Southern Caspian increases from 24,5 °C to 28,0 °C from north to south. Although the latitudinal distribution of surface temperature in the northern part of the southern water area is relatively homogeneous, a significant temperature gradient is recorded to the south.

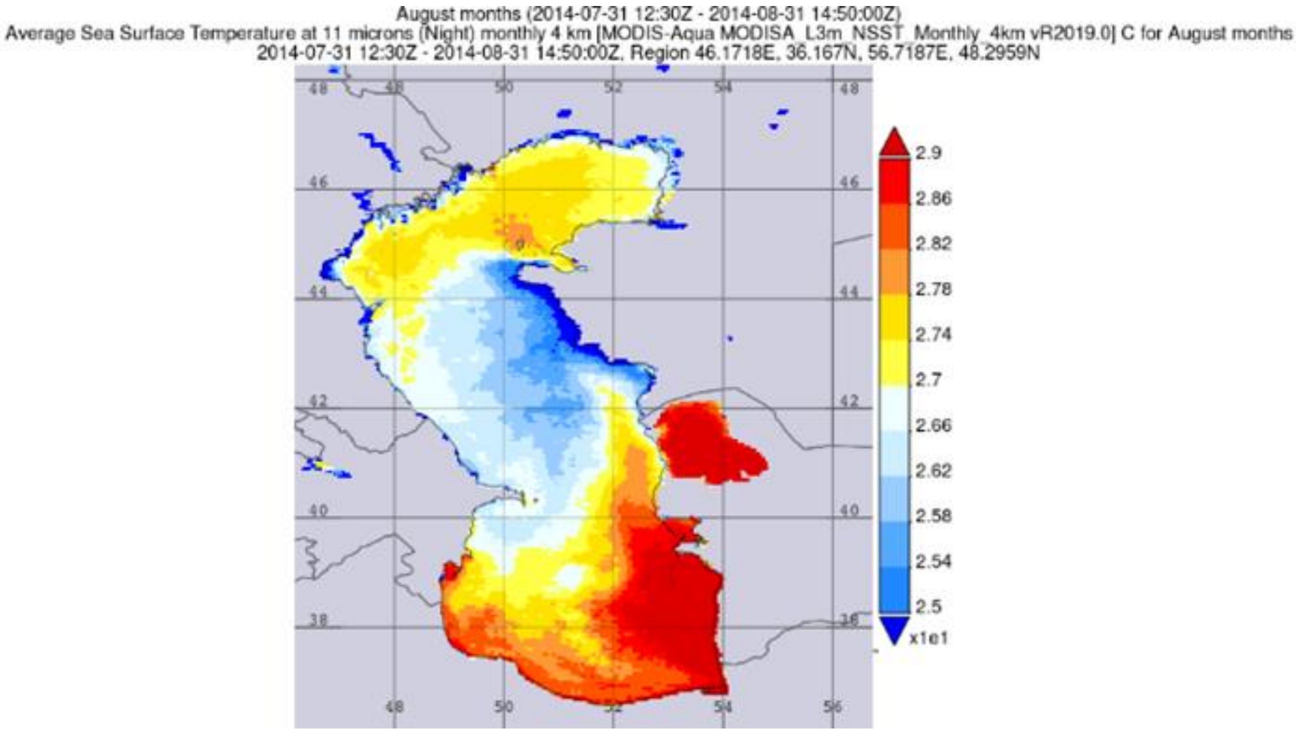

Figure 7. Distribution of the average SST in the Caspian Sea area in August 2014.

