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Study of temporal and spatial variations of electrical conductivity in the Caspian Sea using POM

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Abstract

The electrical conductivity of sea refers to the conductivity of seawater, which affects the electrodynamics and electromagnetic processes observed in the ocean. This study investigates temporal and spatial variations of electrical conductivity across the Caspian basin using Princeton Ocean Model (POM). The POM is an oceanic model with a vertical sigma array, a right-angled curved horizontal grid, free surface boundary conditions and sub-turbulence and wave models. To implement the deep data model from GEBCO, temperature and salinity data obtained from WOA database, as well as meteorological data and atmospheric fluxes achieved from ECMWF daily database with a spatial resolution of 7.5 minutes. The model was run from 2009 to 2019. Temperature, salinity, and flow rate data from the model were used to calculate and simulate the electrical conductivity in the Caspian Sea. The obtained results showed that the maximum electrical conductivity occurred in the southern basin with a value of 2.3s/m in summer and the minimum electrical conductivity occurred in the northern Caspian basin with a range of 0.8s/m in winter and autumn. The vertical profile of the electrical conductivity at the three geographical locations indicated that temperature is the dominant factor in the electrical conductivity.

Keywords: Electrical conductivity; Modeling; POM; Caspian Sea.

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1. Introduction

The electrical conductivity of sea refers to the conductivity of seawater, which affects the electrodynamics and electromagnetic processes observed in the ocean and spreads across the Earth from the interior to the atmosphere. Sea electrical conductivity is assumed constant or variable over time. Therefore, it is necessary to know the conductivity of electrodes in studying these processes and interpreting these domains (Tyler *et al*., 2017). With increasing interest in oceanography, the distribution and variations of seawater electrical conductivity have become important research topics (Ferguson *et al*., 1990). Current theory shows that the vertical distribution of seawater conductivity is related to salinity, temperature, and sea depth (Pawlowicz, 2012). Electrical conductivity can occur due to temperature or salinity variations where temperature is the dominant parameter. Both have major spatial variations in the ocean. The average electrical conductivity of seawater ranges from 3s/m to 4s/m (Irrgang, 2017).

Seawater contains a high concentration of soluble salts. Thus, the ocean acts as a fluid, in which electric charges are transported by soluble cations and anions and make the seawater conductive. As the oceans pass the Earth's main magnetic field, the ionic content in the oceans generates electrical currents. While these electrical currents flow around the world, they in turn produce secondary magnetic fields that evolve in size and geometry over time. This effect, called motion induction, depends on the geometry and spatial scales of ocean currents as well as the electrical conductivity of seawater (Sanford, 1971). The conductivity also increases with increasing temperature and this may be reasonably related to the increase of ion mobility (Tyler *et al*., 2017). Recent studies have focused on the effects of electrical conductivity on the electromagnetic induction .(created in the ocean (Irrgang, 2017

As an example, Zheng *et al*. (2018) analyzed the vertical distribution of seawater electrical conductivity from the sea level to the maximum depth of 7062 m at five different locations in the South China Sea, west of the Pacific Ocean. In the range of 3 to 6 s/m, the highest electrical conductivity occurred between 20 and 100 m below the sea level, while the lowest electrical conductivity occurred between 1800 and 2600 m. For example, at the desired location, electricity initially increased slowly with increasing the depth and decreased rapidly between 80 and 400 m.

Tyler *et al*. in 2017 examined the electrical conductivity of the world's oceans and concluded that electrical conductivity ranged from 1s/m to 6s/m in the oceans of the world. They found that it generally depends on the water temperature, but it also depends on the salinity near the rivers and mountains (Tyler *et al*., 2017).

In this study, using the Princeton Ocean Model (POM) output, the electrical conductivity of the Caspian Sea was studied at different depths with respect to temperature and salinity in the southern, middle and northern basins of the Caspian Sea in winter. Consequently, obtaining a parameter such as magnetic field in the Caspian Sea is essential.

2. Materials and methods

2.1. POM oceanic model

The POM is a numerical oceanic model that can be used to simulate and predict oceanic currents, temperature, salinity and other water properties. In the late 1980s, Alan Blumberg and George Mellor at Princeton University with the assistance of some individuals originally developed and analyzed the model codes. This model is very small, yet powerful, and can be used for a wide range of issues such as circulation and mixing process in rivers, estuaries, continental shelf and slope, lakes, semi-closed and open seas, and oceans. The POM is an oceanic model with sigma vertical coordinates, a right-angled curved horizontal grid, free surface boundary conditions and turbulence and wave sub-models.

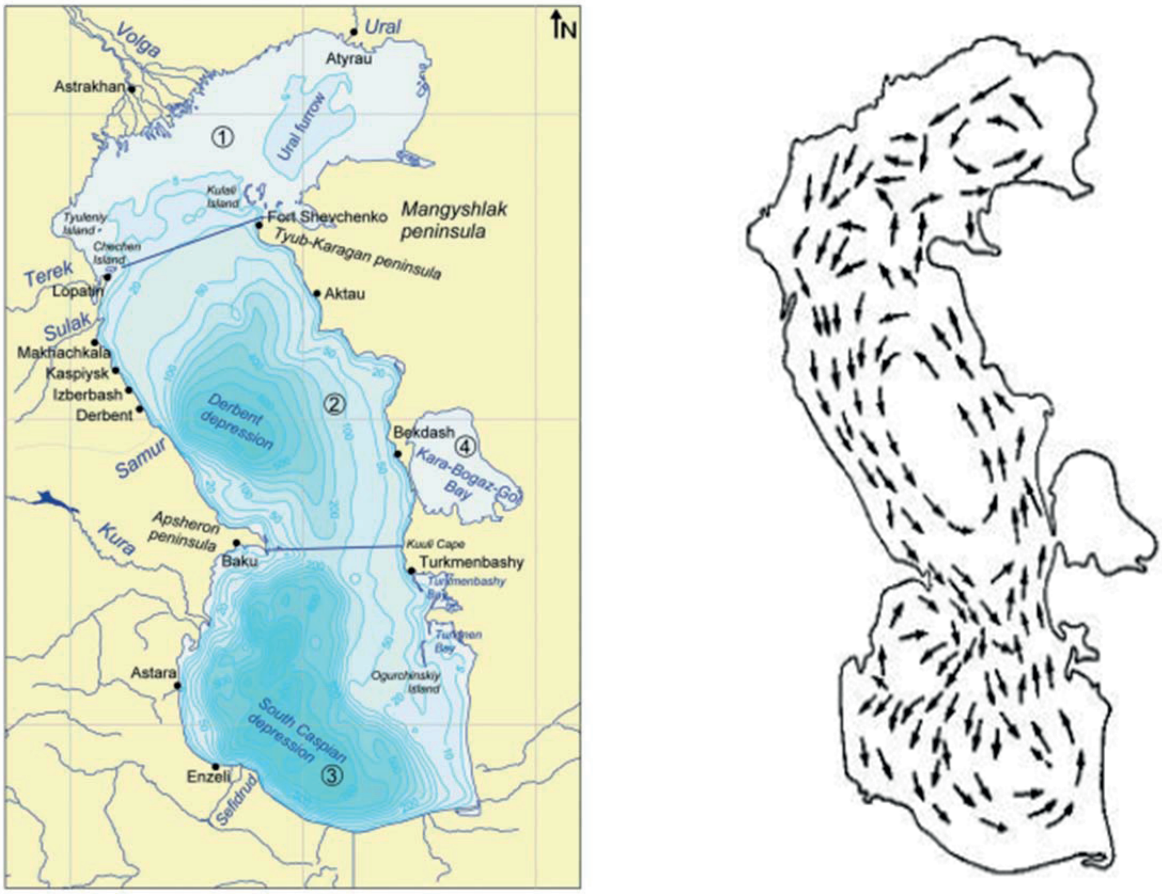
The POM input data include see depth temperature and salinity (baseline climatic conditions), sea surface temperature and salinity (surface boundary conditions), sea level anomaly (boundary conditions), wind data, multi-channel satellite surface temperature, radiation and evaporation rates, tidal data, shortwave radiation, long wavelength radiation, and river discharge (Mansoury *et al*., 2015).

