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Recent global sea levels and land levels

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Abstract

Tide-gauge records from around the world ambiguously document the rise and fall of relative sea levels during the past century. Analyses of these records, non-uniformly distributed in time and space, reveal that land levels as well as ocean levels are changing, complicating the estimation of the eustatic component of sea level change. Because most tide gauges are concentrated in the Northern Hemisphere instead of the Southern Hemisphere (where most ocean area is located), tide-gauge data reflect major continental motions due to glacio-isostasy and neo-tectonism, which suppress and mask the signal from eustatic sea level change.

Estimation of the magnitude of sea level change is important for many reasons, including the interpretation of possible effects of global climate change resulting from carbon dioxide and other trace gas loading of the atmosphere. Proper interpretation of past sea level changes is valuable for the calibration and evaluation of certain global climate, ocean and geophysical Earth models. This interpretation can be accomplished using tide-gauge records and other records of relative sea levels only if land level changes are sufficiently distinguished from actual sea level changes.

Introduction

Past and future climate changes drive various responses in the oceans. One such response is variation in sea levels as the oceans warm or cool, and as water is removed from or returned to the ocean basins and glaciers. During the past 15,000–18,000 years following the last glacial maximum, the Earth has experienced an average warming of about 4–5 °C. As a result, sea levels have risen between 60 and 150 metres (Milliman and Emery, 1968; Blackwelder *et al.*, 1979; Oldale and O'Hara, 1980). On the century time-scale, the Earth's climate has also undergone changes, including the climatic optimum of around AD 1000–1300 and the Little Ice Age of AD 1300–1850 (Thompson *et al.*, 1986). These short-term climate changes have produced global mean temperature fluctuations of perhaps as much as several degrees (e.g., Willett, 1950; Mörner, 1973; Wigley and Jones, 1981; Ellsaesser *et al.*, 1986), as well as unresolved variations in mean sea levels.

In addition to these historic changes in climate, concern has arisen over potential future global warming resulting from increasing atmospheric concentrations of trace gases such as carbon dioxide, methane, nitrous oxide and chlorofluorocarbons (NRC, 1983; Bolin *et al.*, 1986; Houghton *et al.*, 1990). One expected response from global warming is an increase in ocean levels. Based on observational data and on simple models of ocean response to climate change, estimates of sea level rise during the next 100 years range from a few tens of centimetres to several metres (Warrick and Oerlemans, 1990). Given the uncertainty in these calculations and the potential economic impact of increasing coastal inundation (Hoffman *et al.*, 1983; Broadus *et al.*, 1986), it is essential that research reduce this large range of uncertainty. For the sea level rise issue, improved knowledge of the response of sea levels to past climate change is needed, incorporating both the magnitude and phasing of such ocean response to climatic forcing.

Eustatic sea levels

Tide-gauge records have been used extensively during this century to estimate sea level changes (Gornitz, Pugh, this volume; Gornitz *et al.*, 1982; Emery, 1980; Barnett, 1984; Aubrey, 1985). Most estimates of the rate of sea level rise over the last 100 years are in the range of 1.0–1.5 mm/yr, despite the use of records from different geographic regions and the spanning of dissimilar time intervals (Woodworth, this volume). The similarity of these estimates gives false confidence to their validity, since the roles of glacio-isostasy and neo-tectonism on a global basis have only recently begun to be explored systematically (Emery and Aubrey, 1991).

Average sea level rise since deglaciation (due to both steric response and glacial meltwater input) was 6–12 mm/yr prior to about 6,000 years ago, depending on the speed of deglaciation and maximum depression of ocean levels during the Wisconsinan (Würm). Subsequently, the rate of rise of sea level has been less. Estimates of the ocean level at 7,000 and 5,000 BP are, respectively, 10 m and 5 m lower than today (Curray, 1964; Milliman and Emery, 1968; Pirazzoli, 1977). This suggests that the average rate of global sea level rise since then has been between 1.4 mm/yr and 1.0 mm/yr. Some radiocarbon dating indicates that the rate of rise has decreased continuously during the past 4,000 years (Redfield, 1967); however, sparse sampling and lack of discrimination between ocean levels and land levels present difficulties in quantifying the decreased rate of rise (Clark and Lingle, 1979).

