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SATELLITE MONITORING AND SEISMIC ACTIVITY OF THE NORTH-WEST OF RUSSIA

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Abstract. Results of GNSS observations (global navigation satellite system GPS/GLONASS) in 2006–2018 in the study of the modern intraplate geodynamics of North-West of Russian Federation are analyzed.

In the study of modern movements and deformations of the Earth's crust, the data of repeated satellite measurements carried out by the staff of the IPE RAS in Karelia, Leningrad region, as well as measurements from 20 permanent stations of the International geodynamic network were used. In addition, the data obtained at the new geodynamic polygon located in the Kandalaksha Bay area, where several cycles of repeated measurements have been carried out since its foundation in 2015, are considered.

Repeated GNSS measurements confirmed that dome-shaped lifting, confined to the Baltic shield, continues with a velocity 10.4 mm/year. Within the Russian part of the territory the rate of uplifting reaches 6 mm/year. Horizontal displacements of GNSS stations in the ITRF have the North-East direction and average velocities (according to approximated data for 2006–2018) from 19.9 mm/year in the north to 23.9 mm/year in the south. The deformation field of the region is non-homogeneous, the extended compression and extension zones replace each other, with values from $(-0.8)\cdot10^{-8}$ to $1.6\cdot10^{-8}$.

According to the earthquake catalogue for the period 2000–2018, the seismic energy flux (P_E) released as a result of local tectonic earthquakes was calculated. The distribution of velocities of seismic energy flux within the considered area is rather heterogeneous. In the western part, there is a region of meridional orientation, characterized by seismic activity up to 10^{10} J/year, confined to the extension zone with deformations up to $0.6\cdot10^{-8}$ per year. In the Ladoga-Onega region, the seismic activity zone with P_E about 10^6 J/year is extended from the South-West to the North-East and confined to the transition area of compression and extension.

The comparison of the displacements velocities, deformations and seismicity determines the quantitative characteristics of the modern geodynamics of the studied region.

Keywords: GNSS, satellite measurements, seismicity, movements, deformations, monitoring, Baltic shield, seismic energy flux.

Introduction

The presented study is a continuation of studies concerning modern geodynamics of the North-West region of Russia and adjacent territories. We use the data obtained with the help of technologies of global navigation satellite systems GPS / GLONASS (hereinafter - GNSS), which were initiated by the Institute of Physics of the Earth at the end of the last century in the framework of cooperation with foreign experts [*Prilepin et al.*, 2002; *Galaganov et al.*, 2009, 2011; *Guseva et al.*, 2016].

The study area, characterized by low seismic activity, includes the Baltic Shield, which is the protrusion of the Precambrian basement of the East European platform, and the adjacent part of the platform [*Gorshkov et al.*, 2015]. It is assumed [*Yudakhin, Shchukin, Makarov*, 2003], that tectonic seismicity occurs in those areas of the Earth's crust under intense horizontal compression is sufficient to transition of rock mass in the extremely stressed state. The study and analysis of modern movements, deformations and seismicity are necessary in the studied region to improve the safety of construction and operation of engineering facilities, including the existing and those under construction at the Kola and Leningrad nuclear power plants.

In the study of modern movements and deformations of the Earth's crust, data from repeated satellite measurements of GNSS made by the staff of the IPE RAS in Karelia (observations of 2006–2018) and the Leningrad region (observations 2007–2018), as well as measurements at twenty permanently operating stations of International geodynamic network (IGS) in Russia, Finland, Sweden and Norway is used. The study also used data from three cycles of repeated GNSS measurements carried out in 2015–2018 at the points of geodynamic test site created on the coast of the Kandalaksha Gulf to study local movements in the active graben zone.

Repeated synchronous GPS / GLONASS measurements on the regional geodynamic GNSS network of the north-west of Russia were carried out annually (or after a year) in July-August in series of 3–13 days using *Javad Maxor* dual-frequency receivers (recording interval - 30 s). As a result of processing the data of repeated measurements using the *Bernese GNSS software*, the average daily and average geocentric and geodetic coordinates of stations in the ITRF international terrestrial reference system (models ITRF 2008 and ITRF 2014) were determined for the measurement epoch.

