EDITORIAL

Crescendo Events in Sea-Level Changes

There's no doubt about it. In many places sea level is indeed rising. If the rise accelerates, as forecaste by some EPA models, it is well to be prepared. The National Academy of Sciences (Washington, D.C.) has issued an appropriate volume entitled *Responding to Changes in Sea Level: Engineering Implications* (DEAN, 1987.) It spells out the options and what to do about it. If your own particular bit of coast is being inundated, you have two options: (a) to get out; (b) to build dikes and seawalls. It is simply a mater of degree, rates of change and economics.

But then there are still a lot of unanswered questions. Disregarding for the moment questions of cause, if the observed tide-gauge data for your sector of the coast indicates a secular (continuing) mean rise of 10 mm/yr, the accumulated value in 100 yr will be 1 m (roughly 40 inches), which on a low deltaic coastal plain could mean a horizontal retreat of the coast of the order of 100 km (or 60 miles), you must expect fundamental changes in both the physical geography and in human economy. That is point number 1. This is not a hypothetical point: real world examples exist today in the Mississippi, Brahmaputra, and Nile deltas. These deltas are rapidly subsiding, geologically, and being starved of sediment due to dam construction. Any greenhouse-accelerated rise of MSL (mean sea level) would naturally exacerbate the condition. In other words, in extremes like those, the greenhouse factor is not too relevant because, whatever happens to CO_2, the crustal subsidence is inexorable and cannot be stopped.

In the United States about 60% of the coasts are involved in varying degrees of crustal subsidence, so that the problem is not just a local one. In fact, it is a global one (PIRAZZOLI, 1986). In this essay I want to bring out a second point: although secular trends can be established, there is a far greater hazard in *crescendo events* (lasting a few days or likely to recur over several months). These are specific storms, tsunamis, surges, or high-storminess periods (seasons, decades) that are known to raise local high-tide and swash levels by perhaps ten times the spring tidal rise above MSL. Classsical cases in the medieval history of the North Sea, before completion of the present dike systems, document storms that drowned 100,000 people or more (WOOD, 1985). On unprotected coasts, like much of the eastern U.S., those medieval events are likely to be repeated during the next hundred years. It is surely not unreasonable to ask the literate reader to consider a few basic concepts!

Two Fundamental Variables

Discussions about two fundamental variables that govern rise or fall of effective (or "relative") sea level (RSL) go back at least to the 18th century-did sea level change or the land surface shift? This question can be visualized on a modelling basis.

Let us have Δ_E represent the sum of the rates of change of all the factors that control the absolute height of the sea surface; the world-wide factors are *eustatic*: the others are regional. The factors may be (a) *volumetric quantity, i.e.* global shift in Q, the quantity of water in the ocean as a whole (*e.g. glacioeustasy*); or (b) change in V, the shape or *volumetric capacity* of the ocean basins (*e.g. tectonoeustasy*); or (c) *steric* (S, change in the volume of water molecules, due to thermal expansion or contraction); or (d) *hydrodynamic* (H, local or temporary shift in storminess factors, tidal characteristics, currents, change in local morphology such as erosion or bar-building and variations in hydrologic discharge, *i.e.* streams; or (e) geoidal (G, global or regional shift in the height of the gravitational equipotential, such as will be introduced by either change in planetary spin rate or shift in the distribution of mass (*e.g.* externally, like ice caps; or internally, as in the core, mantle or lithosphere). Exogenetic change in spin rate is achieved by the effects of solar radiation and tidal variations upon the atmosphere and hydrosphere. All the Earth's spheres exchange angular momentum (MÖRNER, 1987, *etc.*); a small semantic point concerns Mörner's proposed redefintion of the term eustasy to embrace geoidal change (non-universal, regional effect). This is not recommended because it would destroy the essential point of the eustatic definition: a universal rise or fall of sea level.

Then, let us have Δ_I represent the sum of the rates of change of all the factors that control the absolute height of the land surface with reference to the center of the Earth. They may include (a) glacio-isostasy (g, vertical displacement of the Earth's surface due to glacial ice loading or unloading and to the inverse reaction in the marginal bulge effect), or (b) *diastrophic isostasy* (d, vertical crustal displacement due to diastrophic shift of lithospheric masses in the course of tectonism and/or igneous activity), or (c) *hydroisostasy* (h, vertical crustal displacement due to added or diminished load of water in the ocean, in consequence of mass hydrologic transfer associated with accumulation or melting of glacier ice, or to other transfers conncected with the hydrologic cycle such as those related to changes in fluvial budgets (including man-made interference by agriculture, dam construction, deforestation and so on), in groundwater, artesian basins or soil moisture, and to crystallographically graphicallybound water which can be altered during sedimentary, metamorphic and igneous mineral transformations.

The simple equilibrium formulation is then:

$$\Delta_E - \Delta_I = 0$$

which means that there will be no change in the relative local relative level. It has no global significance. The widespread occurrence of discrete, isolated beachridges on rising coastlines requires episodic "events" (perhaps quite brief ones, for a few hours or over a few days) when $\Delta_E - \Delta_I = 0$ (FAIRBRIDGE, 1983, 1987).