Recent investigations of time series of sea levels over large areas suggest that an increase in the rate of rise of relative sea levels (RSL) may have occurred during the post-1930 era compared with previous records (Barnett, 1984; Braatz and Aubrey, 1987; see Fig. 3.1). Such increases have been found at all locations where sufficiently long record lengths exist, including North America, Northern Europe, and Eastern Asia. On average, rates of RSL increased by approximately 0.5 mm/yr following the decade of the 1930s. The source of this apparent increase in relative sea level rise is uncertain. Although it is tempting to relate this acceleration to human-induced climate change resulting from trace gas effects, there is no direct support for this view. Rather, the recent increase may reflect the delayed ocean response to climate warming following the Little Ice Age (that ended about AD 1850; Thompson *et al.*, 1986). As global mean atmospheric temperatures have risen by approximately 0.5 °C since the end of the Little Ice Age (Jones *et al.*, 1986a, 1986b), sea level would be expected to respond. If this increase in sea level is a response to global warming, then the delay

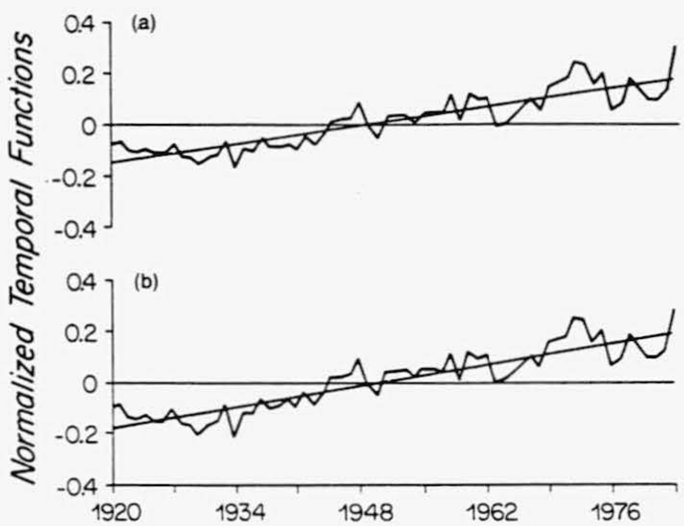


Fig. 3.1 Apparent change in rate of relative sea level rise along the US East Coast from 1920 to 1980, derived from tide-gauge data. (*a*) The first temporal eigenfunction computed from all 44 stations used in the study. (*b*) The first temporal eigenfunction computed from the 26 stations which were in operation before 1935.

There is almost no difference between the two results, indicating that the change in slope of the first temporal eigenfunction at 1934 is not an artifact of lower sampling density between 1920 and 1934, nor is it a bias resulting from the analysis. The reasons for this change in slope are uncertain, the changes having an origin perhaps in oceanographic variability or changes in volume of the world oceans (Braatz and Aubrey, 1987. Reprinted by permission of the Society of Economic Palaeontologists and Mineralogists).

between atmospheric warming and sea level response could be of the order of many decades, instead of the commonly cited 20-year lag (Cess and Goldenberg, 1981; Revelle, 1983). Alternatively, the apparent change in rate of sea level rise may be attributable to oceanographic factors (Sturges, 1987; Pugh, 1987). Finally, it is possible that the apparent mid-century acceleration in sea level rise is not statistically significant (Woodworth, 1990).

