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GLACIAL REBOUND AND RELATIVE SEA LEVELS IN EUROPE FROM TIDE-GAUGE RECORDS *

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ABSTRACT

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Relative sea levels recorded by tide gauges during the past century in northern Europe are dominated by isostatic readjustment of the land following the latest deglaciation of Scandinavia and Scotland. Maximum relative uplift of the land is centered near the northern Gulf of Bothnia (at a rate of 6–7 mm/yr), with a smaller secondary maximum over Scotland (also at a rate of 6–7 mm/yr). Although there probably is a relaxing peripheral bulge surrounding the regions of maximum uplift, such a former bulge is poorly defined by coastal tide gauges; in the North Sea evidence for sinking of a former peripheral bulge of glacial origin is complicated by post-Carboniferous basin deepening with sediment loading and possible rejuvenation associated with glaciation. Other data (gravity, radiocarbon, geomorphology) support the interpretation that glacial isostasy controls the structure of relative sea-level change. Included in this pattern of relative rise of land is a eustatic signal that biases the estimates of glacial rebound. Such a eustatic signal could not be isolated from the isostatic signal using the present data, but glacial isostasy clearly is a major control for relative sea levels of the region.

Absence of significant higher frequency (2–50 yr) cycles in mean annual sea levels of northern Europe reflects the complex hydrologic/oceanographic forces to which sea levels must respond. Whereas other coastal regions show significant higher frequency peaks in the energy spectra of relative sea levels, the many marginal seas in northern Europe preclude a clear relation between hydrologic/oceanographic forcing and relative sea levels, although this relation must exist on a more local scale.

INTRODUCTION

The widely reported trend toward atmospheric warming caused by a "greenhouse" effect of carbon dioxide and other gases liberated by industry may cause the West Antarctic Ice Sheet and smaller glaciers to melt. Their meltwater plus thermal expansion of the upper ocean should produce a eustatic rise of sea level. Thus the

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trends of sea level recorded by tide gauges may confirm a global increase in atmospheric temperature. Indeed, regression analyses of mean annual sea levels measured at 247 tide-gauge stations of the world (Emery, 1980) showed an annual increase averaging 3.0 mm/yr, about three times the rate found by Gutenberg (1941) and Fairbridge and Krebs (1962) from earlier and far fewer data. Uncertainties come from poor global distribution of stations, few long-duration stations, and many records with gaps. Even the wide range of trends (to at least ± 13 mm/yr) indicates the probability that tectonic and isostatic controls exceed eustatic ones, and other distortions are produced by oceanographic controls caused by fluctuations of currents and/or coastal climates. Moreover, most tide gauges are located in harbors and other coastal regions for the benefit of shipping; these regions are known for their long-term vertical instability resulting from thermal contraction of continental crust long after continental rifting, emplacement and subduction of oceanic crust, and from compaction of thick accumulated sediments and isostatic sinking due to sediment and water loading.

At least two approaches may lead to better understanding of the tide-gauge information. One is the weighting of stations according to oceanic region, an approach used by Gornitz et al. (1982) and Barnett (1983). An improvement is the use of modified eigenanalysis to overcome errors caused by comparing records of different and non-concurrent time spans and records having gaps of various lengths; this we have done for the many tide-gauge stations of Japan (Aubrey and Emery, in press). The second approach is to study intensively the areal patterns of sea-level change in regions having numerous well-tended tide-gauge records. In Japan, the relative sea-level change ranges systematically northwestward from -20 to $+4$ mm/yr, reflecting the effects of crustal sinking induced by subduction of oceanic crust. Stations along the "stable" Atlantic coast of the United States exhibit a block-like pattern of sea-level change (Aubrey and Emery, 1983), as though the continental crust were being distorted by major faults, perhaps extensions of ocean-floor fracture zones. Along the eastern Asian mainland, patterns of relative sea levels are consistent with long-term sinking of continental-shelf basins (Emery and Aubrey, 1986). An area that warrants similar study is northern Europe, where glacial rebound of Scandinavia following melting of the late Pleistocene ice sheet probably is accompanied by sinking of a former peripheral bulge generated by lateral flow from beneath Scandinavia. Vertical movement in and near Scandinavia is the subject of this article.

VERTICAL LAND MOVEMENTS DURING THE PAST 15,000 YEARS, GEOLOGICAL INFERENCES

The tectonic effects of glacial loading and unloading of Scandinavia have a long history of discussion, with critical articles appearing at about half-century intervals. In 1840 two apparently unrelated publications were published. One by Bravais

(1840) described raised and seaward tilted shorelines in northern Norway; the other by Agassiz (1840) provided evidence that alpine glaciers had formerly been far more extensive and had carried boulders for long distances, in contrast with advocacy by Lyell (1838, pp. 136–138) and others that the main role of ice was buoying of boulders for transport by floods. These thoughts were combined by Jamieson (1882) and De Geer (1888–1890) in their suggestions that the weight of thick glacial ice had downwarped Scandinavia, and on melting of the ice the land had risen from below sea level in stages marked by now-raised shorelines. De Geer drew contours of the uplift to 213 m above sea level from elevations of shore deposits measured by Bravais and others at 32 sites (Fig. 1). Similar evidence for glacial rebound of Scotland was reported earlier by Jamieson (1865), and Sissons (1983) contoured the first post-glacial shoreline to a maximum elevation of 14 m near Glasgow. Subsequent studies elsewhere by Nansen (1922) and others showed the likelihood of a peripheral bulge caused by lateral flow of subcrustal (asthenospheric) material away from the site of downwarped crust.

