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Recent postglacial rebound, gravity change and mantle flow in Fennoscandia

Martin Ekman[1] and Jaakko Mäkinen[2]

[1] *National Land Survey, Division of Geodetic Research,* S-801 82 *Gävle, Sweden*
[2] *Finnish Geodetic Institute, Geodeetinrinne* 2, FIN-02430 *Masala, Finland*

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SUMMARY

The recent postglacial rebound of Fennoscandia is investigated using sea-level data, levelling data and gravity data. In particular, an analysis is made of the repeated data obtained hitherto on the Fennoscandian land-uplift gravity line along latitude 63°. Methods for this analysis include an iterative procedure for computing the relation between gravity change and absolute land uplift, the mass-flow parameter and the geoid rise; the remaining land uplift is also estimated.

The mass-flow parameter c is used to characterize the relation between additional mass and additional volume due to rebound; it is a number between 0 and 1, 1 corresponding to full inflow of mantle below the rising crust, and 0 to no inflow but some kind of decompression. The main result is that c is significantly different from 0 at the 99 per cent level: we find $c \approx 0.8$. This means that models proposed of the present uplift based on pure decompression must be ruled out, and that a viscous inflow of mantle is a necessary part of the ongoing uplift process. On the other hand, this process might be more complicated than a pure viscous flow.

Key words: Fennoscandian uplift, glacial rebound, gravity.

1 INTRODUCTION

In Fennoscandia the Earth's crust has been rising continuously since the deloading of the ice at the end of the last ice age. This postglacial rebound has been scientifically studied for 300 years; a historical review is given by Ekman (1991a), see also Wolf (1993). We will here deal with the recent postglacial uplift, using data from repeated relative gravity measurements, sea-level recordings and repeated levellings. In particular, we investigate to what extent, if any, the ongoing uplift is associated with a viscous inflow of mass from the upper mantle. The idea of such a viscous flow and its relation to the gravity field goes back to Nansen (1928). Our result will be given in terms of a mass flow parameter, which will be computed through an iterative procedure, involving the relation between gravity change and absolute land uplift and the geoid rise.

2 SOME BASICS ABOUT THE LAND UPLIFT RATE

As a background to the investigation, and in order to perform some of the computations, we need some basic information about the rate of land uplift. A consistent map of the uplift has recently been published by Ekman (1966); it is shown in Fig. 1.

The isobases in Fig. 1 represent the uplift rate of the crust relative to the mean sea level, or the apparent land uplift rate $\dot{H}_a$, during the 100-year period 1892–1991. The maximum apparent uplift, located in the northern part of the Gulf of Bothnia, amounts to

$$\dot{H}_a = 9.0 \text{ mm yr}^{-1}.$$

As is known, the mean sea level has undergone a eustatic rise $\dot{H}_e$ due to the mild climate during this century. Therefore, the uplift rate of the crust relative to the geoid is (ignoring possible minor changes in the mean sea-surface topography)

$$\dot{H} = \dot{H}_a + \dot{H}_e. \quad (1)$$

There are very many estimates of the eustatic rise of the sea level; a good average coincides with the careful estimate of Nakiboglu & Lambeck (1991) of 1.2 mm yr^{-1}. This figure also seems reasonable when comparing the longest sea-level series in the world with climatological data (Ekman 1993). Adopting this value we obtain a maximum land uplift relative to the geoid of

$$\dot{H} = 10.2 \text{ mm yr}^{-1}.$$

This figure will be used later (Section 4) when discussing the rise of the geoid; adding the rise of the geoid will then give the absolute uplift rate.

