**Turkish Journal of Remote Sensing**

https://dergipark.org.tr/en/pub/tuzal

**e-ISSN 2687-4997**

# Detection of Equivalent Water Thickness Changes with GRACE/GRACE-FO Satellites on The Caspian Sea Between 2002-2021

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**Keywords**
Caspian Sea
CSR
DDK Filter
EWT
GRACE and GRACE-FO

**ABSTRACT**

The Caspian Sea is the world's largest inland water body, studied for years. The Caspian Sea, in which water level changes were examined with the data acquired from tide gauges in the past years, is also observing using altimeter satellite data with the improvement of satellite programs. In addition, water mass changes can be investigated with the GRACE and GRACE Follow-On (GRACE-FO) satellites, which can capture mass changes on the earth. Within the scope of the study, the Equivalent Water Thickness (EWT) changes in and around the Caspian Sea were examined using Level-2 Release-06 data obtained from the GRACE/GRACE-FO satellites with a long-term data set covering the years 2002-2021. While making the calculations, a long-term average model was created, and the average value of each year was subtracted from the average model. Center for Space Research (CSR) was preferred as the data center, and the Decorrelation Filtering (DDK) technique was used to eliminate correlation-based errors. Also, the results have been illustrated with a map, and the data obtained has been given in a table. In addition, EWT changes according to years were calculated by selecting a point in the region where EWT changes were observed intensely. When the results are analyzed, negative EWT changes have been detected that have increased rapidly in the last few years. Negative values of EWT changes mean that the water body of that area is decreasing.

# GRACE/GRACE-FO Uydulari ile Hazar Denizi 2002-2021 Yılları Arasındaki Eşdeğer Su Kalınlığı Değişimlerinin Tespiti

**Anahtar Kelimeler:**
Hazar Denizi
CSR
DDK Filtresi
EWT
GRACE ve GRACE-FO

**ÖZ**

Hazar Denizi yıllardır üzerinde çalışmalar yapılan Dünya'nın en büyük iç su kütlesidir. Geçmiş yıllarda mareograf istasyonlarından alınan veriler ile su seviyesi değişimlerinin incelendiği Hazar Denizi, uydu programlarının gelişmesi ile altimetre uydu verileri kullanılarak da gözlemlenmektedir. Ayrıca yeryuvarı üzerindeki kütlesel değişimleri yakalayabilen GRACE ve GRACE Follow-On (GRACE-FO) uyduları ile de su kütlesi değişimleri araştırılabilmektedir. Çalışma kapsamında Hazar Denizi ve çevresinde gerçekleşen eş değer su kalınlığı (EWT) değişimleri GRACE/GRACE-FO uydularından elde edilen Seviye-2 Sürüm-06 verileri yardımıyla incelenmiş ve 2002-2021 yıllarını kapsayan uzun dönemli veri seti elde edilmiştir. Hesaplamalar yapılırken uzun dönemli ortalama bir model oluşturulmuş ve her bir yılın ortalama değeri oluşturulan ortalama modelden çıkarılmıştır. Veri merkezi olarak CSR (Center for Space Research) tercih edilmiş ve korelasyon bazlı hataların ortadan kaldırılması amaçlı DDK (Decorrelation Filter) filtreleme tekniği kullanılmıştır. Sonuçlar haritalandırılmış olup elde edilen veriler tablo şeklinde verilmiştir. Ayrıca EWT değişimlerinin yoğun şekilde gerçekleştiği gözlemlenen bölge içerisinde bir nokta seçilerek yıllara göre EWT değişimleri hesaplanmıştır. Sonuçlar analiz edildiğinde son birkaç yıldır hızla artmakta olan negatif yönlü EWT değişimleri tespit edilmiştir. EWT değişikliklerinin negatif değerleri, o bölgenin su kütlesinin azaldığı anlamına gelir.

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**Cite this article**

Makineci, M.N., Doğanalp, S. (2022). Detection of Equivalent Water Thickness Changes with GRACE/GRACE-FO Satellites on The Caspian Sea Between 2002-2021. *Turkish Journal of Remote Sensing*, 4(2) , 53-61.