In the calculations, four stations were taken as reference (moving in time at a constant velocity) - KIRU (Kiruna, Sweden), SVTL (Svetloye, Russia), VIS0 (Visby, Sweden), ZWE2 (Zvenigorod, Russia); the nearest *IGS* stations were included in the list of identified stations, including the permanently operating LOVJ station (“Lovozero” seismic station), established on the Kola Peninsula in 2009 and operating under the direction of G.M. Steblov. The root-mean-square random error in determining the plan coordinates in the relative reference system with four reference stations taken as fixed, averaged 0.2 mm for fixed *IGS* stations and 0.3–0.5 mm for determined ones.

The velocities of horizontal and vertical movements for different time intervals were determined in ITRF 2008. In July – August 2018, the next GPS / GLONASS observation cycle was performed at geodynamic test sites of northwestern Russia; processing of the obtained data was carried out using the *Bernese software Ver. 5.2* package in the adjusted reference coordinate system ITRF 2014.

Obtained as a result of calculating displacements of the horizontal and vertical coordinates in time relative to the initial measurement epoch, are described by a linear function with a correlation coefficient close to 1. The dispersion of the obtained values for the horizontal coordinates does not exceed 1.1 mm, for vertical coordinates - 1.6 mm. The rates of areal deformations were also calculated and compared with the rate of seismic energy flux.

Movements and deformations

The results of the linear approximation of the coordinate change values for the period of 2006–2018 indicate that the horizontal displacements of GPS points in the studied part of Eurasia occur in the northeast direction at the average velocity from 19.9 mm / year in the north of the region to 23.9 mm / year in the south (Fig. 1).