Our model networking was performed on 134×102 dimensions with 70 vertical layers and a horizontal resolution of 0.08×0.08 degrees, and a time step of 2.5 minutes. To produce and distribute temperature, salinity, and flow velocities, the model uses wind, precipitation, evaporation, ice, heat flux, and short and long wave radiation data from ECMWF daily database with a spatial resolution of 7.5 minutes, as well as temperature and salinity data from WOA2005 with 1-degree accuracy, and topographic data from GEBCO08 with 30 seconds accuracy. Most of the water flows into the Caspian Sea from Volga, Kura and Ural rivers in the north of the Caspian Sea. NRL data from the Naval Research Laboratory .(NRL) were used for the rivers data

The model was run from 2009 to 2019 and the POM outputs, including temperature, salinity and flow velocity data were separated into different locations of the Caspian Sea with longitude of 46.50 - 55.0 °E, and latitude of 36.4 - 47.50 °N. They were finally used to calculate the electrical conductivity in the study area.

2.2. Study area

The Caspian Sea is the largest lake in the world. All features of the Caspian Sea, including the size, depth, chemical properties, as well as thermohaline properties and water circulation make it possible to classify it as an inland deep sea. In 2016, the average level of the Caspian Sea was measured to be -27.43m against the surface of the Atlantic Ocean (Lebedev, 2018). The Caspian Sea has a longitudinal geometry (1000 km long and 200 to 300 km wide) and has three northern, middle, and southern basins (Figure 1a). The maximum depth in the northern basin is 20 m while the maximum depths in the middle and southern basins are 788 m and 1025 m, respectively (Ibrayev *et al*., 2010). Surface water temperature in the northern basin reaches below zero in winter and 25-26 °C in summer. Most changes occur in the southern basin as the temperature ranges from 7-10 °C in winter to 25-29 °C in summer. The Caspian Sea has little salinity. In the deepest region, salinity changes reach about 12psu to 13.5psu (Jamshidi *et al*., 2010). Longitudinal geometry and strong basin topography, affected by variable winds and baroclinic effects, cause the occurrence of spatially and temporally varying currents in the Caspian Sea. Despite the extreme variability of marine currents, the results of research from the late nineteenth century to the 1950s, using indirect currents estimates, have described the general circulation as a cyclic flow. Measurements



(a)

(b)

Figure 1. (a) Depth topography (Lebedev, 2018), and (b) sea currents of the Caspian Sea (Ibrayev *et al*., 2010)

of flow in coastal areas less than 100 m have confirmed some of the characteristics of flow rotation (Figure 1b). Hence, southward currents along the west coast were drawn to the middle basin (Ibrayev *et al*., 2010).

2.3. Electrical conductivity calculations

Using the salinity and temperature values obtained from the POM, the electrical conductivity was estimated (Eiple, 1987), which varies according to the temporal and spatial distribution of the electrical conductivity.

$$\sigma(T,s) = \sigma(25,s)\exp(-\beta\Delta) \tag{1}$$

$$\Delta = 25 - T \tag{2}$$

(2)

$$\beta(\Delta,s) = 2.033\times10^{-2} + 1.266\times10^{-4}\Delta + 2.464\times10^{-6}\Delta^2 - s(1.849\times10^{-5} - 2.551\times10^{-7}\Delta + 2.551\times10^{-8}\Delta^2) \tag{3}$$

$$\sigma(25,s) = s(0.182521 - 1.46192\times10^{-3}s + 2.09324\times10^{-5}s^2 - 1.28205\times10^{-7}s^3) \tag{4}$$

where, T is the temperature, S is the salinity, and is the electrical conductivity.