**Research Article / DOI: 10.51489/tuzal.1152563**

**Received: 01/08/2022; Accepted: 19/09/2022**

## 1. INTRODUCTION

Examining the factors that cause global warming and climate change and making predictions have started to find priority in interdisciplinary studies, especially in recent years. So, these studies have been supported by many different satellite programs. One of the areas where the effects of global warming and climate change are seen intensely is water mass changes. Mainly, water mass changes in closed seas are susceptible to global warming and climate changes. Disruption of the balance between precipitation and evaporation causes extraordinary water mass changes (Elguindi & Giorgi, 2006).

Thanks to the progress of satellite earth observation missions and the increase in studies with satellite data, changes on earth can be monitored with high accuracy through multiple data sources. Level-2 data of the GRACE and GRACE Follow-On (GRACE-FO) satellites are used to examine the temporal changes in the earth's gravity field (Atlı 2022).

Level-2 solutions obtained from GRACE and GRACE-FO satellites are in terms of harmonic coefficients. A long-term average model is needed to eliminate model errors caused by harmonic coefficients. The model used in the study is a long-term model covering the years 2002-2021 as a result of the combined use of GRACE and GRACE-FO satellites. Some of the errors in the coefficients have been corrected with the average model used. Level-2 solutions with the third Decorrelation Filter (DDK-3) obtained from the Center for Space Research (CSR) data center ensured the elimination of correlation errors. DDK methods are offered to users by the International Center for Global Earth Models (ICGEM). No extra smoothing or decorrelation operations are required for DDK filters published in different radius from one to eight (Atlı, 2022).

This study aims to determine the equivalent water thickness (EWT) changes due to global warming and climate change in the Caspian Sea, which has the world's largest inland water body. For this purpose, previous years' changes were examined using the GRACE/GRACE-FO Level-2 Release-06 DDK-3 filtered data obtained from the CSR data center.

In the studies, which investigated the water level changes of the Caspian Sea for years, conducted with tide gauges, positive increases were observed in the water level between 2002-2006 with both gauges stations and altimeter technique (Lebedev & Kostianoy 2008; Chen et al. 2017a; Chen et al. 2017b). The research detected sudden negative decreases from 2010 to 2015 (Chen et al. 2017a; Chen et al. 2017b).

In the study, GRACE-FO data, which started to work as of 2018, were combined with GRACE data, which started to work in 2002, in order to examine recent changes. As the monthly data published on ICGEM is updated, it is designed to be updated in the study. The updateability of EWT changes has been presented as a contribution to the literature.

## 2. MATERIALS AND METHOD

### 2.1. GRACE/GRACE-FO Satellite System

In order to explore the changes in the earth, information about the temporal changes of the gravity field is obtained with the GRACE twin satellites, which started to work in 2002 with the American-German partnership. Low Earth Orbiter GRACE satellites placed in orbit at an altitude of 500 km provide users with three data sets based on gravity information (Level-1, Level-2, Level-3). Although the mission period of the GRACE twin satellites ended in 2017, GRACE-FO, which was placed into orbit in 2018, GRACE's missions have continued from where they left off. While its mission is to examine the temporal variation of the earth's gravity field (Hofmann and Moritz 2006), GRACE also has investigated the distribution of water and glaciers on the planet, bettering glacial mass losses, sea level changes, mass-based changes, and ocean circulation processes during its more than 15-year mission (Figure 1). In addition, it has played an essential role in determining the growth, shrinkage, and drought levels in groundwater resources (Landerer et al., 2020).

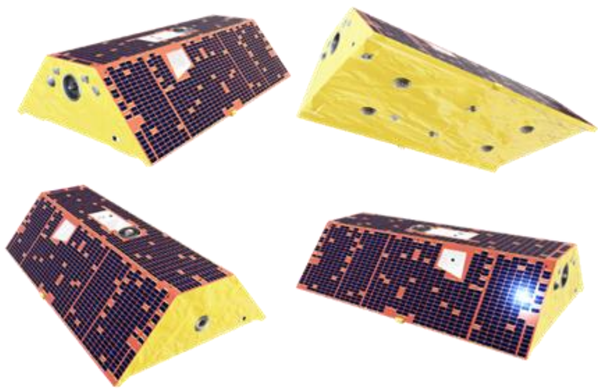

**Figure 1.** The GRACE/GRACE-FO Satellite System (URL-1)

The data received from the GRACE and GRACE-FO satellites are in the form of harmonic coefficients and are published monthly (Atlı 2022). Two periods cannot be directly compared in studies with harmonic coefficients because monthly solutions are loaded with model-based errors due to harmonic coefficients (Wahr et al. 2006, Liu 2008). A static or long-term average model is used to eliminate model-based errors (Liu 2008).

