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ABSTRACT

of the dissertation for the degree of Doctor of Philosophy

INVESTIGATION OF TEMPERATURE ANOMALIES OF EPIPELAGIC ZONE OF THE CASPIAN SEA APPLYING CONTACT AND REMOTE SENSING METHODS

Specialty: 5406.01 – "Hydrology"

Field of Science: Geography

Applicant**:** **Vusal Hakim Ismayilov**

Baku – 2025

The dissertation work was conducted at the Department of "Hydrometeorology" of Baku State University, Ministry of Science and Education of the Republic of Azerbaijan.

Scientific supervisor: Dr. of Sciences in Geography, Docent
Said Hasan Safarov

Official opponents: Dr. of Sciences in Geography, Docent
Mahammad Abdu Abduyev

PhD in Geography, Docent
Ulkar Khalil Mahmudova

PhD in Geography
Sabir Bahman Asadov

BFD 3.14 Disposable dissertation council of the Supreme Attestation Commission under the President of the Republic of Azerbaijan operating at the Institute of Geography named after Hasan Aliyev, Ministry of Science and Education of the Republic of Azerbaijan.

Chairman of the Dissertation Council: Dr. of Sciences in Geography, Docent
Malikmammad Khanoghlan Mammadov

____

Scientific Secretary of the Dissertation Council: PhD in Geography, Docent
Ziyafat Bilal Aghayev

____

Chairman of the Scientific Seminar: Dr. of Sciences in Geography, Prof.
Rza Nadir Mahmudov

____

GENERAL CHARACTERISTIC OF THE WORK

The actuality of the topic and level of research on the topic. The Caspian Sea, recognized as the largest enclosed inland waterbody in the world by surface area, possesses significant biological diversity and substantial hydrocarbon reserves. Owing to its strategic geographical location, the Caspian Sea serves as a essential axis for transportation and communication, thereby playing a critical role in the socioeconomic development of the littoral states. Given its status as a terminal (closed) basin with no direct fluvial or marine connection to the World Ocean, the Caspian Sea’s water level is highly sensitive to various environmental and climatic factors. It is well established that the sea level is governed primarily by the basin’s water balance, with evaporation from the sea surface constituting one of its most influential components. Evaporation rates are, in turn, modulated by multiple meteorological parameters, including air temperature, relative humidity, wind speed and its direction. However, the temperature of the sea surface is considered to be the predominant factor influencing evaporation dynamics. On average, the annual radiation balance of the Caspian Sea’s surface is positive, amounting to approximately 60 kcal/cm². Of this total, a substantial portion, around 54 kcal/cm², is expended through evaporation and convective heat exchange with the overlying atmosphere[1]. Concurrently, sea surface temperature plays a critical role for aquatic organisms.

The spatial variability of sea surface temperature across different regions of the Caspian Sea is governed by a complex interplay of air temperature, surface circulation patterns, the occurrence of upwelling phenomena, lateral heat exchange between distinct water masses, as well as the geomorphological configuration and bathymetric characteristics of the seabed. Additionally, temporal fluctuations in

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[1] Bolgov, M.V. The Caspian Sea: Extreme hydrological events / M.V.Bolgov, G.F.Krasnojon, A.A.Lyubushin. – Moscow: Nauka, – 2007. – 381 p. (In Russ.)

sea level also contribute to modulating surface temperature dynamics.

Numerous scientific works have been devoted to various aspects of the study of surface temperature in the Caspian Sea based on contact measurement data (Arkhipova, 1958; Sheremetevskaya, 1958; Zulfugarov, 1965; Potaichuk, 1978; Skriptunov, 1971; Parmuzina, 1971; Kosarev, 1975; Radionov, 1989; Hydrometeorology…, 1992). The results of research conducted in this field until 1990 [2] were summarized, including the determination of the primary statistical parameters of water surface temperatures for hydrological stations operating in the Caspian Sea aquatorium.

It is recognized over the past 30 years, global air temperature has increased by approximately 1.1ºC relative to the pre-industrial period, a trend that is also evident within the Azerbaijani sector of the Caspian Sea, as in other regions of the world. Concurrently, the Caspian Sea level has exhibited a gradual decline since 1995, accelerating notably after 2005, and is currently approaching the historical minimum of -29 meters observed in 1977. In this context, the investigation of recent changes in the surface temperature regime and its spatial distribution across the sea is of considerable scientific and practical significance, particularly in light of rising air temperatures and the pronounced decline in sea level attributed to global warming. This research is grounded in traditional observations, as well as reanalysis and remote sensing data, and employs contemporary methodological approaches.

The primary hazardous atmospheric phenomena occurring within the territory of Azerbaijan include lightning, hail, ice jams, turbulence, blizzards, and similar events. Among these, lightning and hail are considered to have the most significant impact on agricultural activities. Variability in the precipitation regime is expected to result in serious environmental consequences in the

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[2] Hydrometeorology and hydrochemistry of the seas. Project of the Sea. Volume VI. Caspian Sea. Issue 1. Hydrometeorological conditions / Ed. by F.S.Terzieva, A.N.Kosareva, A.A.Kerimova. – St. Petersburg: Gidrometeoizdat, – 1992. – 359 p. (In Russ.)

future, including increased salinization and flooding. In response to these potential impacts, a foundation has been established for conducting region-specific studies across the country.

Object and topic of the research. The object of the study is the surface temperature of the Caspian Sea, while the subject concerns the examination of the surface temperature regime of the Caspian Sea through the application of modern methodologies based on in-situ observations, reanalysis datasets, and remote sensing data.

The purpose and the missions of investigation. The primary objective of this study is to identify changes in the surface temperature regime across various regions of the Caspian Sea, as well as throughout the entire water area, along with the mechanisms of formation and spatial distribution of upwelling events. This analysis is conducted using contact and remote sensing data under the conditions of global climate change and pronounced sea level fluctuations. To achieve this objective, the following research tasks were formulated and addressed within the scope of the dissertation:

- based on contact observation data, identifying the characteristics of temporal and spatial changes in monthly, seasonal and annual surface temperatures in separate areas of the Caspian Sea for the period 1961-2016 and the impact of climate change on them;
- assessment of the statistical significance of surface temperature anomalies and trend curves characterizing change trends;
- assessment of trends in area-averaged monthly, seasonal and annual surface temperatures in the North, Middle and South Caspian for the period 1980-2021 and their statistical significance based on MERRA-2 reanalysis data;
- based on the monthly data of the MODIS Aqua spectroradiometer with a resolution of 0.05º for the period 2002-2021, construction of time-averaged surface temperature distribution maps for each month and season across the Azerbaijani sector of the Caspian Sea and determination of distribution patterns based on them;
- based on the distribution maps mentioned in the previous paragraph, analysis of upwelling events observed mainly in the eastern part of the Caspian Sea between May and September,

assessment of their distribution areas and intensity, and investigation of the factors affecting their formation and development.

Research methods. The study utilized in-situ observational data from hydrological stations operating within the Caspian Sea, alongside MERRA-2 reanalysis datasets and MODIS Aqua satellite spectroradiometer data. Statistical parameters of the surface temperature data were computed using Excel, with corresponding tables generated and graphical representations constructed. Comparative analysis of statistical parameters across different temporal intervals enabled the identification of anomalies, whose significance was evaluated using Student's t-test. Utilizing MODIS Aqua data, monthly, seasonal, and annual surface temperature distribution maps of the Azerbaijani sector of the Caspian Sea were produced following procedures outlined on the GIOVANNI platform. The statistical significance of temporal trends in surface temperature was assessed employing established methods in mathematical statistics.

The main provisions to be defended.

