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Analysis of Long-Term Gravitational and Seismic Measurements in the Pamir - Tien-Shan Region

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Abstract. Long-term variations (2003–2015) of the Equivalent Water Height (EWH) above the geoid's contour obtained from GRACE satellite measurements are analyzed to establish the relationship between changes in the gravitational field with the stress-strain state of the geological environment and the seismic process in Central Asia (Pamir and Tien-Shan regions). The earthquakes gravitational effects study, based on the use of various GRACE models allows us to distinguish the component of the gravity field, which may be related to seismic activity. The results of temporal and spatial gravitational anomalies identification, the probable causes of which were tectonic factors associated with the redistribution of masses in the lithosphere as a result of large (M>5.5) regional earthquakes, are presented.

1. Introduction

The study of spatial and temporal changes in the gravity field was performed in one of the most seismically active areas of Central Asia, located in the junction of two major mountain systems – Pamir and Tien-Shan. High seismicity of the region is conditioned by intense geodynamic interaction of several large lithosphere plates. It is assumed that regional earthquakes focus generation is direct consequence of submeridional compression high tensions, the energy source of which is pressure exerted by the Hindostan plate from the South [1]. Over several last centuries, more than ten earthquakes of M>7.0 have occurred in the Pamir and Tien-Shan regions [2]. However, the complex and rugged terrain of the study area make it impossible to conduct ground-based studies of geodynamic and deformation processes based on traditional geophysical and geodetic measurements.

Satellite gravimetric data obtained during the GRACE experiment (*Gravity Recovery and Climate Experiment*), are widely used to study various geophysical phenomena and processes. The GRACE data archive contains satellite measurements for 15 years (2002-2017). Monthly gravity models in the form of a breakdown by spherical functions are calculated by several research centers in Switzerland (AIUB), Germany (GFZ), USA (CSR and JPL) and France (CNES/GRGS) [3], that generate monthly gravity fields uniformly covering the Earth surface. The high precision of the GRACE system, being 1×10^{-10} m/s^2

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(tens of micrometers), determines sensitivity of this satellite gravimetric means to integral mass redistribution, that allows to explore not only dynamics of oceans, volume of glaciers, seasonal and interannual hydrologic changes, but geodynamic process, accompanied by density fluctuations in the Earth's crust and mantle in the process of major earthquakes as well. Changes of the gravity field associated with several strongest earthquakes, e.g. Sumatra (2004), Chili (2010) and Japan (2011) [4] are examples of successful detection of post-seismic effects. Sudden changes of gravity field values, representing negative changes of about 4 μGal, were registered in the month when the events occur.

This paper analyzes long-term regional data from satellite measurements (GRACE) in order to identify coseismic gravitational deformations and establish the relationship of gravitational field anomalies with the seismic process in the Pamir and Tien-Shan regions.

2. Gravitational And Seismic Measurements Data

The initial data were monthly gravitational field models of the Geophysical institute in Potsdam (GFZ-RL06) [5], Centre National d'Etudes Spatiales / Groupe de Recherches de Géodésie Spatiale, Toulouse, France (CNES/GRGS-RL05) and the Astronomical Institute of the University of Bern (AIUB-RL02) [6]. Researches of spatial-temporal changes in the gravity field were performed in the most seismically active region of the Central Asia, which is marked with a dashed line in the map of earthquakes focuses distribution, occurred in the region limited by the following coordinates: 37.0–44.0°N, 70.0–79.0°E, in 2003–2015. (Fig. 1).

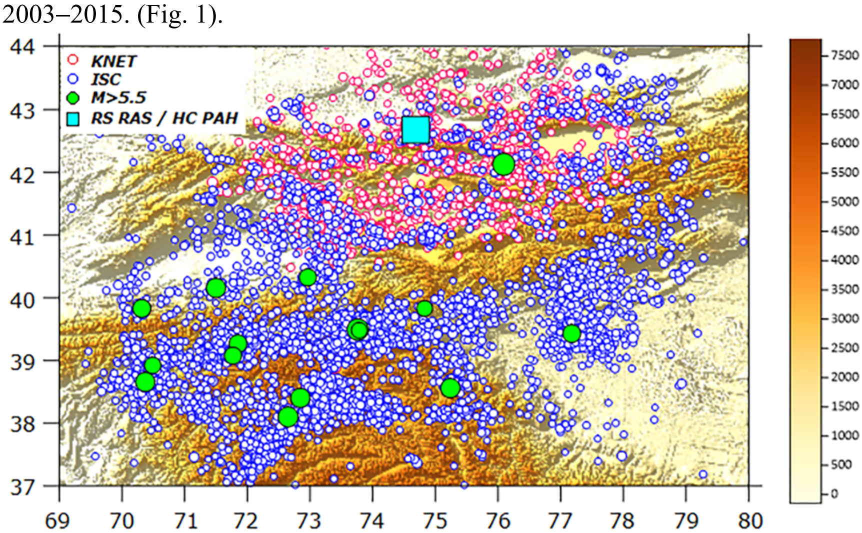

Fig. 1. Location of M≥2.0 earthquake focuses (KNET), M≥3.0 and M≥5.5 (ISC)