$$\Delta C_{nm} = \begin{cases} C_{nm}(t) - \bar{C}_{nm} \\ or \\ \bar{C}_{nm,i} - \bar{C}_{nm,j} \end{cases},$$

$$\Delta S_{nm} = \begin{cases} S_{nm}(t) - \bar{S}_{nm} \\ or \\ \bar{S}_{nm,i} - \bar{S}_{nm,j} \end{cases},$$

$$(2 \leq n \leq n_{max}, 0 \leq m \leq n) \qquad (1)$$

In Equation (1), $C_{nm}$ and $S_{nm}$ are the *n.* degrees and *m.* are ordinary harmonic coefficients. *i* and *j* denote annual models. Within the scope of the study, a long-term annual average model was created, and mappings were made on this model.

## 2.2. Study Area

The Caspian Sea is the world's largest inland water body and the world's largest saltwater lake. It has both sea and lake features. Its surface area is 371,000 km$^2$, and its surface altitude is 28 meters below sea level. The Caspian Sea is not connected to the oceans, and for this reason, the water level is constantly changing (Chen et al. 2017a). Today, its borders are between Iran, Azerbaijan, Russia, Kazakhstan, and Turkmenistan (Figure 2).


**Figure 2.** Study area

### 2.3. The Equivalent Water Thickness (EWT) Changes

The water mass changes are concentrated in a layer about several kilometers thick on the Earth's surface. GRACE and GRACE-FO satellites are very sensitive to mass changes occurring on the Earth (Wahr et al. 2006, Liu 2008). EWT change, one of the changes that occur due to hydrological events, can be obtained by GRACE and GRACE-FO satellites. EWT changes from the GRACE and GRACE-FO satellites correlate with all water layers (Figure 3).

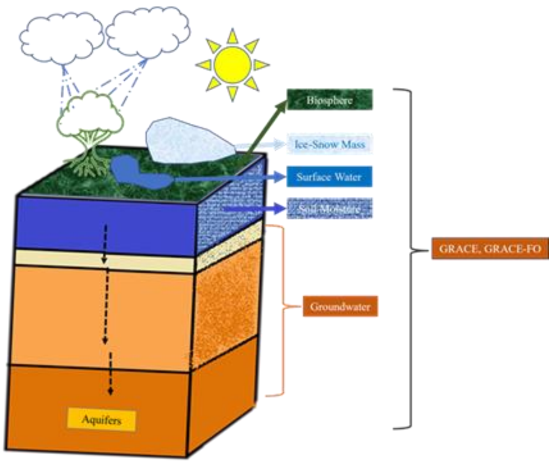


**Figure 3.** Integrated water layers measured by GRACE (Cazenave and Chen 2010)

Surface mass anomalies occur due to changes in the thin water layer (<1 km) on the physical earth. The recognized change can be shown with the harmonic expansion in Equation 2 (Wahr 2007, Liu 2008).

$$\Delta\sigma(\vartheta,\lambda) = a\rho_w \sum_{n=2}^{n_{max}} \sum_{m=0}^{n} (\Delta\check{C}_{nm} cos m\lambda + \Delta\check{S}_{nm} sin m\lambda) P_{nm}(cos\vartheta) \quad (2)$$

In Equation (2), $\Delta C_{nm}$ and $\Delta S_{nm}$ give the surface density coefficient changes, while $\rho_w$ expresses the density of water (1000 km/m$^3$). The water thickness change corresponds to the density change is defined as (Equation 3).

$$\Delta e(\vartheta,\lambda) = \frac{\Delta\sigma(\vartheta,\lambda)}{\rho_w} \quad (3)$$

There is a relationship between the scaled surface density coefficient changes with the major semi-axis of the reference ellipsoid and the coefficient changes given in Equation (1) (Wahr et al 1998, Wahr 2007, Liu 2008).

$$a \begin{Bmatrix} \Delta\check{C}_{nm} \\ \Delta\check{S}_{nm} \end{Bmatrix} = a \frac{\rho_{ave}(2n+1)}{3\rho_w(1+k_n)} \begin{Bmatrix} \Delta C_{nm} \\ \Delta S_{nm} \end{Bmatrix} = K_n \begin{Bmatrix} \Delta C_{nm} \\ \Delta S_{nm} \end{Bmatrix} \quad (4)$$

The $\rho_{ave}$ in Equation (4) shows the average density of the earth (5517 kg/m$^3$), and $k_n$ expresses the n degrees of the Love numbers.

