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Geology

Relative sea levels from tide-gauge records

(land subsidence/ice melt/greenhouse effect)

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ABSTRACT **Mean annual sea levels at 247 tide-gauge stations of the world exhibit a general rise of relative sea level of about 3 mm/year during the past 40 years. In contrast, general uplift of the land is typical of high northern latitudes, where unloading of the crust by melt of Pleistocene ice sheets is significant. Erratic movements are typical of belts having crustal overthrusting and active volcanism. Short-term (5- and 10-year) records reveal recent changes in rates, but such short time spans may be so influenced by climatic cycles that identification of new trends is difficult, especially with the existing poor distribution and reporting of tide-gauge data.**

Relative sea-level changes have received considerable attention for the information that they provide about the extent of submergence of coasts caused by returning meltwater from Pleistocene glaciers. Additional interest comes from their use to measure deformation of continental crust at high latitudes by glacial unloading and at all latitudes by tectonism, mainly associated with plate tectonics. Most of the effort during the past two decades has been based upon the depth–age relationships of radiocarbon-dated materials originally deposited in the shore zone. The results show that sea level rose at least 100 m to about 5 m below present level during the interval between about 15,000 and 5000 years ago (a mean rise of about 10 mm/year). Subsequently, the rise has been much slower (a mean rate of 1 mm/year). This radiocarbon method covers a significant time period, but it is subject to errors in selection of datable materials and in judgment of original water depths; its intense application has been only to the continental shelves of the United States and Europe plus brief studies in other regions.

A completely different data base is provided by tide-gauge records. Mean annual sea level at a given station is the average of hourly water levels for an entire year—nearly 9000 points. Year-to-year irregularities are due to variations in runoff from adjacent land, in weather, and in currents, as shown by Meade and Emery (1) and Lisitzin (2). These same variations are the evident reasons why most irregularities in sea-level curves from different tide-gauge stations cannot be correlated with confidence. However, a best-fit least-squares regression line for the mean annual sea levels at any given station can indicate the general rise or lowering of relative sea level with some assurance. Early efforts to use these data were concentrated on United States tide recordings (3), as were many later ones (4–6). Most United States stations reveal a rise of relative sea level, but some of those for eastern Canada (7) and Alaska exhibit a relative lowering of sea level. These differences merely mean that the tide gauges are recording vertical movements of the land as well as real changes of sea level. An early use of tide-gauge data from additional stations elsewhere in the world was that of Gutenberg (8), who found relative sea level rising at about 1.1 mm/year. Kuenen (9) obtained similar results for 11 stations in the Netherlands. Most recent is a useful comparison of tide-gauge records from 287 stations of the world ocean with records as published up to about 1966; unfortunately, the Soviet authors (10) failed to include recordings from the ocean coasts of their own nation.

Tide-gauge data span a time generally shorter than a century, but they provide more continuous and more precise information than do radiocarbon dates. In fact, monthly average sea levels were used by Pattullo *et al.* (11) to show summer and winter alternation of high sea levels between southern and northern hemispheres. Particularly significant now is the possible 5-m rise of sea level that would result from melting of the unstable West Antarctic Ice Sheet (12, 13) by the increased greenhouse effect of carbon dioxide to be released to the atmosphere during the coming 40 years (14–19).

METHODS

An effort to establish the world pattern and rate of relative rise of sea level was based upon the world compilation of monthly and annual mean sea levels by Lennon (20). This was supplemented by data for six stations in the People's Republic of China obtained during a visit in October 1979 sponsored by the U.S. National Academy of Sciences and the Chinese Academia Sinica. Of the records for more than 725 tide-gauge stations, most were too short, too interrupted, and too irregular for use in this investigation. For stations that appeared to be acceptable, least-squares best-fit regression lines, correlation coefficients, standard errors, and confidence levels for the lines were calculated. Regression lines for only 211 stations have slopes significantly different from zero at a 95% or higher confidence level. To these were added 36 stations with records having slopes of regression lines significantly different from zero at the 80–94.9% confidence level in order to be able to include a representative set of stations from South America and Oceania. The records of the total 247 stations end at a median date of 1975 and have a median span of 39 years, although some of them continue through 1978 and some span a century (lower middle inset of Fig. 1). For most stations the span is much longer than the 19 years required for a complete tidal cycle produced by variations in movements of Earth relative to the rest of the solar system (3).