1. Characteristics of the surface temperature regime at specific observation sites under conditions of global warming and Caspian Sea level decline, along with temporal trends across different periods of the year, derived from the analysis of long-term temperature datasets.
2. Principal characteristics and temporal trends of the surface temperature regime in the Northern, Central, and Southern Azerbaijani sectors of the Caspian Sea.
3. Spatial distribution of mean monthly, seasonal, and annual surface temperatures throughout the Azerbaijani sector of the Caspian Sea, including the identification of anomalies in individual years.
4. Determinant factors influencing the occurrence of upwelling phenomena in the eastern Caspian Sea, as well as the spatial extent and temporal variability of these events across different months.

The scientific innovations of the dissertation:

- Within the context of global warming and the decline in Caspian Sea levels, the characteristics of the surface temperature regime at individual observation points were identified, and temporal trends across different periods of the year were established based on long-term temperature series.
- Utilizing MERRA-2 reanalysis data averaged over relevant spatial domains for the period 1980–2021, the primary characteristics of the surface temperature regime in the Northern, Central, and Southern sectors of the Caspian Sea, as well as their temporal trends, were elucidated.
- Through the use of maps generated from MODIS Aqua spectroradiometer data for 2002–2021, the spatial distribution of average monthly, seasonal, and annual surface temperatures across the Azerbaijani sector of the Caspian Sea and the anomalies observed in specific years were determined.
- Based on the spatial distribution maps of average monthly surface temperatures, upwelling events in the eastern Caspian Sea were thoroughly analyzed, including the factors influencing their development and the identification of their formation and propagation areas throughout different months.

The theoretical and practical significance of the investigation. The novel data presented in this dissertation regarding the surface temperature regime and its spatial distribution under conditions of global climate change and sea level decline contribute to the advancement of hydrological knowledge of the Caspian Sea. Insights into the current state and temporal trends of the surface temperature regime across the Northern, Central, and Southern sectors of the Caspian Sea provide a basis for assessing the present and future ecological conditions of the basin. Moreover, the analysis of surface temperature distribution maps, particularly with respect to upwelling phenomena, enhances the understanding of the physical processes governing the Caspian Sea.

The findings of this research may be applied to the modeling, forecasting, and management of environmental risks affecting both the Azerbaijani sector of the Caspian Sea and adjacent coastal environments.

Approbation and application. The primary results of the dissertation work were discussed at the Baku State University and the Institute of Geography named after academician Hasan Aliyev of the Ministry of Science and Education, as well as at several scientific and technical forums and conferences: International scientific conference on “Actual problems of modern natural and economic sciences” (Ganja, 2022), International scientific and practical conference “EurasiaScience” (Moscow, December 31, 2022), Scientific and practical conference on “Modern problems of geography: Integration of science and education” (Baku, November 29-30, 2022), The 6th Intercontinental Geoinformation Days (Baku, June 13-14, 2023), International scientific and practical conference “Kurazhsk Readings” (Astrakhan, May 18-21, 2023).

The name of the organisation where the dissertation was implemented. The dissertation was conducted at Baku State University.

The structure of the dissertation. The dissertation consists of an introduction, 3 chapters, a conclusion and references. The volume of the work is 157 pages. The work consists of 20 figures, 25 tables, 83 graphs, and 137 references. Introduction are 5 pages, chapter I – 56 pages, chapter II – 36 pages, chapter III – 41 pages, conclusion – 2 pages, references – 15 pages. It consists of 160656 characters without tables, graphs, figures and references.

A BRIEF SUMMARY OF THE DISSERTATION

The Introduction outlines the relevance and degree of scholarly development of the research topic, as well as the objectives, research tasks, methodological approach, key propositions submitted for defense, scientific contributions, and the theoretical and practical significance of the study, along with its approbation and application.

The first chapter of the dissertation, titled **“Investigation of the surface temperature regime of the Caspian Sea based on Contact Measurement Data”**, is dedicated to the analysis of contact-based observational data. This chapter begins with an examination of the physical and geographical characteristics of the Caspian Sea and its basin, highlighting its status as a unique natural water body located at the boundary between the European and Asian continents. Due to its lack of a direct hydrological connection with the World Ocean, the Caspian Sea exhibits significant fluctuations in water level, which as of 2022 stands at approximately 28.4 meters below ocean level (Baltic system).

According to contemporary scientific understanding, changes in sea level are primarily influenced by climatic factors, particularly the degree of moisture input into the watershed basin, which encompasses an area of approximately 3.5 million square kilometers. The Caspian Sea, the largest enclosed inland water body on Earth, contains an estimated volume of 78,000 cubic kilometers and covers a surface area of roughly 371,000 square kilometers. It extends about 1,200 kilometers from north to south and approximately 320 kilometers from west to east. In terms of surface area, the Caspian Sea constitutes approximately 18% of the total surface area of all lakes worldwide.

The sea is bordered by five countries: Azerbaijan, Iran, Kazakhstan, Russia, and Turkmenistan.

According to its physical-geographical and topographic characteristics, the Caspian Sea is subdivided into three distinct sub-basins: the Northern, Middle, and Southern Caspian. The Northern Caspian accounts for 25% of the total sea area, the Middle Caspian for 36%, and the Southern Caspian for 39%. The Absheron Ridge (Threshold), with a maximum depth of approximately 170 meters, serves as the boundary between the Middle and Southern Caspian sub-basins, which reach maximum depths of 788 meters and 1,025 meters, respectively. The average depth of the Caspian Sea is 208 meters. The Northern Caspian, characterized by a highly developed shelf zone, is notably shallow, with an average depth of approximately 5 meters and a maximum depth of around 20 meters in the Ural Trough. It is separated from the Middle Caspian by the Mangyshlak Ridge.

The Caspian Sea is conventionally divided into three sectors: the North Caspian, comprising approximately 25% of the sea's total surface area; the Middle Caspian, accounting for 36%; and the South Caspian, encompassing around 39%. Due to its relatively shallow depth, the share of the North Caspian in the total surface area is gradually diminishing as a result of a marked decline in sea level.

The boundary between the North and Middle Caspian is defined by a notional straight line connecting Chechen Island and Cape Tub-Karagan, while the division between the Middle and South Caspian follows a straight line between Chilov Island and Cape Kuuli.

The total length of the Caspian Sea coastline varies depending on the sea level. At a sea level of -28 meters (relative to oceanic mean sea level), the coastline is estimated to be approximately 6,500–6,700 kilometers in length, and up to 7,000 kilometers when including islands. However, these figures are subject to considerable variation due to fluctuations in sea level. In the North Caspian, the coastline is highly indented, shaped by the river channels and islands formed by the Volga and Ural river deltas. The shores in this region are typically low-lying and marshy.

The bathymetric structure of the Caspian Sea exerts a significant influence on both the direction and velocity of marine currents, which in turn indirectly affect the spatial distribution of sea surface temperature across the basin. This chapter identifies the primary factors influencing the climate of the Caspian Sea, including the variability of its surface temperature as well. The climatic regime over the Caspian Sea is determined by a combination of geographical location, prevailing atmospheric circulation patterns, the nature of incoming air masses, the orographic characteristics of the surrounding land, heat exchange processes between the atmosphere and the sea surface, and the configuration of the coastline. Synoptic-scale processes and the intrusion of various air mass types into the region constitute key determinants in the formation of the Caspian

Sea’s climatic conditions and prevailing meteorological patterns[3]. Additionally, the meridional elongation of the sea contributes to the development of distinct climatic and meteorological conditions across its various regions[4].