Two possible climate-related explanations for a globally coherent rise in sea level at the century time-scale are oceanic thermal expansion and increased glacial melt. Global ocean warming is thought to have occurred during the past century (Roemmich and Wunsch, 1984; Roemmich, 1985), although there are uncertainties about its existence and magnitude (Barnett, 1983b). Roemmich and Wunsch (1984) estimated that steric expansion due to warming in the North Atlantic between water depths of 1,000–3,000 m accounts for about 0.4 mm/yr during the interval 1957–72, assuming that the effects found in the North Atlantic ocean are characteristic of the global oceans as a whole. Available data are inadequate to resolve whether such an expansion is a global or local phenomenon. For global estimates, reliance has to be placed on model-based estimates (see Wigley and Raper, this volume).

Estimation of the contribution of meltwater input to oceans similarly is limited by inadequate data. Recent reviews of contributions of land ice to ocean levels (PRB, 1985; Robin, 1986; Warrick and Oerlemans, 1990) document the uncertainty in estimates of present mass balances of the major ice sheets and mountain glaciers. This makes the estimation of historical changes in mass balances even more problematical.

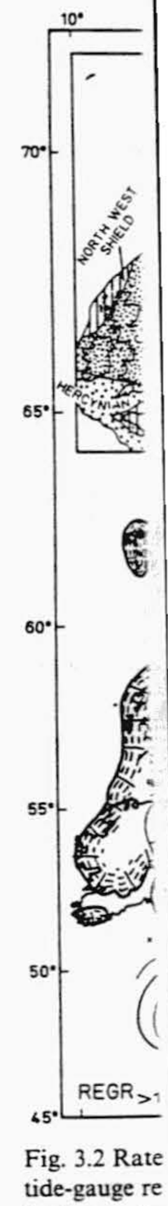
In short, the relative contributions of meltwater and steric effects to the increased rate of absolute sea level rise cannot be adequately resolved at present. An increase in rate is consistent with changes in climate processes as opposed to being tectonic in origin, because no mechanisms have been suggested for a global increase in tectonic processes occurring simultaneously around the globe in such a short time interval. Global warming may have reached approximately 0.25 °C from 1860 through 1940. Whether or not this is the cause of the increase in RSL can be resolved only by modelling studies and improved interpretation of observations.

Glacial rebound isostasy

Glacio-isostasy is a common cause of neo-tectonism (Tooley, this volume). Isostatic adjustment has been widespread, covering both hemispheres, as the Earth's crust continues to adjust to the Wisconsinan (Würm) glaciation and deglaciation (Walcott, 1972; Clark *et al.*, 1978; Peltier, 1984, 1986). Glacio-isostasy dominates the many tide-gauge records of Northern Europe (Emery and Aubrey, 1985; see Fig. 3.2). Centred over the Gulf of Bothnia and also over the Northern British Isles is an isostatic rebound that reflects the removal of large masses of glacial ice during the Late Pleistocene period. Rates of rebound reach 10 mm/yr, about equal in absolute value to the global mean rate of rise of sea level during the deglaciation. Of the available high quality global tide-gauge records, the 134 records from Fennoscandia are contaminated by isostatic adjustment which cannot be removed without using a rebound model. Although numerical models of isostatic effects have been developed (Peltier, 1984, 1986; Mörner, 1980), the approximations needed for the models make it difficult to verify their accuracy, particularly for the past 100 years.

Reconstructions of postglacial rebound in Fennoscandia, based on diverse geological data (Mörner, 1969; Emery and Aubrey, 1985), suggest a rebound of up to 700 m during the past 10,000–15,000 years or so. This implies an average rate of rebound in the central depressed area of about 50–70 mm/yr, much more rapid than the eustatic sea level change. Present rates of rebound, although still significantly higher than eustatic sea level change, are lower than previous rates of rebound by a factor of five. This finding is consistent with numerical model studies (Clark and Lingle, 1979).