There is still a third variable (ΔP, R) which refers to the sedimentation or erosion regime pertaining to any given sector (CARTER, 1987), whether it is a *prograding shore* (P), *e.g.* a beach that is accumulating more and more sand, or a *retreating shore* (R), *i.e.*, one that is eroding, a condition may apply equally well to sandy beach and cliffed coasts. One could alternatively simply express the Δ_R mode as a negative Δ_P.

Thus the complete equilibrium formulation will then become:

$$\Delta\Sigma(Q + V + S + H + G) -$$
$$\Delta\Sigma(g + d + h) +/- \Delta P, R = 0$$

Practical Applications

When faced with field problems, we must ask ourselves a number of key questions the answers to which can permit a number of simplifying steps.

Question 1, the time-frame problem. We are sometimes asked: Is a beach cottage that is situated at point "X" (at 5 m above high spring tide) and has a serviceable life expectancy of say 50 yr likely to be destroyed by any future change from Δ_E-Δ_I = 0 value? In this time frame the values of Q, V, and G are seen as variables with overly sluggish reaction times, and so are g, d, and h. This leaves H, P, and R to consider. Here the value of H may be critical, especially the storm frequency hazard, because at "point X" although the annual incidence of storm swash brings hazardous conditions to say 2 m below the cottage foundations, there is a long-term hurricane threat ("once in 50 yr") that will bring the swas limit to 7 m above high spring tide. The actuarial assessment of the cottage can be made accordingly. The factors P or R may alternatively alleviate or exacerbate the problem. On the time-frame selected (50 yr) P or R are rarely significant as natural phenomena, but are often extremely important under anthropogenic (man-induced) stress.

Question 2 is analogous to question 1, but we shall raise the time-frame by an order of magnitude to 500 yr. This would take us back well into the Little Ice Age. Under the Δ_E variable, Q has probably varied by something of the order of 100,000 km^3 (reflecting more glacial ice, more forests, more soil and ground water retention), equivalent to around 30 cm lowering of sea level for glacioeustasy, plus another 20-30 cm off the MSL for S. The H, P, and R factors would be much as for question 1. The variable Δ_I on this time scale is not to be dismissed. If much of the U.S. Atlantic coast is subsiding at 3 mm/yr, then 500 yr suggests a 1.5 m subsidence. This would lead to transgressive (landward) shifts of the shoreline and geomorphic "drowning" of low relief areas (*e.g.* Chesapeake Bay, Pamlico

Sound). Only where sand supply is abundant and barrier islands are active (P is potentially important) is the coastline maintained in a near-equilibrium condition, although longshore drift from an eroding upwind spit may well lead to redeposition on a down-wind spit.

Question 3 considers a similar, 500 yr time-frame but in a positive neotectonic setting, such as glacioisostatic uplift regions of Arctic Canada and Scandinavia. I have conducted study expeditions to both areas in the last two years (1987, 1988). In both the eastern Hudson Bay and Gulf of Bothnia, (Δ_I is about 9 mm/yr. If, for sake of argument during the 20th century Δ_E were taken as 1 mm, an equilibrium shoreline could not possibly be maintained here at more than decadal time scale. It is however true, that seasonally, generally only for a few stormy days, Δ_E may temporarily be greatly enhanced by the H (hydrodynamic) factor, when effective MSL rises rapidly by 1.5 to 2.5 m. Factor P is briefly but enormously enhanced by the shorewards transport of sand and gravel.

It has been found, as a result of careful levelling surveys and chronological studies, that those brief storm-enhanced episodes recur on an average about once in 45 yr in the Hudson Bay (FAIRBRIDGE & HILLAIRE-MARCEL, 1977) or 20-25 yr in the Baltic (ALESTALO, 1979). In the meantime Δ_I is operative in both areas, but at an even, uniform rate, so that for example in 20-25 yr a given shoreline is 18-22.5 cm higher. If the successive peak storm intensities are of the same order, then the swash limit of one major storm event will not be reached by the later ones. In the meantime (20-25 yr), in a P-positive region, minor storms will be up the foreshore and beach face, so that each peak storm event builds a new and distinct ridge. The result is a very distinctive step-like or staircase style of landscape (FAIRBRIDGE & HILLAIRE-MARCEL, 1976). On a low relief coast this ridge may be 5-10 m seawards of the preceding one. Classic examples may be seen at Nayarit, Mexico (CURRAY *et al.*, 1967), or landward of Point Peron, Western Australia (SEMENIUK, SEARLE and WOODS, 1988).

It is not without interest that a nearly flat, but undulating beachridge plain builds up in any P-positive region with abundant sand supplies even when Δ_I is essentially zero (ORFORD, 1987). No strandplain will survive, however, if Δ_I is negative.