The atmospheric air over the sea surface is in continuous thermal interaction with the underlying sea water. During the winter months, particularly in January and February, the average monthly air temperature in the Northern Caspian ranges from -8 to -10°C, in the Middle Caspian from +3 to -5°C, and in the Southern Caspian from +8 to +12°C. In contrast, during the peak summer period (July-August), the average air temperature increases progressively from approximately +24°C in the north to +27–28°C in the southern part of the basin. A notable temperature gradient is also observed between the western and eastern sectors of the sea. For instance, in July, the average air temperature in the western region is approximately +24.5°C, whereas in the eastern region it reaches +27.0°C[5]. The atmosphere above the Caspian Sea is in continuous thermal exchange with the sea surface. During colder periods of the year, the temperature of the sea surface typically exceeds that of the overlying air, whereas in warmer periods, the sea surface temperature is generally lower than the ambient air temperature. The effects of global climate change, particularly global warming, have become increasingly evident in the Caspian Sea region, contributing to observable changes in the thermal regime of the sea.

Although atmospheric pressure over the sea is not directly linked to the surface water temperature, it may influence it to some extent through its association with prevailing synoptic conditions. Over the Caspian Sea, atmospheric pressure generally ranges between 1014 and 1018 hPa, exhibiting a gradual increase from the southern to the

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[3]Madat-zade A.A. Main types of atmospheric processes determining the wind field in the Caspian Sea // Transactions of the Oceanographic Commission. Problems of the Caspian Sea. – 195 9. Vol. 5. – pp. 140-145. (In Russ.)

[4]Panin, G.N. Current state of the Caspian Sea / G.N.Panin, R.M.Mammadov, I.V.Mitrofanov. – Moscow: Nauka. – 2005. – 356 p. (In Russ.)

[5]Water balance and fluctuations of the Caspian Sea level. Modeling and forecast/ Ed. by E.S.Nesterova. – Moscow: Triada Ltd., – 2016. – 378 p. (In Russ.)

northern sectors. During the colder months, atmospheric pressure is typically higher than in the warmer period, with an average seasonal difference of approximately 10-12 hPa. Frequent changes in air masses significantly affect the synoptic conditions prevailing over the Caspian Sea area in all seasons of the year.

Precipitation, in addition to being a fundamental component of the Caspian Sea's water balance, also exerts an influence on the surface temperature regime. The spatial distribution of atmospheric precipitation over the Azerbaijani sector of the Caspian Sea is markedly uneven. Specifically, the western coast receives 2-3 times more precipitation than the eastern coast, with the highest average annual totals recorded in the southwestern sector of the basin. Over 70% of the annual precipitation occurs during the autumn-winter period. Based on long-term estimates, the average annual precipitation over the sea is approximately 190-200 mm.

The wind regime existing over the Azerbaijani sector of the Caspian Sea plays a significant role in the formation of surface temperature, alongside other contributing factors. This influence is primarily attributed to wind-driven advection processes, the generation of surface currents, and the occurrence of upwelling phenomena. The speed and direction of winds observed over the Azerbaijani sector of the Caspian Sea are directly influenced by atmospheric circulation patterns, the meridional orientation of the sea from north to south, atmospheric pressure fields over the sea surface, and the orographic characteristics of the surrounding coastline[6]. 80-90% of the winds blowing over the Caspian Sea have a speed of less than 10 m/sec., and the probability of storm winds with a speed of more than 20 m/sec. is close to 1%[7]. In the Northern Caspian, north and south-east winds are prominent for most of the year. On the western coast of the Middle Caspian, the strongest winds are

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[6]Мамедов, Р.М. Гидрометеорологическая изменчивость и экогеогра-фические проблемы Каспийского моря / Р.М.Мамедов. – Баку: Элм, – 2007. – 453 с. (In Russ.)

[7] Imrani, Z.T., Safarov, S.H., Safarov, E.S. Analysis of Wind-wave Characteristics of the Caspian Sea Based on Reanalysis Data // Russian Meteorology and Hydrology, – 2022, Vol. 47, No. 6, – p. 479-484. (In Eng.)

recorded in the Absheron Peninsula zone. In this area, the average annual wind speed is 6.2-8.0 m/sec., with north and north-west directions prevailing[8]. On the east coast, the wind speed is slightly lower (5.0-6.3 m/sec.), and its maximum values are observed in the Fort Shevchenko and Kara-Bogaz-Gol regions.

Along the eastern coast of the Southern Caspian, northern and northwestern winds constitute approximately 50% of the observed wind directions, while eastern, northeastern, and southeastern winds account for 30-34%. In the southern and western sectors of this region, northern and northeasterly winds are predominant. In contrast, the southeastern part of the Southern Caspian is characterized by a seasonal variation in wind direction, with southwesterly winds prevailing during winter and southeasterly winds dominating in summer.

The wind regime over the Caspian Sea plays a critical role in the development of surface currents and wave dynamics. It also exerts a significant influence on the surface temperature distribution, particularly in the Middle and Southern Caspian regions during the warmer periods of the year.

As the Caspian Sea is a closed inland water body with no direct connection to the World Ocean, its water level is subject to continuous fluctuations driven by various natural factors. The magnitude and underlying causes of these fluctuations have varied across different historical periods. Throughout its long-term evolution, the sea level has experienced both transgressive and regressive phases. Geomorphological studies indicate that the magnitude and duration of sea-level fluctuations in the Caspian Sea have been significantly greater over geological timescales than those observed in the modern instrumental record. For instance, during the Pleistocene epoch, sea-level variations exceeded 100 meters; in the Holocene, fluctuations reached up to 15 meters; and over the past two millennia, changes have approached approximately 12 meters.

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[8]Safarov, S.H., Safarov, E.S., Ismayilova, N.N. Study of the wind regime in the Oil Rocks area // – Bakı: H.Əliyevin 100 illik yubileyinə həsr olunmuş elmi konfrans, – 2023. – s. 38-42. (In Aze.)

Variations in the level of the Caspian Sea influence a range of hydrological parameters and physical processes, including the surface water temperature and its spatial distribution across the basin[9]. This effect particularly pronounced in the shallower region, the Northern Caspian.

The annual radiation balance of the Caspian Sea surface is positive, averaging approximately 60 kcal/cm². In the Northern Caspian, this value reaches around 50 kcal/cm², while in the Middle and Southern Caspian it increases to approximately 65 kcal/cm². A substantial portion of this energy input, about 54 kcal/cm², is expended on evaporation and convective heat exchange with the overlying atmosphere[10].

It is important to note that existing studies on the surface temperature regime of the Caspian Sea predominantly cover recent decades. In the context of accelerating contemporary climate change and significant sea level fluctuations, there is a pressing need for expanded research based on modern data.

The relatively shallow depth of the Northern Caspian, the complex geomorphological structure of the coastal zone, as well as ongoing climatic variability and sea level changes, collectively influence the spatial characteristics of surface temperature distribution in this part of the basin. Graph 1 illustrates the temporal evolution of annual average surface water temperature in the northeastern sector of the Northern Caspian, specifically in the region of the Ural River delta, encompassing the coastal zone near the Peshnoy Peninsula and Tyuleny Island in the western portion of the area.

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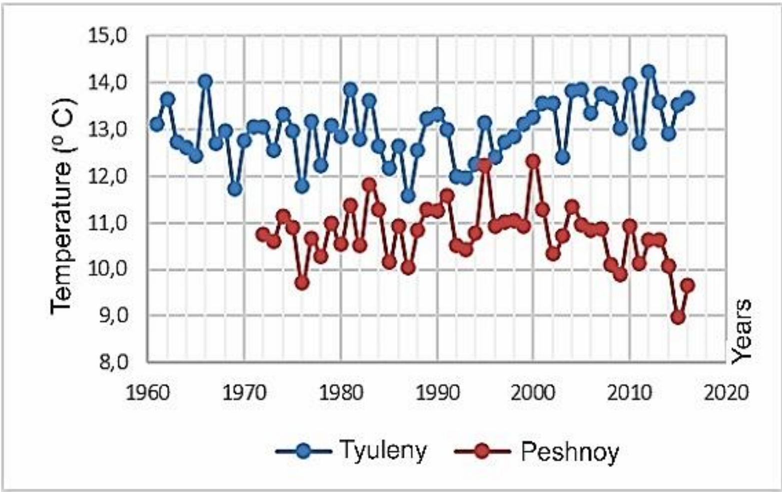
[9] Physical processes in the Caspian Sea in connection with fluctuations in its level / G.K.Gul, M.I.Abakarov, T.I.Furman [et al.] – Baku: Elm, – 1971. – 223 p. (In Russ.)