If the coefficient changes given in Equation (4) are used in Equation (2) and then the density change obtained is substituted in Equation (3), linear expression of the EWT changes can be found depending on the GRACE harmonic coefficient changes (Equation 5).

$$\Delta e(\vartheta,\lambda) = \sum_{n=2}^{n_{max}} \sum_{m=0}^{n} (\Delta C_{nm} cos m\lambda + \Delta S_{nm} sin m\lambda) K_n P_{nm}(cos\vartheta) \quad (5)$$

### 2.4. The Method

The data used in the numerical application are Level-2 Release-06 data of 60 × 60 degrees covering the GRACE and GRACE-FO satellites of the CSR data center located on the ICGEM page. Data are published monthly in terms of harmonic coefficients. The method used to remove the noise in the high order coefficients of these data is the DDK-3 filtering method. Filtered data with the DDK-3 filtering method can be obtained from ICGEM. In the data consisting of harmonic coefficients, abnormal changes were detected in the $C_{20}$ coefficients, representing the ground's kurtosis (Cheng and Tapley 2004). For this reason, the $C_{20}$ coefficients obtained from the GRACE and GRACE-FO tasks were replaced with the $C_{20}$ coefficients obtained from the Satellite Laser Ranging (SLR). In addition, GRACE and GRACE-FO gravity solutions do not contain short-term atmospheric and ocean mass signals. Therefore, the GAD background models need to be reintroduced to the GRACE monthly solutions (Figure 4) (Atlı, 2022).

