Analysis and Interpretation of GRACE and GRACE-FO Mission Data*

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Abstract. The study is devoted to the analysis of the features of the change in the Equivalent Water Height (EWH) parameter over the geoid based on satellite measurements of space systems. The GRACE and GRACE-FO satellite data archive was used in the study. The assessment was made on the Earth as a whole including areas of the Land and World Ocean. Interpretation of the disturbed state of the geo environment is performed using digital maps of the EWH parameter spatial distribution based on the histogram approach and correlation analysis. A comparative analysis was also carried out of the studied data of the GRACE mission and the data of the new GRACE-FO satellite system which was launched into orbit in the summer of 2018.

Keywords: Gravitational Field, Geoid, EWH Parameter, Underwater EarthQuakes, Space Systems GRACE and GRACE-FO, Satellite Data Processing.

1 Introduction

The GRACE and GRACE-FO missions were originally aimed at studying the global climate of the Earth [1-4]. Satellite measurements of the height of the water surface in relation to the geoid contour make it possible to determine the deviation of the free sea surface from its mean level [5]. The geoid is an equipotential surface of the gravity field which corresponds to the average sea level at rest. Monthly data contain the information on the deviation of the World Ocean surface from the geoid in units of equivalent water height.

The data obtained from the site [6] contain the information on the deviation of the World Ocean surface from the geoid in units of the Equivalent Water Level (EWH) in cm. Basically, the EWH parameter is used to analyze the dynamic topography of the oceans and to refine the parameters of the Earth's external gravitational field [7].

The EWH parameter reflects undifferentiated movements of the generalized mass. Redistribution of water in the hydrosphere occurs in a thin layer around the Earth's surface only a few kilometers wide. The masses between the geoid and water surface have a constant density ρ_w equal to 1000 kg / m^3.

The value of the EWH parameter is calculated based on the harmonic coefficients of the geopotential models minus the coefficients of the averaged model EIGEN-6C [7]. In the global model, the initial data are ground-based gravimetric measurements, laser trajectory observations of the LAGEOS satellites (1985-2010) as well as satellite information from the GOCE and GRACE systems.

In the high-power EIGEN-6C model, the decomposition of the geopotential occurs to the power of the order of 1420, which corresponds to a 14-km spatial resolution. The equivalent water is found from the ratio of the surface density $\Delta\sigma$ to the density of water ρ_w: EWH = $\Delta\sigma / \rho_w$.

The analysis performed in the paper is limited to the relative changes in EWH over the geographic space (Land and Ocean regions) through time at intervals of approximately one month. Observations of gravity anomalies allow one to analyze both local and global spatial and temporal aspects in search of correlations with tectonic processes on the Earth [8-13].

Searching for spatial and temporal dependences in satellite data on the gravity anomalies of the Earth's oceans is the purpose of the study. This requires building and comparing a model map of random gravitational anomalies with the observed one; building maps of the average values of the gravity anomalies and their variances; highlighting characteristic areas and determining time dependences for the gravitational anomalies.

2 Analysis of the GRACE System Observation Data

As part of the research it is advisable to expand the possibilities of using data from the GRACE satellite system for analyzing global climatic and geodynamic changes on the Earth. In this regard, it is proposed to study the new data of the GRACE-FO system in a single time series with the data of the previous GRACE mission after their recent revision by the development teams.

To analyze global temporal changes in the distribution function of the EWH parameter it was decided to use histograms [14]. Using the histograms we determine the average value of the EWH parameter as well as other statistical values (variance, mode, median, etc.).

Based on the integral characteristics of the gravitational disturbance as a cumulative equivalent displaced mass (areas: Ocean, Land), time dependences are analyzed.