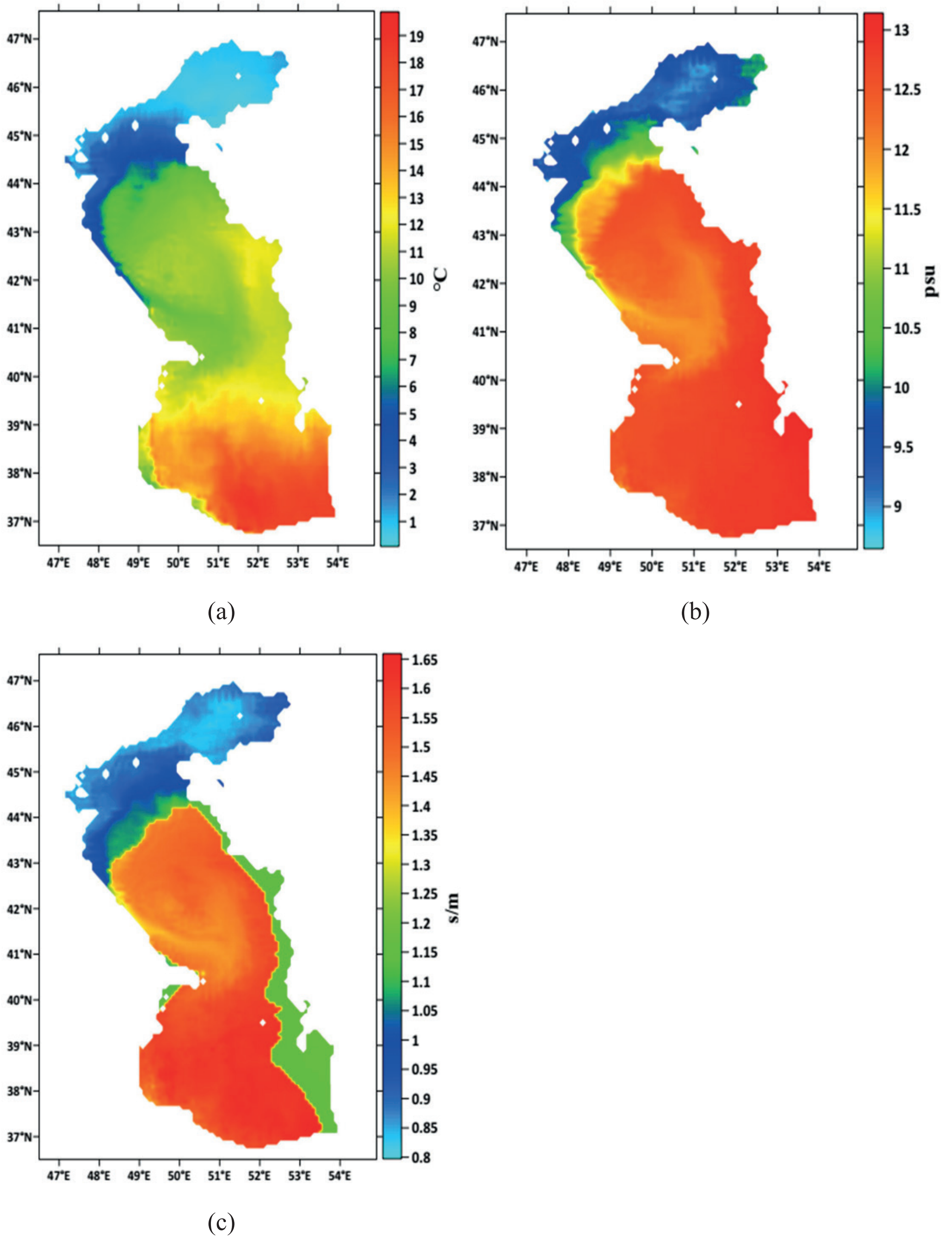


Figure 2. Variations of (a) temperature, (b) salinity, and (c) electrical conductivity in the Caspian Sea surface in January

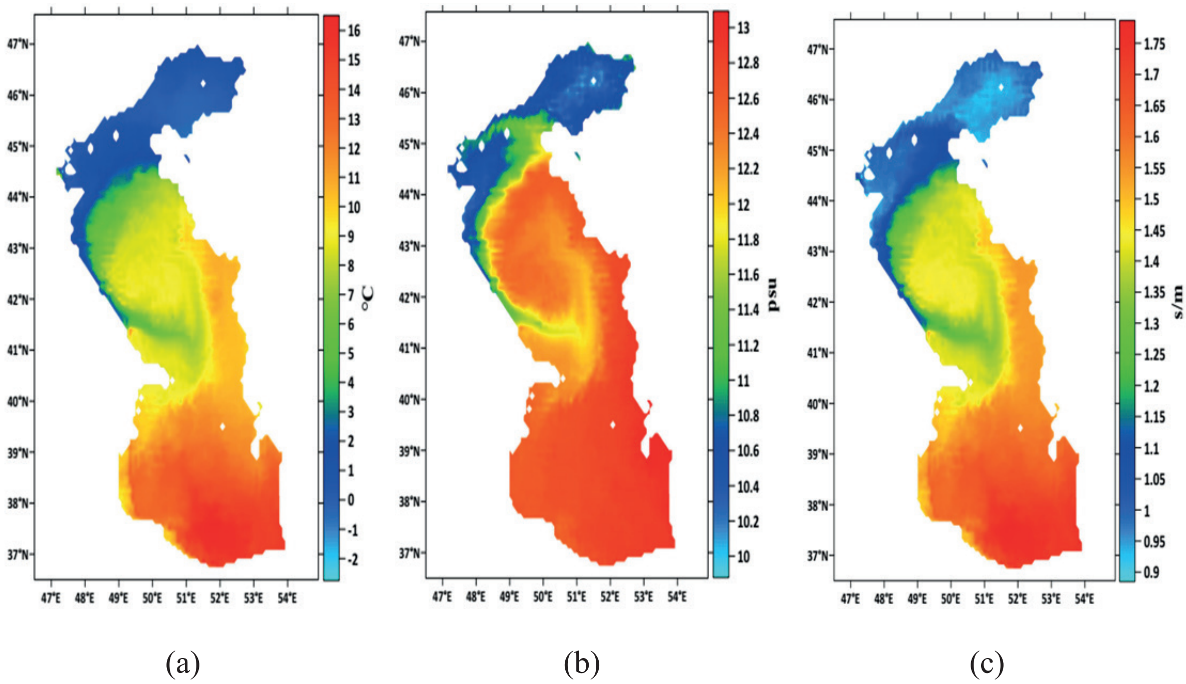


Figure 3. Variations of (a) temperature, (b) salinity, and (c) electrical conductivity in the Caspian Sea surface in February

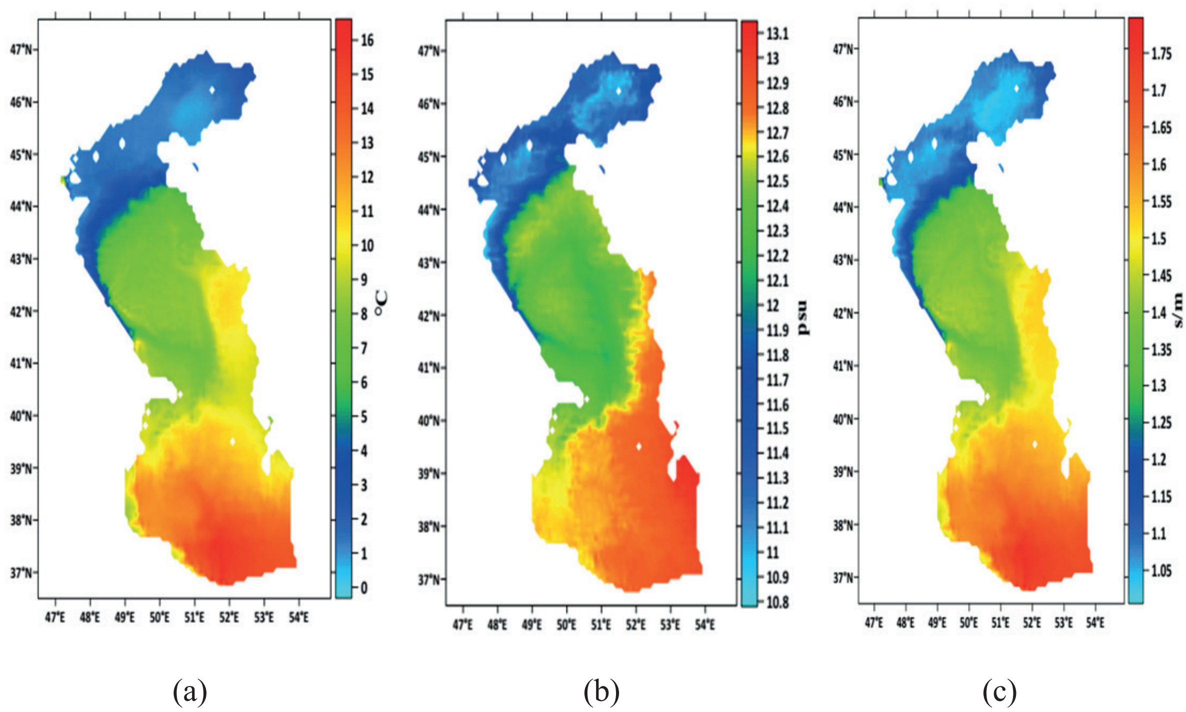
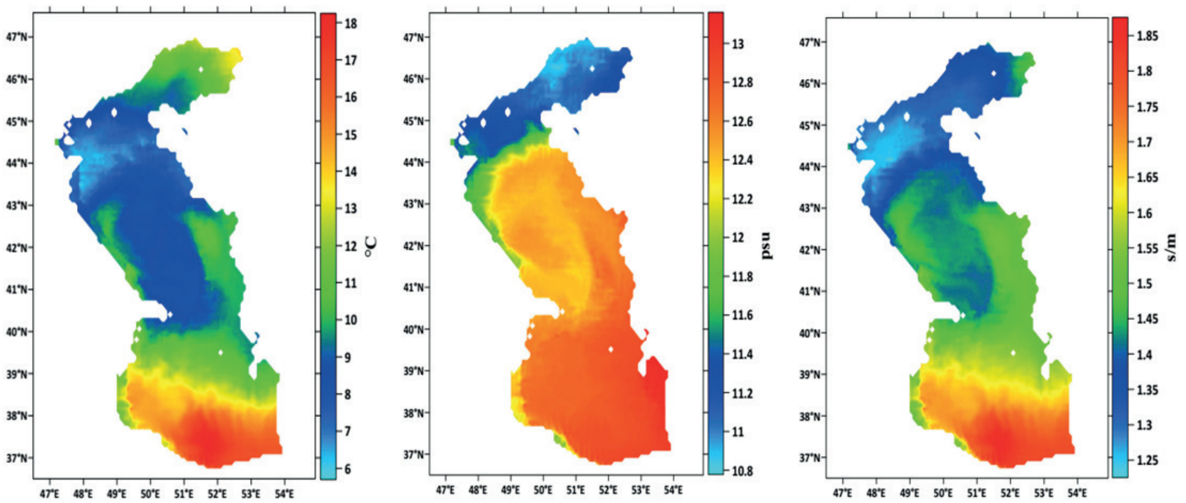