[10] Bolgov, M.V. Caspian Sea: Extreme hydrological events / M.V.Bolgov, G.F.Krasnojon, A.A.Lyubushin. – Moscow: Nauka, – 2007. – 381p. (In Russ.)



Source: Compiled by the author (V.H.Ismayilov) based
on archival materials from CASPCOM.

Graph 1. Temporal variability of average annual sea surface temperature at the Peshnoy and Tyuleny hydrological stations

As illustrated in Figure 1, a generally weak decreasing trend in the average annual sea surface temperature was observed in the Peshnoy area during the period 1972–2016. However, this decline became more pronounced after 1995, and particularly after 2000. In contrast, the Tyuleny hydrological district exhibited a general increasing trend in average annual sea surface temperature over the period 1965–2016, with a more distinct rise evident after 1987, and especially post-1993. These findings indicate that opposing temporal dynamics are present in the annual average sea surface temperatures between the eastern and western sectors of the Northern Caspian. This pattern is further substantiated by the data presented in Table 1.

Nominately, while the average annual sea surface temperature at the Peshnoy hydrological station decreased by 0.3°C during the period 1991-2016 compared to 1972-1990, a corresponding increase of 0.3°C was recorded at the Tyuleny station.

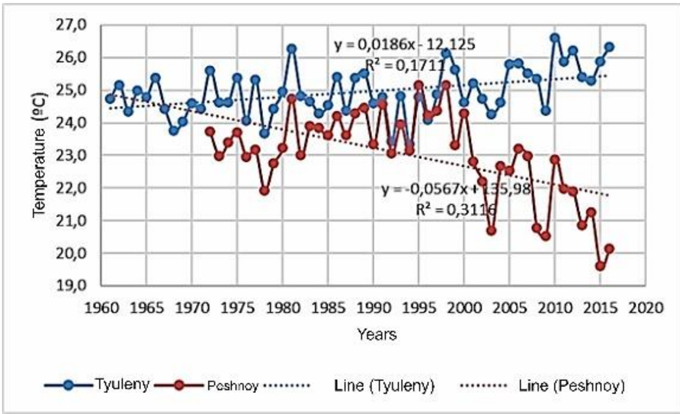
Table 1

Monthly distribution of the average sea surface temperature for the periods 1972–1990 and 1991–2016 at the Peshnoy and Tyuleny hydrological stations

Periods	Months												Year
	1	2	3	4	5	6	7	8	9	10	11	12	
Peshnoy													
1972-1990	0,1	0,1	1,1	9,7	17,4	22,4	25,0	23,1	17,6	9,3	3,0	0,7	10,8
1991-2016	1,7	1,6	2,7	8,7	16,8	21,1	22,5	21,4	15,2	8,0	3,7	2,1	10,5
Anomaly	1,6	1,5	1,7	-1,0	-0,5	-1,3	-2,5	-1,7	-2,5	-1,3	0,7	1,4	-0,3
Tyuleny													
1972-1990	0,9	0,9	4,1	12,4	19,2	23,7	25,9	24,7	19,9	12,7	6,9	2,6	12,8
1991-2016	0,9	1,1	4,4	11,8	18,7	23,6	26,1	25,7	20,8	14,6	7,8	2,5	13,2
Anomaly	-0,1	0,2	0,3	-0,6	-0,6	-0,1	0,2	1,0	0,9	1,9	0,9	-0,1	0,3

This divergence is generally consistent across most months of the year, with the exception of the spring months. Seasonal analysis also reveals contrasting trends in surface temperature at the two stations, with the most pronounced differences observed during the summer and autumn seasons. Specifically, beginning in 1995, the rise in surface temperature at Tyuleny during both seasons has been accompanied by a marked decline at Peshnoy (see Graph 2). Consequently, the thermal contrast in autumn surface temperatures between the two stations has increased progressively over time. Another notable observation is that, while synchronous variability in surface temperature trends was evident at both stations prior to 1995, this pattern is no longer clearly observable in subsequent periods.

From the above, it can be inferred that the divergent trends in annual, summer, and autumn mean sea surface temperatures between the Peshnoy and Tyuleny regions in recent years may lead to significant disruptions in existing water exchange mechanisms and other physical processes between different parts of the Northern Caspian. Such changes have the potential to adversely affect the ecological stability of the region.



Source: Compiled by the author (V.H.Ismayilov) based on archival materials from CASPCOM.

Graph 2. Temporal variation of summer average sea surface temperature at the Peshnoy and Tyuleny hydrological stations, 1960-2016

All of these observations indicate that the distribution and dynamics of surface temperature variability in the Northern Caspian exhibit complex spatial characteristics. These are influenced by the shallowness of the basin, the sharp decline in sea level, the diversity of physical and geographical conditions, the complexity of physical processes at the interface of sea water and inflowing riverine systems, the specific nature of heat exchange with the atmosphere, and the influence of water masses advected from the Middle Caspian[11].

The Middle Caspian is significantly deeper than the Northern Caspian, and its surface temperature regime is influenced by several factors, including air temperature over the sea surface, the inflow of water masses from both the Northern and Southern Caspian, and vertical exchange with deeper waters. During the cold season, the western part of the Middle Caspian is affected by the intrusion of

[11]Гидрометеорология и гидрохимия морей. Проект Моря. Том VI. Каспийское море. Вып. 1. Гидрометеорологические условия / Под ред. Ф.С.Терзиева, А.Н.Косарева, А.А.Керимова. – СПб.: Гидрометеоиздат, – 1992. – 359 с.

cold water masses from the Northern Caspian, whereas the southeastern regions are predominantly influenced by the advection of warmer waters originating from the Southern Caspian. In contrast, during the warm season, intense upwelling events, primarily occurring along the eastern coastal zones, play a critical role in shaping the surface temperature regime of the Middle Caspian[12].

Table 2 presents the hydrological stations used for sea surface temperature data in the Middle Caspian, along with their geographical coordinates and respective observation periods.