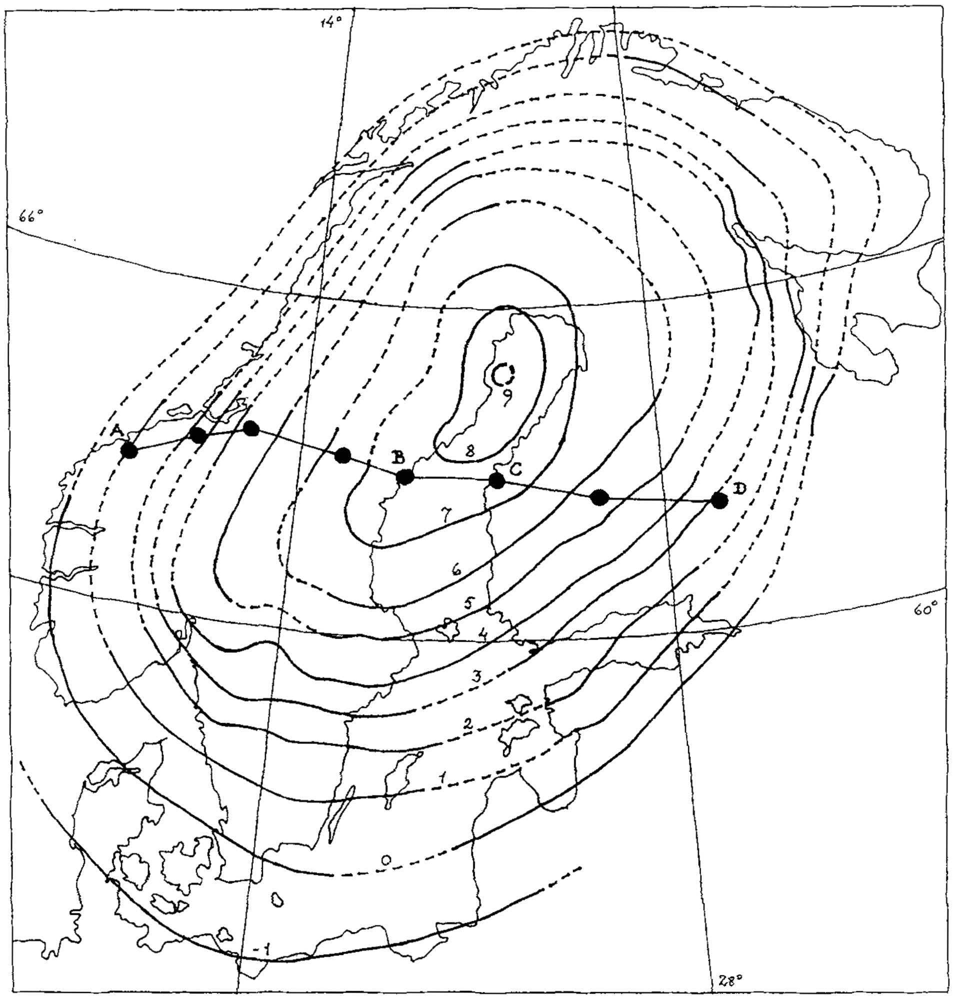

Figure 1. Apparent postglacial uplift of Fennoscandia, 1892–1991, in mm yr^{-1} (Ekman 1996), and the 63° land-uplift gravity line (A = Vågstranda, B = Kramfors, C = Vaasa, D = Joensuu).

3 GRAVITY CHANGE AND LAND UPLIFT ALONG THE 63° LINE

Since 1966 repeated high-precision relative gravity measurements have been performed along a line across the Fennoscandian land-uplift area, following an idea of Honkasalo & Kukkamäki (1963); see also Kiviniemi (1974). This line runs close to latitude 63°; see Fig. 1. A detailed description of measuring methods and computational methods may be found in Mäkinen *et al.* (1986), together with comprehensive results for each gravimeter up to 1984. The additional measurements performed since then will be published in Mäkinen *et al.* (in preparation). The line has been measured with up to 10 gravimeters about every 5th year. Corrections were applied for earth tides, atmospherical pressure, polar motion, and the vertical gradient; ocean-loading and ground-water effects were more or less negligible.

The gravity differences for the various observation years on the 63° line, divided into one part west of the land-uplift maximum and one part east of it, are collated in Table 1. We perform a weighted linear regression of the annual means, weighting them according to the number of gravimeters; see Fig. 2. On the western part of the line (Fig. 2a) we obtain a gravity change rate of

$$\dot{g} = -1.52 \pm 0.20\ \mu\text{gal yr}^{-1},$$

and on the eastern part (Fig. 2b)

$$\dot{g} = 1.00 \pm 0.14\ \mu\text{gal yr}^{-1}.$$

The gravity changes obtained are only slightly different from those calculated earlier by Ekman *et al.* (1987) and Ekman & Mäkinen (1990). The standard errors, however, are reduced considerably due to the longer time span.