Information about earthquakes was obtained according to data of the KNET seismic stations regional network (M≥2.0) and on the ISC interactive service (M≥3.0) [7]. To characterize the seismic regime, the slope parameter of the repeatability graph (*b-value*) was used, which reflects the distribution of the earthquakes number by magnitude (M). The *b-value* parameter was estimated by the least squares method for the cumulative representation of the initial seismic data in a sliding time window of 6 months. The *b-value* parameter depends on the ratio between the number of strong and weak earthquakes and is directly related to the distribution of stresses in the Earth's crust [8].

3. Results and Discussion

3.1. Anomalous variations in the gravitational field associated with strong earthquakes

To identify gravity field anomalies associated with seismic activity, GRACE data was analyzed in the form of solutions from two analytical centers AIUB-RL02 and CNES/GRGS-RL05 (Fig. 2a). These variations reflect integral changes relative to the average gravitational field (converted to the equivalent water level above the geoid's contour, EWH) in the area of M≥5.5earthquake concentration (Fig. 1). The results presented in Fig. 2a indicate a seasonal component as a dominant part of EWH time series. They also show that the peak values of seasonal components of changes in the gravitational field are observed in spring and autumn.

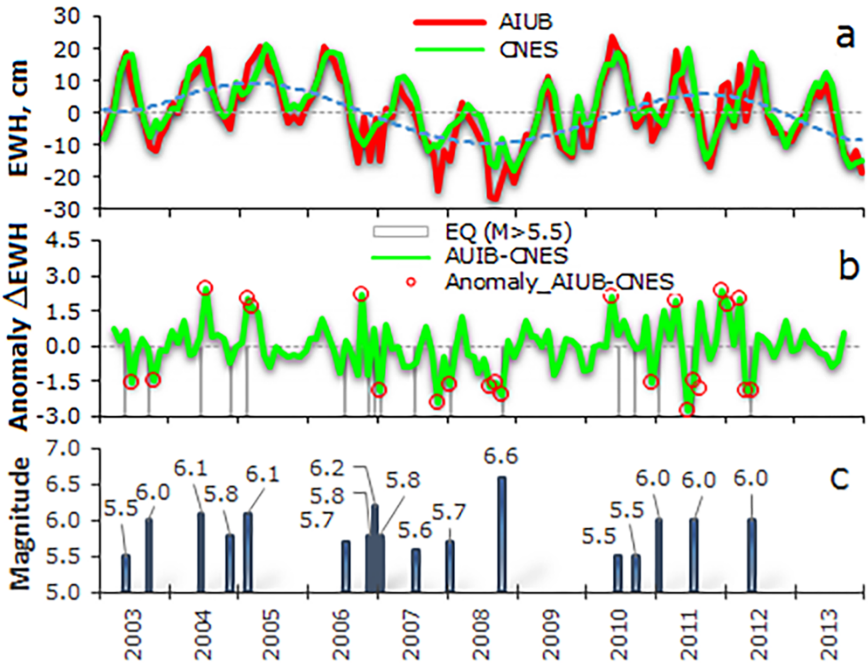

Fig. 2. Time series of gravitational field variations AIUB-RL02 and CNES/GRGS-RL05 (a), the gravitational field high-frequency component anomalies (b) and the sequence of M≥5.5 earthquake magnitudes (c) in 2003-2013

It should be noted that the models of the gravitational field provided by these research centers are obtained using different approaches to satellite observations processing, considering different numbers of spherical harmonics coefficients, and differ in the filtering method. Accordingly, in spite of obvious consistency between two GRACE time series (Fig. 2a), that have similar phases, a close amplitude and identical trend, there are some significant differences. AIUB-RL02 models have more high-frequency variations, than those of CNES/GRGS-RL05. Taking into consideration that the gravity field changes under the influence of various geophysical processes, most significant of which are conditioned by natural seasonal periodicity and interannual hydrologic changes on the Earth surface, the above specifics of the time series allow to identify the gravity field component that may be associated with seismic activity. Calculation of difference between time series of AIUB-RL02 and CNES/GRGS-RL05 (ΔEWH) allowed to exclude seasonal and trend changes while not applying traditional methods of seasonal decomposition:

$$\Delta EWH(t) = EWH_{AIUB}(t) - EWH_{CNES/GRGS}(t) \quad (1)$$

As the AIUB-RL02 time series do not cover the whole available GRACE measurement set and contain a lesser number of monthly models than CNES/GRGS provides, comparison results for the 2003–2013 period are presented. Within the assumption of normal distribution of ΔEWH with an average value of μ(ΔEWH) and the standard deviation of σ(ΔEWH) the anomality of the selected gravity field irregular constituent of ΔEWH (Fig. 2b) was determined according to the condition of δEWH values overrunning of the ±1.34σ interval limits in accordance with the expression presented in the [9] paper. In this case the level of confidence was 82%:

$$\delta EWH(t) = [\Delta EWH_i(t) - \mu(\Delta EWH)] / \sigma(\Delta EWH) \quad (2)$$

Analyzing the EWH variations, it can be seen that sharp anomalous changes of δEWH are simultaneous with most major earthquakes (M≥5.5), occurred in the territory under consideration, or precede them by a month (Fig. 2c). It allows to conclude that the observed anomalies of the gravity field were of seismic origin. The differently directed nature of δEWH is probably conditioned by pre- and coseismic mass deformations and redistribution, emerging in a density inhomogeneous geologic environment due to formation of areas of higher and lower stresses.

Preliminary analysis of the results showed obvious relation between δEWH gravity field anomalies and M≥5.0 earthquake magnitude. For negative anomalies we obtained a higher correlation coefficient equal to ~0.55.

3.2. Long-Period Changes in the Gravitational Field

Despite the limited duration of the GRACE mission, the results of satellite observations allow us to analyze variations in the gravitational field, the period of which exceeds 12 months. Fig. 3a shows the EWH variations smoothed with a moving average over a time window of 12 months with a time shift of 1 month and a polynomial of the 6th degree.

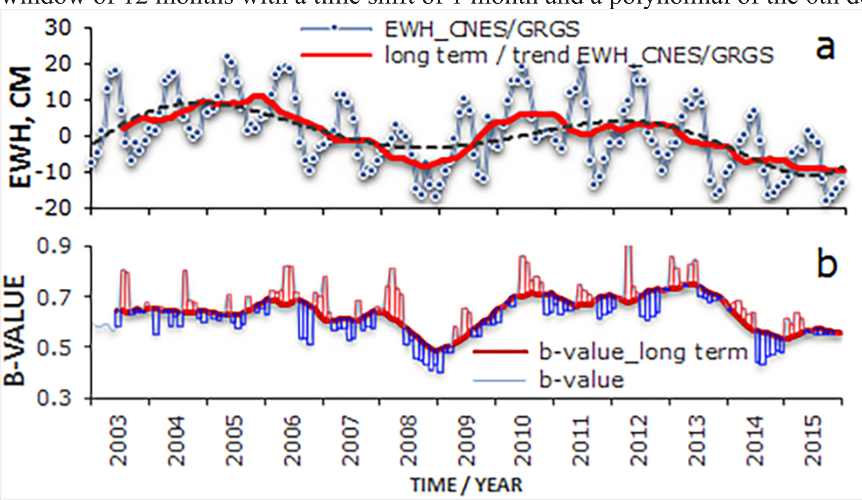

Fig. 3. Long-period / trend changes of EWH (a) and the b-value parameter (b) in 2003-2015

The feature of the identified long-period EWH variations is a significant unevenness of the change over time with a pronounced decreasing trend in 2007–2008 and 2014–2015. These time intervals were characterized by maximum decreases in the density of the geological environment, which is probably due to a high level of seismicity and, consequently, changes in the stress-strain state of the geological environment. Activation of the seismic mode corresponds to a decrease in the slope of the repeatability graph to

~0.45–0.50 (Fig. 3b). Periods of relatively weak seismicity without strong M≥6.0 earthquakes in the study area, such as in 2010, were characterized by higher *b-value* parameters of ~0.65–0.70. The minima in the equivalent water level changes and slopes of the earthquake recurrence graphs (*b-value* parameter) corresponded to periods of regional seismicity enhancement and coincided with the major Nurinsk earthquake (magnitude M=6.6; October 10, 2008) and the seismic event with M=6.5 magnitude that occurred in December 07, 2015.

3.3 The Spatial Distribution of the Gravitational Field Anomalies

Along with temporal changes, the spatial distribution of the gravitational field during periods of seismic activity plays an important role. The main focus in this regard was on the study of the most powerful earthquakes gravitational effects that were observed during the GRACE mission. One illustrative example is the time interval from October 2006 to January 2007, during which 7 earthquakes of M>5.0 were registered (Fig. 4). Over several months, starting in September 2006, slow changes in EWH (GFZ-RL06) gradually focused near the epicenter of the upcoming strong seismic events: November 8, 2006 (M=5.8), December 25, 2006 (M=6.2) and January 8, 2007 (M=5.8) (Fig. 2c).