During following decades many more measurements of raised shorelines were coupled with varve counting, glacial-aqueous stratigraphy, pollen analyses, lichenometry, archeology, and finally radiocarbon providing dates. Results by many workers, summarized by Sauramo (1939), revealed at least 26 shorelines to 280 m above sea level, several complicating hingelines, and the presence of brackish changing to freshwater lacustrine and back to brackish-marine sediments between the levels marked by shorelines. The oldest post-glacial sediments, of the Rhabdonema Sea (or Yoldia IV Sea) deposited about 9000 yrs ago (Sauramo, 1939, fig. 3), mark the highest uplift of land above present sea level (Fig. 1), but prior uplift during several thousand years was required before the land rose to sea level from its depressed position beneath the ice sheet.

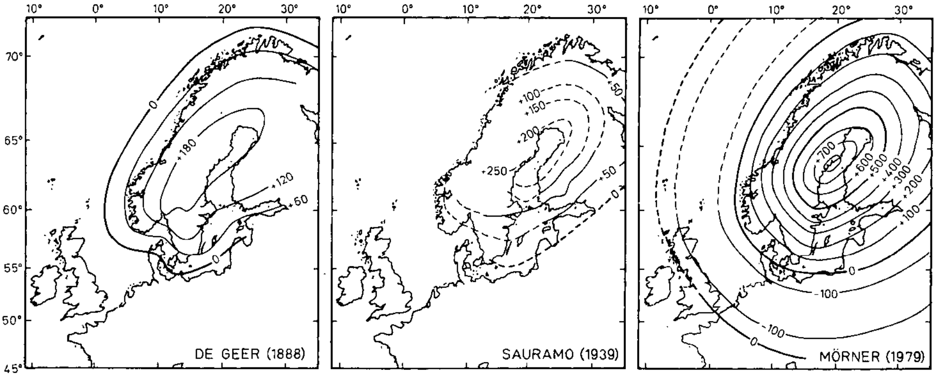

Fig. 1. Contours in meters of total post-glacial uplift of Scandinavia. Those by De Geer (1888) and Sauramo (1939) denote uplift above sea level at the time of their investigations; those by Mörner (1979, fig. 26) show his computation of total absolute post-glacial uplift of land above lowest glacial sea level plus concurrent downwarp of the peripheral bulge (assumed to circumscribe the uplift core uniformly).

The next major synthesis was by Mörner (1969, 1979, 1980) in a long series of publications. Beginning his work in the Kattegat, he continued it into the entire Scandinavian peninsula. At least 49 shorelines were identified, most extending from below present sea level, the highest reaching 280 m, the oldest being 13,700 yrs. B.P., and the tilt proportional to age. Dates are based upon varves, radiocarbon, and pollen. Slopes and elevations of the tilted shorelines and functions of both isostatic rebound of land and nearly concurrent eustatic rise of sea level. Isostatic rebound was isolated by correcting the observed shoreline elevations by a eustatic sea-level curve (obtained by trial and error comparisons with the raised shorelines and by comparison with published "eustatic" curves from elsewhere in the world). Resulting isostatic profiles reveal changes in rate of uplift that may be related to shifting effects of ice unloading and water loading coupled with structural inhomogeneities of the crust. In fact, Mörner (1979, p. 305) attempted to show that the uplift has two independent causes: an exponential uplift from glacial ice melt (now finished), and a linear tectonic uplift (continuing) unrelated to removal of ice load. However, as will be shown later, the present contours of uplift based upon tide-gauge records correspond well with contours of total isostatic uplift and with the distribution of thick glacial ice, favoring a single rather than two different causes for uplifts. His linear non-glacial uplift is controversial, particularly because he has advanced no convincing tectonic arguments for it.

Mörner (1979, 1980) projected known shoreline positions at specific dates (10,000, 13,000 yrs B.P.) linearly upward to estimate maximum absolute uplift, obtaining a value of 830 m. Similarly, he projected the tilt of the shorelines downward to obtain a maximum subsidence of 170 m in the North Sea, estimated also on the basis of equal volume of uplift beneath the former ice sheet and downdrop of the original peripheral bulge. This maximum subsidence is questionable because of the linear assumption and poorly constrained data on the outer periphery of the subsidence area (outside of Fennoscandia). Mörner postulates an annular peripheral bulge (Fig. 1) around the Fennoscandian ice-sheet, represented as areas of negative contours to indicate relaxation of the former peripheral bulge.

In spite of their complications, the three maps of glacial rebound in Fig. 1 reveal similar positions of maximum uplift near the shore of Sweden in the Gulf of Bothnia, and diminishing uplift along the general periphery of the Scandinavian countries.

