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# Fennoscandian uplift study as an example of Russian-Finnish cooperation in Arctic geodesy (Advisory)

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**Abstract.** Today, the Arctic region is a fertile place for international scientific cooperation in the field of earth sciences. A positive example of such cooperation is a bilateral Russian-Finnish study in the field of geodesy carried out over two decades. The main object of the joint Russian-Finnish research is the post-glacial uplift of Fennoscandia. As a result of joint research, estimates of the velocities of the vertical movements of the earth's crust in the Northeast part of the region have been obtained. Regional map of the recent vertical crustal movement is compiled. The results obtained are compared with the existing geophysical models and estimates of other authors. High-precision absolute measurements of the acceleration of gravity contribute to the independent control of the estimates of the speeds of the post-glacial uplift. Much attention is paid to the metrological control of

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measuring equipment. Bilateral and 1multilateral comparisons of absolute gravimeters are periodically performed. The paper briefly reviews the work carried out and the results obtained. International cooperation is expected to continue.

## Introduction

One of the most interesting natural processes in the European Arctic is the post-glacial rebound (PGR) of Fennoscandia. It is occurring due to the cessation of the ice age in this region, which has started more than 10 thousand years ago, the melting of the ice sheet and the resulting removal of ice loads from the earth's crust. The research of this phenomenon go back three centuries of history. Scientists from Russia, the Scandinavian and Baltic countries and from all over the world have studied this process in depth and in detail.

For a long time, rather little has been known about the contemporary rates in the region of the Kola Peninsula and in Eastern Fennoscandia. At the beginning of this century, Finnish and Russian geodesists organized joint studies of this territory within the framework of the program of bilateral scientific cooperation between the Finnish Geodetic Institute (now the Finnish Insti-

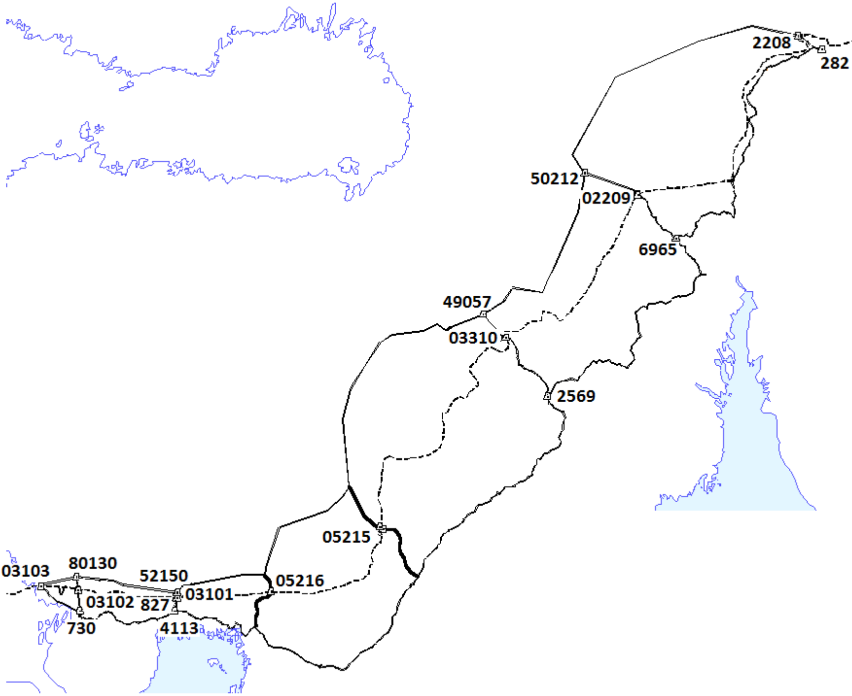


**Figure 1.** Circuit closures of Russian-Finland leveling connections.

tute of Geospatial Research) and the Central Research Institute of Geodesy, Aerial Survey and Cartography of Russia (now the Federal Scientific Research Center of Geodesy, Cartography and SDI).

Studies were conducted by investigating the vertical movements of the earth's crust using repeated high-precision leveling, as well as repeated absolute grav-