Unfortunately, the 247 acceptable tide-gauge records are only slightly better distributed in the world ocean than are radiocarbon measurements for more ancient sea levels. Most (65%) are concentrated along the coasts of continental United States, Japan, and Scandinavia. Only one station of mainland Africa and four of South America have confidence levels higher than 95% for the slopes of the regression lines. Few useful stations are available for southeastern Asia and for Communist nations. The strong bias for the northern hemisphere (228 or 247 stations) further reduces the number and value of conclusions that can be reached with the tide-gauge data. There is a general correlation in number of tide-gauge stations per unit population, in continuity of record, and in confidence levels of regression lines with the standards of living of the coastal nations in which the stations are located.

RESULTS

Long-term

A simplified presentation (Fig. 1) shows that the norm is a rise of relative sea level (or lowering of land) between 0 and 5 mm/year at low and middle latitudes of both hemispheres. A faster (to 14 mm/year) lowering of land is typical of United States stations in the Gulf of Mexico. More erratic values (either rising or sinking of the land) occur along western North America, western South America, and the Caribbean Sea; this is attributed to thrusting of continental crust atop oceanic crust at convergence boundaries of crustal plates. Even more erratic are records for stations in Japan and the Philippines, where instability is ascribed to local volcanism. Also striking is the broad rise of land in Scandinavia that must be due to unloading of the crust by melt of the former ice cap, as shown by many previous workers. In fact, the middle of the area (around the Gulf of Bothnia) is rising at a rate in excess of 5 mm/year relative to sea level. The hinge line (or line of zero change) passes off southern Norway, off northern Denmark, through southern Sweden, and off southern Finland. The eastern hinge line is undefined, because data for few stations in the U.S.S.R. are available. The northern hinge line is at least 900 km north of the limit of Fig. 1, because two stations at nearly that distance (on Spitsbergen and Novaya Zemlya) reveal rises of the land of 1.9 and 4.1 mm/year. Unfortunately, the same precision is not permitted in positioning the rise of the land in Greenland and northern Canada owing to lack of satisfactory station records; the one station, Churchill in Hudson Bay, does show a relative rise in land of 4.1 mm/year.

A plot of the frequency distribution of mean annual sea level may have two modes, one for rising land and one for rising sea level separated by low frequency at zero change (lower left inset of Fig. 1). The same is true for both continental and island shores. If we accept that rise of land is due to glacial unloading and tectonic or volcanic causes, most of the rise of sea level elsewhere must be due to return of glacial meltwater plus downwarping of continental shelves under their loads of water (21). Exhibiting a relative sea-level rise between 0 and 5 mm/year are 137 stations, 55% of the total and 73% of all those showing sinking of the land. Many of the stations where land is sinking faster than 5 mm/year also appear to be controlled by tectonics or compaction of underlying sediment; included are rates as highly aberrant as 24, 30, and 75 mm/year. To avoid undue effects of sinking of land other than by rising sea level, *median* rather than mean rates were computed. These medians are 3.0 mm/year for continental stations and 2.5 mm/year for oceanic-island ones. The rates may be interpreted to mean that sea level due to returning meltwater is rising 2.5 mm/year, to which 0.5 mm/year must be added for downwarping of continental shelves by cooling of the lithosphere (22) and weighting by meltwater atop the shelves (21). The 0.5 mm/year figure is about 70 times higher than the long-term stratigraphic record yields for the continental shelf, but the shorter-term rate of sinking under the weight of returned meltwater is less well established.

Short-term

Estimates of the rate of eustatic rise of sea level based upon tide-gauge records up to about 1960 are in the range of 1.0–1.5 mm/year, in contrast with 3.0 mm/year obtained in this study. Relative rises of sea level along the Atlantic coast of the United States compiled by Hicks and his associates (4–6) at intervals between 1962 and 1975 also exhibit a general increase. A similar finding is suggested in the compilation by Klige *et al.* (ref. 10, pp. 138 and 156) but is uncertain because their tide-gauge data end too early (about 1966).