Figure 4. Variations of (a) temperature, (b) salinity, and (c) electrical conductivity in the Caspian Sea surface in March

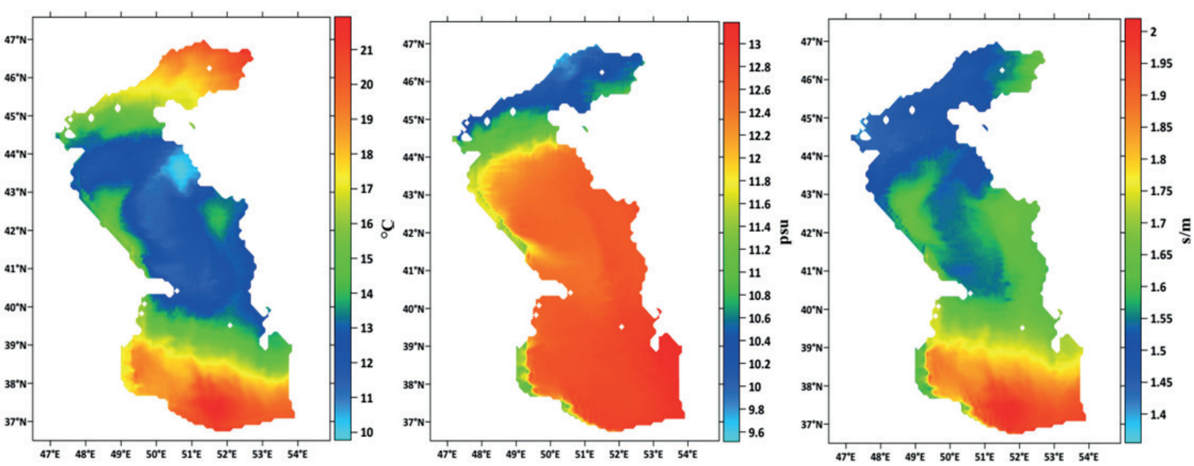
3. Results and Discussion

In this study, after running the POM from 2009 to 2019, the electrical conductivity phenomenon was studied based on the changes in temperature, salinity and flow rate of the Caspian Sea. The spatial and temporal distributions of the electrical conductivity indicate variations in different geographical locations. Figures 2 to 13 show the monthly surface distribution of temperature, salinity, and electrical conductivity of the Caspian Sea for winter, spring, summer, and autumn seasons. Due to high temperature and salinity in the southern basin, the highest amount of surface electrical conductivity occurs in the



(a) (b) (c)

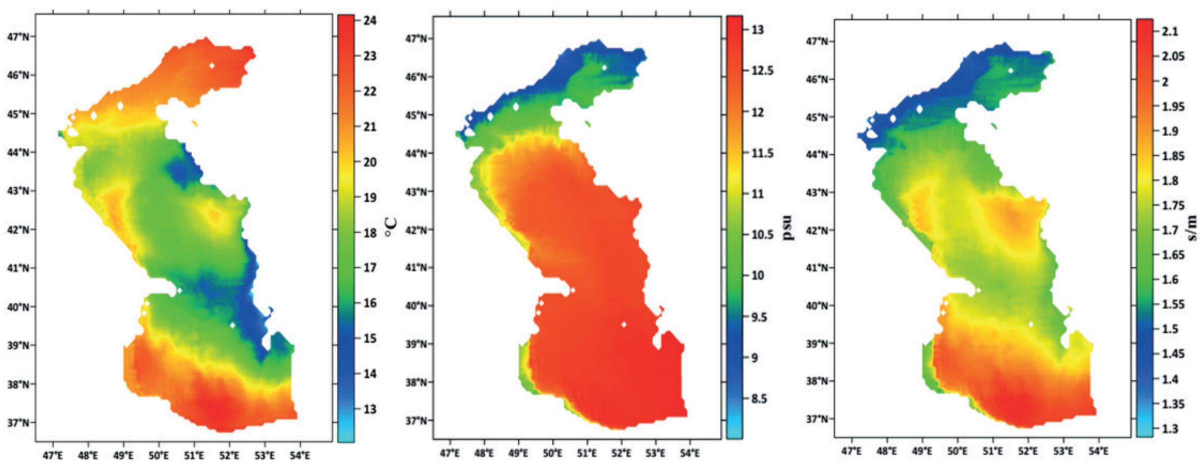
Figure 5. Variations of (a) temperature, (b) salinity, and (c) electrical conductivity in the Caspian Sea surface in April



(a) (b) (c)