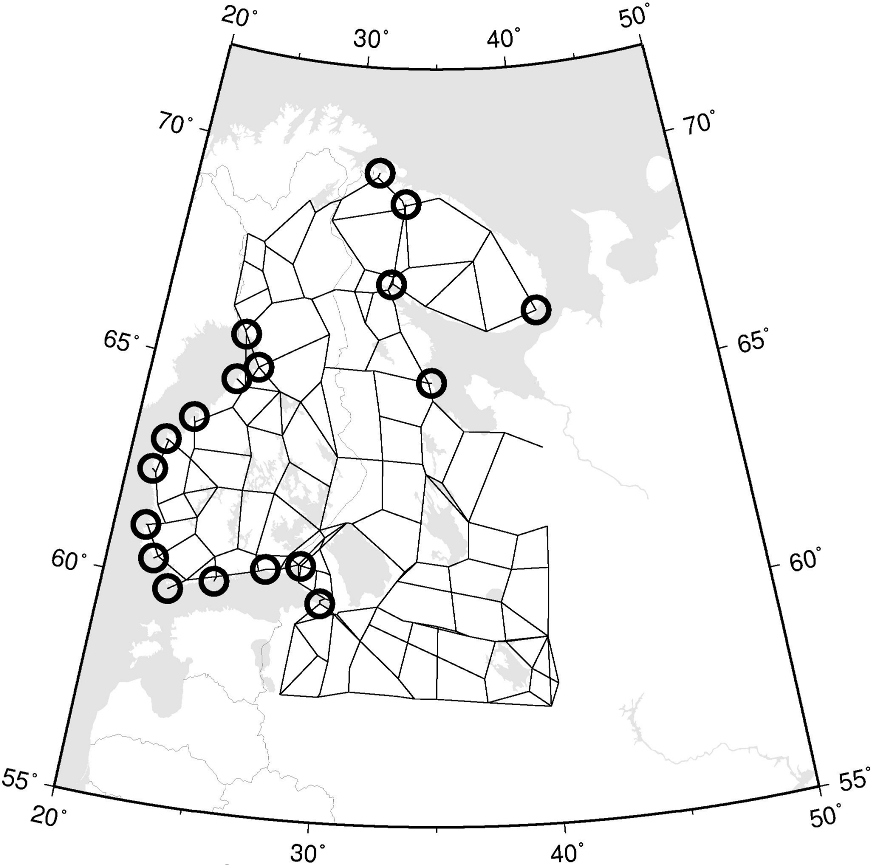


**Figure 2.** The total levelling network and the tide gauges (open circles). In this paper only the Baltic tide gauge rates are used. For the purposes of the adjustment, the a-priori standard error of 0.5 mm/year was assigned to them. The presentation of the network is schematic, straight lines connect the nodal points.

ity measurements. Important elements of the research were also bilateral and multilateral comparisons of absolute gravimeters at points of state gravimetric networks in order to reliably estimate the accuracy of gravity measurements.

## Leveling Network Combination and Vertical Movement Analysis

To determine the vertical movements of the earth's crust, the national leveling networks of the two states were united by seven leveling connections across the Russian-Finnish state border [*Takalo et al.,* 2006]. The discrepancies between the elevations of the two sides transmitted across the border did not exceed 0.1 mm. The border leveling circuits are shown at Figure 1. As a result, an integrated network of highest-order leveling of Finland and leveling of I and II orders of Russia of 42 level polygons was formed (Figure 2).

The largest time span of the leveling repetitions was obtained within 1937–1991. The velocities of the vertical movements were obtained within the specified interval. The length of the leveling lines was equal to 11.6 thousand km (Russia) and 7.9 thousand km (Finland).

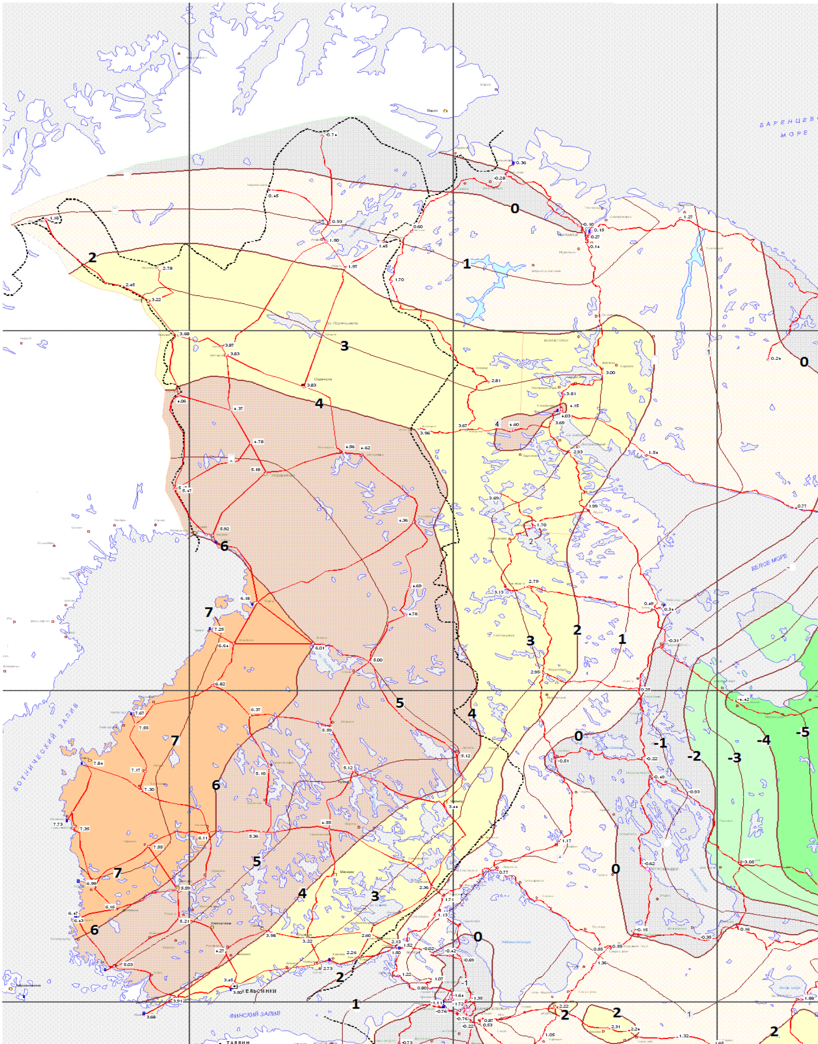


**Figure 3.** Map of the velocities of the vertical recent crustal movements of the region compiled by TsNIIGAiK. Interval between isolines is 1 mm/yr.