Table 2

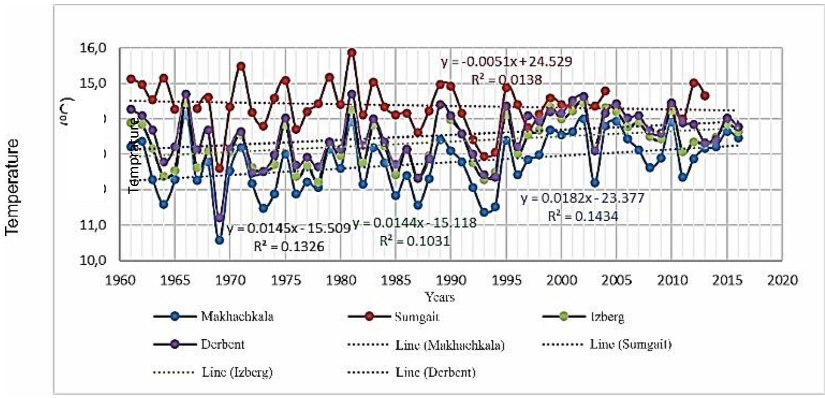
Geographical coordinates and observation periods of sea surface temperature stations in the Middle Caspian

Western coast				Eastern coast			
Name of the Observation Station	Geographical latitude (º)	Geographical longtitude (º)	Observation period	Name of the Observation Station	Geographical latitude (º)	Geographical longtitude (º)	Observation period
Makhachkala	43,00	47,30	1961-2016	Aktau	43,36	51,11	1961-2016
Izberg	42, 33	47,53	1961-1988 1990-2016	Bekdash	41,50	52,60	1961-1998 2000-2015
Derbent	42,04	48,18	1961-2016	Gara-Bogaz-Gol	41,10	52,90	1961-1997 2000-2015
Sumgait	40,60	49,60	1961-2012				

Graph 3 illustrates the temporal variation of average annual sea surface temperature at hydrological stations located along the western coast of the sea. As evident from the data, sea surface temperature exhibits a general increase from north to south. Over the period 1960-2016, a statistically significant rise in surface temperature was recorded at the Makhachkala, Izberg, and Derbent

[12]Safarov, S.H., Valizadeh, Kh.K., Ismayilov [et al.] Detection of upwelling events in the Caspian Sea using thermal satellite image processing // International Journal of Engineering and Geosciences, – 2024. No9(2), – p. 247-255. (In Eng.)

stations, whereas a decreasing trend was observed at the Sumgait station. As shown in Graph 3, the synchronicity observed in the temporal variations of average surface temperature across different stations prior to 1995 appears to weaken in the subsequent period. This disruption may be attributed to changes in sea level and inconsistencies in observational data. The highest recorded annual average surface temperature at Sumgait, located on the western coast of the Middle Caspian, occurred in 1981, while at the other stations, the highest values were observed in 1966. The lowest annual average surface temperature for all stations was recorded in 1969. The time-dependent dynamics presented in Graph 3 are further supported by comparative data in Table 3, which indicates the average sea surface temperatures for the periods 1961-1990 and 1991-2016. The table also presents monthly averages for each period. As indicated, the lowest monthly temperatures for all stations occur in February, while the highest are observed in August. Compared to the 1961-1990 period, the annual average sea surface temperature from 1991-2016 increased by 0.8°C in Makhachkala, by 0.5°C in Derbent and Izberg, and decreased by 0.3°C in Sumgait.



Source: Compiled by the author (V.H.Ismayilov) based on archival materials from CASPCOM.

Graph 3. Temporal evolution of average annual sea surface temperature at western coastal hydrological stations in the Middle Caspian Region (1961-2016)

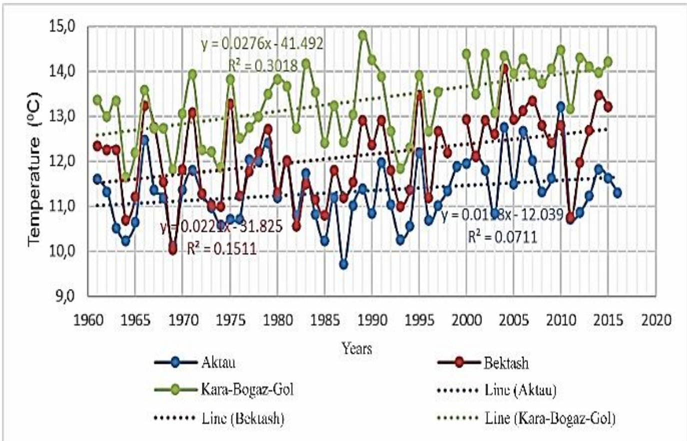
Temperature anomalies exhibit a decreasing trend from north to south. The lowest anomaly values are observed during the periods of April-July and December, while the highest values occur in March, August, and October.

Table 3

Monthly distribution of average surface temperature at observation stations along the Western Coast of the Middle Caspian during the Periods 1961-1990 and 1991-2016

Periods	Months												Year
	1	2	3	4	5	6	7	8	9	10	11	12	
Makhachkala													
1961-1990	2,6	1,8	3,6	9,0	15,2	20,1	22,9	23,5	20,8	15,3	10,0	5,4	12,5
1991-2016	3,2	2,6	4,8	9,3	15,4	20,4	23,4	25,1	21,8	16,7	10,8	5,8	13,3
Anomaly	0,6	0,8	1,3	0,3	0,2	0,3	0,5	1,6	1,0	1,3	0,8	0,3	0,8
Derbent													
1961-1990	3.7	2.7	4.2	9.3	15.1	20.8	24.4	24.3	21.4	16.0	11.0	6.8	13.3
1991-2016	4.1	3.2	5.2	9.6	15.2	21.0	24.5	25.7	21.8	17.1	11.4	6.7	13.8
Anomaly	0.4	0.5	1.0	0.3	0.1	0.2	0.0	1.4	0.4	1.1	0.4	-0.2	0.5
Izberg													
1961-1990	3.3	2.1	3.5	8.8	15.2	20.7	24.3	24.3	21.4	16.1	11.0	6.4	13.1
1991-2016	3.8	2.9	5.0	9.8	15.6	21.2	24.3	25.3	21.6	16.8	10.9	6.1	13.6
Anomaly	0.4	0.9	1.6	1.0	0.4	0.5	0.0	1.0	0.2	0.6	-0.1	-0.3	0.5
Sumgait													
1961-1990	5,4	4,9	6,7	11,1	16,3	21,6	25,0	25,0	21,7	16,5	12,0	7,8	14,5
1991-2012	5.4	4.9	6.8	10.5	15.6	20.9	25.0	25.2	21.0	16.7	11.5	7.1	14.2
Anomaly	0.0	0.0	0.1	-0.6	-0.7	-0.7	0.0	0.2	-0.7	0.2	-0.5	-0.8	-0.3

Surface temperature data from the Aktau, Bektash, and Kara-Bogaz-Gol observation stations, located along the eastern coast of the Middle Caspian from north to south, were scrutinized. The geographical coordinates of these stations are provided in Table 2. Graph 4 presents the temporal evolution of average annual surface temperature at these eastern coastal stations. The data indicate a general increase in mean annual surface temperature across all three stations, with the most pronounced and statistically significant (at the 5% level) warming trends observed at the Bektash and Kara-Bogaz-Gol stations. Temporal variations in annual average temperature across all studied hydrological stations are largely synchronous, with some exceptions in specific years. Among the three stations, the highest temperatures are consistently recorded at Kara-Bogaz-Gol in the south, while the lowest are observed at Aktau in the north.



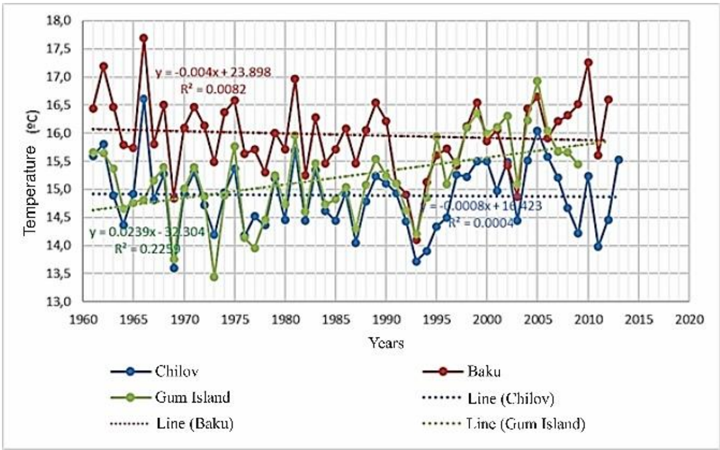
Source: Compiled by the author (V.H.Ismayilov) based on archival materials from CASPCOM.