Let us define the cumulative equivalent mass displacement (Mass). This value determines the total amount of the equivalent mass of water at each time interval. It is calculated by the formula:

$$Mass \cong \sum_{\theta=-90}^{90} \sum_{\phi=0}^{360} \left| EWH(\theta,\phi) \right| \cdot R^2 \sin(\frac{\pi}{180}\theta) \cdot \Delta\phi \cdot \Delta\theta \,, \quad (1)$$

where | EWH (Θ, φ) | is the modulus of the gravitational anomaly, depending on the latitude (Θ) and longitude (φ), R is the Earth's radius, ΔΘ = Δφ = π / 180.

The value of the gravitational anomaly EWH is measured in meters and consequently, the resulting value of Mass will be measured in tons. The value of Mass can equivalently be determined using the histogram as an analogue of the distribution function of the magnitude of the gravity anomalies.

Let us justify the introduction of the new distribution parameter Mass. The fact is that the intuitively clear mean value (of the gravitational anomaly) is responsible for the balance of approximately equal values – the decreasing and increasing equivalent mass (EWH) which for a sufficiently long observation interval (~ a month) turns out to be approximately equal. Consequently the average value will tend to zero.

However, if we add the decreasing and increasing masses (hereinafter Mass), then this will be a global characteristic of the "excitation" of the climate in a given month. This value can be determined using the histogram or using equation 1 directly from GRACE data, taking into account the correction factor which considers the dependence of the linear area on the latitude of the partition cell of 1 square degree.

The data on the Earth's gravitational anomalies studied in this work using the histograms were taken from the official website of the GRACE mission (2003-2016) [6]. The site contains materials from three processing centers: University of Texas Center for Space Research (CSR), GeoForschungsZentrum (GFZ), and Jet Propulsion Laboratory (JPL). In this study the data processed by the Texas Center for Space Research were used.

The collected material of the first GRACE mission provides an interesting subject for statistical research. Histogram analysis allows one to determine the probability distribution function for gravitational anomalies created by the redistribution of mass on the Earth. It is shown that the histogram, i.e. the distribution density function on the value of the gravitational anomaly, is symmetric and close to exponential with singularities on the distribution tails [8]. For this kind of large distribution values (positive and negative) the anomalies should have a low probability.

The analysis of the spatial distribution of anomalies made it possible to identify 9 geographic regions in the oceans with the strongest gravitational anomalies and maximum gravitational variability. Since gravitational anomalies are a reflection of processes of the mass redistribution on the Earth and in this case of the oceans it is advisable to use correlation analysis to assess the relationship.

The matrices formed based on the Pearson's correlation coefficients for the time series of the considered areas allowed one to identify strong positive and negative correlations, as well as the lack of communication. For the comparative analysis of the GRACE and GRACE-FO observation data (new mission) a joint processing of the corresponding data of the L3 level was performed.

The GRACE-FO observation data was obtained from the website: "https://podaac-tools.jpl.nasa.gov/drive/files/allData/gracefo/L3/ocean_mass/RL06/v03/CSR". It should be noted that the available GRACE measurements were at the L5 level. In this regard, it was necessary to evaluate the obtained distributions as well as the possibility of using the developed methodology for new data from the GRACE-FO mission.

The experimental data from GRACE (2002-2017) GRACE-FO (2018-2030) were taken from a pair of satellites located at a distance of ~ 200 km from each other in the polar orbit at an altitude of ~ 400 km. The data include the spatial position of each satellite relative to the Earth, their mutual distances and absolute (proper) accelerations. To correctly compare the old and new data it is necessary to analyze the data of the level L3. For the desired estimate the corresponding histograms of the gravitational anomalies were generated in logarithmic coordinates (Fig. 1) where the value of the gravitational anomalies (in meters) is indicated along the X axis.

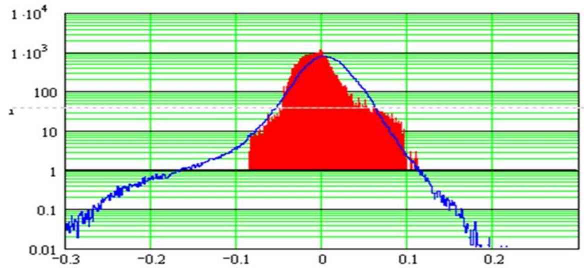

Fig. 1. Average histogram for GRACE-FO data (blue) and histogram for GRACE data (red).