In order to test the concept of recent increase in rate of sea-level rise, computations were made for only the years 1970–1975 (Fig. 2), for which 82 stations have regression lines significant at the 95% level of confidence. Of these, 69 stations have mean annual sea levels for 5 years, and 13 for only 4 years. Only 44 of these 69 stations are represented also in Fig. 1. The 5-year span stations are even more poorly distributed in the world ocean than those for longer but not identical time spans. Relative sea-level changes again exhibit a bimodal pattern (inset at lower left of Fig. 2) and the median for the sinking of land (or rise of sea level) is 14 mm/year, much larger than the 3 mm/year for the longer time span of Fig. 1.

Comparison of Figs. 1 and 2 reveals several important differences. Changes of relative sea level per year are greater for the shorter time span, and relative sea level rose for stations of northeastern United States, eastern Canada, and southern Europe instead of sinking as for the longer time span that is illustrated by Fig. 1. To investigate further the difference between short- and long-time spans, the inset at the lower middle of Fig. 2 incorporates mean sea levels for the time span of 1966–1975, using data from all tide-gauge stations in areas A and B (off eastern North America) whether or not those stations qualified for acceptance on the main figure. The data for southeastern North America reveal an irregular rise of sea level (or sinking of the land), and a regression line through the median sea levels has a slope of 7 mm/year. Sea levels for area A, northeastern North America, are less uniform in their year-to-year changes. The plot indicates that either sea level rose (or the land sank) or more likely that the 10-year span merely represents only part of a cyclic change of sea level. A similar plot for 16 tide-gauge stations of southern Europe is more irregular, with a peak of relative sea level during 1969. For Scandinavia, where the records are too erratic for inclusion on the main part of Fig. 2, 39 stations yielded data for the 10-year span that exhibit a very high sea-level peak during 1967 and no clear trend after 1968.

CONCLUSIONS

Long-term tide-gauge records show that mean annual sea levels are rising (or the land is sinking) in low and middle latitudes at a median rate of about 3 mm/year. In glaciated regions at high latitudes the land is rising due to rebound because of past and present melting of ice sheets. Local irregularities at all latitudes are due to tectonism (including volcanism) and to other causes (probably mostly compaction of sediments in river mouths, where many tide gauges are installed). The distribution pattern of useful tide-gauge records is too imbalanced in favor of parts of the northern hemisphere for confirmation or denial of a deformation of the geoid, as is advocated by Newman *et al.* (23) on the basis of radiocarbon measurements for relative sea levels for the past 6000 years.

At most stations the rate of relative rise of sea level is 2 or 3 times the rate obtained by similar studies prior to the 1970s, and the reason appears to be a recent increase in rate of sea-level rise (or far less likely of regional land subsidence). For the 1970–1974 period the median rise of relative sea level is about 14 mm/year, enough to account for differences between the present and earlier longer-term averages. The recent change in rate is more likely to be due to higher levels of water than to general subsidence of the land, as indicated by some cyclicity in the relative changes. This seems particularly true for the Scandinavian records because of the partly land-locked nature of the Baltic Sea and its gulfs. Whether the recent rise of sea level is due to melting of glaciers caused by the carbon dioxide greenhouse effect is not yet clear.