Support for a now-depressed peripheral bulge around the Scandinavian and Scottish ice caps is provided by a compilation of radiocarbon dates on shore sediments of about 9000 yrs; B.P. (Fig. 2). The depth or elevation of this surface in specific regions of previous detailed investigations are noted, and generalized contours show the upwarp or downwarp during the past 9000 yrs. Largest of the upwarps is the Scandinavian one, whose shape is outlined by the +100-m contour that largely was guided by the maps of Fig. 1. A small upwarp occurs in Scotland, but a broad downwarp to at least 45 m occupies the southern North Sea, the English

Channel, southern England, and the northwestern mainland coast from Brittany to southern Sweden. Only the general outline of the downwarp is revealed by existing data which are confined to coastlines, but this outline may support the concept of

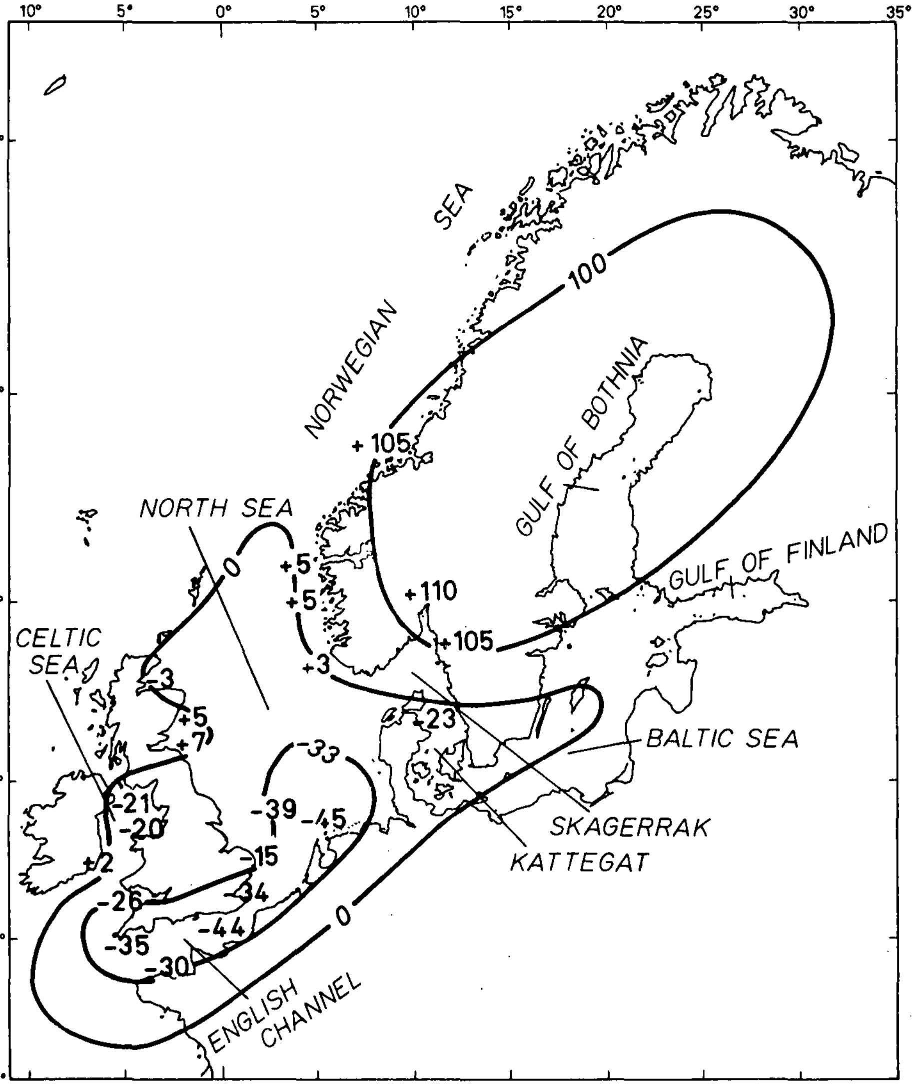

Fig. 2. Present position of 9000-yr B.P. shore level estimated from radiocarbon-dates of shore sediments in studies published by: Veenstra (1965), Andrews et al. (1973); Bloom (1977); Clarke (1970); Delibrias and Guillier (1971); Hafsten (1979); Jardine (1979); Jelgersma (1979); Kidson and Heyworth (1976); Larsson (1983); Mitchell and Stephens (1974); Mörner (1969); Morzadec-Kerfourn (1974); Ters (1973); Tooley (1974); Witting (1940). Numbers indicate elevation in meters relative to present sea levels in areas of detailed investigations.

peripheral reaction to glacial loading and unloading. The contours of Fig. 2 also correspond well with the outline of the North Sea basin and its associated grabens (Ziegler, 1982, especially the isopach map of Permian and younger sediments–encl. 34), whose sediments exceed 7 km thickness off Denmark, southwestern Norway, and westernmost France. One cannot clearly evaluate the relative roles of basin sinking continuing from ancient times, sinking of a peripheral bulge produced by glacial unloading of Scandinavia and Scotland, and rejuvenation of graben faults caused by the glacial loading and unloading.

VERTICAL LAND MOVEMENTS DURING RECENT DECADES, CONVENTIONAL METHODS

Precise levelling began with a survey in southern Finland in 1938 (Sauramo, 1939, fig. 6) and it has expanded to cover all of Finland for the period between 1892–1910 and 1935–1975 (Kiviniemi, 1981) and most of the rest of Scandinavia at various times (Hafsten, 1979; Balling, 1980, fig. 2; Mörner, 1980, fig. 22). This levelling reveals tilting of the land in the same directions shown by raised shorelines and tide-gauge data, and the rates are about the same as those derived from regression analyses of the tide-gauge records, which served as the base levels for the levelling surveys anyway.

Gravity measurements in the region compiled by Balling (1980) denote negative free-air residual anomalies whose contours closely resemble those of the past total uplift and those derived from tide-gauge records. The gravity field and other data support a total uplift of 900–1000 m after melt of an ice sheet 3400–3700 m thick and involving a crustal thickness of 42 km above mantle in the Gulf of Bothnia region. The present field indicates a remaining potential uplift of 100–150 m. Bjerhammar (1980) investigated the geoid surface in Fennoscandia for harmonics between degrees 10 and 30, also finding a subsidence that corresponds well with the boundaries of ice sheets.