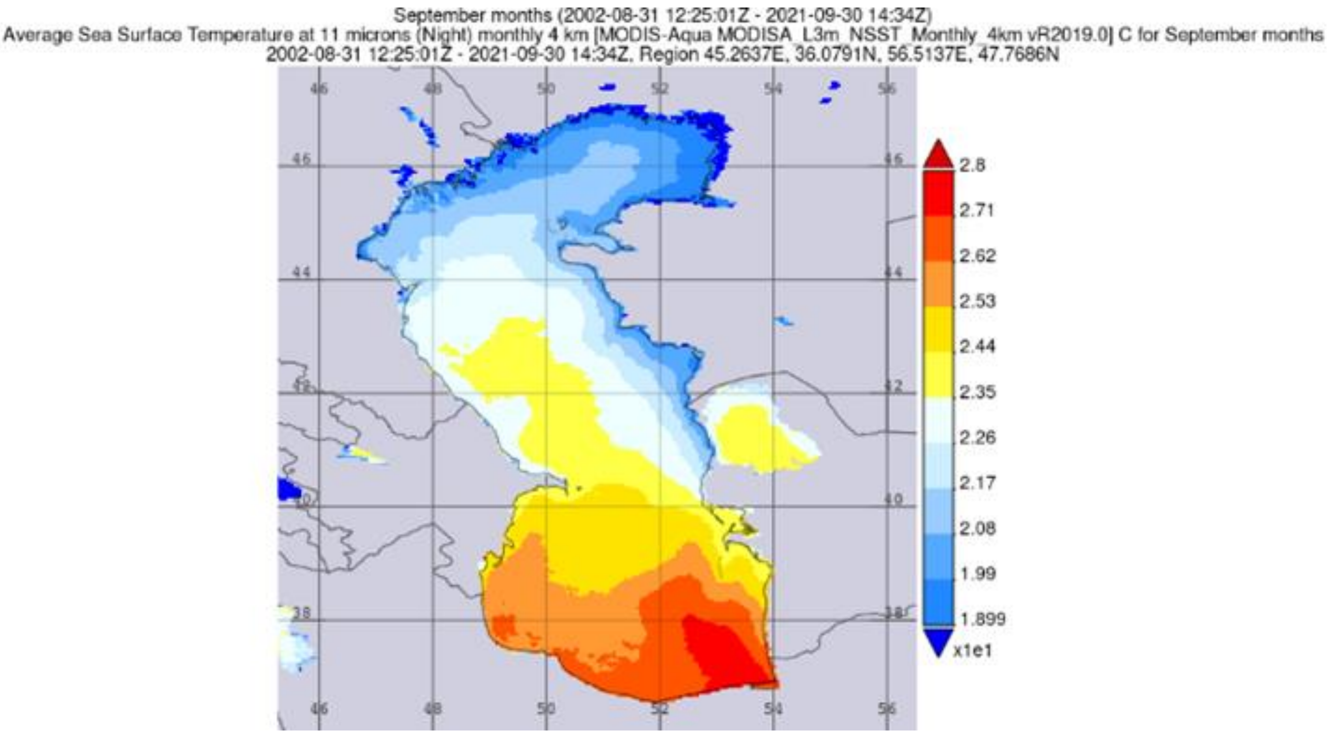

Figure 8. Distribution of SST in the Caspian Sea in September for 2003-2021.

In September, the southern border of the upwelling zone in the east of the Caspian Sea (isotherm 22,6 °C) passes through the latitude 40,5°, as in August. Since the water temperature in the North Caspian begins to decrease in September, it becomes difficult to determine the northern boundary of the upwelling zone. The main difference between the upwelling observed in this month and August is that the upwelling zone is narrower, against the background of a relatively lower temperature.

It should be noted that the upwelling processes observed in September of different years can manifest themselves in different ways. During the years of intense advection of warm water mass from the South Caspian to the Middle Caspian, the southern border of upwelling is significantly shifted to the north. For example, in September 2014, warm advective currents moving north along the east coast from the South Caspian extended to about the 42th parallel, preventing the upwelling process from spreading south, and instead, the transformed upwelling waters moved westward from the coastal zone to the direction to the south and reached a latitude of 38,5° in the South Caspian [7]. On the contrary, in years when there is no advection of the waters of the South Caspian into the Middle Caspian, the southern boundary of the upwelling belt can move up to the 40th parallel [24].

According to coastal observations in the area of Fort Shevchenko and Aktau for the period 1961...2018. it was revealed that upwelling near the Kazakh coast is seasonal. Out of 179 cases of upwelling, 87,7% were observed in summer and 6,7% in autumn. Only 18% of the considered cases of upwelling were associated with surge events [25].

This means that in most cases upwellings with Ekman transport mechanism prevail in the eastern part of the Middle Caspian. In other words, in the summer season, long moderate winds blowing along the shores of the eastern part of the Middle Caspian (mainly north and northwest winds) create surface currents, which, in turn, are deflected to the right under the influence of the Coriolis force, creating a corresponding pattern of temperature distribution of upwelling phenomenon (Figure 2, Figure 5, Figure 8). Sometimes strong east and northeast winds can somewhat distort the Ekman transport mechanism of upwelling formation. Since the wind force is proportional to the square of its velocity and the Coriolis force to its first degree, the role of the Coriolis force is significantly reduced at high velocities. In such cases, the upwelling zone can occupy significant areas (Figure 7).

4. Conclusion

Analysis of MODIS Aqua data showed that in the period May-September, upwelling occurs in the eastern and western coastal waters of the Middle Caspian and partly in the South Caspian. It occurs regularly on the east coast, and fragmentarily on the west coast. The most intense upwelling is observed on the eastern coast of the Middle Caspian in July-August. According to averaged long-term data, the upwelling phenomenon during this period is mainly observed between 40-44° latitude, and its width increases from north to south, reaches 60-70 km in the direction of the Kazakh Gulf and decreases to the south. In the upwelling zone, the temperature gradient sometimes reaches 4,0 °C/100 km. In some years, the upwelling zone that has arisen on the eastern coasts can spread over long distances and even reach the western coasts. In most cases, the upwelling phenomenon occurs against the background of advection of warm waters from the South Caspian to the Middle Caspian.

Author contributions

Said Safarov: Developed the theoretical framework and performed the experiments **Khalil Valizadeh Kamran:** Conceptualization, Methodology, Data collecting. **Vusal Ismayilov:** Analysis, Visualization, Writing-Reviewing. **Elnur Safarov:** Investigation, Editing, Writing-Reviewing

Conflicts of interest

The authors declare no conflicts of interest.

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