Many kinds of computations are beyond the present limit of

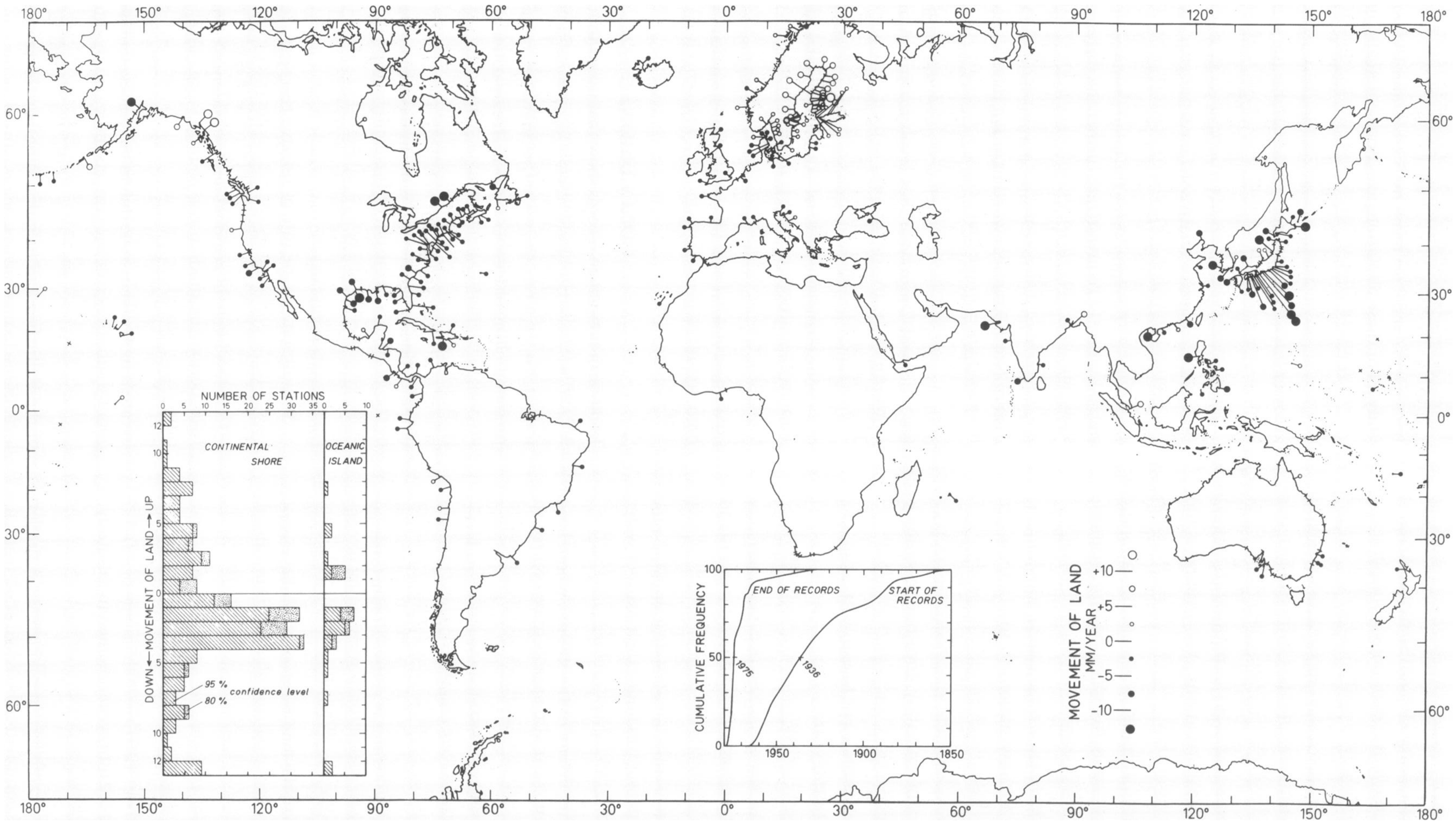

FIG. 1. Changes in relative sea level at 247 tide-gauge stations of the world grouped into six categories of direction and rate. The rates (slopes of regression lines) have confidence levels of 95% or higher for 211 stations and 80–94.9% for 36 stations. Short lines along the coasts indicate positions of additional stations for which existing data were considered too brief or too erratic for serious use. (*Inset* at lower left) Grouping of rates of relative sea-level change in units of 1 mm/year to show bimodal distribution at the 247 stations of the main figure. (*Inset* at lower middle) Frequency of starting and ending dates for the 247 stations having acceptable data.