To find the relation between gravity change and land uplift we also need the land-uplift differences on the 63° line. Hitherto they have been taken from a map similar to the one in Fig. 1, but the accuracy of the gravity change is now high enough to warrant improved land-uplift estimates. Furthermore, we need to take their uncertainties into account.

On the western part of the line the best value of the land-uplift rate is found from the Norwegian and Swedish sea-level recordings. The question is then how the time periods should be chosen. We know that within the Baltic Sea, including the Gulf of Bothnia, there is quite a close correlation between different mareographs of interannual sea-level variations influencing a land-uplift calculation. Such a correlation, how-

Table 1. Annual means of gravity differences, 63° line. For each year t the gravity difference g in μgal and the number n of gravimeters involved are given.

(a) Western part (Vågstranda → Kramfors)

t	g	n
1967.5	532.6	3
1972.7	534.1	9
1977.7	519.1	10
1982.7	509.9	4
1987.7	504.8	9
1993.7	499.5	8

(b) Eastern part (Vaasa → Joensuu)

t	g	n
1966.8	134.6	4
1967.9	129.6	4
1971.8	131.9	5
1977.7	133.8	10
1979.8	143.3	5
1982.7	144.1	6
1984.7	151.0	4
1986.8	156.6	2
1987.7	150.9	10
1988.7	153.7	2
1989.7	144.6	2
1991.7	145.5	1
1993.7	155.4	8

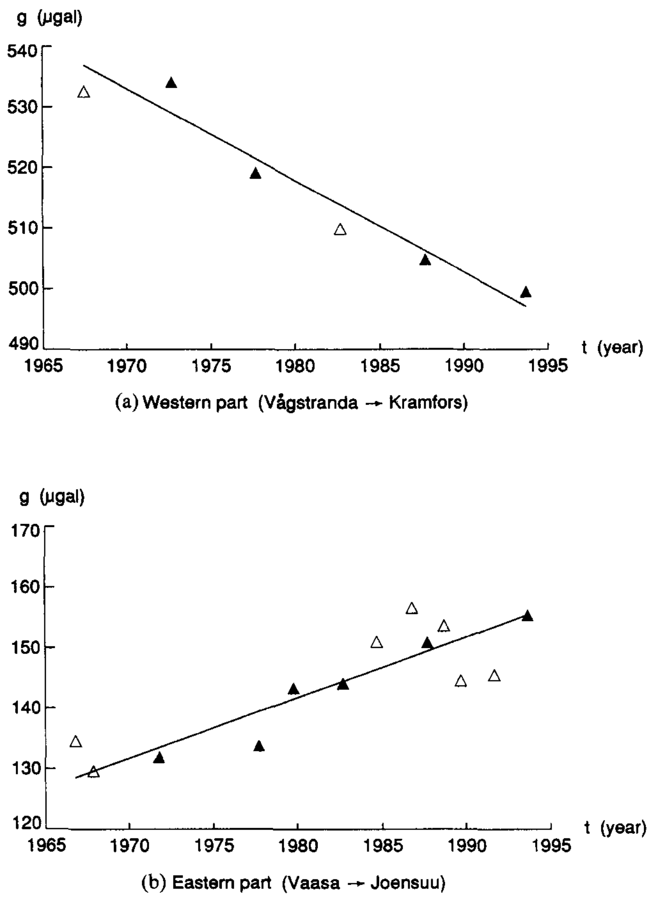

Figure 2. Change of gravity difference with time, 63° line. △ = 1–4 gravimeters, ▲ = 5–10 gravimeters.

ever, is not very pronounced between a mareograph in the Gulf of Bothnia and one at the Atlantic coast of Norway. Therefore, rather than extracting a common time period for these mareographs, we have used as long sea-level series as possible, which means about 50 years for Norway and 100 years for Sweden. This is especially important for the Gulf of Bothnia, where the interannual variations are large. At the same time, we have avoided extreme high-water and low-water years at the ends of the periods. The influence on the result of a possible non-linearity in the eustatic rise of the sea level has been found more or less negligible through comparisons with a 100-year series in the Skagerrak (Smögen).