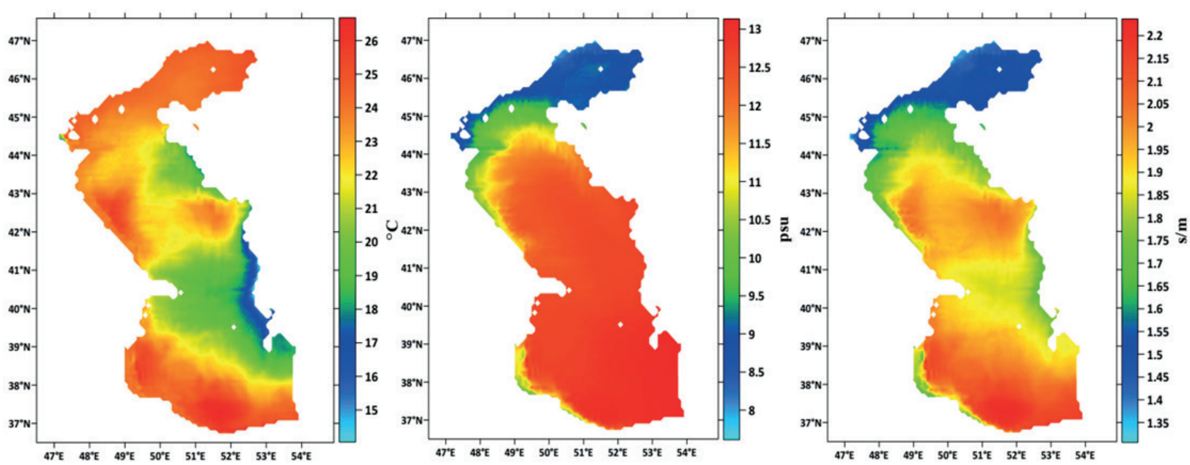
Figure 6. Variations of (a) temperature, (b) salinity, and (c) electrical conductivity in the Caspian Sea surface in May

southern Caspian basin. The decrease in surface electrical conductivity at higher latitudes in the Caspian Sea, especially in the northern Caspian basin, is due to the decrease in temperature and salinity. The values and changes of surface electrical conductivity are much larger than the subsurface electrical conductivity at the Caspian Sea, because the electrical conductivity changes are temperature-dependent and decrease with increasing the depth. However, in areas near the rivers in the north of the Caspian Sea such as Volga and Kura Rivers, the amount of electrical conductivity depends on the water salinity. During winter (January, February, and March), Figures 2 to 4 which respectively show the cold, relatively cold, and nearly warm surface temperatures affected by weather changes in the three northern, middle,



(a) (b) (c)

Figure 7. Variations of (a) temperature, (b) salinity, and (c) electrical conductivity in the Caspian Sea surface in June

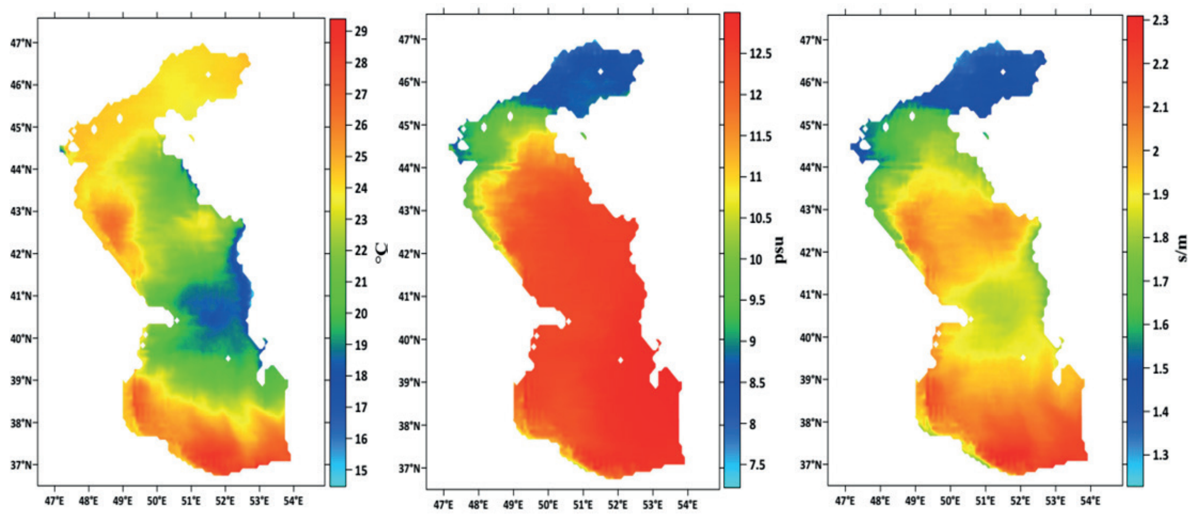


(a) (b) (c)

Figure 8. Variations of (a) temperature, (b) salinity, and (c) electrical conductivity in the Caspian Sea surface in July

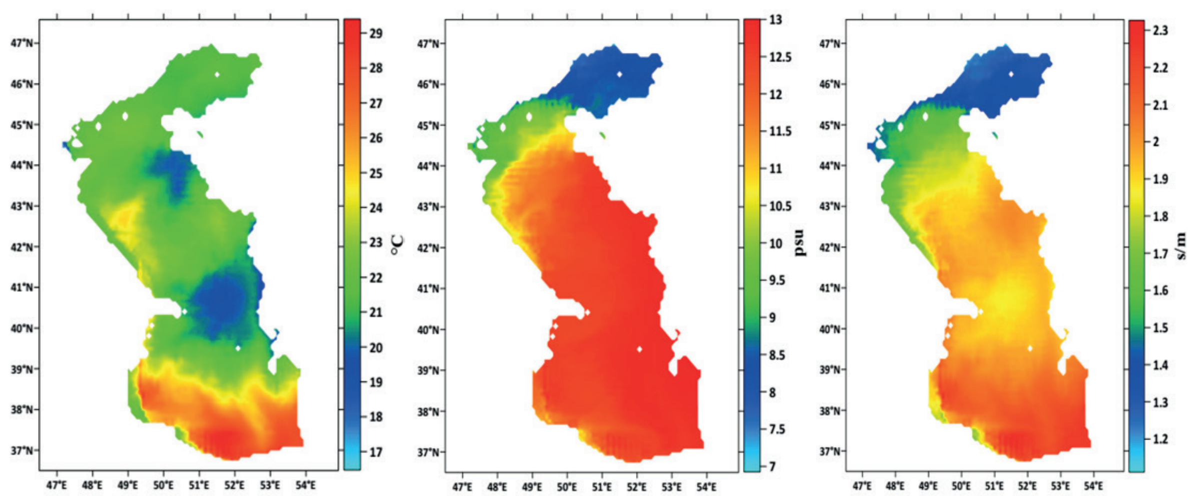
and southern regions. Actually, the weather changes in the northern basin occurred due to its low depth and proximity to higher latitudes. The results show that the amount of surface electric conductivity in the winter changed from 1.65s/m in January to more than 1.75s/m in February and March.