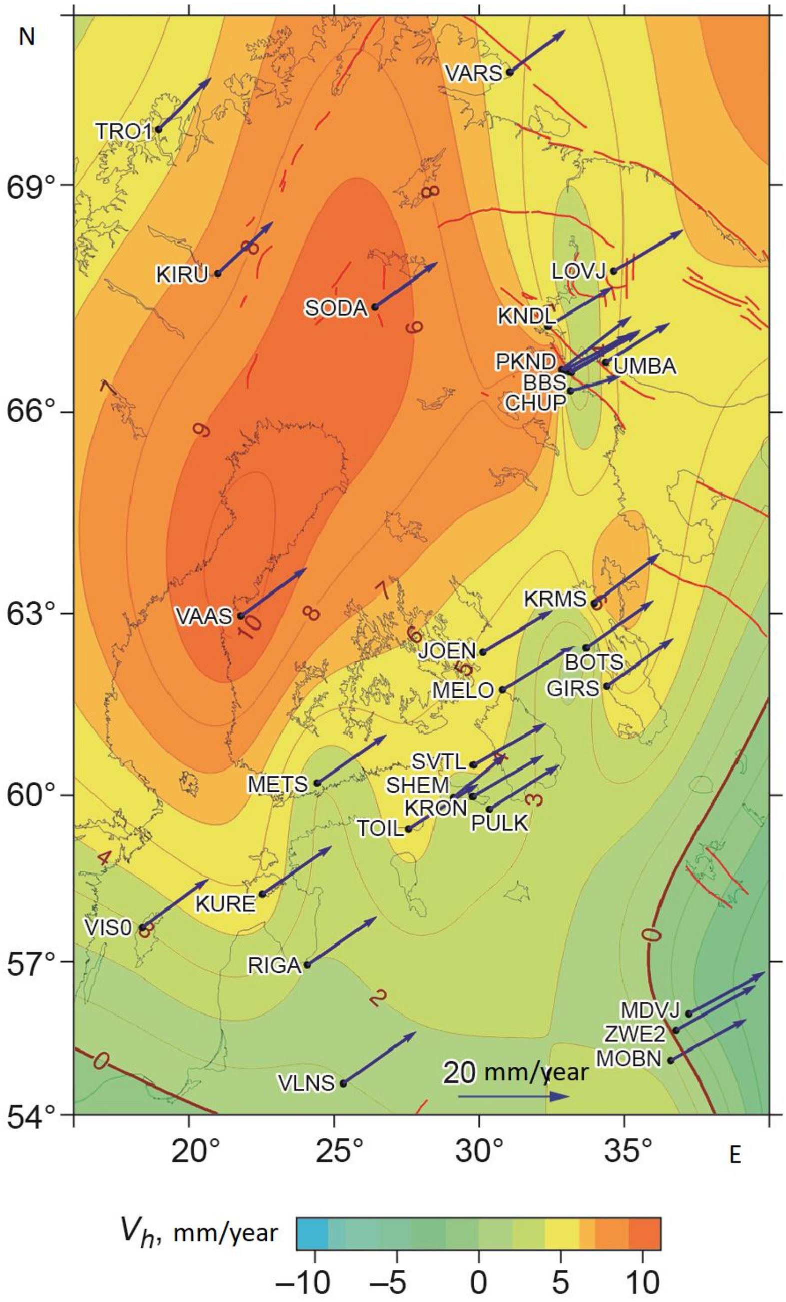

Fig. 1. Map of velocities of vertical (contours) and vectors of horizontal (arrows) movements for the period of 2006–2018 in the international terrestrial reference system ITRF. Red lines are major faults

As noted in earlier publications (see, for example, [*Galaganov et al.*, 2009, 2011; *Guseva et al.*, 2016]), vertical movements reflect the process of dome-shaped uplifting at the velocity of up to 10.4 mm / year (at the Russian territory no more than 5-6 mm / year). The recorded lifting rates according to GNSS measurements are comparable with the results of repeated gravimetric measurements of gravity acceleration [*Kaftan, Mäkinen,* 2019]. The velocity values of horizontal movements, determined by the ITRF model, largely reflect the movement of the Eurasian tectonic plate.

To estimate the values of horizontal movements within the studied region, displacements were calculated relative to the KIRU station located in the northwest of the studied area (Fig. 2). It can be seen that the rates of horizontal displacements predominantly have south-eastern direction, ranging from 0.8 mm / year in the northwest to 5.8 mm / year in the south-east.

