Sea Levels on Canada's Pacific Coast: Past and Future Trends

by John J. Clague

Increasing concentrations of atmospheric carbon dioxide, methane, nitrous oxide, chlorofluorocarbons, and other greenhouse gases are expected to warm the Earth by several degrees in the next century (Hansen et al., 1984). This is likely to increase melting of mountain glaciers and continental ice sheets and cause oceans to warm and expand. Global sea level will probably be higher as a result in coming decades. Many of the world's great cities are situated on low-lying deltas and coastal plains within a few metres of present sea level, and may thus be threatened, not only by inundation, but also by erosion and possible contamination of groundwater supplies. Governments must therefore begin to plan for the anticipated rise in sea level and implement measures to mitigate some of its adverse impacts. This article examines the late Quaternary history of sea-level change on the Pacific coast of Canada and discusses the magnitude and impact of future sea-level rise.

Late Quaternary Sea Levels

As a result mainly of tectonism and glaciation there have been complex shifts in the level of the sea relative to the land along the British Columbia coast during the Quaternary Period (Mathews et al., 1970; Clague et al., 1982; Clague, 1983). Western British Columbia is located in a tectonically

active region near the west edge of the America lithospheric plate (Fig. 1; Riddihough and Hyndman, 1976; Riddihough, 1977, 1982). Interactions of this plate with the offshore Juan de Fuca, Explorer, and Pacific plates have affected land-sea positions during the Quaternary. The repeated growth and decay of the Cordilleran Ice Sheet during the Pleistocene generated complex lithospheric deformations that were largely isostatic in nature. These, in combination with eustatic changes related to water transfers between oceans and ice sheets, altered relative sea-level positions along the Pacific coast.

At the end of the last glaciation, about 11,000-13,000 years ago, shorelines on eastern Vancouver Island and the British Columbia mainland were significantly higher than at present because the crust was isostatically depressed by the Cordilleran Ice Sheet (Fig. 2). Shortly thereafter the crust rebounded, causing the sea to fall relative to the land (Fig. 3). Rebound occurred at different times on different parts of the coast due to diachronous glacier retreat. There was a rapid regression during and shortly after deglaciation and, in general, areas that were deglaciated first rebounded earlier than those that were deglaciated at a later date. By 9000-10,000 years ago, the sea in most areas was lower, relative to the land, than it is today (Fig. 3). During the past three thousand years, shorelines on the British Columbia mainland and eastern Vancouver Island have been within a few metres of present positions, and there is no evidence for high sea levels during this period.

A radically different pattern of sea-level change has been documented for the Queen Charlotte Islands, which lie near the boundary between the Pacific and America plates and which had a limited ice cover during the late Pleistocene (Figs. 1, 3). Sea level in this area was much lower at the end of the last glaciation than it is today, a consequence of the fact that ice loads were insufficient to depress the crust below lowered eustatic water levels prevailing at that time. Sea level rose at the end of the Pleistocene and was higher throughout the Holocene than at present (Fig. 3). During the last several thousand years, sea level has fallen on the Queen Charlotte Islands at a rate of about 1 m/1000 years.

The opposing character of sea-level change on the mainland and the Queen Charlotte Islands is best explained in terms of differing ice loads and forebulge migration during deglaciation (Clague, 1983). As the Cordilleran Ice Sheet decayed, mantle material flowed away from peripheral glaciated areas such as the Queen Charlotte Islands. As a result, the atmosphere was depleted beneath the Charlottes, the crust subsided, and lowland areas were flooded by the sea. In contrast, eastward forebulge migration beneath the mainland caused uplift and a marine regression there. Tectonic factors also may account for some of the differences in the sea-level histories of these two areas, for parts of the outer coast probably are being uplifted as a result of plate interactions in the northeast Pacific Ocean. This may explain the relative sea-level fall on the Queen Charlotte Islands (and also on parts of western Vancouver Island) during the late Holocene.

Figure 1: Plate tectonic framework of southwestern British Columbia. Modified from Rogers (1988, Fig. 1). Arrows indicate plate motions relative to the America plate. Triangles mark major Quaternary volcanoes.

Figure 2: Maximum late Quaternary marine overlap in British Columbia. Modified from Clague (1981, Fig. 5).