The simplest evidence of modern uplift along the coasts of Scandinavia comes from measurement of changing relative sea levels. The first recorded benchmark was cut in 1704 (Mörner, 1979) with others installed in following decades (Bergsten, 1954; Rohde, 1975; Sjöberg, 1984). Records of sea levels at six German coastal sites and of heights reached by storm surges (Rohde, 1977) indicate a sinking of the German coast averaging about 2.5 mm/yr since the 16th century. More systematic regional recording began during the late 19th century with measurements on tide staffs and notches cut into rocks along the shore; they allowed construction of maps (Witting, 1918, 1922) that showed a general rise of land from Denmark through the Gulf of Bothnia, at the north end of which is indicated a rise of the land averaging 11 mm/yr. Later maps compiled by West (1968) from sources dating back to 1953 and by Winterhalter et al. (1981) were based on more data, covered more area, and showed the maximum rise of land to be only about 9 mm/yr. Another, by Rossiter (1967), indicated a maximum between 7 and 8 mm/yr. Most of these and other studies included not only tide-gauge data but information from precise levelling, tectonics, topography, archeology, and other sources. General discussions of land-sea-level movements in areas beyond Scandinavia are provided by many authors:

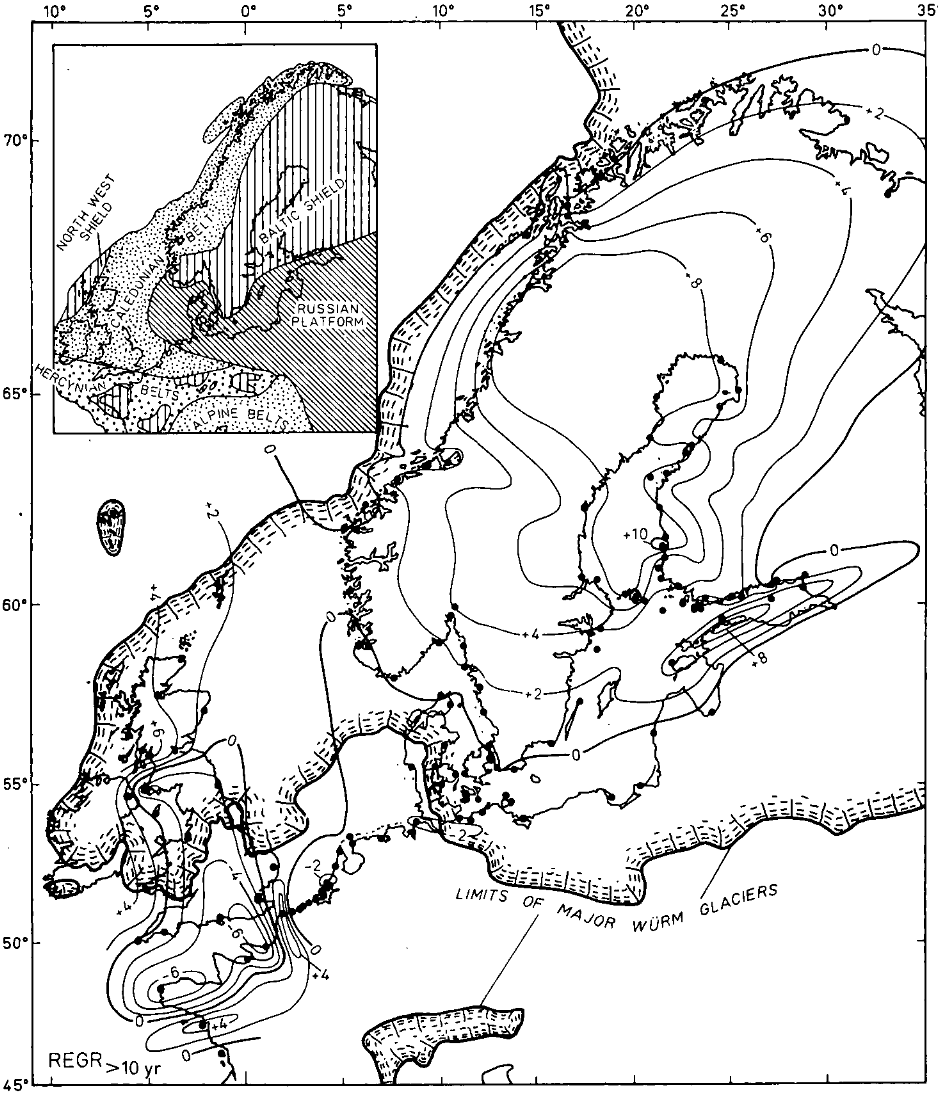

Fig. 3. Mean annual uplift of Scandinavia and Scotland and downdrop of England and western France derived from least-squares regression analysis of 134 tide-gauge records having time spans longer than ten years. Maximum extent of Würm glaciers is from Andersen (1981). Insert shows tectonic provinces as compiled by Naylor and Mounteney (1975). Positive values indicate land uplift, negative values indicate land subsidence (relative to sea level).

Germany—Rohde (1975, 1977), Netherlands—Jelgersma (1980), England and Wales—Shennan (1983), Scotland—Sissons (1983), and Ireland—Devoy (1983).