Glacio-isostasy also may dominate records from the northeastern coast of North America (Aubrey and Emery, 1983; Braatz and Aubrey, 1987; see Fig. 3.3). Using numerical model estimates of glacial rebound (Peltier, 1986), the total relative sea level record can be reconstructed, as can the residual following removal of the estimated deglaciation effect (in the Eastern US isostatic submergence is taking place as the glacial forebulge that formerly covered most of this area relaxes, while the central glaciated area over Canada is rebounding, leading to belts of submergence and emergence). Removal of the glacio-isostatic effect suggests a residual relative sea level rise of between 1.0 and 1.5 mm/yr, certainly within the range of previous estimates of sea level rise. Superimposed on this mean rate is a variability that bears some relationship to the distribution of exotic terranes, although the relationship is qualitative (Uchupi and Aubrey, 1988). Thus the 44 most usable tide gauges of Eastern North America are contaminated by glacio-isostatic and tectonic processes. Although adjust-



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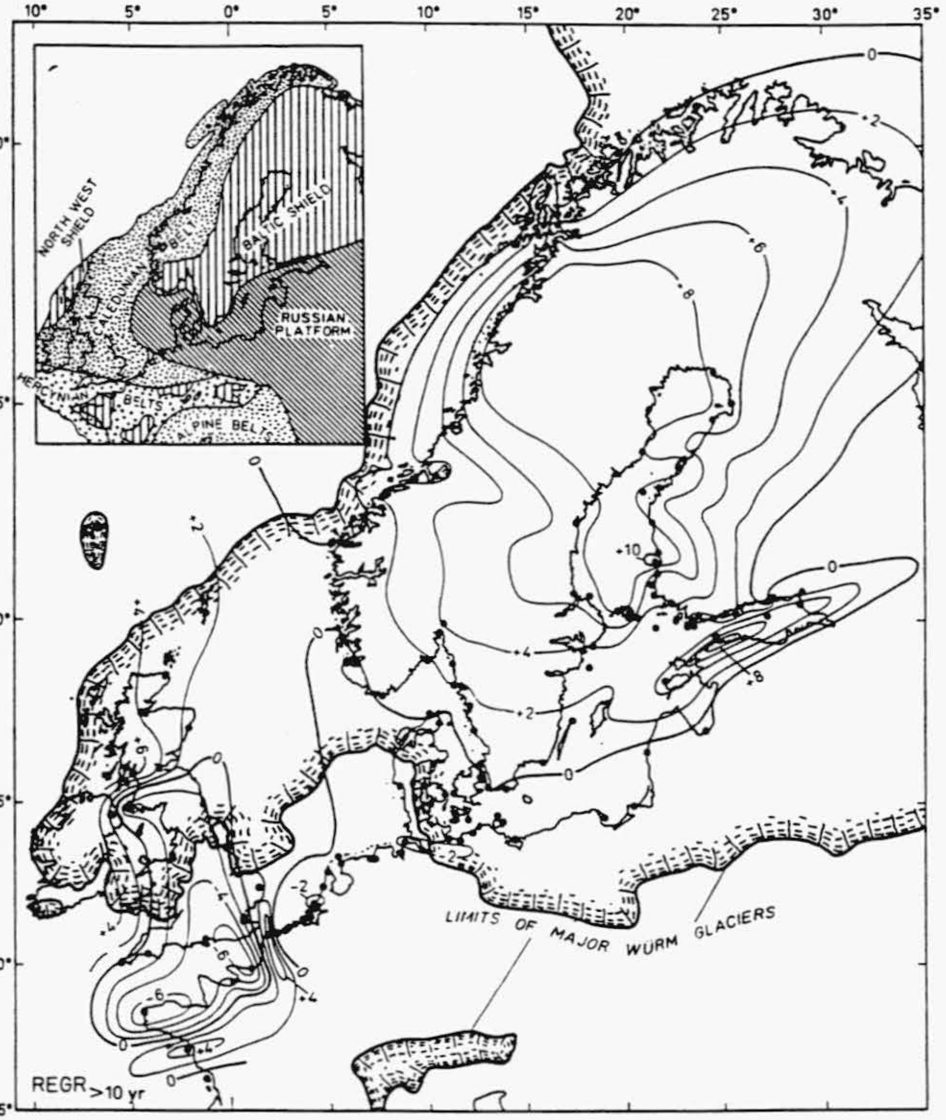