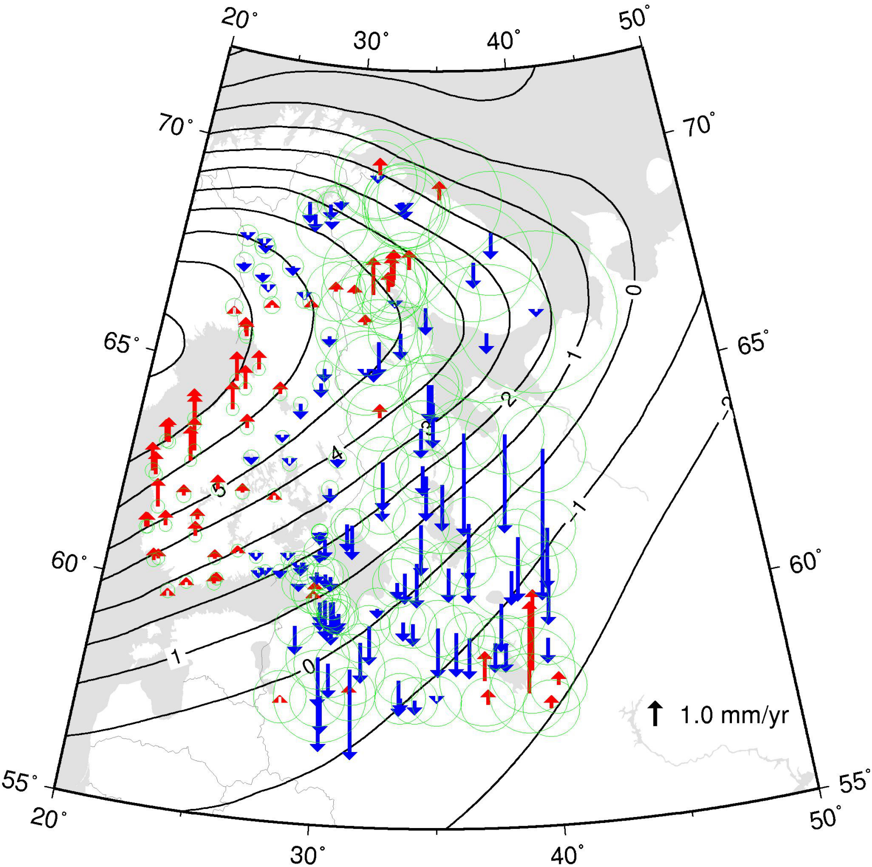


**Figure 4.** The arrows give the residuals of our result w.r.t. the model of Glacial Isostatic Adjustment (GIA) by *Lambeck et al.* [1998]. The isolines were digitized from the paper. The −2 mm/year isoline is our own extrapolation Most of our TG rates were used in the construction of the GIA model. The green circles show our formal 1-sigma error estimates.

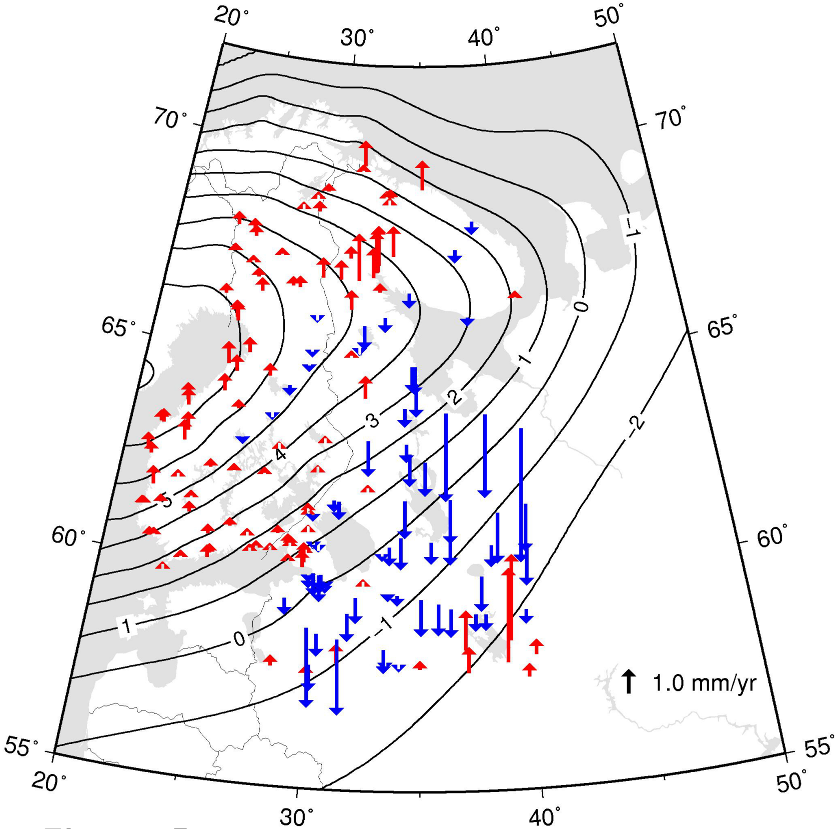


**Figure 5.** The same rates as in Figure 2 but residuals are w.r.t. to the hybrid model of vertical motion NKG2005LU (version NKG2005LU_app relative to MSL) by *Vestol,* [2006] and *Agren and Svensson* [2007]. The NKG2005LU merges results from TGs, repeated levelling and continuous GPS in Finland and other Nordic counties with the *Lambeck et al.* [1998] isolines in the east. The Finnish repeated levelling and TG data (same as ours) was used in the construction of the model.