Figures 5 to 7 indicate that during spring, the salinity varied per month, as the air temperature increased from April to June. As the surface electrical conductivity was affected by these variations, it had a different distribution in spring in the three basins, so that in June; the middle basin had the maximum electrical conductivity due to changes in temperature and salinity. In the northern basin in April, the lowest electric



(a) (b) (c)

Figure 9. Variations of (a) temperature, (b) salinity, and (c) electrical conductivity in the Caspian Sea surface in August

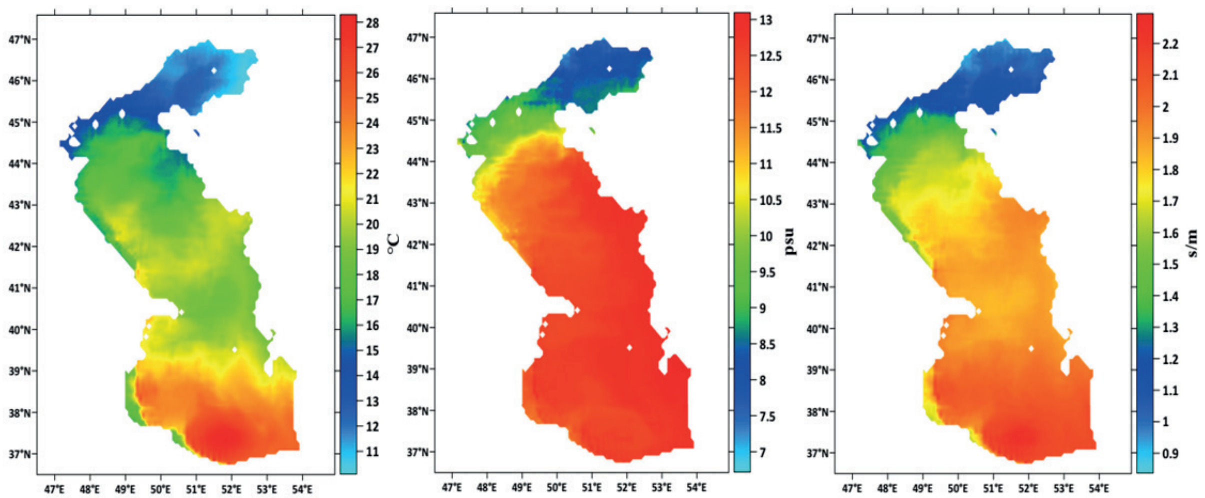


(a) (b) (c)

Figure 10. Variations of (a) temperature, (b) salinity, and (c) electrical conductivity in the Caspian Sea surface in September

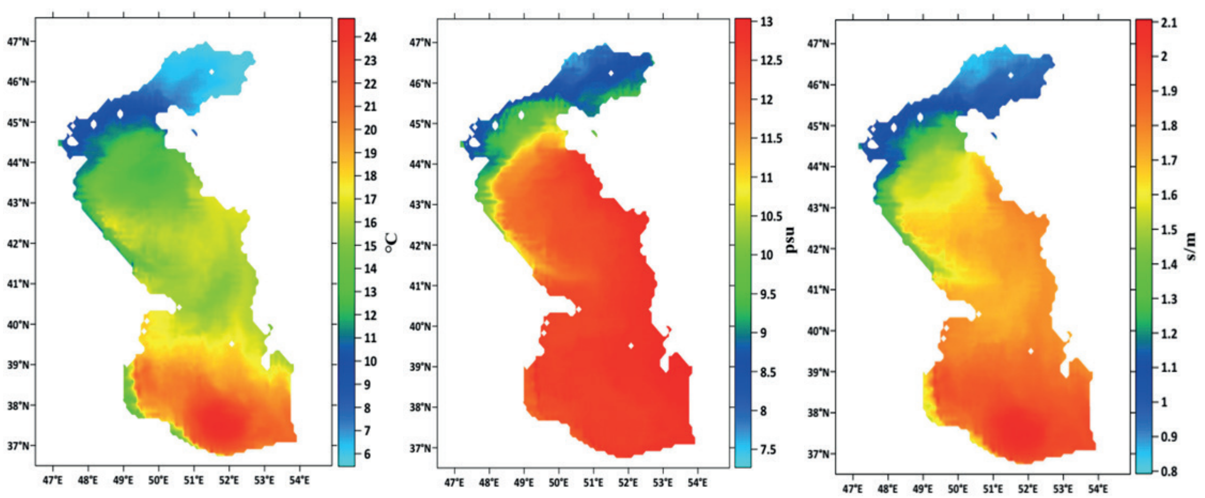
conductivity occurred and with the increase of the temperature in May and June, the electrical conductivity in the northern basin increased. As a result, the electrical conductivity ranged from more than 1.85s/m in April to 1.2s/m in June, with the highest amount of electrical conductivity observed in the southern basin.

The temperatures are at their maximum in summer while the salinity is constant in the three months. As a result, the amount of surface electric conductivity in summer is higher than other seasons. As the temperature of the northern basin has increased compared to the middle basin in July, the electrical conductivity in the northern basin changed from 1.4 to 1.5s/m (Figure 8). As the temperature of the northern basin decreased in August compared to July, while the salinity was constant there,



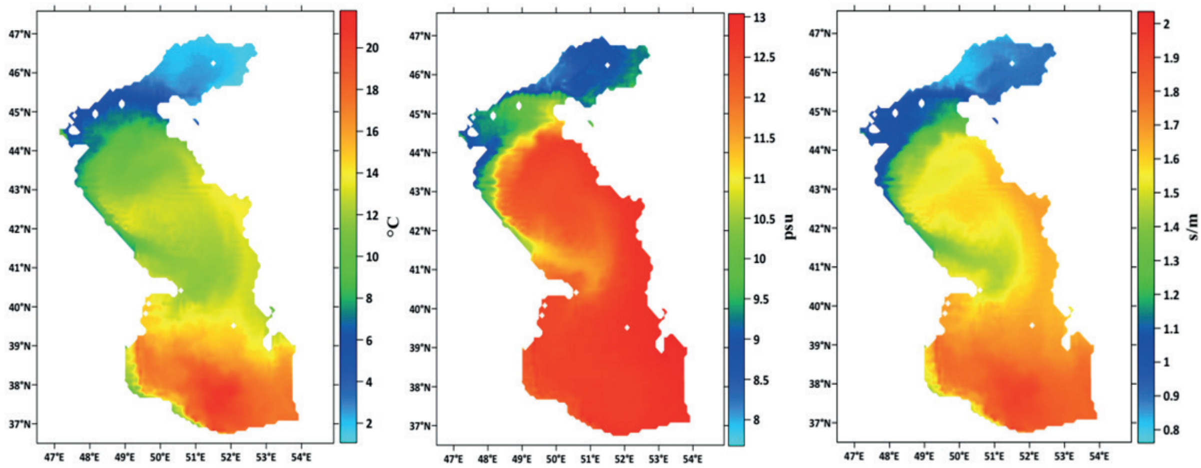
(a) (b) (c)

Figure 11. Variations of (a) temperature, (b) salinity, and (c) electrical conductivity in the Caspian Sea surface in October



(a) (b) (c)

Figure 12. Variations of (a) temperature, (b) salinity, and (c) electrical conductivity in the Caspian Sea surface in November



(a) (b) (c)

Figure 13. Variations of (a) temperature, (b) salinity, and (c) electrical conductivity in the Caspian Sea surface in December

the electrical conductivity was in the range of less than 1.4s/m (Figure 9). Maximum surface electrical conductivity in the southern basin was 2.2s/m in July in the southern basin and 2.3s/m in August and September (Figures 9 and 10)

In autumn, the salinity level was almost constant, and the temperature was lower than summer, indicating that the electrical conductivity changed due to the changes in weather conditions. In October, the maximum electrical conductivity exceeded 2.2s/m (Figure 11), which was mainly due to the decrease in the minimum electrical conductivity temperature in November (Figure 12). In addition, the electrical conductivity of 2s/m was observed in December (Figure 13).