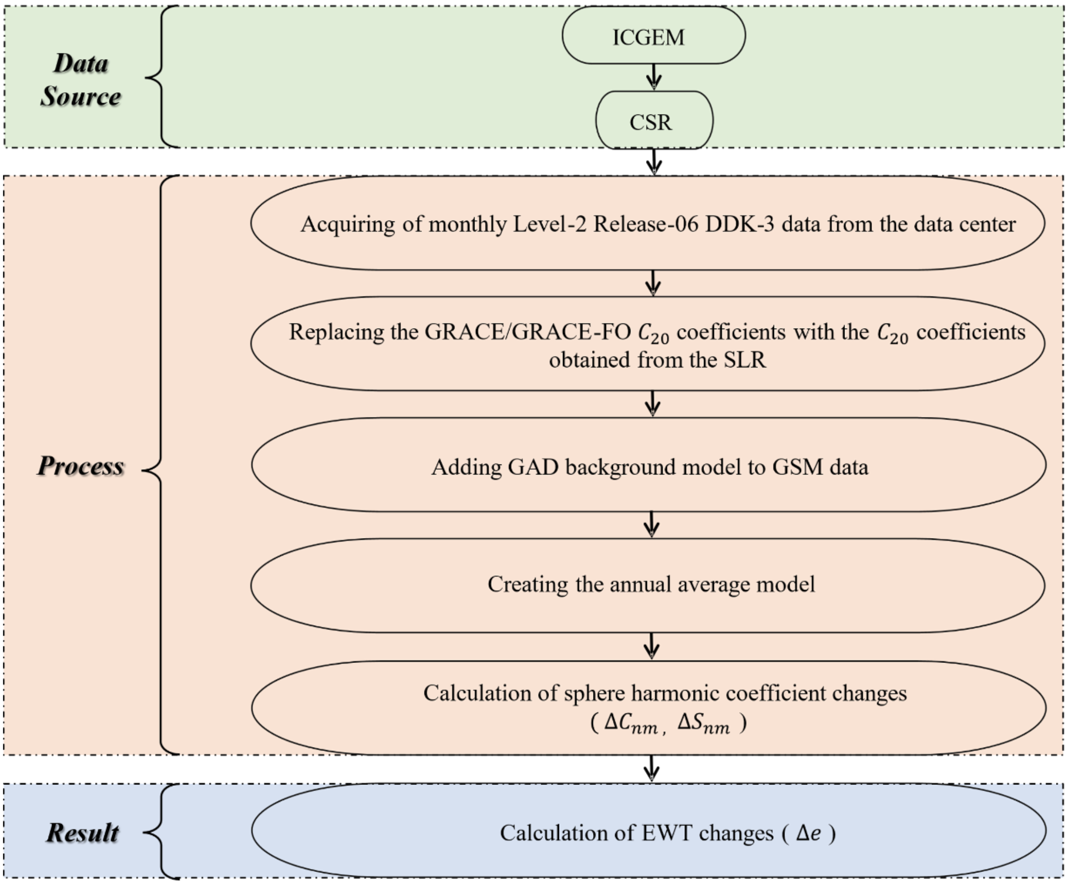


**Figure 4.** The workflow schema of the study

## 3. RESULTS AND DISCUSSION

EWT variations in the region within the latitude of $35° \leq \vartheta \leq 50°$ and longitude $40° \leq \lambda \leq 60°$ covering the Caspian Sea were calculated as $0.5° \times 0.5°$ grids. In the model in which the annual change is examined, the results are obtained by subtracting the average value of the relevant year from the average value of all years (Figure 5). When Figure 5 is examined, it is seen that there are positive values between 2002-2010. However, EWT changes from 2012 are in the form of negative values.

Table 1 shows the minimum, maximum, mean, and standard deviation (std) values of the EWT changes in the area selected as the study area. The std value is a measure of the distribution of a data group, and it is a measure of how close or far our data is from the arithmetic mean which is the expected value. While a high std shows that the values are dispersed throughout a wider range, a low std indicates that the values tend to be close to the mean and the calculated estimate values are quite good (Bland and Altman 1996). In this study, the std values for the EWT changes were calculated based on the harmonic coefficients and the std values of these coefficients obtained from the data centers. However, the std values of the coefficients obtained from the data centers contain some systematic effects. Therefore, the computed std values can be considered as the precision (Atayer 2012). According to the Table 1, the average values with positive EWT values between 2002 and 2010 have followed a negative trend since 2011 (Figure 6). Similarly, when the std values obtained by years are examined, it is seen that there was a decreasing trend in general between 2002 and 2011, while there was a general increase after 2011 (Figure 7).

Similar results were obtained in the study of Chen et al. It was studied until 2015 and it was observed that the EWT changes measured from 2010 to 2015 were negative values, while the values between 2002 and 2006 were positive (Chen et al. 2017a; Chen et al. 2017b). Similarly, Lebedev et al. obtained solutions with positive values between 2002 and 2006 (Lebedev and Kostianoy 2008).

In order to observe the EWT changes on a point-based basis, a point was selected in the area where the intense change was experienced, and the EWT changes were analyzed. The analysis results between 2002-2021 on the point at 40° 54' 36.77" latitude and 50° 23' 23.12" longitude chosen from the region where EWT changes are observed intensely are given in Table 2. According to Table 2, while positive values were checked until 2011, negative values began to be seen in 2012. While the most significant positive value was observed in 2005 (33.59 cm), the most significant negative (-54.20 cm) was observed in 2021. In addition, it was observed that the EWT changes were upward from 2002 to 2005 and downward after 2005 (Figure 8).