We made a new map of vertical land movements relative to mean annual sea level with best-fit straight-line regressions drawn through mean annual sea levels at each of 134 stations having records at least ten years in duration. The data are primarily from compilations by the Permanent Service for Mean Sea Level (PSMSL), courtesy of D. Pugh, some of which are not included in PSMSL publications because of format problems; Germany and the Netherlands are two examples of this. Other European data were acquired from compilations by Witting (1940) and Rossiter (1967). The data extend exceptionally through 1980, more than a decade later than those used for the latest published map known to us. Thus our Fig. 3 reveals some details not present in earlier maps, and it also includes the region peripheral to the areas of loading by Würm glacial ice. The contours of mean annual uplift of land range to between 8 and 10 mm/yr, with the +8 contour extending to newer stations along the Norwegian Sea. A curious separate uplift follows the Gulf of Finland, though it is largely based upon two stations of only 11-year spans just southwest of the Gulf. Another separate uplift coincides with Scotland, and an irregular region of sinking (to a rate of about 7 mm/yr) occupies southern England and western France across the English Channel. The area of sinking probably is a part of the former bulge peripheral to the large Scandinavian area of crust downwarped beneath its former load of ice during the Würm glacial epoch, and it is peripheral also to the former smaller ice cap in Scotland. The pattern is more complex than the peripheral belt of sinking shown schematically by Mörner in our Fig. 1, but it appears to correspond well with the general contours of Fig. 2 derived from radiocarbon dates and relative elevations of the 9000-yr B.P. surface.

Several geological attributes are associated with the pattern of Fig. 3. Firstly, the two areas of downwarp lie within southward projections of the glacial ice sheets. Secondly, both areas of former downwarp and now of uplift are within shields (Fig. 3, insert) that consist mainly of Precambrian intrusive and metamorphic rocks (see geological map of Europe, Von Gaertner and Walther, 1971). Thirdly, the area of possible secondary present uplift in the Gulf of Finland corresponds closely with the contact between the Baltic shield and the Russian platform—a possible belt of structural weakness that is marked by block faulting (Winterhalter et al., 1981). Seismic activity is concentrated in several belts: along the entire coast of Norway, the west coast and northeast coast of Sweden, and to a much lesser extent along the south coast of Finland (Stephansson and Carlsson, 1980).

VERTICAL LAND MOVEMENTS DURING RECENT DECADES, EIGENANALYSIS

Changes in mean annual sea levels studied at individual stations by regression analysis can be investigated simultaneously for all stations in a given region as a group by eigenanalysis. This method allows comparison of year-to-year variations that identifies and rejects aberrant records. It also allows the use of records from stations having different but overlapping time spans of recording; regression analysis for such stations can yield different results if the rate of relative sea-level movement changes with time, or if there is substantial high-frequency variability in sea levels. A modification of the method allows inclusion of station records having gaps without