3.1. Validation

Using field measurements in the southern Caspian basin, the electrical conductivity was monthly measured, the result of which are available in Table 1 (Vahidi Ghahroudi, 2013). Given that the POM was implemented in this study for ten years, it is almost in line with 2018 data.

3.2. Vertical structure of electrical conductivity

For a more detailed examination of the electrical conductivity, its vertical structure from sea surface to depth was investigated at

Table 1. Electrical conductivity obtained by field measurement (Vahidi Ghahroudi, 2013)

Month	May	June	July	August	September	October	November	December
Electrical conductivity	1.71	1.9	1.98	2.08	2.04	2.01	1.72	1.60

Table 2. Different locations for electrical conductivity measurement

Location	Longitude	Latitude	Depth (m)
A	50.71	45.79	7
B	50.71	41.12	235
C	50.71	37.37	735

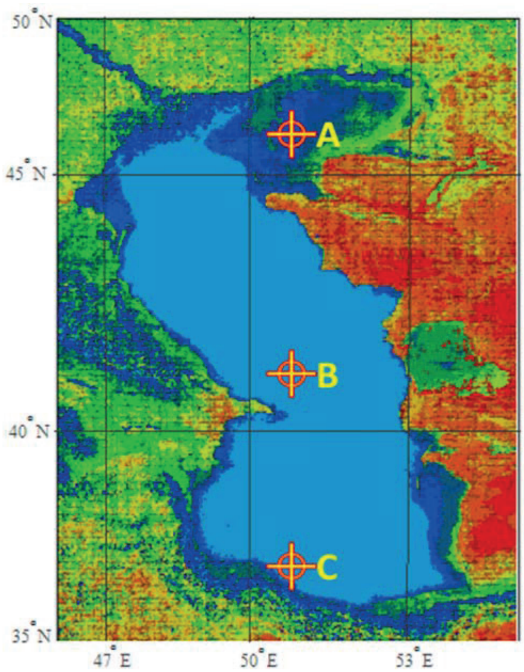


Figure 14. Different sites in the study area

three locations with different depths for the months of February and July in the northern, middle and southern basins of the Caspian Sea. The geographical locations of these points are available in Table 2 and illustrated in Figure 14. The results of the depth range analysis of the three locations (Table2 and Figure 14) show that at position A of the northern basin, there is a large variation in the electrical conductivity from the surface to the depth of 735m and. This relationship between the depth and the electrical conductivity is shown in Figure 15 for July (left) and February (right).

In July, the temperature and electrical conductivity decreased with increasing the depth, while salinity rose with increasing the depth and approaching the seabed. At this location, the greatest amount of electrical conductivity occurred from the surface to a depth of about 70 meters and decreased with increasing the depth. At the depths of 140-160m, the conductivity and temperature increased partially and then decreased to the seabed. In February, the electrical conductivity decreased with temperature and depth, and most electrical conductivity changes occurred up to a depth of about 70 meters. The electrical conductivity structure of the southern basin in these two months was almost the same, except that the slope of the electrical conductivity changes was more in February in comparison with in July.

Figure 16 illustrates the vertical structure of electrical conductivity in July (left) and February (right) for B in the middle basin. In July, the temperature was at its maximum level, and as the depth increased, the temperature decreased. This is while the salinity was at its minimum level, and increased to its maximum value as the depth increased. According to the obtained temperature and conductivity diagrams, the electrical conductivity changes are subject to temperature changes, that is, at the surface, the conductivity has maximum value and decreases with depth increasing. Changes in the electrical conductivity, temperature, and salinity are similar to those in the southern basin, that is, most changes occurred in the thermocline. Due to the cold air in January, the temperature in the surface layer was cooler. The figure shows that the temperature in the surface layer was lower than July, and increased with the depth and then the decreased again at the depth of 40m. The electrical conductivity was also low at the surface and increased with the depth, and then decreased to the seafloor, while salinity increased with the depth.

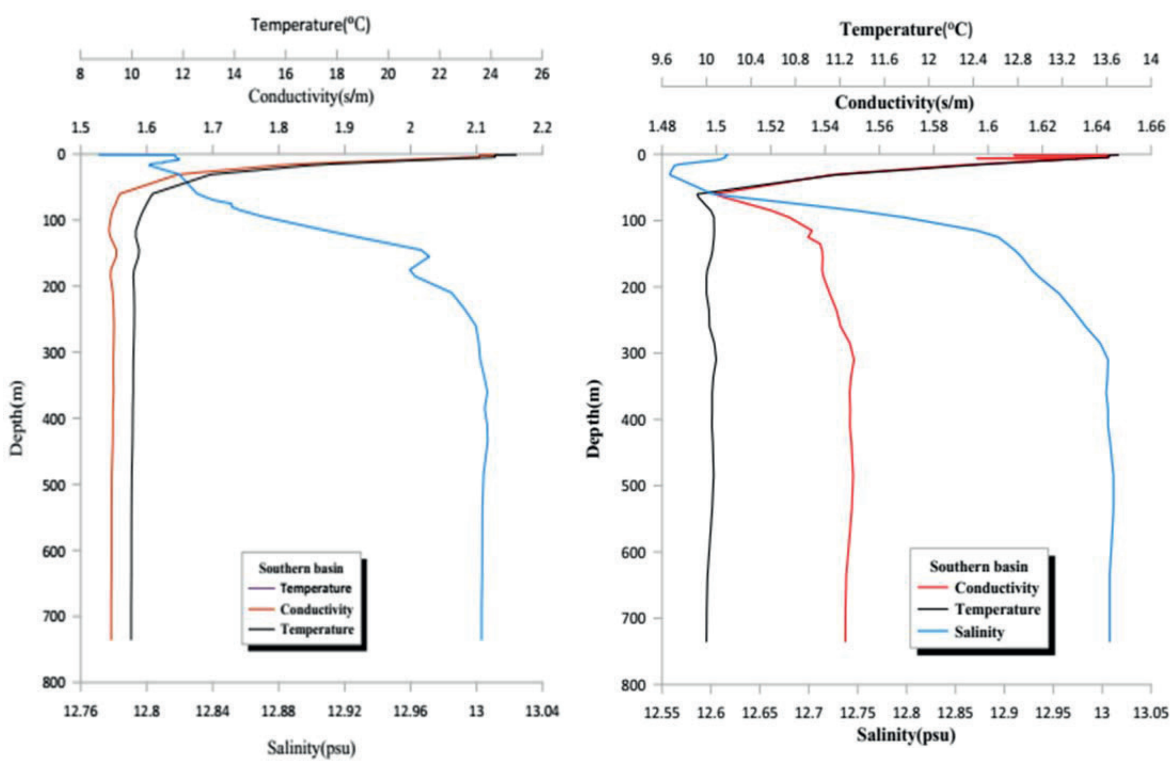


Figure 15. Profile of conductivity, temperature and salinity changes in the southern basin in July (Left) and February (Right)