3 Results of the Time Dependence Analysis in GRACE Observational Data

This section presents the results of the analysis of the vibrational components of the studied quantities. These are the movements of mass in the atmosphere, in the ocean on the surface and below the Earth. All these components add up and cease to be distinguishable in the EWH parameter. It is necessary to distinguish the terms in the general motion of mass on the Earth.

This is possible using additional knowledge about a specific type of the mass motion. The most important and significant contribution to changes in the gravity field is made by the movement of water. A joint analysis of the data on the Land and Ocean identifying common and individual patterns will improve the understanding of global climate change on the Earth.

In the analysis of the spatial component, we will limit ourselves only to the division of the geo-environment into the Land and Ocean. The time dependence is set by the time intervals for which the average value of the EWH parameter is determined, depending on the geographic coordinates on the Earth's surface. Each time interval corresponds to a histogram of frequencies of various EWH values.

Histograms are quite a complex object (vector) for analysis since they are subject to changes. Therefore, each histogram was characterized with a more simple value – a scalar. A more suitable parameter of the histogram is the sum of the decreasing and increasing masses in the current time interval. This value characterizes the intensity of the mass transfer, i.e. the intensity of climatic processes that are actually associated with the transfer of water – these are clouds, precipitation, etc.

From the methodological point of view the spectral analysis of the time dependence of the mass transfer intensity is not a standard Fourier analysis. This is due to the fact that we are dealing with time intervals of different duration and average (which are not instantaneous) values of the investigated quantity. There will be a significant uncertainty in the resulting spectrogram or periodogram. As for the monthly period which is set by the motion of the moon and which determines tidal phenomena both on the Land and Ocean, the irregularity in the time intervals greatly aggravates the situation.

If the time intervals coincide with the synodic (for example, the period of the Moon's revolution), then the error in determining the influence of tides on the EWH parameter will be more or less systematic. In the study we will restrict ourselves to identifying only the annual and semiannual oscillatory components and polynomial trend – a polynomial of the 3rd degree.

To assess the existing data we use the least squares method. First we define the polynomial trend and eliminate it from the data, and then, we isolate the indicated annual and semi-annual oscillatory modes. The stepped graph below highlights this feature of the data. Let us start with the simplest model – we assume that the average values are reached in the middle of each interval.

Consider the time dependence of the Mass value for the Ocean and Land according to GRACE & GRACE-FO data. The polynomial trends for the Land and Ocean are presented in Fig. 2, the blue graph corresponds to the Ocean and the red one to the Land, and the dots represent the corresponding trends (3rd degree polynomials). Along the axes, time is given in years and the mass is presented in tons. Note that in 2007 there was a minimum, and now the trend is increasing.

As it can be seen, the trends for the Land and Ocean are approximately similar to each other, and this is indeed the case since the polynomial coefficients for the Land are about 3 times larger than those for the Ocean.

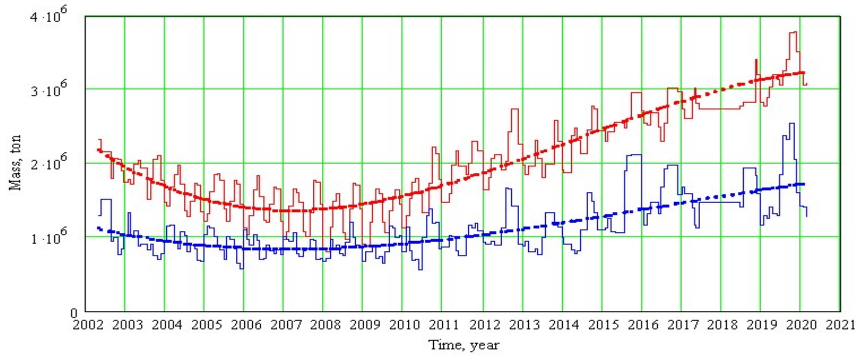

Fig. 2. Polynomial trends of Mass for the Ocean and Land according to GRACE and GRACE-FO.