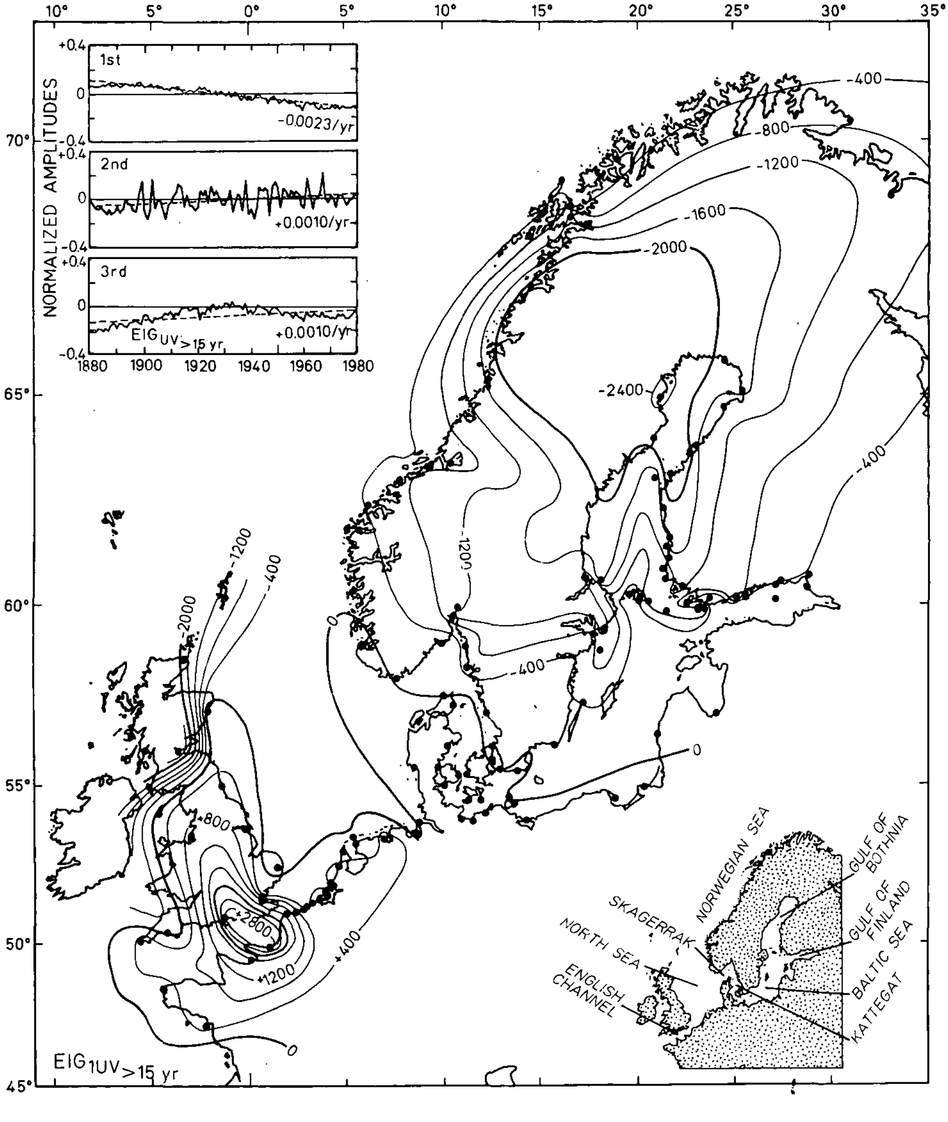

Fig. 4. First spatial eigenfunction for northern Europe at intervals of 400 units at 128 stations, each having unit variance and spanning at least 15 years. Insert at upper left has first three temporal functions for same stations and with units dimensionless and normalized; these functions account for 58, 13, and 6%, respectively, of total variation in records. Insert at lower right denotes water bodies mentioned in text.

recourse to simple interpolation of missing data. Description of eigenanalysis and its application to vertical changes in level of the ocean or land surface is given by Aubrey and Emery (1983, in press), and another application is discussed in Emery and Aubrey (1986); these references should be examined for a more complete discussion of the methodology.

Eigenanalysis yields both spatial and temporal functions whose percentage of the total variation in the records diminishes with level of function so that most of the total variation in a region is incorporated in the first three functions. The first spatial function (Fig. 4) has contours in arbitrary units, and they resemble the pattern of contours of vertical land movement based on regression analyses (Fig. 3). The main difference is the diminished pattern along the Gulf of Finland, but this may be due to omission of two critical Soviet stations southwest of the Gulf that span only 11 years—enough to qualify for the 10-year minimum for regression but not for the 15-year minimum for eigenanalysis. A second difference between regression (Fig. 3) and eigenanalysis (Fig. 4) is a northerly shift in the center of uplift determined by eigenanalysis. The peripheral bulge is well-defined, both for the Fennoscandia ice cap and the Scottish ice cap. The line of zero uplift is in approximately the same position for eigenanalysis and regression. The second spatial function (Fig. 5) exhibits only a low-relief pattern of contours (in arbitrary units), and trends are related only distantly with those of the first spatial function. It describes much of the variability in relative sea levels not described by the first spatial function.

Associated with the spatial functions are temporal functions (insert, Fig. 4) that describe how the spatial maps vary through time. The first function, accounting for 58% of the variability in sea levels, has a monotonic decrease, with an increase in slope during 1924. The interpretation of the changes in slope is uncertain at this time, although the difference in slope is statistically significant at the 95% level. The slope change may represent an acceleration in crustal response or alternatively may be a bias introduced by eigenanalysis. The second temporal function, describing 13% of sea-level variability, shows no statistically significant linear trend from 1880 to 1980 but consists of large-amplitude, high-frequency fluctuations. The third temporal eigenfunction, accounting for 6% of the variability of the data, has a low-frequency variability with some superimposed higher frequencies.

Spectral analysis of the temporal functions (insert, Fig. 5) reveals no dominant frequencies of sea-level variability, in contrast with our previous regional sea-level studies (Aubrey and Emery, 1983; Aubrey and Emery, in press; Emery and Aubrey, 1986). Instead, the trends of the spectra are flat, with superimposed fluctuations that are not significant at the 90% level. Reasons for the lack of significant high-frequency peaks are discussed later.

Finally, the products of the first three corresponding spatial and temporal functions for the period 1924 to 1980 were added to determine the relative uplift of the land surface at the various stations (Fig. 6). This synthetic pattern of uplift is an improvement on linear regression results (such as Fig. 3), because the eigenfunctions