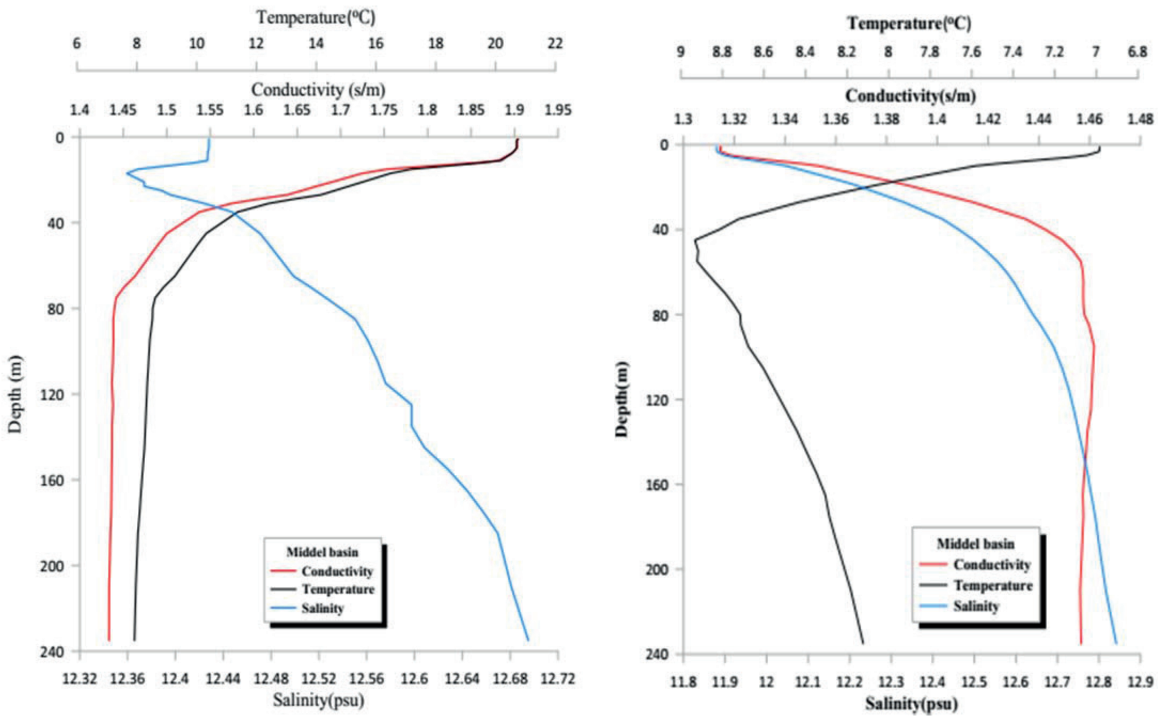


Figure 16. Profile of conductivity, temperature and salinity changes in the middle basin in July (Left) and February (Right)

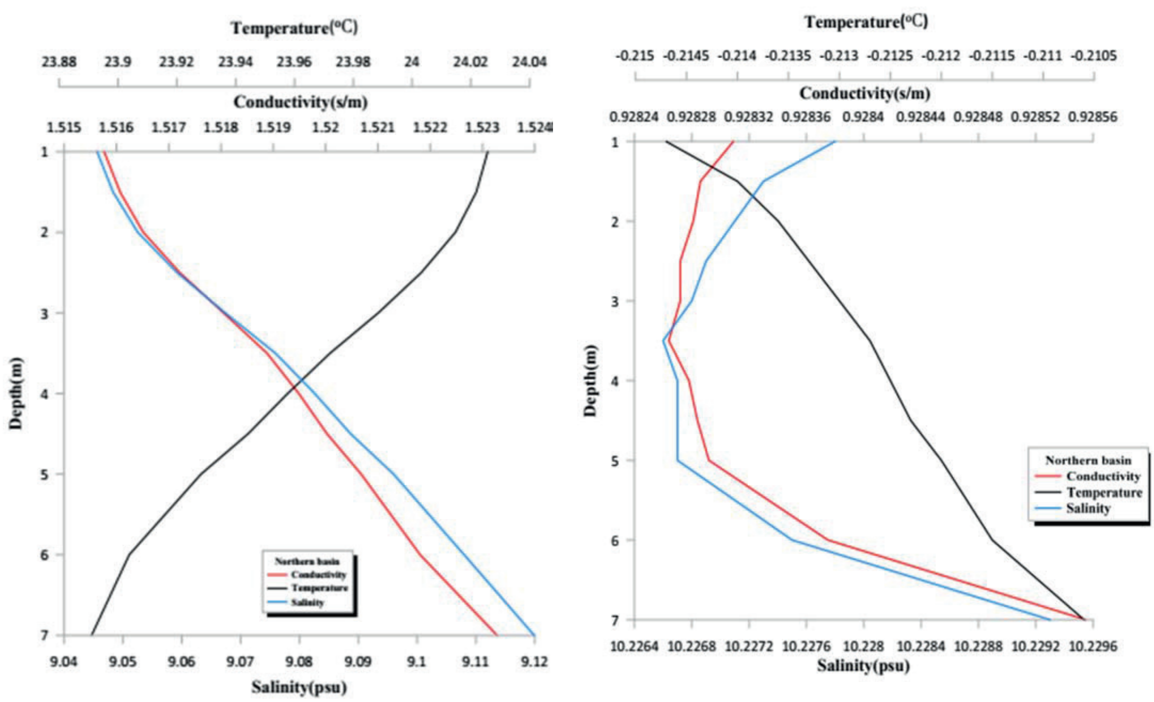


Figure 17. Profile of Conductivity, Temperature and Salinity Changes in the northern basin in July (Left) and February (Right)

Figure 17 indicates the variations of electrical conductivity, temperature and salinity in the northern basin during July (Left) and February (Right). In July, the changes of the mentioned parameters are visible from the surface to the depth of 7m. The dependence of electrical conductivity on salinity is higher than temperature. According to this figure, the salinity value and consequently the electrical conductivity increase with increasing the depth, while the temperature value decreases with increasing the depth. In February, the changes in electrical conductivity and temperature reduced to a depth of 3.5m and then by increasing the depth to the seabed, the amount of these parameters increased. In addition, the reduced surface temperature in the northern Caspian basin led to freezing sea levels. The temperature in surface layer decreased compared to the temperature in depth. The results explain that the electrical conductivity changes were subject to salinity changes in the northern basin in February.

Conclusion

The electrical conductivity coefficient in the Caspian Sea has spatial and temporal variability. It has different values in different seasons. In summer, electrical conductivity has the highest values due to rising temperatures. On the other hand, the lowest amount of electrical conductivity happens in January, so that there were changes in the electrical conductivity from 1.6s/m to 2.3s/m, and vertical changes from surface to the seabed showing that the electrical conductivity decreased with increasing the depth and temperature in the middle and southern basins. This is while salinity increases with increasing the depth as it approaches the seabed. The vertical distribution of electrical conductivity and its relationship with temperature, salinity and sea depth can lead to this conclusion that there is a direct relationship between temperature and electrical conductivity from the surface to the depths of 235 and 735m. Since temperature is only one of the three variables that decrease with the depth in the middle and southern basins every two months, this may indicate that the Caspian Sea conductivity is regulated by temperature. Thus, the vertical structure of seawater electrical conductivity is temperature dependent.

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