On the Norwegian coast we use mainly the mareographs Heimsjø and Måløy reduced to the period 1928–1992, from which the apparent uplift at Vågstranda is estimated at 0.9 ± 0.4 mm yr^{-1}. On the Swedish coast we use the mareographs Draghällan/Spikarna and Ratan reduced to the period 1892–1992 [together with the repeated high-precision levellings in between; see Ussisoo (1977)], from which the apparent uplift at Kramfors is estimated at 7.8 ± 0.3 mm yr^{-1}. This yields a land-uplift difference relative to the geoid (the eustatic sea-level rise being eliminated in the difference) of

$$\dot{H} = 6.9 \pm 0.5 \text{ mm yr}^{-1}$$

(former value 7.0 mm yr^{-1}).

On the eastern part of the line the best estimate of the land uplift is obtained from the readjustment of the Finnish repeated high-precision levellings by Suutarinen (1983) who, however, only computed values for the junctions. We have filled in details using data published by Kääriäinen (1966). This yields a land-uplift difference relative to the geoid of

$$\dot{H} = -4.7 \pm 0.5 \text{ mm yr}^{-1}$$

(former value -4.3 mm yr^{-1}).

4 THE RELATION BETWEEN GRAVITY CHANGE AND LAND UPLIFT, THE MASS-FLOW PARAMETER, AND THE GEOID RISE

The relation between gravity change rate $\dot{g}$ and absolute land-uplift rate $\dot{h}$ should be bound by two theoretically predicted extreme values. One is

$$(\dot{g}/\dot{h})_B = 2g/R + 2\pi G\rho = -0.17 \text{ μgal mm}^{-1}, \quad (2)$$

being valid for a 'Bouguer model', i.e. crustal uplift with full addition of mass from the upper mantle. Here R is the radius of the Earth, G is the gravitational constant and ρ is the density of the upper mantle. The other extreme value is

$$(\dot{g}/\dot{h})_f = 2g/R = -0.31 \text{ μgal mm}^{-1}, \quad (3)$$

being valid for a 'free-air model', i.e. crustal uplift without additional mass.

To handle more general models, Ekman (1991b, 1993) introduced the mass flow parameter

$$c = \frac{\dot{g}/\dot{h} - (\dot{g}/\dot{h})_f}{(\dot{g}/\dot{h})_B - (\dot{g}/\dot{h})_f}, \quad (4)$$

or numerically,

$$c = \frac{0.31 + \dot{g}/\dot{h}}{0.14}. \quad (5)$$

For a Bouguer model we have $c = 1$, for a free-air model $c = 0$, and for any intermediate model $0 < c < 1$. A model of type $c = 1$ corresponds to pure viscous flow of the mantle, and a model of type $c = 0$ to pure decompression (no inflow of mass).

To determine $\dot{g}/\dot{h}$ or c we need to calculate the absolute land-uplift rate

$$\dot{h} = \dot{H} + \dot{N}, \quad (6)$$

where $\dot{H}$ is the uplift rate relative to the geoid and $\dot{N}$ is the rate of the geoid rise. $\dot{N}$ can be found from the surface layer integral,

$$\dot{N} = \frac{G\rho c}{g} \int_0^{2\pi} \int_0^r \dot{h}(s, \alpha)\, ds d\alpha, \quad (7)$$

s and α being polar coordinates. To find the maximum value of $\dot{N}$ in a simple but sufficiently accurate way we approximate the shape of the uplift with a cosine surface,

$$\dot{h} = \dot{h}_0 \cos ks,$$

subscript 0 denoting the value at the centre of the uplift area (maximum value). Inserting this into (7), together with $k = \pi/2r$, we obtain, as in Ekman (1991b),

$$\dot{N}_0 = \frac{4G\rho cr}{g} \dot{h}_0, \quad (8)$$

where r is the mean radius of the uplift area. Numerically we have (using $\rho = 3.3$ g cm^{-3})

$$\dot{N}_0 = 0.90 \times 10^{-4} cr\dot{h}_0, \quad (9)$$

where r is in km. With this simple formula one can easily see how the land-uplift model, the size of the land-uplift area and the rate of the land uplift combine to produce the geoid rise. Furthermore, the formula may also be used for investigating the remaining land uplift, as will be shown in Section 6.