Fig. 3.2 Rates of relative sea level rise (mm/yr) in Northern Europe derived from analysis of tide-gauge records covering the time period 1900–85. Positive values indicate relative rise of land; negative values indicate relative sinking of land. The patterns of relative sea level change are consistent with ongoing crustal response to the latest glaciation/deglaciation cycle (Emery and Aubrey, 1985. Reprinted by permission of Elsevier Science Publishers).

ments have been made for these processes, they represent only approximations that are certain to be refined in the future.

Plate Movements

Tectonism affects tide-gauge records both by changing the volume of ocean basins and by altering the level of recording instruments. Ocean-basin volume changes can arise

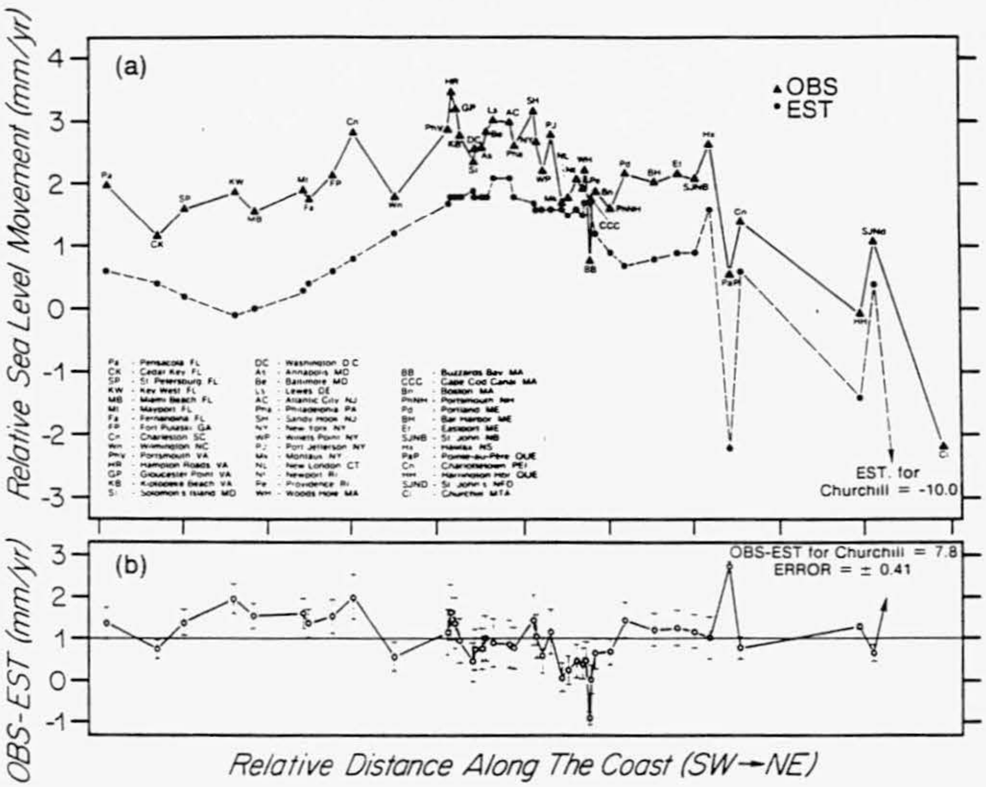

Fig. 3.3(*a*) Mean annual RSL movement for 1920–80 from reconstructed eigenfunction data (synthetic rates, OBS), and estimates of annual RSL movement due to postglacial isostatic adjustment (EST, Peltier, 1986), plotted in a relative sense along the coastline. These relative distances are obtained by drawing perpendiculars from the stations to lines drawn approximately parallel to the coastline. From Pensacola to Key West, this line trends 146° measured clockwise from true North; from Key West to St. John's, Newfoundland, the line trends 40° measured clockwise from true North. Churchill, located along the west central coast of Hudson Bay, is placed at an arbitrary distance from St. John's. (*b*) Residual annual RSL movement, i.e., synthetic (OBS) minus estimated (EST) isostatic adjustment. Relative sea level change shows relative rise of land to the south. This pattern is consistent with glacial loading/unloading following the Wisconsin glaciation, on which is superimposed a eustatic rise of poorly constrained magnitude. The convention for land rising/sinking is negative for relative rise of the land, positive for sinking of the land (Braatz and Aubrey, 1987. Reprinted by permission of the Society of Economic Palaeontologists and Mineralogists).

from changes in rates or directions of sea-floor spreading (for instance, Pitman, 1979; Kennett, 1982). During the Cretaceous Period, sea levels stood about 350 m above present levels, flooding nearly 35% of the present land surface; the rates of sea-floor spreading were higher than present rates. When spreading rates decreased, the average ocean depth increased and sea levels fell. Estimates for the maximum rates of sea level fall responding to such rate changes are approximately 0.01 mm/yr, clearly important on a geological time-scale if persistent, but not significant on historical time-scales.