Graph 4. Temporal trend of annual average surface temperature at Eastern Coastal hydrological stations of the Middle Caspian (1961–2016)

The slope of the linear trends in annual average temperature increases from north to south, resulting in a widening gap between the annual mean surface temperatures of the stations (Graph 4).

Specifically, the Aktau, Bektash, and Kara-Bogaz-Gol stations exhibit increases in annual mean surface temperature of approximately 0.4°C, 0.8°C, and 0.6°C, respectively. Although all three stations indicate warming trends during the October-March period, significant anomalies in the opposite direction are observed during May-July at the Aktau and Bektash stations, with deviations reaching -1.8°C. Notably, during the summer months, particularly between 1961 and 1995, the surface temperature at the northernmost Aktau station exceeds that of the more southerly Bektash station, a phenomenon likely attributable to upwelling. Furthermore, during summer and autumn, the eastern coast of the Middle Caspian displays anomalously lower surface water temperatures (up to 7°C cooler) compared to the western coast, as observed at the Makhachkala and Bektash stations, which can be explained by upwelling dynamics as well.

No significant trend in annual average surface temperature was detected at other stations along the western coast of the South Caspian, with the exception of Gum Island station (Graph 5).

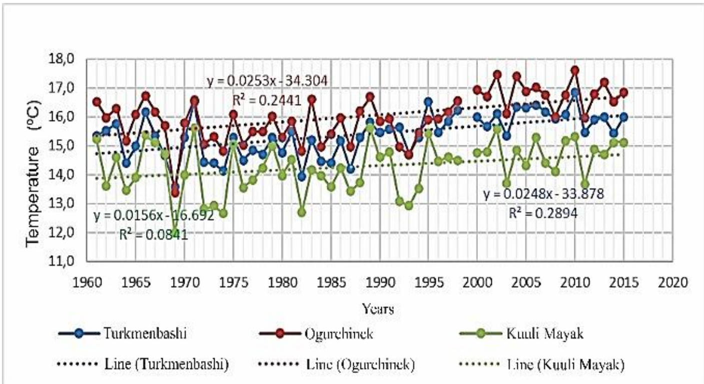


Source: Compiled by the author (V.H.Ismayilov) based on archival materials from CASPCOM.

Graph 5. Temporal trends in average annual surface temperature at Western Coastal hydrological stations of the South Caspian (1961–2012)

An increase in the annual average surface temperature of approximately 0.5°C, 0.9°C, and 0.8°C was observed at the Kuuli Mayak, Turkmenbashi, and Ogurchinck stations, respectively, located in the eastern sector of the South Caspian (Graph 6).

Temperature trends are primarily observed on a monthly basis. While more pronounced temperature increases generally occur during the colder months, smaller anomalies are recorded between April and July. During the colder seasons, the typical latitudinal distribution of surface temperature is disrupted. Moreover, in summer and autumn, the eastern coast of the South Caspian exhibits an anomalous decrease in surface water temperature relative to the western coast, a phenomenon likely attributable to upwelling.

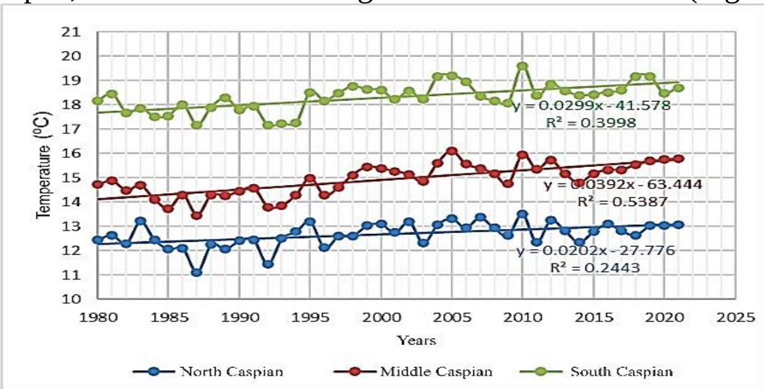


Source: Compiled by the author (V.H.Ismayilov) based on archival materials from CASPCOM.

Graph 6. Temporal variation of average annual surface temperature at Eastern Coastal hydrological stations of the South Caspian (1961–2015)

Consequently, the analysis of surface temperature regimes across the hydrological stations reveals significant spatial variability, which precludes drawing definitive conclusions about the overall surface temperature regime of the Caspian Sea and its three sub-regions, as well as their temporal dynamics. To address these limitations, it is recommended to integrate modern remote sensing data and hydrodynamic modeling for a more comprehensive assessment.

The second chapter of the dissertation is devoted to the **"Study of Caspian Sea Surface Temperature Based on Reanalysis Data."** This investigation utilizes monthly sea surface temperature data from the MERRA-2 (Modern-Era Retrospective analysis for Research and Applications) reanalysis model, accessed via the GIOVANNI online portal[13], covering the period from 1980 to 2021. These reanalysis data were calibrated against corresponding in situ observational datasets to enhance their accuracy. Utilizing this dataset, statistical characteristics of surface temperature in the open waters of the Caspian Sea were analyzed, and the influence of climate change was assessed separately for the northern, middle, and southern sub-regions. To quantify trends in the averaged surface temperature values across these distinct zones, linear trend models were developed, and their statistical significance was evaluated (Figure 7).



Source: Compiled by the author, V.H.Ismayilov, using MERRA-2 reanalysis data.

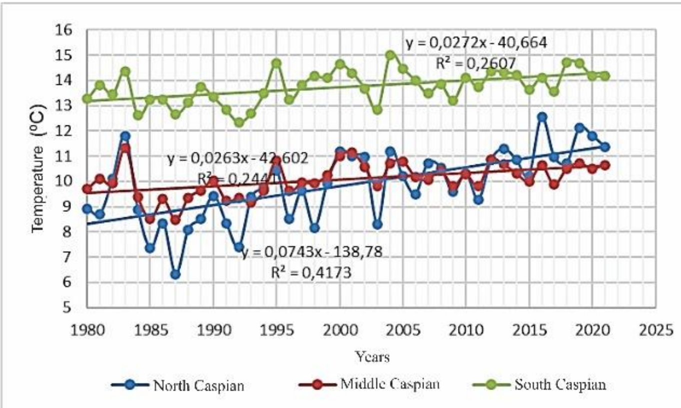
Graph 7. Temporal dynamics of average annual surface temperature across different regions of the Caspian Sea

As illustrated in Figure 7, a statistically significant increase in surface temperature was observed across all three regions of the Caspian Sea during the study period. The most pronounced warming occurred in the Middle Caspian, while the North Caspian exhibited the smallest increase. Absolute temperature values are highest in the South Caspian, ranging from (17,0÷19,7ºC), and lowest in the North Caspian, ranging from (11,0÷13,7ºC). The Middle Caspian’s surface temperature falls between these ranges, varying from 13,3÷16,1ºC. Generally speaking, there is a latitudinal gradient characterized by a

[13] https://giovanni.gsfc.nasa.gov/giovanni/#service

decrease in the annual average surface temperature from south to north; however, this pattern is disrupted during the spring and, notably, the summer months.

The surface temperature of the North Caspian has gradually approached and, after 2005, even surpassed that of the Middle Caspian (Figure 8). During the summer season, the lowest temperatures are recorded in the Middle Caspian, while the North Caspian's surface temperature closely approximates that of the South Caspian. This phenomenon is primarily attributed to the shallowness of the North Caspian, which causes its surface waters to warm more rapidly. Furthermore, this effect has been amplified in recent years because of a decline in sea level.



Source: Compiled by the author, V.H.Ismayilov, using MERRA-2 reanalysis data.