The estimation of the correlation of the Mass value between the Ocean and Land according to GRACE and GRACE-FO data is shown in Fig. 3. It can be seen that the graphs of the mass dependence on the Land and Ocean are rather strongly correlated. Here, the corresponding cloud of correlations and the Pearson correlation coefficient = 0.728 are given.

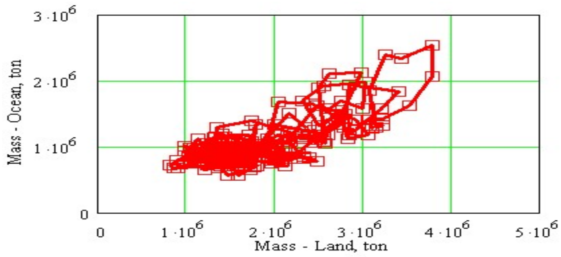

Fig. 3. Correlation field between the time series of the Land and Ocean Mass values according to GRACE and GRACE-FO data.

4 Results of the Vibrational Component Analysis of the Ocean and Land Mass Quantities

When using the standard Fourier analysis methods in processing time series of data from the GRACE & GRACE-FO missions, one encounters difficulties due to the fact that (possibly contrary to the original intentions), the time intervals in these data are not regular and there are gaps in the data.

The method which appears to be convenient in this situation is the Least Squares Method. At the same time, first a polynomial trend is identified - this is a polynomial of the 3rd degree, and after its removal, the oscillatory semi-annual and annual components of the time series are determined by the same method. The results of the analysis of the vibrational components of the Ocean and Land Mass values are shown in Figures 4-7.

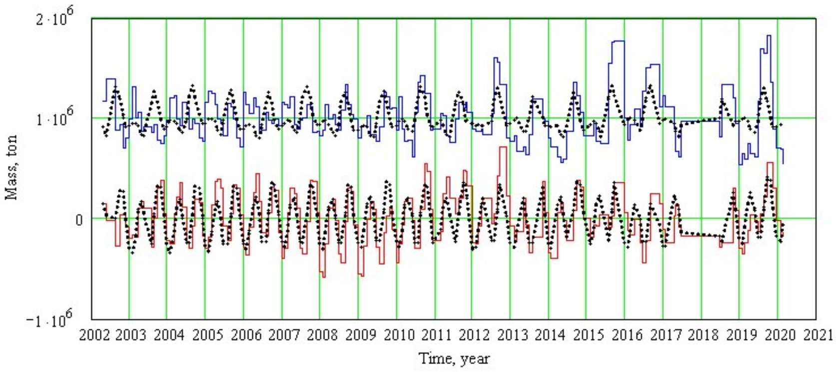

Fig. 4. Time dependance of vibrational components of Ocean and Land mass.

The spaced plots for the Ocean (blue + 106 tons) and Land (red) of the equivalent mass of water involved in the movement, presented together with the annual and semi-annual fluctuations revealed by the least squares method, are shown in Fig. 4. In Fig 4 the dotted line demonstrates the annual and semi-annual vibrational modes.

The annual and semiannual vibrational modes of the Ocean and Land mass quantities are shown in Fig. 5. The figure represents only the vibrational trends of the Land (red) and Ocean (blue) free from "noise". It should be noted that the range of fluctuations increases markedly, especially for the Ocean as we approach the current maximum.