To determine the velocities of vertical movements, sea level observations were used at the tide gauges of the Baltic, Barents and White seas. The joint adjustment of the re-leveling using tide gauges was carried out according to a specially developed technique that takes into account time-varying and two or three repetitions of the leveling. The adjustment algorithm is based on the application of the combined observation equations to the measured elevations taking into account the velocities and accelerations of the vertical movements of the earth's crust. As a result, maps of the vertical movements of the crust of the region were obtained. The rates of vertical movements were obtained in the range from $-5$ to 7 mm/year. Accuracy of determining velocities according to estimates from adjustment is obtained equal to 1.1 mm/km for Finnish and 1.9–2.7 mm/km for I and II classes of Russian leveling, respectively. The regional vertical earth crust velocity map (Figure 3) is the result of Russian-Finnish leveling study.

The FGI in its processing used three precise levellings of Finland with observation epochs ranging from 1892 to 2006. Based on a variance component-estimation [*Mäkinen and Saaranen,* 1998], the following a-priori standard uncertainties were applied: 2.0, 0.6, and 0.9 mm

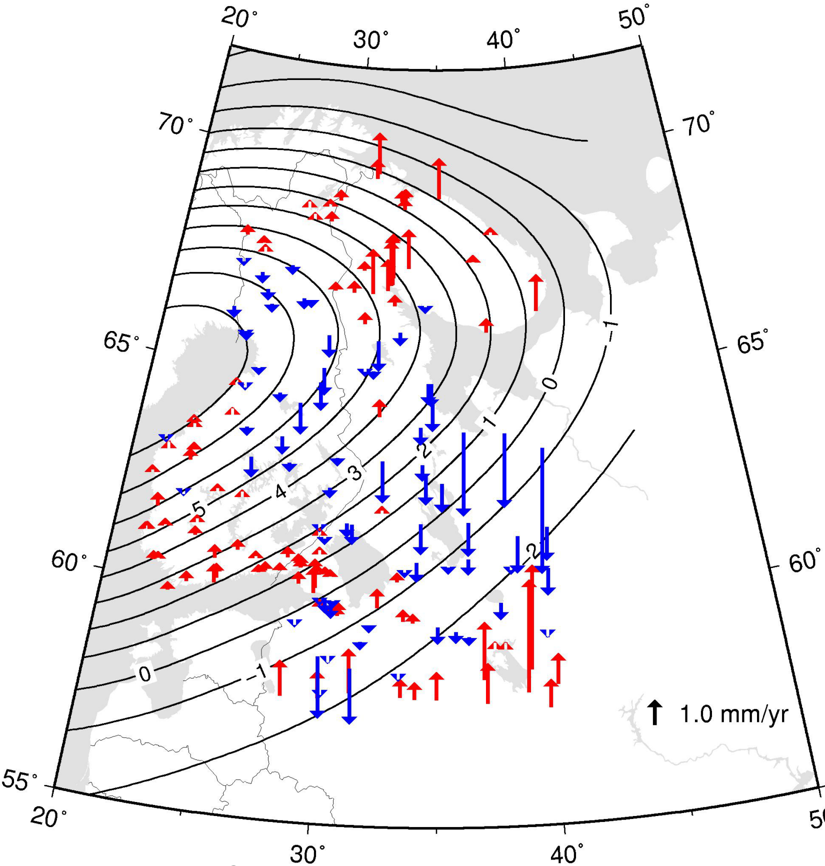


**Figure 6.** The same rates but residuals are now relative to the GIA model by Milne et al. (2001). The "absolute" GIA rates relative to the Earth's center of mass were converted to rates relative to MSL assuming a geoid rise of 6% of the absolute rates and a MSL rise of 1.3 mm/yr (1892–1991).