Neo-tectonism also affects tide-gauge records by changing the level of the tide-gauge station. At present, changes in mean sea level measured at a single station cannot be separated into vertical land movement and eustatic sea level components, because they cover the same part of the spectrum (although geodetic techniques in development may achieve such a separation in the future; Diamante *et al.*, 1987; Carter *et al.*, this volume). Alternatively, analyses of regional arrays of tide gauges, in combination with geological studies, provide a promising means of estimating the various contributing factors.

Plate tectonics directly affect relative sea levels as the surfaces of plates continuously adjust to relative horizontal plate motion, deforming the continental margins on which tide gauges are located. Intra-plate earthquake activity (Sykes, 1963) concentrated about the margins of the Pacific reflects this plate interaction. Since the tide gauges are located along the oceanic margins where much tectonic activity exists, it is expected that their records would mirror these effects.

Using tide-gauge data from around the world (approximately 1243 stations, of which 563 exceed 10 years in length and 332 exceed 20 years in length; Pugh *et al.*, 1987; Pugh, 1987), recent investigations have clarified the extent of tectonic impact on relative sea levels (Hicks, 1972; Aubrey and Emery, 1983, 1986; Emery and Aubrey, 1985, 1986a, 1986b, 1989, 1991; Braatz and Aubrey, 1987; Aubrey *et al.*, 1988; Pirazzoli, 1986). The tide-gauge records of Western North America, long known to be tectonically active, also are affected by tectonism (Emery and Aubrey, 1986b; see Fig. 3.4). Similarly, the records of the many tide gauges of Japan and other island chains contain a broad-scale tectonic trend related to plate convergence processes that mask changes in ocean level itself (Aubrey and Emery, 1986; Emery and Aubrey, 1991; see Fig. 3.5). From none of these records can a change in eustatic sea level be extracted with confidence. Of the 200 tide gauges covering these locations, none is obviously free from tectonic impact. Thus, they must be used with care in deriving estimates of sea level rise.

Continental margins consist in large part of exotic or suspect terranes composed of oceanic and continental fragments from past plate interactions, creating a complex mélange of geology and hence variable structural strength (Coney *et al.*, 1980; Uchupi and Aubrey, 1988). As stress fields are set up due to deglaciation and plate interactions, one might expect the response of different suspect terranes to vary. The pervasiveness of such tectonic fabrics and stresses argues strongly for more local tectonic control on tide-gauge records than has been envisioned previously (Barnett, 1983a; Chelton and Davis, 1982).