Graph 8. Temporal dynamics of average spring surface temperature across different regions of the Caspian Sea

The years in which extreme surface temperature values were observed largely coincide, as indicated in Graphs 7 and 8. The correlation coefficients between the surface temperatures of the North Caspian and the Middle and South Caspian regions are 0.82 and 0.68, respectively, while the correlation between the Middle Caspian and South Caspian is 0.89.

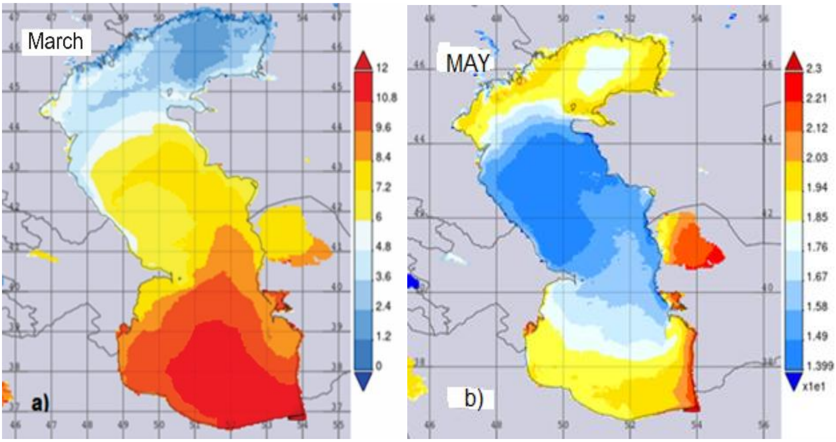
To more precisely characterize temporal variations in surface temperature, the corresponding time series were divided into two equal intervals (1980-2000 and 2001-2021). For each interval, average annual, seasonal, and monthly surface temperature values were calculated and compared. The statistical significance of observed changes in the temperature regime was evaluated using the Student's t-test.

Notably, the highest summer surface temperatures occur in the North Caspian, a pattern likely attributable to the region's relatively shallow bathymetry.

The third chapter of the dissertation focuses on the **"Study of Caspian Sea surface temperature and its anomalies based on MODIS Aqua Spectroradiometer Data."** In addition to examining temporal variations in the Caspian Sea's surface temperature, this chapter emphasizes spatial variability and distribution patterns across the water body. For this purpose, Sea Surface Temperature (SST) data spanning 2003 to 2021 were obtained from the NASA Giovanni online information system. These data are derived from night-time measurements of the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the Aqua satellite. The MODIS spectroradiometer operates at an 11 μm wavelength with a spatial resolution of 4 km, enabling the detection of mesoscale anomalies in surface temperature, including upwelling zones and their characteristic features.

A comparison between the MODIS Aqua SST data at 11 μm wavelength and in-situ observational records revealed a high correlation coefficient ranging from 0.91 to 0.98, demonstrating the reliability of these satellite data for investigating surface temperature regimes and associated anomalies.

The perennial average annual surface temperature across Azerbaijani sector of the Caspian Sea exhibits a positive latitudinal gradient, increasing from north to south (Figure 1a). However, this gradient is disrupted during the warmer months (April-August) and seasons (spring and summer). Specifically, from April to August, the temperature gradient at the boundary between the North and Middle Caspian reverses direction, shifting from the Middle Caspian toward the North Caspian and peaking in April-May with a value of approximately -3.0ºC per 100 km (Figure 1b). (*Note: In images marked with the symbol x1e1, temperature values should be multiplied by 10.*)

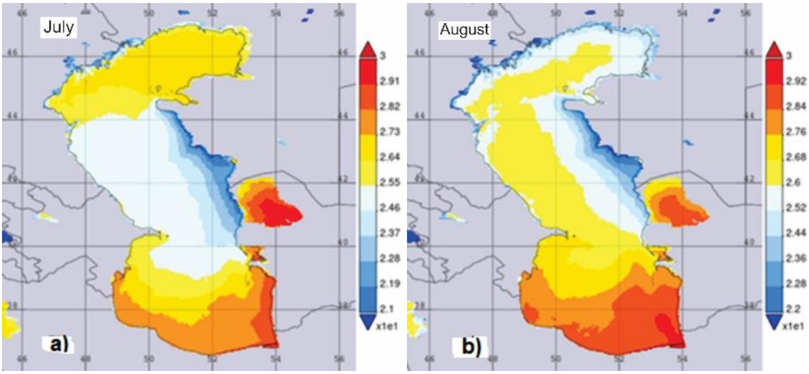


Source: Compiled by the author, V.H.Ismayilov, using MODIS Aqua data.

Figure 1. Spatial distribution of average surface temperature over Azerbaijani sector of the Caspian Sea in March (a) and May (b) for the Period 2003-2021

The surface temperature in the North Caspian exhibits greater continentality compared to the Middle and South Caspian regions. Based perennial data, the difference between the warmest and coldest months in the North Caspian is approximately 24.5°C, whereas in the Middle and South Caspian, the corresponding differences are 18.2°C and 19.2°C, respectively. These values indicate that the Middle Caspian has the least continentality among the three regions.

Between May and September, upwelling phenomena are primarily observed along the eastern and western coastal waters of the Middle Caspian, and to a lesser extent in the South Caspian. Driven by wind-induced surface water displacement from the coast toward the open sea, these upwelling events result in the ascent of cooler, deeper waters. On the eastern coast, upwelling is a regular and recurring phenomenon, whereas on the western coast, it occurs more sporadically. The most intense upwelling is typically observed in the eastern coastal waters of the Middle Caspian during July and August.



Source: Compiled by the author, V.H.Ismayilov, using MODIS Aqua data.

Figure 2. Spatial distribution of average upwelling zones over Azerbaijani sector the Caspian Sea in July (a) and August (b) for the Period 2003-2021

According to perennial averaged data, upwelling events during this period are primarily concentrated between 40° and 44°N latitude. The width of the upwelling zone increases from north to south, reaching up to 60-70 km near the Gulf of Gazakh, before narrowing again further south. Within these zones, the surface temperature gradient can occasionally reach as high as 4.0°C per 100 km.

CONCLUSIONS

Key findings on the surface temperature regime of Azerbaijani sector of the Caspian Sea based on contact (in-situ) observations, MERRA-2 reanalysis, and MODIS Aqua Satellite Data in the context of global warming and sea level decline:

1. Despite differing and, in many cases, opposing trends in surface temperature between the western and eastern sectors of the North

Caspian, the average annual surface temperature across the region increased by 0.5°C during the 2001-2021 period compared to 1980-2000. Seasonal analysis reveals the most pronounced warming occurred in spring (+1.8°C), followed by summer (+1.0°C) and autumn (+0.4°C). In contrast, a notable cooling was observed in winter, with temperatures decreasing by 1.1°C [9, 10].

2. In the Middle Caspian, the average surface temperature increased by 0.9°C during the period 2001-2021 compared to 1980-2000. The most pronounced increases were recorded in summer (1.2°C) and autumn (1.3°C), while smaller increases occurred in winter (0.7°C) and spring (0.6°C). Although a general warming trend was also observed in coastal zones, changes with opposite signs were identified in the annual surface temperature distribution, particularly along the eastern coastal areas. In summer and autumn, anomalously low surface temperatures, reaching differences of up to 7°C, were observed on the eastern coast of the Middle Caspian in comparison to the western coast (notably between the Makhachkala and Bektash stations). This phenomenon is attributable to coastal upwelling, which also manifests, albeit to a lesser extent, in the eastern part of the South Caspian.