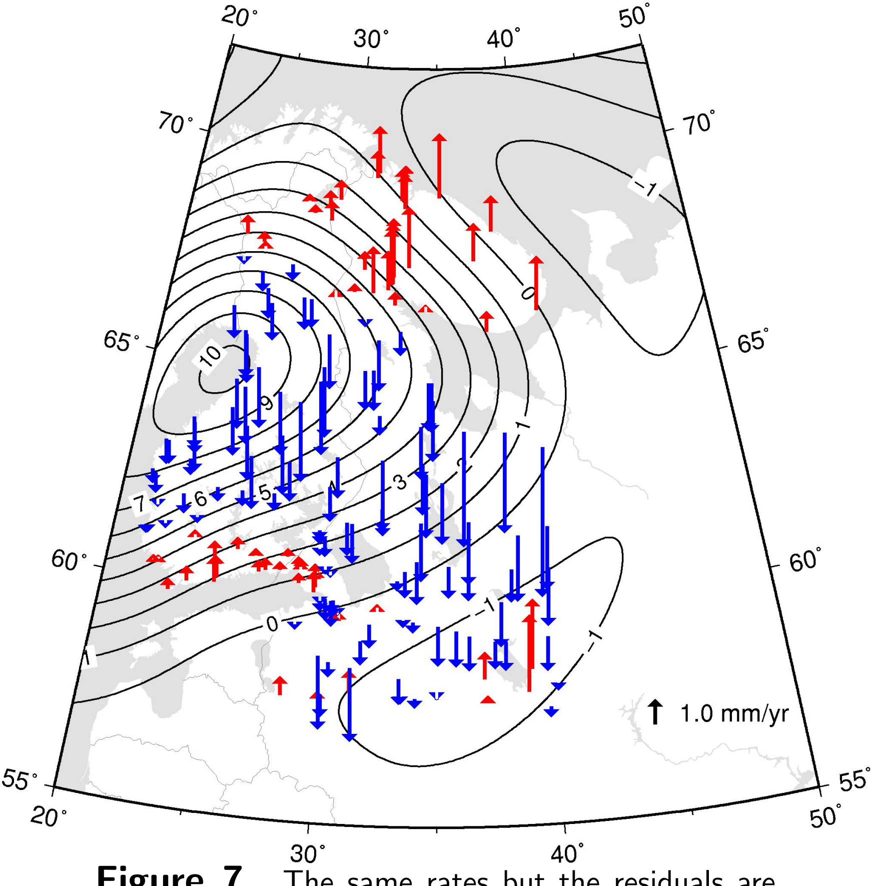


**Figure 7.** The same rates but the residuals are here relative to the GIA model ICE-5G (VM2) by *Peltier* [2004]. Same conversion as in Figure 6.

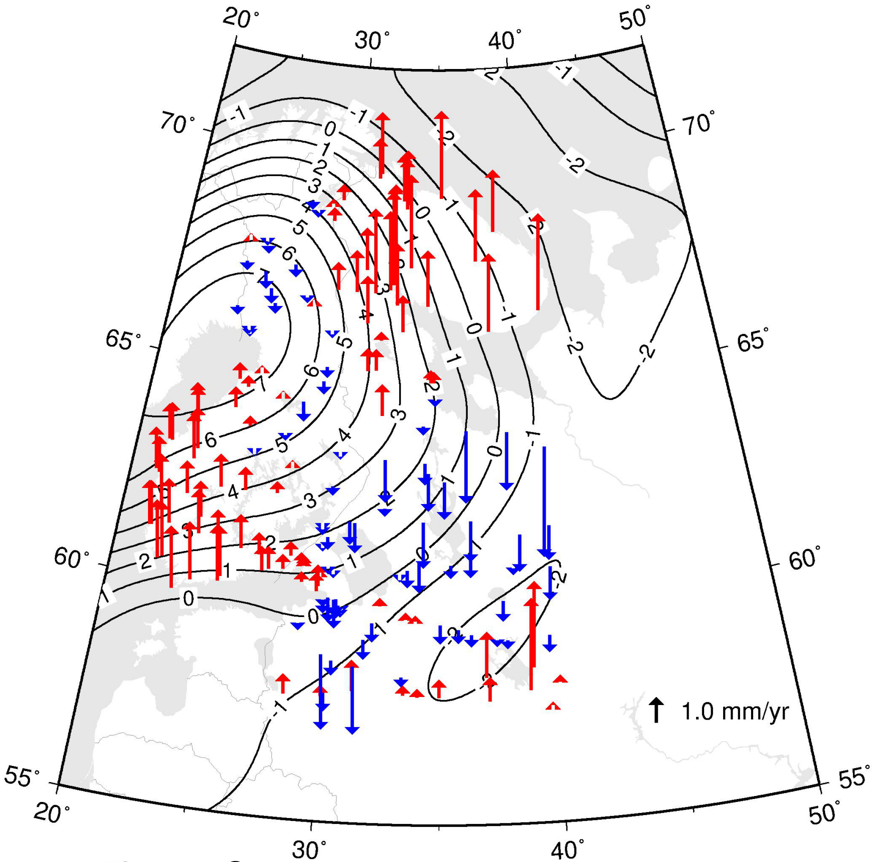


**Figure 8.** The residuals are relative to the GIA model ICE-6G_C (VM5a) by *Argus et al.* [2014] and *Peltier et al.* [2015]. From model rates relative to the geoid 1.3 mm/yr was subtracted to account for the rise in MSL (1892–1991).

for the lines of the First, Second, and Third levelling, respectively. The vertical velocities were referred to rates relative to the mean sea level for the period 1892–1991 using the methods and in part also the results by *Ekman* [1996]. All tide gauge rates were assigned the a-priori standard uncertainty 0.5 mm/yr. The standard error of weight unit from the adjustment was 1.1. The formal a-posteriori standard uncertainties of the vertical velocities are shown in Figure 4. It is the same for Figure 4–Figure 9.