The determination of $\dot{h}$ with (6), and thereby also of $\dot{g}/\dot{h}$ and c according to (5), requires knowledge of $\dot{N}$, which, in its turn, presupposes knowledge of both $\dot{h}$ and c through (9). Hence, all these quantities have to be computed iteratively.

At the same time as doing that we estimate their uncertainties. The standard errors obtained in Section 3 are associated with different degrees of freedom and, consequently, with different confidence levels. Therefore, from now on we calculate with confidence intervals (or, rather, their half-lengths) at the 95 per cent level. For the relevant t distributions this corresponds to between 2.0 and 2.8 times the standard errors.

We start the iteration by putting $\dot{N} = 0$ in (6) so that $\dot{h} = \dot{H}$. Then the initial value of $\dot{g}/\dot{h}$ equals $\dot{g}/\dot{H}$. On the western part (W) of the 63° line the standard error of the numerator $\dot{g}$ has 4 degrees of freedom (see Fig. 2a). Thus

$\dot{g} = -1.52 \pm 0.56$ μgal yr^{-1} (95 per cent, W).

The denominator $\dot{H}$ has formally over 50 degrees of freedom (from the regression of sea-level data) and

$\dot{H} = 6.9 \pm 1.0$ mm yr^{-1} (95 per cent, W).

This leads to

$\dot{g}/\dot{H} = -0.220 \pm 0.086$ μgal mm^{-1} (95 per cent, W).

Here we have resorted to linearization through Taylor expansion of $\dot{g}/\dot{H}$ to calculate the uncertainty. As can be seen from the relative sizes of the uncertainties, it is that in $\dot{g}$ that dominates in the combined uncertainty. Similarly, for the eastern part (E) of the line we have, with 11 degrees of freedom for the numerator (see Fig. 2b), and 18 degrees of freedom for the denominator (from the levellings),

$\dot{g} = 1.00 \pm 0.31$ μgal yr^{-1} (95 per cent, E)

and

$\dot{H} = -4.7 \pm 1.0$ mm yr^{-1} (95 per cent, E).

This leads to

$\dot{g}/\dot{H} = -0.213 \pm 0.080$ μgal mm^{-1} (95 per cent, E).

Combining the two independent values of $\dot{g}/\dot{H}$ above, we obtain

$\dot{g}/\dot{H} = -0.216 \pm 0.058$ μgal mm^{-1} (95 per cent).

When inserted into (5) this yields

$c = 0.67 \pm 0.41$ (95 per cent).

Putting this into (9), together with $\dot{H}_0 = 10.2$ mm yr^{-1} (from Section 2) and $r = 750$ km, we find

$\dot{N}_0 = 0.46$ mm yr^{-1}.

Since the geoid change is nearly proportional to the land uplift, we adopt a geoid-change difference on the western part of the line of $\dot{N} = 0.4$ mm yr^{-1}, yielding

$\dot{h} = 7.3 \pm 1.0$ mm yr^{-1} (95 per cent, W).

Correspondingly, on the eastern part of the line we get $\dot{N} = -0.3$ mm yr^{-1}, yielding

$\dot{h} = -5.0 \pm 1.0$ mm yr^{-1} (95 per cent, E).

Now we can run the whole procedure again, and this second iteration already converges to

$\dot{g}/\dot{h} = -0.208 \pm 0.086$ μgal mm^{-1} (95 per cent, W),

$\dot{g}/\dot{h} = -0.200 \pm 0.080$ μgal mm^{-1} (95 per cent, E).

In the uncertainties we have here allowed for the slight correlations introduced by the iteration. The final values become

$\dot{g}/\dot{h} = -0.204 \pm 0.058$ μgal mm^{-1} (95 per cent),

$c = 0.76 \pm 0.41$ (95 per cent),

$\dot{N}_0 = 0.6$ mm yr^{-1},

$\dot{h}_0 = 10.8$ mm yr^{-1}.