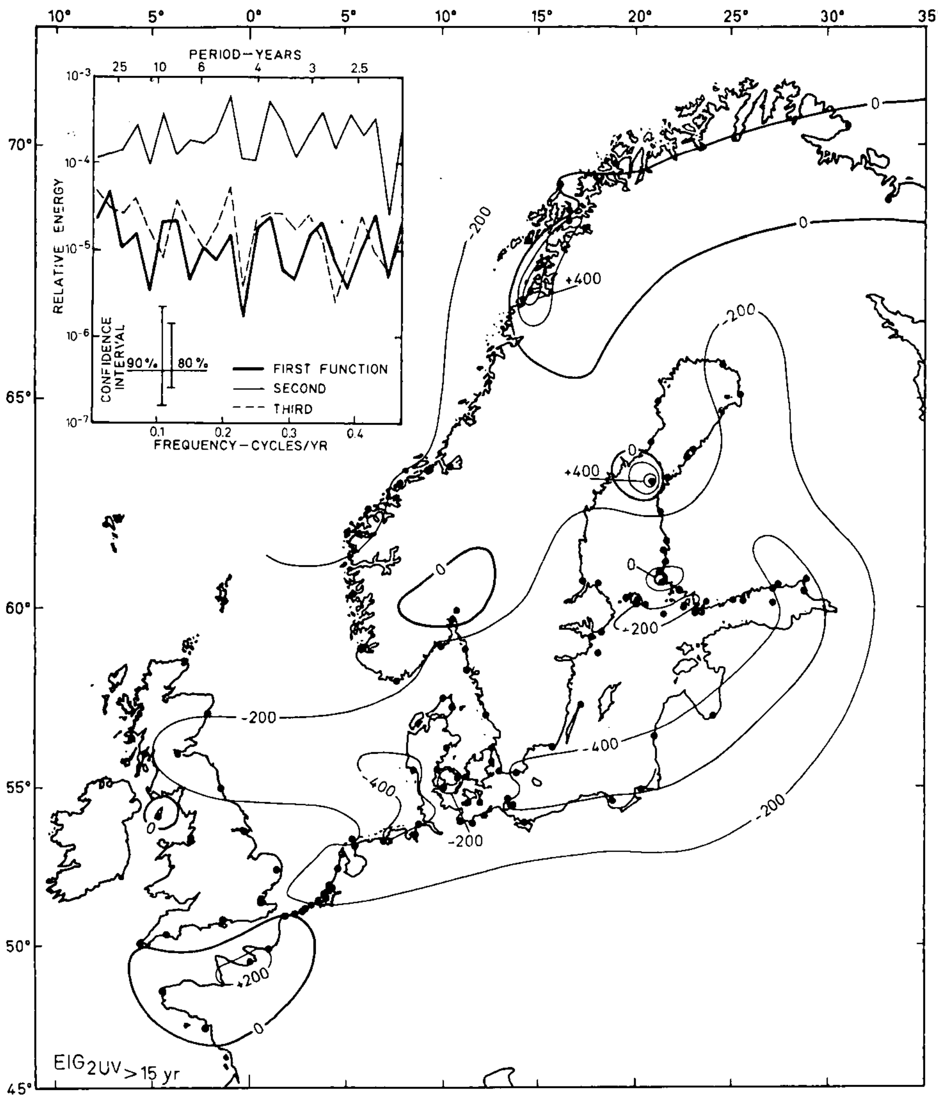

Fig. 5. Second spatial eigenfunction for same stations used in Fig. 4 at intervals of 200 units. Insert has spectra of first three temporal functions. Estimates have 4 degrees of freedom, with confidence levels indicated.

extract patterns of variability over identical intervals of time. Whereas regression analysis may compare trends from two stations reporting different time intervals, eigenanalysis yields sea-level trends for the entire period of study even if an individual station reported during only a small part of the total period. The contours and their values are rather similar to those obtained for regression analysis (Fig. 3) except for their elimination of some extreme rates from regression analysis. The center of uplift also has shifted to the northwest in the eigenanalysis results. Some of the differences also are illustrated by the $X-Y$ plot (insert diagram at upper left corner of Fig. 6), especially the string of six points having eigenanalysis values of about +1 mm/yr and regression values of +5 to +10 mm/yr. Five of these six aberrant points reported for only 16–19 yrs, so they are less representative of long-term trends than the stations reporting for longer periods.