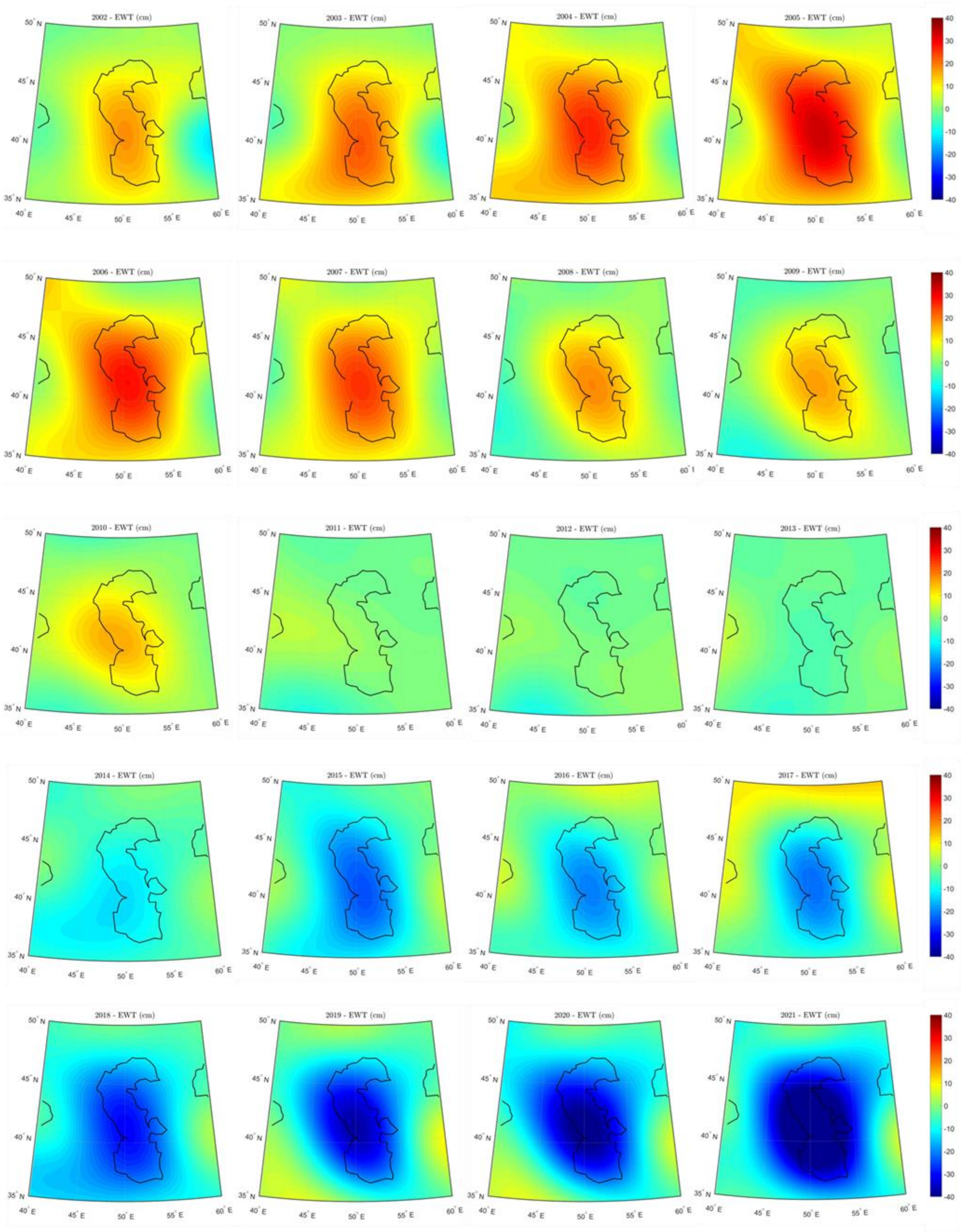


**Figure 5.** EWT changes in and around the Caspian Sea between 2002-2021

**Table 1.** EWT changes in the study area between 2002-2021

| Year | min (cm) | max (cm) | mean (cm) | std (cm) | Year | min (cm) | max (cm) | mean (cm) | std (cm) |
|---|---|---|---|---|---|---|---|---|---|
| **2002** | -13.22 | 17.98 | 3.79 | 5.76 | **2012** | -9.19 | 8.49 | -0.85 | 2.47 |
| **2003** | -10.19 | 22.77 | 5.85 | 7.06 | **2013** | -6.55 | 7.60 | -0.79 | 3.26 |
| **2004** | -5.36 | 27.23 | 10.14 | 6.57 | **2014** | -13.20 | 1.87 | -5.78 | 3.54 |
| **2005** | -2.42 | 33.62 | 12.17 | 8.21 | **2015** | -24.55 | 8.45 | -6.76 | 7.83 |
| **2006** | -3.53 | 28.80 | 10.09 | 7.51 | **2016** | -20.79 | 8.09 | -3.54 | 7.21 |
| **2007** | -8.20 | 25.71 | 6.57 | 8.16 | **2017** | -22.30 | 13.53 | -0.65 | 9.04 |
| **2008** | -8.32 | 18.83 | 1.66 | 6.96 | **2018** | -30.74 | 3.60 | -11.75 | 7.44 |
| **2009** | -9.05 | 16.85 | 1.48 | 6.05 | **2019** | -37.78 | 9.80 | -8.36 | 10.84 |
| **2010** | -5.98 | 16.14 | 3.54 | 4.72 | **2020** | -42.11 | 7.48 | -11.96 | 11.16 |
| **2011** | -8.08 | 4.32 | -0.11 | 2.50 | **2021** | -54.26 | 6.18 | -15.57 | 13.85 |