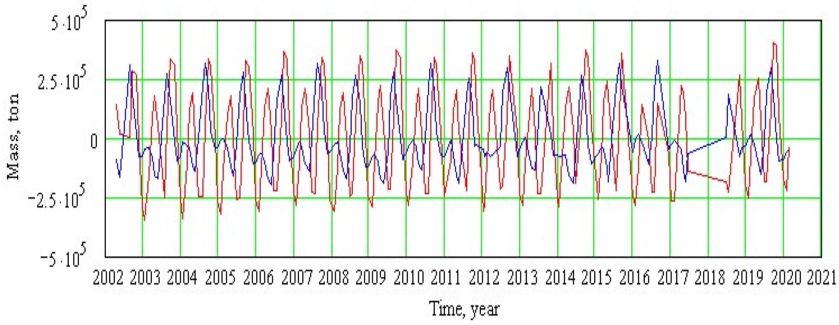

Fig. 5. Annual and semiannual vibrational modes of the Ocean and Land mass quantities.

The global annual and semiannual vibrational modes of the total value of Mass of the Ocean and Land are shown in Fig. 6. Fig. 6 shows the total value (i.e. Land and Ocean) free from the trend and noise fluctuations in EWH moving throughout the Earth. The image demonstrates only the points corresponding to the experimental time intervals of the data files.

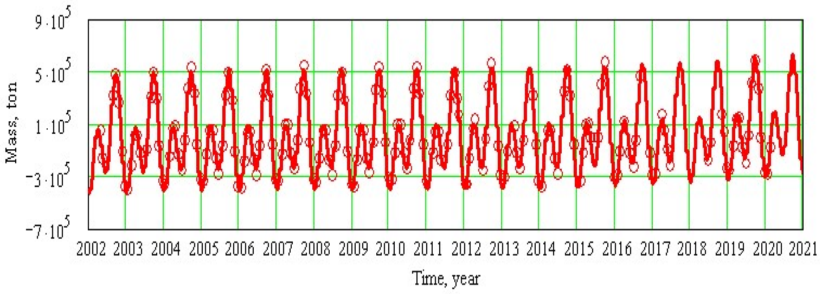

Fig. 6. Global annual and semi-annual oscillatory modes of the total mass of the Ocean and Land.

In order to better demonstrate the changes in the intensity of the mass transfer on the Earth during the year –we will give the annual and semi-annual harmonics on a separate graph for each season (Fig. 7). Here, we can see that for the Land the minima are reached at the beginning and in the middle of the year. This corresponds to winter in the Northern and Southern hemispheres of the Earth, and the maxima are shifted by 3 months. As for the Ocean the minima occur in April and November and the maxima are observed in early February and mid-July.

Fig. 7. Annual and semi-annual harmonics of the changes in the intensity of the mass transfer on the Earth during the year (seasonally).

5 Conclusion

In our previous study, using GRACE-OCEAN data we came to the conclusion that in general the Ocean behaves in an intuitive way with a certain variability which may be natural (thermodynamic). Also earlier within the framework of this variability, several zones of the Ocean were identified for which the variability was the strongest and of oscillatory origin with the annual and semi-annual components. It has now been established that the fluctuations identified earlier occur on the Earth as a whole and the fluctuations in the Ocean are gaining momentum.

In addition, the identified trends (polynomial of the 3rd degree) both for the Ocean and Land have now an increasing character. However, if to look at the trends as at a long-period fluctuation, one can see that at the beginning of the analyzed time interval (2002-2020) the trends had a descending character and passed (simultaneously) a minimum (~ 2007) and then, started to grow. Therefore, we are probably dealing with an oscillatory process with the periodicity of 13-14 years.

Based on the statistical analysis of the changes in the EWH parameter for the Land and World Ocean it is shown that the temporal patterns obtained according to the observations of the GRACE mission persist in the data of the new GRACE-FO mission for the main detected anomalies.

Consequently, GRACE and GRACE-FO data are in good agreement with each other. In the data for the Earth as a whole as well as for the Land and over the Ocean, long-term and short-term trends are revealed, i.e. oscillatory components. The identified trends are likely to be associated with global climate changes on the Earth.

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