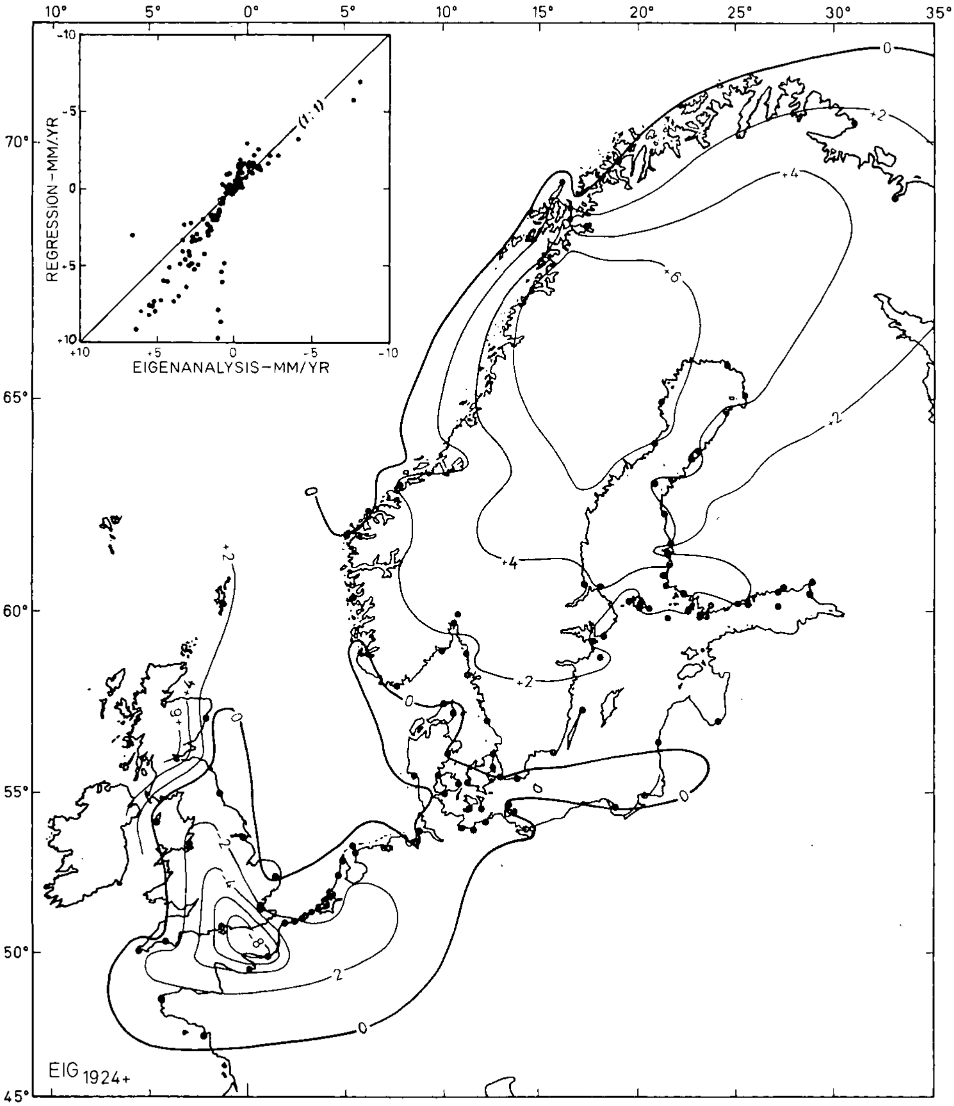

Fig. 6. Mean annual vertical movement of land in northern Europe relative to sea level as constructed from eigenfunctions of Figs. 4 and 5. Contours are in mm/yr and are comparable with those of Fig. 3 based upon regression analysis. Insert compares relative changes in elevation based upon eigenanalysis and regression analysis.

OCEANOGRAPHIC FACTORS

In our previous studies, the higher frequency variability of sea levels has been attributed to oceanographic factors, such as fluctuations in position of major ocean currents (Gulf Stream or Kuroshio). This study differs because the coastal water masses in the area are varied. Part of the coast is bounded by the open Atlantic Ocean, but most of the coastal waters consist of the marginal Irish Sea, English Channel, North Sea, Baltic Sea, Gulf of Bothnia, and Gulf of Finland (Fig. 2). Oceanographic forcing is different for each of these water bodies, with some responding to oceanographic factors such as fluctuations in major ocean currents and others perhaps to precipitation cycles especially in nearly land-locked waters such as the Baltic Sea. As a result of the presence of so many different water bodies, correlation of high-frequency sea-level fluctuations with oceanographic factors is very difficult (see Rossiter, 1962, for a discussion of major influences on relative sea levels).

Spectra of eigenfunctions of sea levels (insert, Fig. 5) in fact have no dominant frequencies that suggest deterministic oceanographic forcing. To examine the possible influence of correlation of oceanographic and hydrographic variability with sea-level fluctuations, records of precipitation, salinity, river runoff, and flow through Dover Strait were collated (Grindley, 1972; Prandle, 1978; Taylor et al., 1981, 1983) for the English Channel and North Sea. For the overlapping periods of observation there was no significant correlation between these variables and the temporal eigenfunctions. Information for the Baltic Sea, Gulf of Bothnia, and Gulf of Finland were more difficult to locate. Data presented by Ehlin (1981) and Kullenberg (1981) reveal no obvious correlation with sea levels over the entire northern Europe. Presumably, if each separate water mass were studied individually, stronger relationships between hydrography/oceanography and sea levels would emerge. This was not done in the present study, although Rossiter (1967) performed such analyses on a shorter record for part of the European coast.

CONCLUSIONS

Similarity of contours of land uplift from tide-gauge records in the heavily glaciated area of Scandinavia and contours of total elevation from tilted shorelines support the concept that the uplift is due to rebound after removal of ice load by melting and that glacial rebound is continuing. These conclusions are supported by gravity measurements. The present uplift in Scotland must be due to melt of its ice cap, and the sinking of southern England and western France is an indication of a complex former peripheral bulge produced by the glacial downwarps at Scandinavia and Scotland. This bulge is poorly defined because tide-gauge stations exist only along shorelines. The present data do not support Mörner's (1980) concept of non-isostatic tectonic control of present-day land uplift in Fennoscandia.

The possible uplift associated with the Gulf of Finland is interesting because of its relation with the contact between the Baltic shield and the Russian platform. Its existence largely depends upon two 11-year Soviet stations whose known record ends in 1937–1938, probably interrupted or ended by war. This is not a site where neotectonism has previously been suggested to occur.

The northern European region of abundant tide-gauge stations has undergone and continues to undergo complex vertical movements caused by crustal movements resulting from late Pleistocene glacial loading. These vertical movements include both uplift and downdrop—a maximum range of about 16 mm/year by eigenanalysis, far larger than any possible eustatic change of sea level and mostly in a direction opposite that expected of thermal expansion and addition of meltwater to the ocean. Accordingly, we believe that selection of one or more tide-gauge records in the region that are representative of eustatism is impossible at the present state of knowledge of land-sea-level movements.

With the present data it is not possible to separate eustatic sea-level changes from isostatic ones. We question Mörner's (1980) method of separating the two effects based on raised terraces. Our study can define only relative trends in sea levels, with the major structure of the sea-level patterns being consistent with continued isostatic rebound, superimposed by a more-or-less uniform eustatic rise of unknown sign and magnitude.

Higher frequency sea-level oscillations have a "white" spectrum, with no dominant frequencies of oscillation. Because of the wide variety in exposure of the coastal water bodies, the response of the entire north European region to hydrographic and oceanographic factors is expected to be complex. Lack of direct correlation between precipitation, runoff, salinity, and temperature with changes in relative sea levels over the entire region is not surprising, although locally such correlations should be good (see Taylor et al., 1981, 1983).

ACKNOWLEDGEMENTS

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