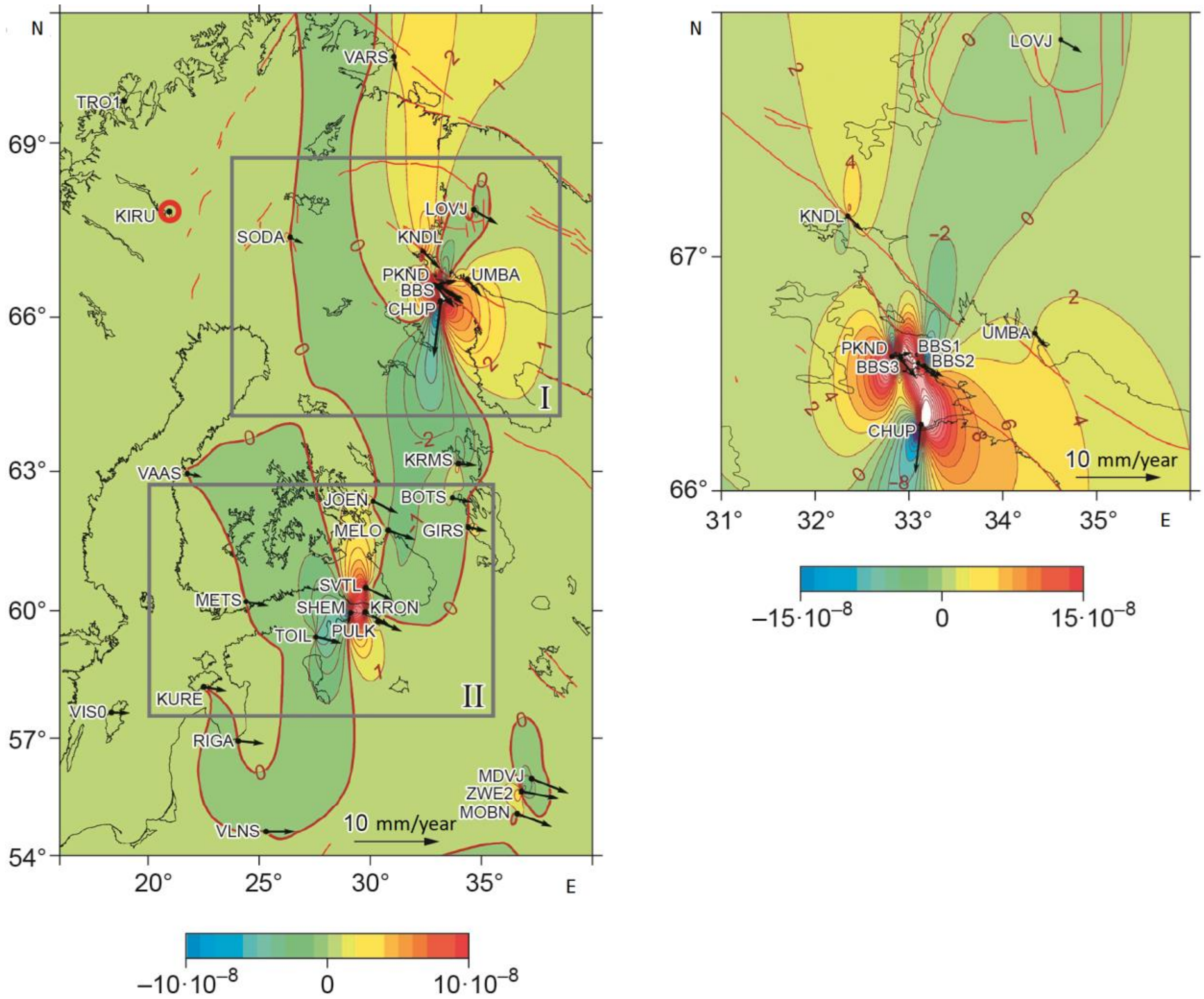

Fig. 2. Map of the velocities of areal deformations (contours) and the velocity vectors (arrows) of horizontal displacements relative to the fixed point KIRU (marked as a red circle) for the North-West part of Russia (*on the left*, observations 2006–2018) and for the Kandalaksha Bay area on a larger scale (*on the right*, observations 2015–2018). Here and in Fig. 4 blue-green shades – compression mode, yellow-red – extension mode. Contours I and II are the boundaries of the sections for which a comparison of seismic energy flux with deformations is shown below

Using the coordinates of the points and the rates of their change, the first deformation tensor invariant is calculated to determine the compressive and tensile deformations for the considered time interval. In this case, the initial measurements were interpolated onto a uniform grid with a small step, after which the spatial differentiation of the components of the vector field was performed according to the finite-difference scheme.

The deformation field of the region is uneven, and the extended compression and extension zones replace each other. Deformation values vary from $–0.8{\cdot}10^{–8}$ to $1.6{\cdot}10^{–8}$ per year (see Fig. 2). Anomalous manifestations of the deformation field were revealed for the coast of the western part of the Gulf of Finland and the coast of Kandalaksha Gulf (see Fig. 2, *on the right*).

Seismicity

To evaluate the seismic activity of the studied region, the data from the earthquake catalog provided by the Kola Branch of the Unified Geophysical Survey of the Russian Academy of Sciences and the catalog of the US Geological Survey were used. In 2000–2018 within the considered territory, 192 seismic events with magnitudes M_s=0.7–4.1 occurred. Basically, these were weak events with magnitudes up to 3.3, except for nine earthquakes with M_s from 3.5 to 4.1. The calculation of seismic energy released as a result of earthquakes was carried out using software developed by the authors. To compare the deformation of the territory with seismic activity, we used the parameter of the amount of released earthquake energy (E), calculated from the Guttenberg – Richter relation lg$E$=1.5M_s + 4.8.

The territory was divided into cells of 10 thousand km^2 and for each of them the seismic energy of all earthquakes during 2000–2018 was summarized. The obtained total values are assigned to the center of each cell. Thus, the seismic energy flux P_E, J / year [*Tarasov*, *Tarasova*, 2011, 2019] was calculated. The areal distribution of seismic energy flux is shown in Fig. 3.