Historical Sea-Level Trends

Tidal records and levelling data suggest that the sea is presently stable or rising relative to the land on the British Columbia mainland, but that it is falling on the Queen Charlotte Islands and parts of Vancouver Island (Fig. 4; Vanicek and Nagy, 1980; Wigen and Stephenson, 1980; Clague et al., 1982; Riddihough, 1982). This is generally consistent with the long-term trends deduced from geological evidence. However, rates of sea-level change determined from tidal and levelling data, in general, are higher than long-term, late Holocene rates. This may be due to inaccuracies in tidal and levelling data, to the short length of tidal records, or to the fact that recent rates of sea-level change are not representative of rates averaged over thousands of years.

Figure 3: Generalized patterns of sea-level change on the British Columbia coast since the end of the last glaciation. Modified from Clague (in press, Fig. 1.15). Each envelope depicts a range of sea-level positions, reflecting regional and local differences in ice loads and time of deglaciation as well as uncertainties in locating former shorelines. The vertical axis shows elevation of past shorelines relative to present mean sea level.

Future Sea Level Trends

The combustion of fossil fuels, deforestation, and other human activities have raised the atmospheric concentration of CO_2 20% since the Industrial Revolution and 8% since 1958 (Keeling et al., 1982). Carbon cycle modellers and energy economists generally expect CO_2 concentrations to increase an additional 50% by 2050 and 100% by 2075. Recently, atmospheric concentrations of other greenhouse gases have also been increasing rapidly (Lacis et al., 1981; Ramanathan et al., 1985). It is estimated that these gases, acting together, will directly raise the average temperature of the Earth's atmosphere 1.2°C by 2050 (Hansen et al., 1983). This warming, however, may produce secondary effects that will amplify the direct effect of greenhouse gases. A warmer atmosphere, for example, will retain more water vapour, which is itself a greenhouse gas. In addition, a reduction in snow and ice cover will lower the albedo of the Earth, causing an additional rise in temperature. After evaluating all the evidence, two panels of the United States National Academy of Sciences concluded that the atmosphere will be $1.5\text{--}4.5^\circ\text{C}$ warmer in 2050 than today (Ad Hoc Study Group on Carbon Dioxide and Climate, 1979; CO_2 /Climate Review Board, 1982).

Figure 4: Historical, relative sea-level change and vertical crustal movements on the British Columbia coast, based on tidal records and levelling data (modified from Clague et al., 1982, Fig. 11).

Such warming will raise sea level through thermal expansion of oceans and increased melting of glaciers. Uncertainties in rates of emission of greenhouse gases, their atmospheric lifetimes, oceanic heat absorption, and many other factors make it difficult to predict sea levels at various times in the future. However, a reasonable range of estimates can be made from "best-case" and "worst-case" scenarios (Hoffman et al., 1983, 1986). Such an analysis suggests that sea level is likely to rise 3–5 cm by 2000, 10–21 cm by 2025, 20–55 cm by 2050, and 36–192 cm by 2075 (Fig. 5). It should be noted, however, that rising seas could destabilize the marine-based West Antarctic Ice Sheet and cause it to retreat catastrophically. Sea level would rise 5–7 m in the event of a complete collapse of this ice sheet (Mercer, 1970), which might take place over a period of a few hundred years.

Figure 5: Estimates of sea-level rise caused by atmospheric warming. Data from Hoffman et al. (1986).

The net change in sea level along the British Columbia coast during the next century can be assessed by integrating the predicted greenhouse-induced values shown in Figure 5 with extrapolated values of emergence and submergence based on past records (Fig. 6). Such an exercise assumes that rates of sea-level change determined from geological records and historical data are, in fact, representative of current rates, and that current rates can be extrapolated linearly through the next century. In a strict sense, these assumptions are not valid because vertical crustal movements in an active tectonic area such as the Pacific coast can be expected to be somewhat irregular or episodic. A large earthquake, for example, could occur within the next several hundred years along the subduction zone separating the America and Juan de Fuca-Explorer plates (Heaton and Kanamori, 1984; Atwater, 1987; Rogers, 1988).

Such an earthquake might instantly change the level of the sea relative to the land in southwestern British Columbia. Unfortunately, the likelihood that a great subduction earthquake will occur in this region in the next century is unknown. Also, it is not possible to estimate, with any assurance, the amount and extent of uplift and subsidence

Figure 6: Estimates of sea-level change on the British Columbia coast between 1980 and 2075. The first column (LHA) of each tripartite group is an extrapolation of past and present rates of sea-level change; the second column (GIC) is the rise that would likely result from atmospheric warming (from Fig. 5); the third column (NET) is the net change obtained by summing the first two.

that would accompany such a quake. In view of these uncertainties, the analysis discussed above and summarized in Figure 6 assumes linear rates of uplift and subsidence over the period of concern here, i.e., the next 100 years. Even if this assumption is incorrect, the conclusions that follow will still be valid for most of the British Columbia coast.