There are several models of the postglacial rebound (PGR) of Fennoscandia (Figure 4–Figure 9). Originally [*Mäkinen et al.,* 2008b] we used the geophysical models by *Lambeck et al.* [1998], *Milne et al.* [2001], and the ICE-5G (VM2) by *Peltier* [2004]. These are comprehensive models of the process of glacial isostatic adjustment (GIA) and predict, among other things, vertical velocities. In addition, the kinematic model NKG2005LU of vertical velocities by *Vestol* [2006] and *Ågren and Svensson* [2007] was applied. In it, empirical velocities from GNSS, tide gauges, and precise levelling were complemented by the geophysical model by *Lambeck et al.* [1998] in areas of missing empirical data.

Since 2008, many new PGR models have been published. Of particular interest are the GIA model ICE-

6G_C(VM5a) by *Argus et al.* [2014] and *Peltier et al.* [2015] in Figure 8, and the new hybrid model NKG2016LU (Figure 9). The hybrid model is based on the merging of the GIA model of *Steffen et al.* [2016] with observed contemporary vertical velocities [*Vestol et al.,* 2006]. In Northwest Russia the NKG2016LU is based on the GIA model only.

When comparing our velocities with the PGR models the references of the velocities must be taken into account. The model by *Lambeck et al.* [1998] and the NKG2006_app have the same MSL reference as our velocities ("apparent uplift"). The results we have from *Milne et al.* [2001] provide the velocity relative to the Earth's center of mass ("absolute uplift") as does the ICE-5G(VM2). We have used a geoid rise of 6% of the absolute rates and a MSL rise of 1.3 mm/yr (1892–1991) to convert them to apparent land uplift. For the NKG2016LU and the ICE-6G_C(VM5a) we have used the versions relative to the geoid and subtracted 1.3 mm/yr. In all cases (Figure 4–Figure 8) we plot the isolines after the conversion, for direct comparability.

There are appreciable differences between the PGR models which is visible in their comparison to our velocities [*Mäkinen et al.,* 2008c]. The best consistency was obtained with respect to the NKG2016. In Fin-

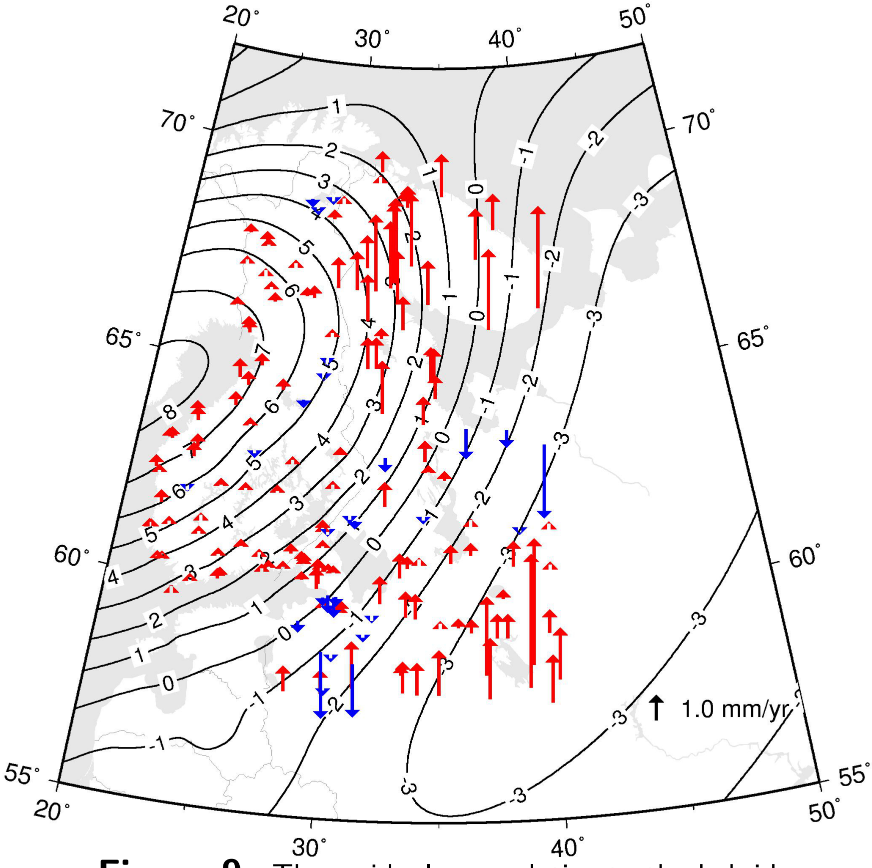


**Figure 9.** The residuals are relative to the hybrid model NKG2016LU (version KG2016LU_lev relative to the geoid). We have subtracted 1.3 mm/yr to account for the rise in MSL (1892–1991).

land its fit is very good which is largely explained by the fact that it uses the same repeated levelling data as we. In the territory of Karelia its fit is reasonable but discrepancies remain in the south and in the Kola Peninsula. A possible explanation for this effect may be the influence of exogenous factors on the stability of leveling benchmarks in sediments and non-solid rocks. This requires further investigation.