5 GEOPHYSICAL MODELS

Most geophysical models of the postglacial rebound rely more or less on the viscoelastic theories of Peltier (1974, 1982) or Cathles (1975). The Earth is treated as a viscoelastic body that behaves as a purely elastic solid in the short-time limit and as a purely viscous fluid in the long-time limit. Thus, for the ongoing uplift, these models are of the type $c = 1$. Such models for Fennoscandia, with differing viscous properties, have been presented by Wolf (1987), Mitrovica & Peltier (1989, 1993), Lambeck, Johnston & Nakada (1990), Fjeldskaar & Cathles (1991) and Fjeldskaar (1994).

On the other hand, Mörner (1980, 1990) claims that the postglacial rebound is composed of two separate mechanisms: the glacial isostatic one, which, according to him, has already faded out, and another one, which is linear in time and which is the one that can be observed today. This linear component should probably represent a phase-boundary adjustment due to decompression, initiated at the end of the deglaciation; see O'Connell (1976). In any case, it does not involve any inflow of mass; see also Mörner (1991a). Thus, for the present uplift this model is of type $c = 0$. A critical discussion on some of Mörner's methods has taken place between Wolf (1991) and Mörner (1991b).

The results obtained at the end of the previous section show that the case $c = 0$ is far outside the 95 per cent confidence limit; in fact, it can be shown in the same way to be clearly outside the 99 per cent limit. Even allowing for things like linearization errors in the uncertainty estimation, outliers in the gravimeter data, and eventual unmodelled errors in the land-uplift differences, the evidence is strongly against a model of the type $c = 0$. We conclude that Mörner's model in this respect has to be ruled out, and that a viscous inflow of mass is a necessary part of the ongoing uplift process. On the other hand, this process might be more complicated than a pure viscous flow; our confidence interval of c encompasses the $c = 1$ models as well as a fairly wide range of intermediate models.

6 A NOTE ON THE REMAINING LAND UPLIFT

Inverting (8) and replacing the rates $\dot{N}$ and $\dot{h}$ by the corresponding remaining quantities ΔN and Δh we find, as in Ekman (1991b), a formula for the remaining land uplift,

$$\Delta h_0 = \frac{g}{4G\rho cr} \Delta N_0 . \quad (10)$$

Numerically, we can write, in correspondence with (9),

$$\Delta h_0 = \frac{1.1 \times 10^4}{cr} \Delta N_0 . \quad (11)$$

We note that if $c = 0$, then $\Delta N_0 = 0$, and (10) and (11) have no solution, which simply illustrates the fact that without any mass change this formula is meaningless. Since we have shown above that $c \neq 0$, this is no problem. The formula presupposes that c (and r) do not change significantly with time.

ΔN_0 may be identified as a depression in the geoid, filtered to exclude long wavelengths due to mantle convection, and corrected for crustal structure. The most recent estimate is that of Sjöberg, Nord & Fan (1992), $\Delta N_0 \approx 5$ m. Inserting this into (11), together with $c = 0.8$ and $r = 750$ km, we obtain an approximate value of the remaining land uplift of

$$\Delta h_0 \approx 90 \text{ m} .$$

7 CONCLUSIONS

We have found the following characteristic values for the postglacial uplift of Fennoscandia:

$c = 0.8$ $\quad (\dot{g}/\dot{h} = -0.20\ \mu\text{gal mm}^{-1})$;

$\dot{h}_0 = 10.8\ \text{mm yr}^{-1}$ $\quad (\dot{H}_0 = 10.2\ \text{mm yr}^{-1}, \dot{N}_0 = 0.6\ \text{mm yr}^{-1})$;

$\Delta h_0 \approx 90$ m.

The value of c is highly significantly different from that of proposed decompression models, $c = 0$. Consequently, the ongoing postglacial uplift process must be associated with an inflow of mass, i.e. viscous currents in the upper mantle. The c value is compatible with proposed viscous-flow models, $c = 1$, as well as with a fairly wide range of intermediate models.

In the future the ratio $\dot{g}/\dot{h}$ might perhaps be used in combination with repeated absolute gravity measurements to determine the absolute land uplift directly. Such results could then be compared with those from permanent GPS observations. If compared with the apparent land uplift from mareograph recordings, the secular sea-level change might also be obtained.

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