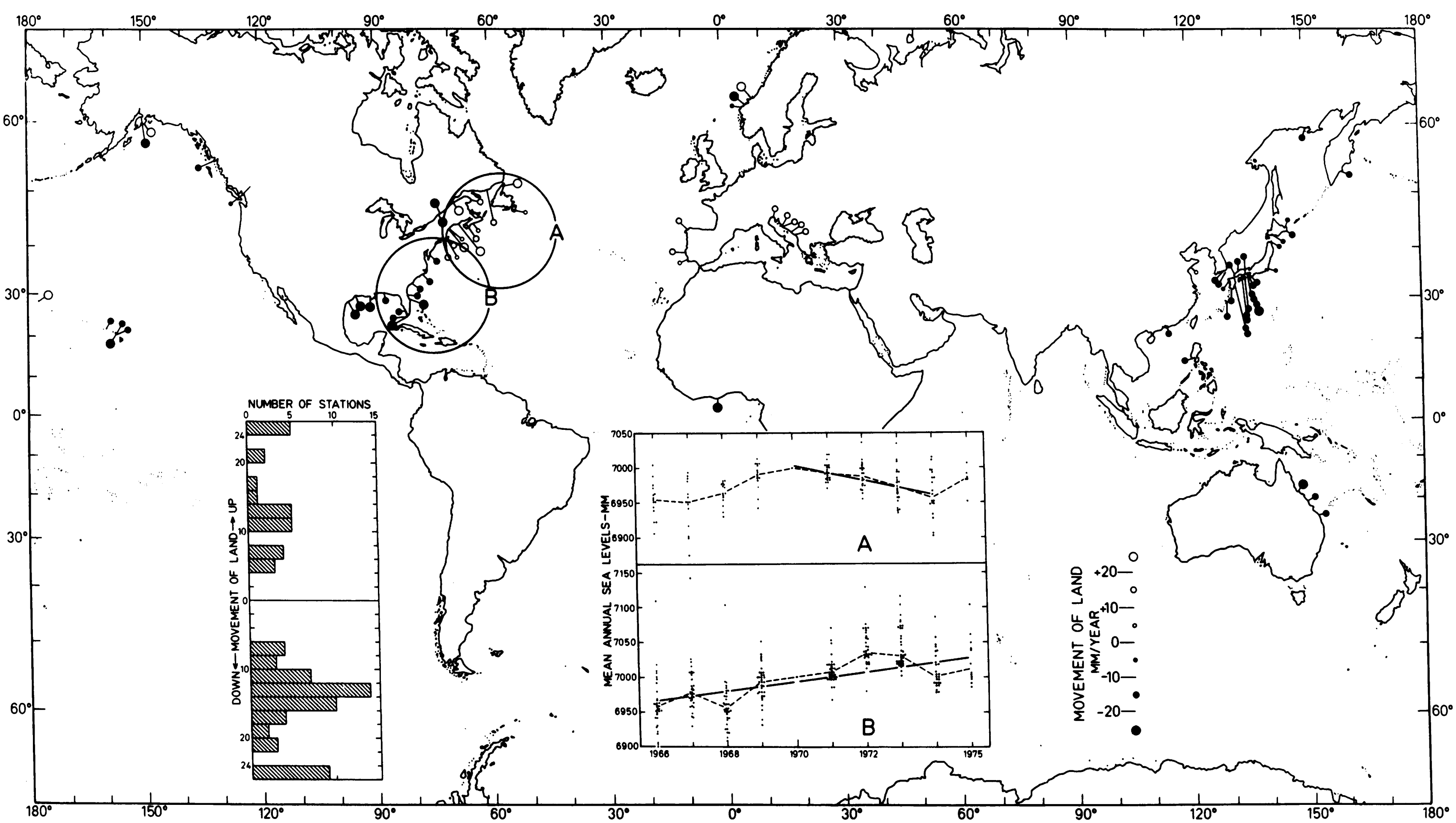

FIG. 2. Changes of relative sea level at 82 stations having confidence levels of 95% or higher for regression lines through mean annual sea-level points for the 5-year period 1970–1974. (*Inset* at lower left) Grouping of rates of relative sea level change in steps of 2 mm/year to show bimodal distribution pattern. (*Inset* at lower middle) Plots of mean annual sea levels at 22 stations of northern North America and 36 of southeastern North America for the period 1966–1975 to reveal trends beyond the averages of the main figure; the annual sea levels were normalized for 1970 sea levels at 7000 mm above an arbitrary base level.

precision permitted by the reporting of tide-gauge measurements and by the world distribution pattern of the stations. It is hoped that most existing long-term tide gauges will be continued, with improved reporting, and additional ones will be installed, particularly in the southern hemisphere. Thus our measures of rising sea level and their complications by tectonic processes may permit us to recognize a rise of sea level due to accelerated melting of glaciers caused by increased industrial production of carbon dioxide. Costs of rising sea levels in terms of a 5-m submergence of coastal cities and agricultural land would far exceed the costs of additional tide gauges and support for proper measuring and reporting of sea-level data.

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