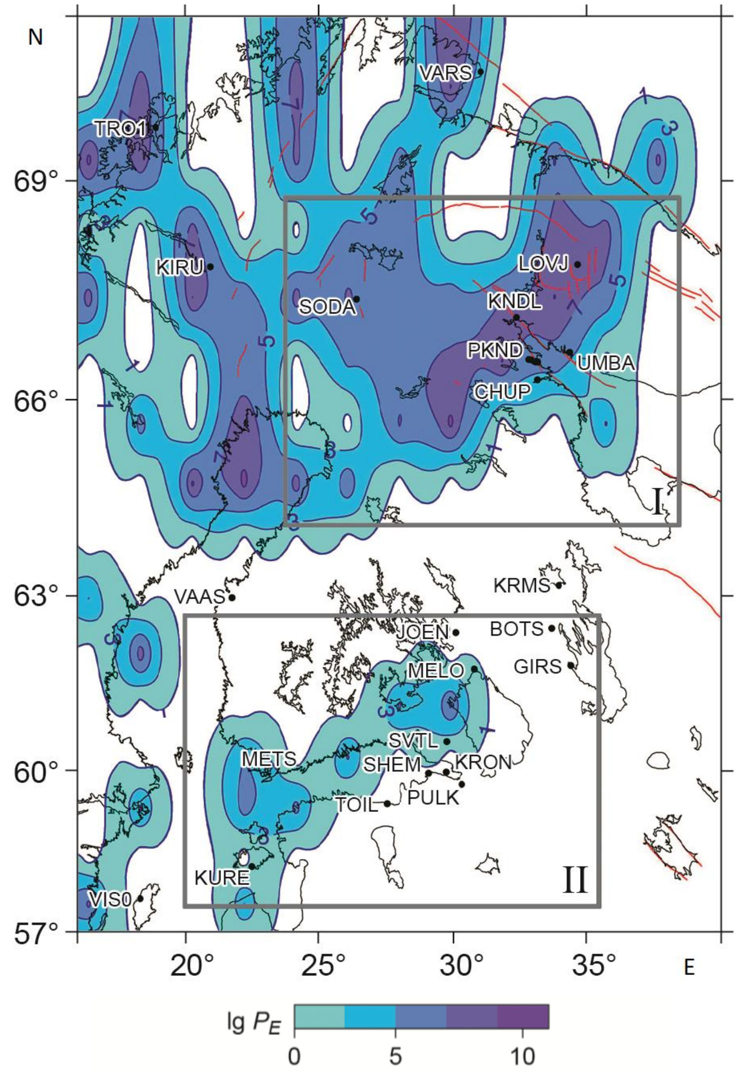

Fig. 3. Distribution of seismic energy flux P_E, J/year for 2000–2018. Contours I and II are the boundaries of the sections for which a comparison of seismic energy flux with deformations is shown below: I – Kandalaksha Bay area, II – Baltic-Ladoga region

As can be seen in Fig. 3, the distribution of the flux of seismic energy within the considered region is heterogeneous. A greater intensity of seismic manifestations is characteristic of the dome-shaped uplifting of Fennoscandia. In the west, seismic activity is manifested in the form of an ordered chain of fragments of meridional orientation with P_E values up to 10^{10} J / year; one of them is confined to the zone with an extension of $0.6{\cdot}10^{-8}$ per year. The deformation of the territory was compared with the average annual flow rates of seismic energy P_E.

Fig. 4, *above* presents the comparison of the areal distribution of average annual deformation values and seismic energy flux for the Kandalaksha Bay area (contour I in Fig. 3), and *below* for the Baltic-Ladoga region (contour II in Fig. 3). In the first case (the Kandalaksha Bay area), the increased seismic activity accompanied the abnormal manifestation of deformation field. The Baltic-Ladoga region of seismic activity (see Fig. 4, *below*) calls attention to itself, elongated in space from the southwest to the northeast, where the average annual changes in the flux of seismic energy P_E reach 10^6 J / year. This region is characterized by a transition from compressive deformations to tensile deformations. Here, an incomplete coincidence of anomalous tensile deformation and increased changes in the flux of seismic energy can be noted.