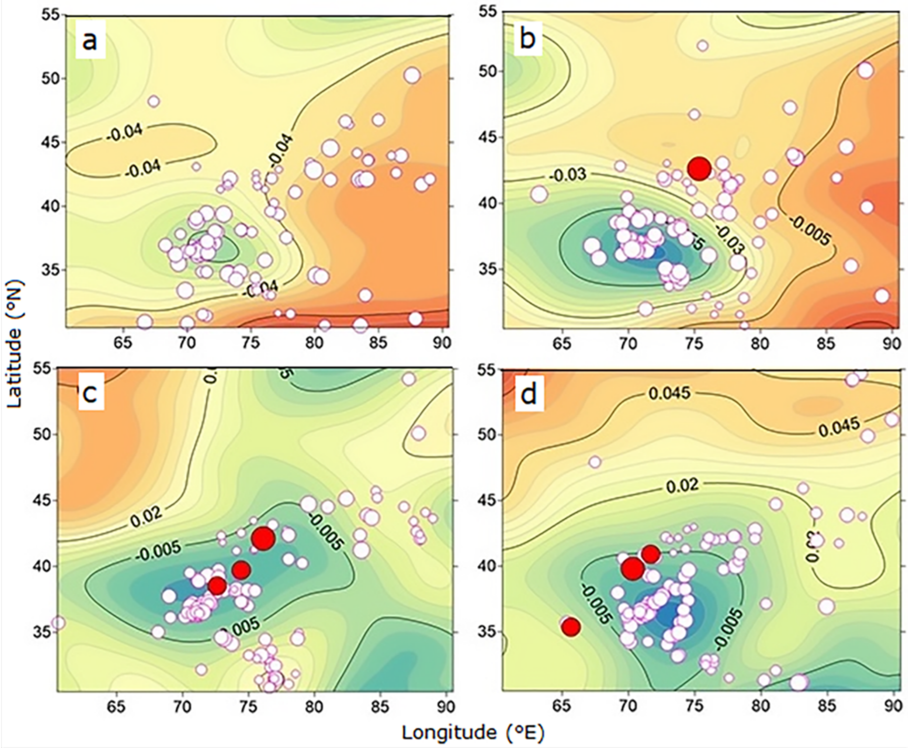

Fig. 4. Evolution of the gravitational field spatial distribution and seismicity in October (a), November (b), December (c) 2006 and January 2007 (d)

Gravitation field anomalies of seismic origin are usually associated with the displacement of the density boundaries and the effect of changes in density as a result of deformation (dilation, changes in the porosity structure) [10]. It can be assumed that the negative anomaly of the gravitational field observed in the junction zone of the Pamir and Tien-Shan, was associated with changes in the stress-strain state of the entire seismogenic region. Comparison of the gravitational field distribution with the location of M≥3.0

earthquake epicenters allows to conclude that the overwhelming number of events that occurred during the month spatially coincided with the anomalous zone EWH, which is characterized by a deformation process that increases the porosity (decompression) of the geological environment.

Similar results were obtained when constructing difference maps of the spatial distribution of gravitational field anomalies, at each point (pixel) of which the gravitational field value of the month of previous year was subtracted from the EWH values of the current month. Epicenters of major events also coincided with anomalous areas of decreased EWH values.

4. Conclusion

In this study, based on retrospective data from GRACE satellite measurements (2003-2015), we analyzed the dynamics of long-term changes in the gravitational field, presented in terms of the equivalent water level average monthly values above the geoid contour, and the relationship of these variations with the seismic process in the Pamir and Tien Shan territories. The research results allow to draw the following conclusions:

1. Studies of the earthquakes gravitational effects based on the use of various GRACE models allow to identify the gravity field component (ΔEWH), which may be associated with seismic activity.
2. The correlation between changes in the gravitational field and the geodynamic process as well as the probable seismic origin of positive / negative ΔEWH anomalies due to the redistribution of masses in the lithosphere during the preparation and passage of large regional (M≥5.5) earthquakes is established.
3. The spatial distribution of seismogenic zones coincides with the regions of negative anomalies of the gravitational field, which can be explained by the dynamics of lithosphere decompression.
4. The consistent behavior of long-term time series of equivalent water level (EWH) and the slope of the earthquake recurrence graph (*b-value*) reflects the intensity of geodynamic processes in a seismically active region.
5. The threshold for detecting gravitational effects of earthquakes is probably lower than the generally accepted level of magnitudes (M>7.5).

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