3. In the South Caspian, the average surface temperature increased by 0.7°C in the period 2001–2021 compared to 1980–2000. The highest seasonal increase was observed in summer (1.1°C), followed by spring (0.6°C), autumn (0.7°C), and winter (0.4°C). Along the western coast, with the exception of the Gum Island station (which exhibited an increase of 0.7°C), no statistically significant changes were detected at other coastal stations. In contrast, eastern coastal stations witnessed more substantial warming, with increases in annual average surface temperatures (0.5°C-0.9°C).

4. The analysis of surface temperature regimes at the investigated hydrological stations indicates significant spatial heterogeneity, which prevents a definitive characterization of the thermal regime and its temporal evolution for Azerbaijani sector of the Caspian Sea as a whole. For a more comprehensive assessment,

the application of remote sensing data and hydrodynamic modeling is recommended [9].

5. On average, the annual surface temperature of the Caspian Sea decreases from south to north, reflecting the latitudinal gradient. However, this pattern is disrupted in spring, and particularly in summer, as the surface temperature in the North Caspian approaches, and after 2005, exceeds that of the Middle Caspian during spring. In summer, the lowest seasonal surface temperatures are observed in the Middle Caspian, while temperatures in the North Caspian are comparable to those in the South Caspian [9, 10].

6. A high correlation has been identified between surface temperature values derived from the MODIS Aqua satellite spectroradiometer (11 μm wavelength) and contact (in-situ) observational data over the Caspian Sea. This strong correspondence supports the use of MODIS satellite data for investigating the surface temperature regime and associated anomalies across the entire Azerbaijani sector of the sea [11, 12, 14].

7. Within Azerbaijani sector of the Caspian Sea, the perennial average annual surface temperature generally increases from north to south, indicating a positive latitudinal temperature gradient. However, this pattern is disrupted during the period from April to August. During these months, the gradient reverses at the boundary between the North and Middle Caspian, with the temperature increasing in the direction from the Middle Caspian to the North Caspian, reaching a maximum inverse gradient (-3,0ºC/100 km) in April-May [11].

8. Surface temperature in the North Caspian exhibits greater continentality compared to the Middle and South Caspian. According to perennial data, the amplitude of the annual temperature cycle-defined as the difference between the warmest and coldest months-is 24.5°C in the North Caspian, 18.2°C in the Middle Caspian, and 19.2°C in the South Caspian. The lowest degree of continentality is observed in the Middle Caspian [11].

9. Between May and September, upwelling processes predominantly occur in the eastern and western coastal waters of the Middle Caspian, and to a lesser extent in the South Caspian. On the

eastern coast, upwelling is a regular phenomenon, while on the western coast, it occurs sporadically. The most intense upwelling is observed in the eastern coastal waters of the Middle Caspian during July-August. Based on perennial averaged data, these events are primarily concentrated between 40° and 44°N latitude. The spatial extent of the upwelling zone increases from north to south, reaching a maximum width of 60–70 km near the Gulf of Gazakh, and then narrows further to the south. In these zones, the surface temperature gradient can occasionally reach 4.0°C/100 km [12, 14].

Published scientific works on the dissertation

1. Ismayilov, V.H. Spatiotemporal changes in the seawater temperature in the Caspian Sea // – Baku: News of Baku State University. Series of Nature Sciences. – 2015. №1, – pp. 165-169. (In Aze.)
2. Ismayilov, V.H. Study of the hydrometeorological parameters in the Absheron sector of the Caspian Sea // Republic Scientific and Practical Conference on "Global economic condition and economic-geographical position of Azerbaijan". – Baku: – 2017. – pp. 282-285. (Co-authors: Abdullayev I.M., Asadov S.B.). (In Aze.)
3. Ismayilov, V.H. Detecting the wind, wave, and current parameters in the "Karabakh-Gunashli" sector of the Caspian Sea where the underwater pipelines will be laid // – Baku: News of Baku State University. Series of Nature Sciences. – 2022. №1, –pp. 282-285. (In Aze.)
4. Ismayilov, V.H. Study of the anomalies of the water surface temperature of the Caspian Sea via remote sensing methods // International Scientific and Practical Conference on "Contemporary problems of Geography: Integration of the Science and Education". – Baku: – 2022, II Vol. – pp. 215-222. (In Russ.)
5. Ismayilov, V.H. Study of water surface temperature in the Gizilaghaj Bay sector of the Caspian Sea based on reanalysis

data // International Scientific Conference on “Actual problems of modern natural and economic sciences”. – Ganja: 2022. Part III, – pp. 87-88 (Co-authors: Safarov S.H., Ahlimanova I.V). (In Aze.)

6. Ismayilov, V.H. Application of NOAA satellite data to study Caspian Sea surface temperature anomalies // International Scientific and Practical Conference on “EurasiaScience”. – Moscow: – 2022. – pp. 166-170. (In Russ.)
7. Ismayilov, V.H. Study of wind, wave and current parameters in the water area where the submarine pipeline between the Pirallahi and West Absheron fields located, named after “Absheronneft” Oil and Gas Extraction Department // – Baku: Water Problems. – 2023. №1, – pp. 86-91 (Co-author: Asadov S.B.). (In Aze.)
8. Ismayilov, V.H. Study of temperature anomalies in the Caspian Sea using satellite data // – Astrakhan: Astrakhan Bulletin of Environmental Education. – 2023. №2, – pp. 16-21. (In Russ.)
9. Ismayilov, V.H. Study of the impact of the climate change on the water surface temperature of the Caspian Sea // – Baku: Geography and Natural Resources. – 2023. №2, – pp. 84-90 (Co-authors: Safarov S.H., Safarov E.S.). (In Aze.)
10. Ismayilov, V.H. Study of the Caspian Sea surface temperature based on MERRA-2 reanalysis data for the period 1980-2021 // – Baku: ANAS Transactions Earth Sciences. – 2023. №2, – pp. 79-88 (Co-authors: Safarov S.H., Safarov E.S.). (In Russ.)
11. Ismayilov, V.H. Study of the features of spatial distribution of surface temperature in the Caspian Sea // – Makhachkala: News of the Dagestan State Pedagogical University, series Natural and Exact Sciences. – 2024. №1, – pp. 81-92 (Co-author: Safarov S.H.). (In Russ.)
12. Ismayilov, V.H. Detection of upwelling events in the Caspian Sea using thermal satellite image processing // – Mersin: International Journal of Engineering and Geosciences. – 2024. No 9(2), – p. 247-255 (Co-authors: Safarov S.H., Valizadeh Kh.K., Safarov E.S.). (In Eng.)

13. Ismayilov, V.H. Study of Caspian Sea surface temperature anomalies using low Earth Orbit Satellite Data // – Astrakhan: İnternational Scientific and Practical Conference on "Kurazhskov Readings". – 2023. – pp. 234-238. (In Russ.)
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The defense of the dissertation work will be held on 24 october 2025, at 14:00 at the meeting of the BFD 3.14 Disposable dissertation council of the Supreme Attestation Commission under the President of the Republic of Azerbaijan operating at the Institute of Geography named after Hasan Aliyev, Ministry of Science and Education of the Republic of Azerbaijan.

Address: AZ 1073, Bakı city, 117 H. Javid Ave., Institute of Geography named after Hasan Aliyev, Ministry of Science and Education of the Republic of Azerbaijan.

Email: institute@geograph.science.az, cografiya_inst@mail.ru

The dissertation is accessible at the library of the Institute of Geography named after Acad. Hasan Aliyev, Ministry of Science and Education of the Republic of Azerbaijan.

Electronic versions of the dissertation work and its abstract are available on the official website https://igaz.az/az.

The abstract was sent to the required addresses on 23 september 2025.

Signed for print: 22.09.2025

Paper format: A5

Volume: 41556

Number of hard copies: 20