Other studies have been made of South American, Mediterranean, East Asian, Indian, and Australian tide gauges (Aubrey *et al.*, 1988; Aubrey and Emery, 1986; Emery and Aubrey, 1986a; 1989; 1991; Emery *et al.*, 1988). These studies show similar results: that tectonism and isostatic processes dominate tide-gauge records and make interpretation of sea level rise difficult. Of the total number of tide gauges available for analysis, more than 90% of the Permanent Service for Mean Sea Level (PSMSL) stations exceeding ten years in length are located in the nine localities discussed above. Given the tectonic bias at these stations, estimation of absolute sea level rise is not unique. In addition, Man's direct impacts on tide gauges are severe and pervasive. River diversion, pore-fluid mining and sedimentation control negate data from dozens of tide gauges world-wide (Emery and Aubrey, 1991). However, much has been learned about relative land level changes and about the response of continental margins to plate

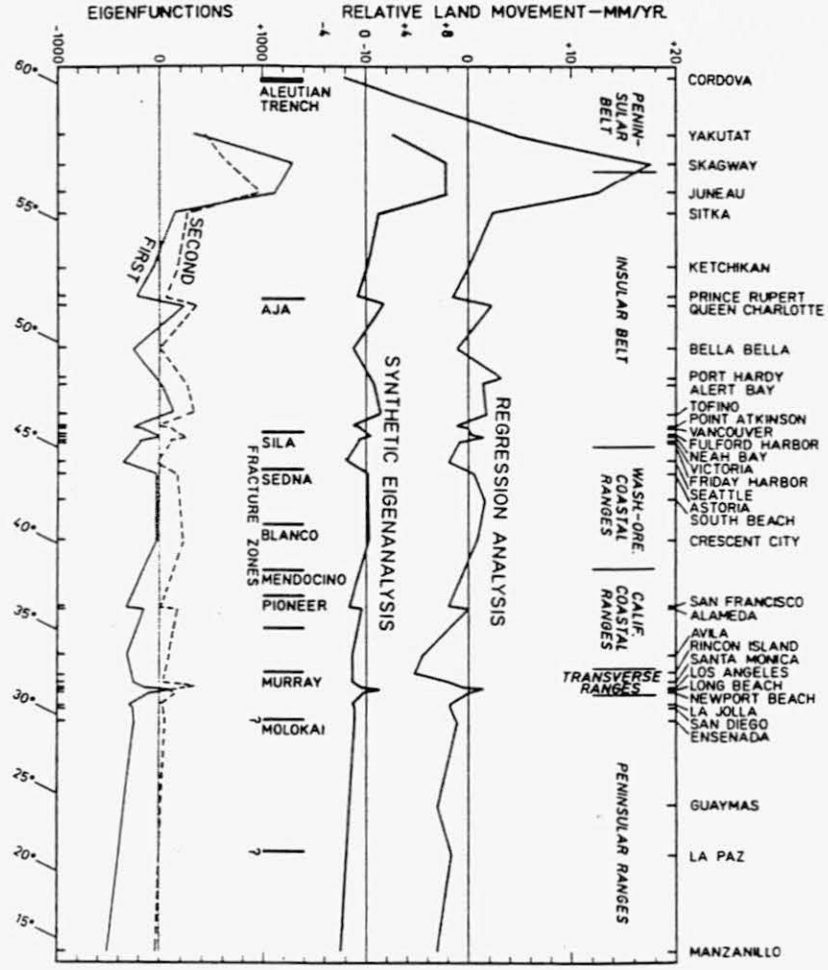

Fig. 3.4 Tide-gauge data from the Western North American region reflect the importance of tectonism on relative sea level. While some of the variability is due to differing record lengths of station data, larger scale trends are thought to reflect trends in relative sea level variability arising from tectonic causes (Emery and Aubrey, 1986b. Reprinted by permission of the American Geophysical Union).

motions. Because of the difficulty in estimating sea level changes, their use in calibrating models of ocean response to climate change is limited by available data.

Conclusions

The data relating historical climate change to relative sea levels are incomplete. Yet, judicious analysis of past observations in combination with modelling programmes should provide important information regarding climate–sea level relationships.