Figure 7: Moderate- to high-relief, rocky coastline east of Vancouver Island.

It is evident from Figure 6 that projected rates of greenhouse-induced, sea-level change along the British Columbia coast over the next century will be much higher than late Holocene and historical rates. Those parts of the outer coast presently rising will soon be submerging unless uplifted during a large earthquake. Submergence rates will be lower in these areas than along the mainland coast, although the differences probably will not be large (Fig. 6).

Impact of Rising Sea Levels

A rise of even 2 m over the next 100 years will have little effect on the 85% of the British Columbia coastline that is rocky and relatively steep (Fig. 7). Some erosion can be

Figure 8: Distribution of beaches and bluffs developed in Quaternary sediments on the British Columbia coast. A rise in sea level will cause severe erosion in these areas unless protective measures are taken.

Figure 9: Coastal bluff eroded in late Pleistocene sediments (mainly sand and silt) near Vancouver. This photograph was taken in 1975, several years before the beach was armoured with coarse gravel to protect buildings at the top of the cliff.

expected, however, in areas of Cretaceous and Tertiary sedimentary rocks, for example, parts of southwestern and southeastern Vancouver Island.

In contrast, a sea-level rise of even a few tens of centimetres will have a major impact on those parts of the British Columbia coastline that are developed on unconsolidated Pleistocene deposits (Fig. 8). Shorelines in these areas comprise gravel and sand beaches and bluffs of Pleistocene sediments that are highly susceptible to erosion by waves and currents (Fig. 9). Even at present, some coastal bluffs are receding relatively rapidly due to erosion by waves and currents (Clague and Bornhold, 1980). At a few sites, groins, walls, and other structures have been constructed at considerable expense to slow the erosion and protect nearby roads, houses, and other development.

It is likely that shoreline erosion will become more severe and widespread as the sea rises in response to climatic warming. Much of the coastline around the Strait of Georgia in southwestern British Columbia is highly susceptible to such erosion. Expensive remedial measures will be required to stabilize these shores and protect existing property. The erosion problem is compounded by the direct effect of inundation. A sea-level rise of a few tens of

centimetres will result in flooding of some waterfront homes and port facilities during severe storms. Obviously, the larger and more rapid the rise, the greater this problem will be.

Deltas, which constitute 1-2% of the British Columbia coastline, will also be severely affected. Low-lying areas on delta plains will be inundated by the sea unless protected by levees. As the sea rises, the lower reaches of rivers may flood more frequently than in the past. This, in turn, may cause an increase in sedimentation on floodplains and delta tops. Estuarine environments, which are important to the survival of waterfowl and salmon, may be adversely affected, both by flooding and by changes in patterns of sedimentation at river mouths. Coastal wetlands in inhabited areas may be lost between the advancing sea and development which does not retreat.

The Fraser delta, just south of Vancouver (Fig. 10), is the largest and most developed delta on the British Columbia coast. Its subaerial surface, covering about 400 km², is almost entirely below 4 m elevation. The delta is home to over 125,000 people, most of whom live in the municipality of Richmond. The delta and the floodplain of Fraser River to the east are protected from flooding by a system of dikes

Figure 11: Dike protecting the Fraser delta from flooding.

(Fig. 11), which will have to be upgraded at considerable expense if the sea rises as expected in coming decades. Such a rise also will bring groundwater levels in Richmond to the surface, forcing governments to spend additional funds on pumping.

Conclusions

Early in the Twenty-first Century, sea level will rise along the British Columbia coast as glaciers melt and oceans expand. Shorelines formed on Pleistocene sediments may be severely eroded as the sea rises. In addition, low-lying delta plains and some roads and buildings may be inundated during storm surges, and important estuarine environments will be damaged or destroyed. A major effort and considerable money will be required to protect existing coastal development around the Strait of Georgia and elsewhere. Governments should begin

Figure 10: Satellite image of the Fraser delta and surrounding region, September 21, 1987.

to plan for this apparently inevitable rise in sea level by phasing in protective measures and by limiting future development in low-lying areas.