## Gravimetric Studies

An independent method for estimating the rates of vertical movements is to re-determine the acceleration of gravity, which should decrease on the earth's surface as it rises. To take an example, in the central area of the regional uplift (in Finland and Sweden) where the rebound rates are of the order of 10 mm/yr, absolute measurements of gravity have been repeated for up to 30 years already. Maximum rates of gravity change at the different stations are $-1.5$ to $-2$ $\mu$Gal/yr with a standard uncertainty of 0.1–0.2 $\mu$Gal/yr. This is in good agreement with vertical velocities according to GNSS data, repeated leveling, and tide gauges. Recently, a comprehensive summary of the absolute-gravity results in the Nordic and Baltic countries was

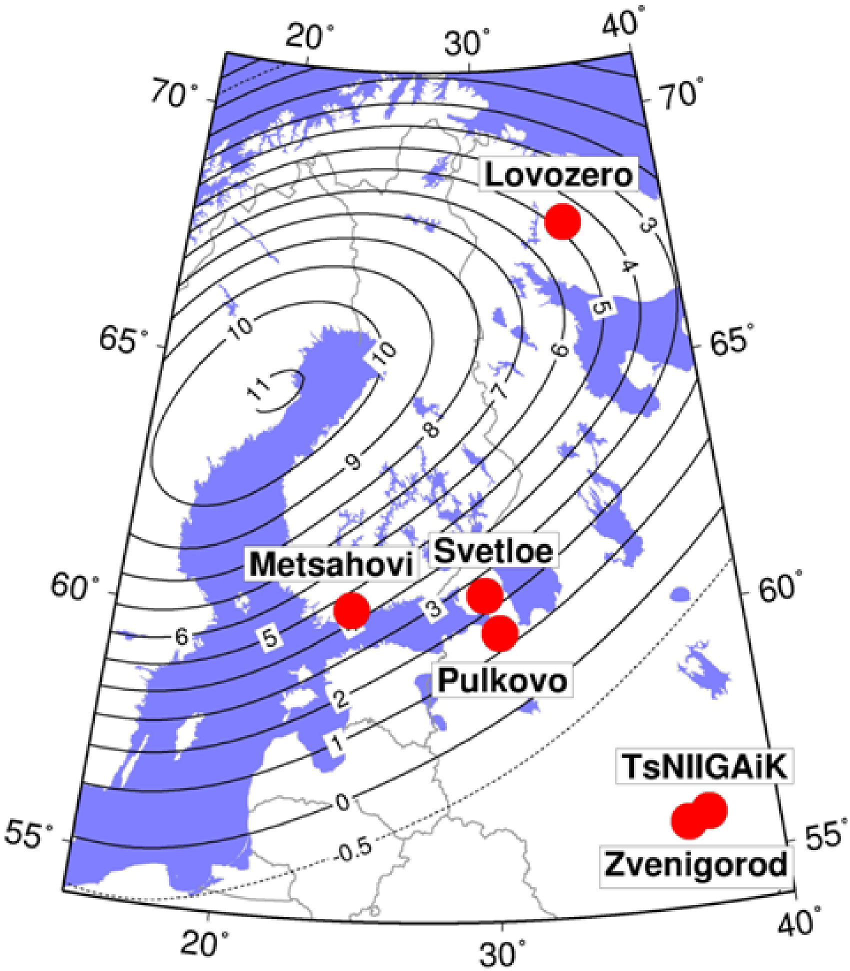


**Figure 10.** Absolute gravity stations of the Russian-Finnish geodetic study.

published by *Olsson et al.* [2019].

International comparisons of absolute gravimeters were carried out to assess their metrological characteristics at Russian (Pulkovo, Svetloye, Lovozero, Zvenigorod, TsNIIGAiK) and Finnish (Metsähovi) reference gravimetric sites [*Mäkinen et al.,* 2008a, 2016]. Gravimeters FG5 (manufactured in the USA, Micro-g Lacoste), GBLP 001, GBL-M 002, GABL-PM, GABL-M (made in Russia, IAE SB RAS) participated in the comparisons. The new ballistic gravimeter GABL-M was tested especially in the Arctic conditions [*Yushkin et al.,* 2012]. The comparisons were purposefully carried out at sites (Figure 10) with different physiographic conditions [*Mäkinen et al.,* 2016]. Metrological estimates of the accuracy of all types of gravimeters were obtained and the levels of their accuracy and the possibility of using them in precision measurements were confirmed.

# Conclusion

Joint Russian-Finnish studies of the Fennoscandian uplift have demonstrated considerable potential for scientific cooperation in the Arctic region and adjacent territories. Repeated leveling in the north-west of Russia could fruitfully complement the so-called Baltic Leveling Ring [*Mäkinen et al.,* 2006]. In this case, a network of regional observations of the postglacial uplift would be a more complete and perfect geodetic construction. Repeated absolute determinations of gravity are expected to continue in order to supplement the overall composition of the research with new high-precision data.

In recent years, the Russian-Finnish cooperation continues the study of the metrological characteristics of precision absolute gravity meters and the development of technologies for the creation of state and international gravity reference frames.