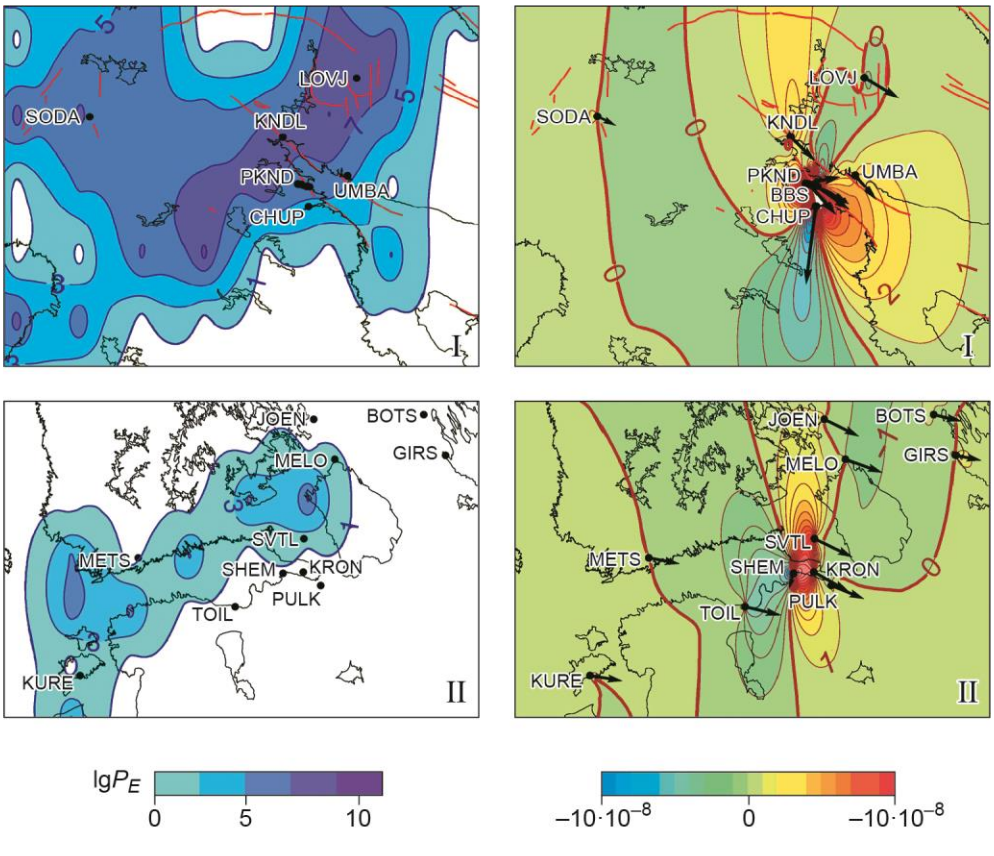

Fig. 4. Comparison of the results obtained for the Kandalaksha Bay region (*above*) and the Baltic-Ladoga region (*below*): *on the left* is the distribution of seismic energy flux in J/year; *on the right* is the distribution of deformations. Other symbols correspond to Fig. 1, 2

Conclusions

The results of the studies using GNSS technology and seismicity analysis allow us to evaluate the recent tectonic activity of the Russian part of Fennoscandia and the features of its manifestation in the first twenty years of the current century.

The dome-shaped uplifting of the Baltic Shield continues with the rate of up to 10.4 mm / year. Within the Russian territory, the rate of rise reaches 6 mm / year, which is confirmed by the decrease in the values of the acceleration of gravity according to gravimetric measurements.

The horizontal displacements of GNSS points occurring in the northeast direction with the average velocity from 19.9 mm / year in the north to 23.9 mm / year in the south reflect the general character of the movement of Eurasia according to the ITRF model. Local intraplate horizontal displacements in the southeast of the region under consideration reach 5.8 mm / year relative to the point in the north assumed as a fixed.

The method used to analyze the deformation of the Earth's crust revealed the presence of alternating zones of extension and compression with deformation values from $(–0.8)\cdot10^{–8}$ to $1.6\cdot10^{–8}$ per year.

The manifestation of seismicity within the territory under consideration is heterogeneous – there are areas that are confined both to zones transitioning from extension to compression, and to zones of extension. In the west, an area of meridional orientation is distinguished with annual average changes in the seismic energy flux P_E reaching 10^{10} J / year, confined to the extension zone with deformations up to $0.6\cdot10^{–8}$ per year. The Baltic-Ladoga region of seismic activity with P_E~10^6 J / year, elongated from southwest to northeast, is confined to the area with the change in compression – extension and marks the transition zone from the dome to the platform.

The proposed comparison of rates of displacements, deformations and seismicity determines the quantitative characteristics of the modern geodynamics of the region under consideration for the specific time interval.

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