Acknowledgement: This paper is published with the permission of the Geological Survey of Canada as Contribution Number 51988.

Dr. J. J. Clague is a Research Scientist with the Geological Survey of Canada (100 West Pender Street, Vancouver, Canada V6B 1R8) and Editor of the *Canadian Journal of Earth Sciences*. He has studied the Quaternary geology of British Columbia and Yukon Territory for 20 years, focusing on the glacial history of the region and natural hazards to development.

References

- Ad Hoc Study Group on Carbon Dioxide and Climate, 1979. Carbon dioxide and climate: a scientific assessment. Report to Climate Research Board, Assembly of Mathematical and Physical Sciences, National Research Council (U.S.). National Academy of Sciences, Washington, D.C., 22 p.
- Atwater, B.F., 1987. Evidence for great Holocene earthquakes along the outer coast of Washington state. *Science*, v. 236, no. 4804, p. 942-944.
- Clague, J.J., 1981. Late Quaternary geology and geochronology of British Columbia, part 2: summary and discussion of radiocarbon-dated Quaternary history. Geological Survey of Canada, Paper 80-35, 41 p.
- Clague, J.J., 1983. Glacio-isostatic effects of the Cordilleran ice Sheet, British Columbia, Canada. In: Smith, D.E. and Dawson, A.G. (eds.), *Shorelines and Isostasy*. Academic Press, London, p. 321-343.
- Clague, J.J. (compiler), in press. Quaternary geology of the Canadian Cordillera. In: R.J. Fulton (ed.), *Quaternary Geology of Canada and Greenland*. Geological Survey of Canada, Geology of Canada, no. 1.
- Clague, J.J. and Bornhold, B.D., 1980. Morphology and littoral processes of the Pacific coast of Canada. In: McCann, S.B. (ed.), *The Coastline of Canada, Littoral Processes and Shore Morphology*. Geological Survey of Canada, Paper 80-10, p. 339-380.
- Clague, J.J., Harper, J.R., Hebda, R.J. and Howes, D.E., 1982. Late Quaternary sea levels and crustal movements, coastal British Columbia. *Canadian Journal of Earth Sciences*, v. 19, no. 3, p. 597-618.
- CO₂/Climate Review Panel, 1982. Carbon dioxide and climate: a second assessment. Report to Climate Board, Commission on Physical Sciences, Mathematics, and Resources, National Research Council (U.S.). National Academy Press, Washington, D.C., 72 p.
- Hansen, J., Lacis, A. and Rind, D., 1983. Climate trends due to increasing greenhouse gases. In: Magoon, O.T. and Converse, H. (eds.), *Coastal Zone '83*. Proceedings, Symposium on Coastal and Ocean Management, San Diego, California, no. 3, p. 2796-2810.
- Hansen, J.E., Lacis, A., Rind, D. and Russell, G., 1984. Climatic sensitivity to increasing greenhouse gases. In: Barth, M.C. and Titus, J.G. (eds.), *Greenhouse Effect and Sea-Level Rise: A Challenge for This Generation*. Van Nostrand Reinhold, New York, p. 57-77.
- Heaton, T.H. and Kanamori, H., 1984. Seismic potential associated with subduction in the northwestern United States. *Seismological Society of America Bulletin*, v. 74, no. 3, p. 933-941.
- Hoffman, J.S., Keyes, D. and Titus, J.G., 1983. Projecting future sea level rise; methodology, estimates to the year 2100, and research needs. U.S. Environmental Protection Agency, Office of Policy and Research Management, Washington, D.C., 121p.
- Hoffman, J.S., Wells, J.B. and Titus, J.G., 1986. Future global warming and sea level rise. In: Sigbjarnarson, G. (ed.), *Iceland Coastal and River Symposium*, Proceedings. National Energy Authority, Reykjavik, p. 245-266.
- Keeling, C.D., Bacastow, R.B. and Whorf, T.P., 1982. Measurements of the concentration of carbon dioxide at Mauna Loa Observatory, Hawaii. In: Clark W.C. (ed.), *Carbon Dioxide Review: 1982*. Oxford University Press, New York, p. 377-385.
- Lacis, A., Hansen, J., Lee, P., Mitchell, T. and Lebedeff, S., 1981. Greenhouse effect of trace gases, 1970-1980. *Geophysical Research Letters*, v. 8, no. 10, p. 1035-1038.
- Mathews, W.H., Fyles, J.G. and Nasmith, H.W., 1970. Post-glacial crustal movements in southwestern British Columbia and adjacent Washington state. *Canadian Journal of Earth Sciences*, v. 7, no. 2 (pt. 2), p. 690-702.
- Mercer, J.H. and Emiliani, C., 1970. Antarctic ice and interglacial high sea levels. *Science*, v. 168, no. 3939, p. 1605-1606.
- Ramanathan, V., Cicerone, R.J., Singh, H.B., and Kiehl, J.T., 1985. Trace gas trends and their potential role in climate change. *Journal of Geophysical Research*, v. 90, no. D3, p. 5547-5566.
- Riddihough, R.P., 1977. A model for recent plate interactions off Canada's west coast. *Canadian Journal of Earth Sciences*, v. 14, no. 3, p. 384-396.
- Riddihough, R.P., 1982. Contemporary movements and tectonics on Canada's west coast: a discussion. *Tectonophysics*, v. 86, no. 4, p. 319-341.
- Riddihough, R.P. and Hyndman, R.D., 1976. Canada's active western margin - the case for subduction. *Geoscience Canada*, v. 3, no. 4, p. 269-278.
- Rogers, G.C., 1988. An assessment of the megathrust earthquake potential of the Cascadia subduction zone. *Canadian Journal of Earth Sciences*, v. 25, no. 6, p. 844-852.
- Vanicek, P. and Nagy, D., 1980. The map of vertical crustal movements in Canada. Canada Department of Energy, Mines and Resources, Earth Physics Branch, Open File 80-2.
- Wigen, S.O. and Stephenson, F.E., 1980. Mean sea level on the Canadian west coast. In: NAD Symposium 1980. Proceedings, 2nd International Symposium on Problems Related to the Redefinition of North America Vertical Geodetic Networks, Ottawa, Ontario, p. 105-124.