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# References


Agren, J., R. Svensson (2007) , Postglacial land uplift model and system definition for the new Swedish Height System RH 2000. Lantmäteriet, *Reports in Geodesy and Geographic Information Systems, 4*, p. 124, Gävle, Sweden (https://www.lantmateriet.se/contentassets/4a728c7e9f0145569edd5eb81fececa7/lmv-rapport_

Argus, D., W. Peltier, R. Drummond, A. W. Moore (2014), The Antarctica component of postglacial rebound model ICE-6G_C (VM5a) based on GPS positioning, exposure age dating of ice thicknesses, and relative sea level histories, *Geophysical Journal International*, *198*, p. 537–563, **Crossref**

Ekman, M. (1996) , A consistent map of the postglacial uplift of Fennoscandia, *Terra Nova*, *8*, p. 158–165, **Crossref**

Lambeck, K., C. Smither, J. Ekman (1998) , Tests of glacial rebound models for Fennoscandia based on instrumented sea- and lake-level records, *Geophysical Journal International*, *135*, p. 375–387, **Crossref**

Mäkinen, J., V. Saaranen (1998) , Determination of post-glacial land uplift from the three precise levellings in Finland, *Journal of Geodesy*, *72*, p. 516–529, **Crossref**

Mäkinen, J., et al. (2006) , Regional Adjustment of Precise Levellings around the Baltic, *J. Agria Torres and H. Hornik (eds.), Report on the Symposium of the IAG Sub-commission for Europe (EUREF) held in Vienna, 1–4 June 2005. EUREF Publication No. 15. Mitteilungen des Bundesamtes für Kartographie und Geodäsie, Frankfurt am Main, Band 38*, p. 171–183, Mitteilungen des Bundesamtesfür Kartographie und Geodäsie, Frankfurt am Main.

Mäkinen, J., M. Bilker-Koivula, H. Ruotsalainen, V. Kaftan, N. Gusev, N. Korolev, V. Yushkin, R. Falk, W. Hoppe, O. Gitlein (2008a) , Comparisons of six absolute gravimeters at four sites 2004–2007, *IAG International Symposium "Gravity, Geoid and Earth Observation 2008" GGEO2008, Chania, Crete, 23–27 June 2008 Abstract*, **Crossref**

Mäkinen, J., et al. (2008b) , Comparison of Absolute Gravimeters in Metsahovi in 2004 and in Zvenigorod in 2005, *International Symposium, Terrestrial Gravimetry: Static and Mobil Measurements, 20–23 August 2007, Saint Petersburg, Russia, Proceedings*, p. 123, State Research Center of Russia Elektropribor, Saint Petersburg, Russia.

Mäkinen, J., V. I. Kaftan, G. V. Demiyanov, Yu. G. Kuznetsov, V. I. Zabnev, P. Lehmuskoski, M. Poutanen, M. Takalo (2008c) , Crustal uplift in eastern Fennoscandia: results from repeated Russian and Finnish levellings, *Geophysical Research Abstracts*, *10*, p. EGU2008-A-04855 (2008 SRef-ID: 1607-7962/gra/EGU200 A-04855).

Mäkinen, J., R. A. Sermyagin, I. A. Oshchepkov, A. V. Basmanov, A. V. Pozdnyakov, V. D. Yushkin, Yu. F. Stus, D. A. Nosov (2016) , RFCAG2013: Russian-Finnish comparison of absolute gravimeters in 2013, *Journal of Geodetic Science*, *6*, p. 103–110, **Crossref**

Milne, G., J. Davis, J. Mitrovica, H.-G. Scherneck, J. M. Johansson, M. Vermeer, H. Koivula (2001) , Space-geodetic constraints on glacial isostatic adjustment in Fennoscandia, *Sci-*

*ence*, *291*, p. 2381–2385, **Crossref**

Olsson, P.-A., K. Breili, V. Ophaug, H. Steffen, M. Bilker-Koivula, E. Nielsen, T. Oja, L. Timmen (2019) , Postglacial gravity change in Fennoscandia – three decades of repeated absolute gravity observations, *Geophysical Journal International*, *217*, p. 1141–1156, **Crossref**

Peltier, W. (2004) , Global glacial isostasy and the surface of the ice-age earth: the ICE-5G(VM2) model and GRACE, *Annu. Rev. Earth Planet. Sci.*, *32*, p. 111–149, **Crossref**

Peltier, W. R., D. F. Argus, R. Drummond (2015) , Space geodesy constrains ice-age terminal deglaciation: The global ICE-6G_C (VM5a) model, *J. Geophys. Res. Solid Earth*, *120*, p. 450–487, **Crossref**

Steffen, H., V. R. Barletta, K. Kollo, G. A. Milne, M. Nordman, P. A. Olsson, M. J. R. Simpson, L. Tarasov, J. Ågren (2016) , NKG201xGIA a model of glacial isostatic adjustment for Fennoscandia, *Kempe, C. (ed.), Proc. NKG General Assembly, Göteborg, Sweden, 1–4 September 2014, Lantmäterirapport 2016:4*, p. 85–86, NKG, Sweden.

Takalo, M. (2006) , Connection of the Russian and Finnish leveling networks, *Reports of the Finnish Geodetic Institute, 2006:1*, p. 40, Finn. Geodet. Inst., Kirkkonummi.

Vestol, O. (2006) , Determination of postglacial land uplift in Fennoscandia from leveling, tide-gauges and continuous GPS stations using least squares collocation, *Journal of Geodesy*, *80*, no. 5, p. 248–258, **Crossref**