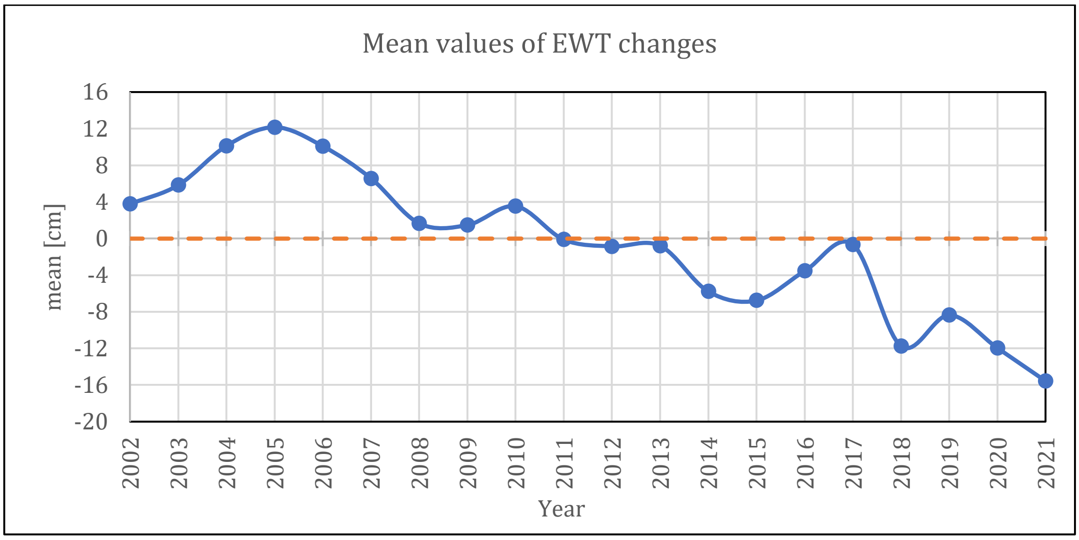


**Figure 6.** Mean values of EWT changes

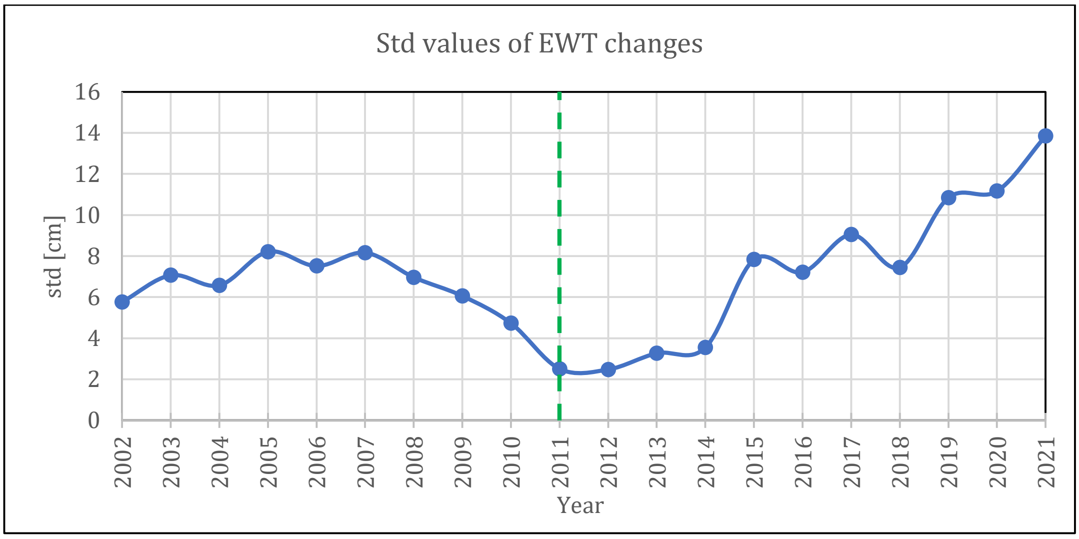


**Figure 7.** Std values of EWT changes

**Table 2.** EWT changes at the chosen point between 2002-2021

| Year | EWT changes (cm) | Year | EWT changes (cm) |
|---|---|---|---|
| **2002** | 18.00 | **2012** | -0.62 |
| **2003** | 22.55 | **2013** | -4.50 |
| **2004** | 27.25 | **2014** | -12.87 |
| **2005** | 33.59 | **2015** | -24.51 |
| **2006** | 28.51 | **2016** | -20.75 |
| **2007** | 25.65 | **2017** | -22.16 |
| **2008** | 18.72 | **2018** | -30.72 |
| **2009** | 16.75 | **2019** | -37.54 |
| **2010** | 15.84 | **2020** | -42.07 |
| **2011** | 1.60 | **2021** | -54.20 |

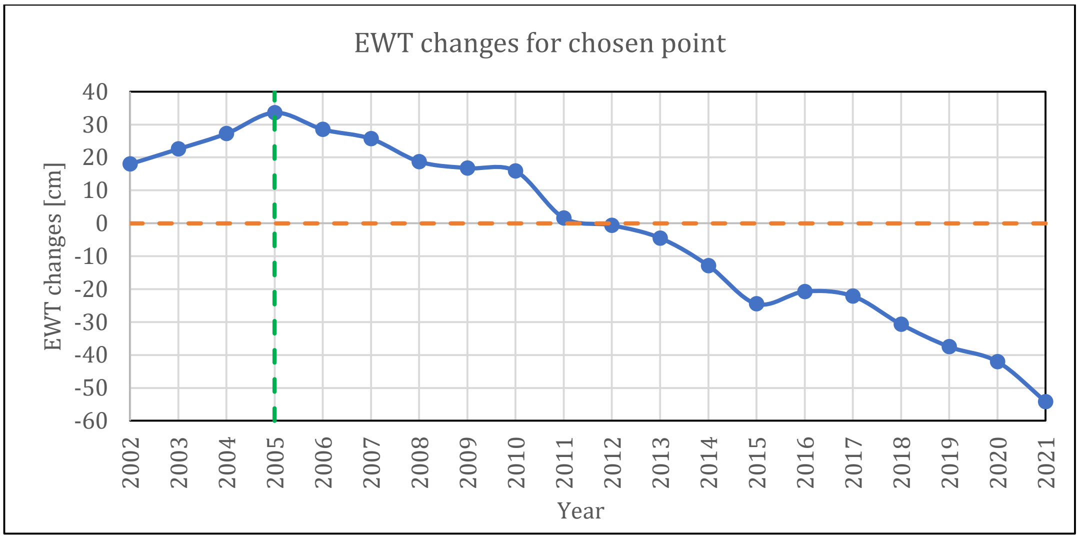


**Figure 8.** Chosen point EWT change

## 4. CONCLUSIONS

The aim of the study is to determine the EWT changes due to global warming and climate change in and around the Caspian Sea with GRACE/GRACE-FO satellites Level-2 Release-06 data. In the study, the harmonic coefficients were analyzed, and the changes over the years were presented in the form of visual maps. Since most of the water mass changes in the Caspian Sea, which has the world's largest inland water body, depend on the balance between precipitation and evaporation, water mass changes are highly affected by global warming and climate change. When the average values calculated annually as a result of the study are examined, the negative EWT changes observed since 2011 show the decrease in water bodies in those years. Especially when Figure 5 is examined, intense EWT decreases from 2014 to 2021 can be seen formally. It supports the map created with the values given in Table 1. With the help of the maps created, when the data on the selected point in the area where the change is most intense in the study area is examined, it is seen that the EWT values, which are rapidly decreasing from 2012 to 2021. The EWT values for the years 2020-2021, when the highest negative change is seen, can be shown as a reflection of the negative effects of global warming and climate change on the Caspian Sea.


## Acknowledgment

The authors would like to thank ICGEM, NASA, and CSR data centers for all their contributions to the creation of this study.


## Author contributions

MN. Makineci (First Author): Created the datasets and figures, Methodology, Discussion.
S. Doğanalp (Second Author): Designed the research, Analyzed the data, Review and editing.

## Conflicts of Interest

The authors declare no conflict of interest.

## Declaration of research and publication ethics

In the study, the authors declare that there is no violation of research and publication ethics and that the study does not require ethical committee approval.

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