JUST RELEASED

IUGS Publication No. 24

THE CAMBRIAN SYSTEM IN EASTERN ASIA

by
W.T. CHANG

Correlation Chart and Explanatory Notes covering China, Korea, Vietnam, Cambodia, Thailand, Malaysia, and Burma. 6 figures plus 4 correlation charts in colour. 81 pages, 1988. ISBN 0-930423-13-5.

Price: \$18.00(US), including surface postage. For airmail add \$3(US) within North America and \$5(US) elsewhere. Payments are to be drawn on a Canadian or US bank and made payable to Episodes. Payment may also be made by Mastercard or Visa.

Order from:

Episodes
Room 177, 601 Booth Street
Ottawa, Ontario
CANADA K1A 0E8

Copies may also be purchased from the IUGS Secretariat, P.O. Box 3006, N-7001 Trondheim, Norway; and from the IUGS Liaison Office, 103 rue de Lille, 75007 Paris, France.

NEED TO MATCH SCALES ACCURATELY?

**MODEL PRO 450
REFLECTING PROJECTOR**

- Finest quality Optics
- Motorized controls
- 1st Surface mirrors
- 4.5X Enlargement to .22X Reduction
- Precise & dependable operation
- Table-top convenience
- Decorator colors
- Bright clear image

For a well crafted projector, at a reasonable price, with fast delivery, please write or phone:

PROJECTORS INC.

1523 Tennyson St. Denver, Colorado 80204

Phone: 303/572-8875

The Quarterly Journal of Engineering Geology

An International Journal encompassing Engineering Geology and Hydrogeology

Edited by A. B. Hawkins

The Quarterly Journal of Engineering Geology is published by The Geological Society of London through its publishing house. It is an international journal with a wide circulation, open to contributions from all those working within the field of geology as applied to civil engineering, mining practice and water resources, including rock mechanics and geotechnics. Its wide scope also includes applied sedimentology, pedology, mineralogy and petrology, geohydrology, hydrogeology, engineering seismology, engineering geomorphology and the engineering application of geophysics. Case histories and review articles of a more general character are also published, particularly those of a timely nature.

Subscription Information 1989: £90.00 (UK); £108.00 (overseas);
\$193.00 (N America and Japan)

Orders and requests for specimen copies and back issues should be sent to :

Journals Subscription Dept.,
The Geological Society, Burlington House,
Piccadilly, London W1V 0JU, UK.

Typescripts and all editorial correspondence should be addressed to :

D C Ogden, The Geological Society Publishing House, Unit 7, Brassmill Enterprise Centre, Brassmill Lane, Bath, Avon BA1 3JN, UK.