With respect to estimating globally coherent changes in sea level during the last 100 years, the biases arising from vertical land movements mean that estimates based on crude averages of tide-gauge data are subject to large uncertainties; significant elements

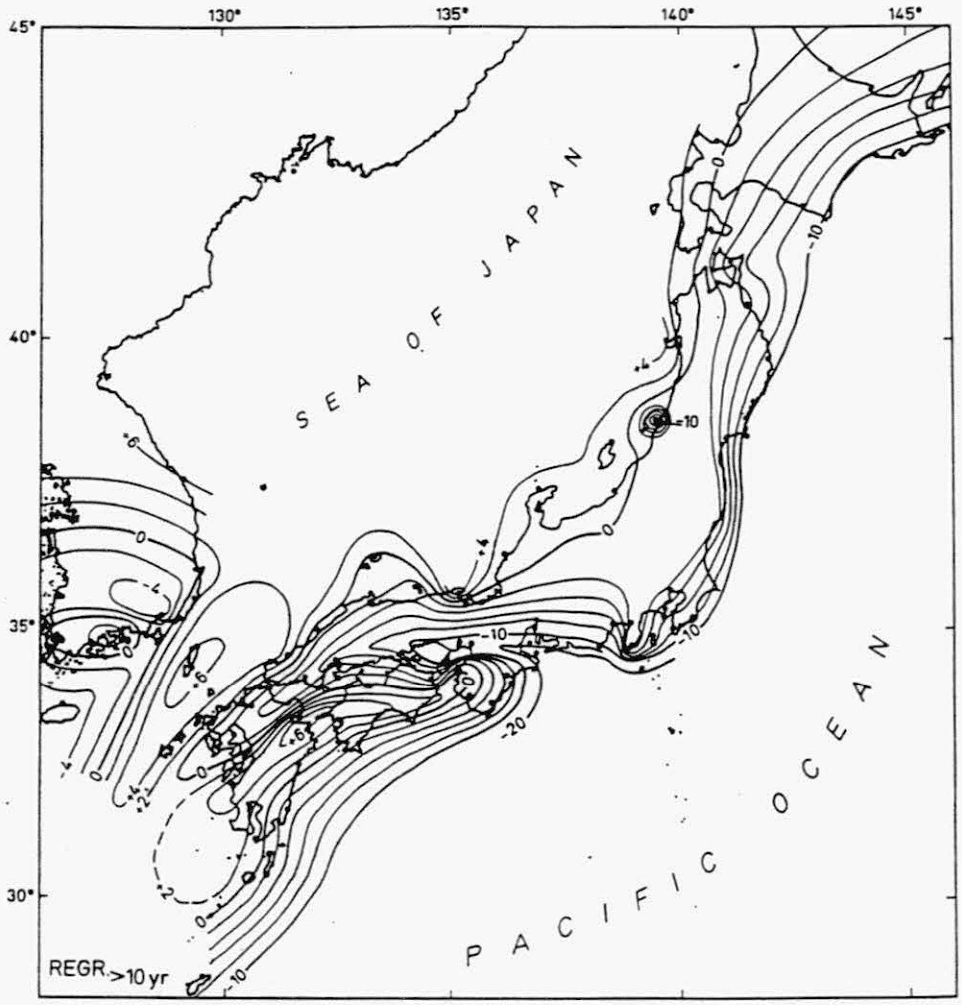

Fig. 3.5 Rates of relative sea level rise (mm/yr) along the coast of Japan as indicated by study of more than 100 tide gauges of that country. The strong geographic variability in this region is consistent with previous hypotheses of crustal deformation along convergent margins, notably along the trenches bordering Eastern and Southern Japan (Aubrey and Emery 1986. Reprinted by permission of the American Geophysical Union).

of the physics involved may be missed. New geodetic technologies such as Very Long Baseline Interferometry, differential Global Positioning System, and absolute gravity meters should allow for more precise discrimination between land motion and ocean volume change. This information, gathered over decades, should significantly reduce the uncertainties in estimates of past, present and future sea level behaviour.

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Abstract

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by

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