Problem of a Sudden Rise of Sea Level

On both high uplift and on relatively stable coasts in regions of high sand supply (P-positive), the parallel "sheafs of beachridges are interrupted by a higher-than-usual ridge and often by a minor shift in orientation. These breaks in sequence occur every 300-400 yr on average. What seems to happen is this: Δ_I remains constant but one or more of the Δ_E controls goes strongly negative for a brief episode (probably some decades); it may be exacerbated by a temporary change to a Δ_R mode (Δ_P is positive), because the renewed beach-building often truncates that partly eroded older sheaf at an oblique angle.

We have no actualistic example to provide precise demonstration, but it would appear that a brief but extreme climatic fluctuation causes a drop in local MSL (in the range of 30-60 cm), and this is accompanied by a significant switch in wind systems resulting in the erosive episode (see example in CURRAY *et al.*, 1967). If the erosional break is several decades, ther persistence of Δ_I in an uplift region will cause the odler ridges meanwhile to continue their emergence. Thus, when "normal" conditions return the next beachridge will be separated from the older one by an abrupt slope. This return to normality is not a gradual one, because the renewed sedimentation abuts the steep slope quite distinctively, often with a reversed (shoreward) slope. I interpret this relationship to be a result of a sudden rise in sea level, Δ_E. The same problems has been faced, for example, by ANDREWS (in VAN DE PLASSCHE, 1986, p. 81), but it is not without controversy. Which of the controlling variables will it be? Is it Q, V, S, H, or G? The chronology of the interruptions can be illuminating. They seem to relate peruasively to cool/warm fluctuations, *i.e.* climatic extremes. If this is true then a scenario could be constructed on the following model:

Q: warming of mid-latitude, temperature-sensitive glaciers will cause melting and MSL rise, but there will be a serious lag factor (latent heat principle, *etc*), so this aspect must be reserved for longer cycles;

V: tectonic change in the ocean basin shapes is also a slow-reaction variable;

S: expansion and contraction of a water body is rapid (especially shallow ones like Hudson

Bay or the Baltic), and the whole water column responds within weeks; this could raise MSL by perhaps 5 to 10 cm (see WIGLEY and RAPER, 1987);

H: a climatic shift from a low zonality index (blocking anticyclones, meridional circulation, high continentality) to a high zonality regime (increased westerly air flow in summer with moderating temperatures and oceanic moisture) will create more ice-free weeks and increased onshore beach-building storm events;

G: changes in spin rate will accompany the climate fluctuation but amplitude and rate of geoidal shift will probably be both minor and sluggish, thus not significant on a decadal scale, but spin rates link with atmospheric momentum and deserve serious study.

Interannual Fluctuation

From the above analysis it is concluded that a climatic induced shift or change in the zonality regime associated with rise in summer temperatures is sufficient to cause an effective rise of seasonal MSL by up to 60 cm that can be achieved in one year. For a sustained rise in MSL the value of Q would need to rise, involving 100,000 km^3 of water per 25 cm of sea level rise, thus a transfer in the geohydrologic budget, such as from glacier melt, soils and other terrestrial reserves, to the world ocean.

If, over some interval in the future, such as anticipated by some CO_2/greenhouse models (as yet to be substantiated), there should be a rapid MSL rise, mankind can usefully profit from the Holocene record which provides relevant information. In a region of ample sand supply (P-positive), without human interference, where the neotectonic factor is positive, or neutral, beach equilibrium will adjust itself to a sustained MSL rise as much as 5-10 mm/yr; in other words, if the rise is not too fast the well-nourished beach will maintain itself following the Bruun Rule. In contrast, in low-relief areas without that sand reserve (P neutral or negative) in the same tectonic settings, the same MSL rise will lead to notable transgressions and coastal retreat. Thus barrier islands would probably survive, while lagoons and estuaries become enlarged.

IGCP-274 – "Coastal Environments"

A successor to two earlier coastal projects, IGCP-61 and IGCP-200, jointly sponsored by UNESCO and IUGS, will be IGCP-274. It was launched September 19-24, 1988, with Orson van de Plassche (Amsterdam) as leader. He is the editor of an invaluable manual on sea-level research (1986). He invited me to set up a Working Group (number 1) with the provisional title: *Crescendo Events in Coastal Dynamics, Past and Future.* I had earlier laid some foundations for it through a working group of IGCP-200 dedicated to Astronomic Cycles and Coastal Processes.

I suggest that IGCP-274:WG1 should have three priority objectives:

(a) Preparation of a computer-based timetable of perhaps 50 yr of upcoming astronomically predictable events or intervals, lunar and solar, that may conceivably relate to or trigger coastal storms or lead to systematic rise of sea level. Some randomness is introduced by the fact that several of the disturbing factors need to be superimposed in order to create catastrophic situations.

(b) Preparation of an historical catalog of the last 1,000 yr of astronomically determined events that appear to be related to major coastal storms or related conditions, *e.g.* dike breaks, El Niño incidence, *etc.* This catalog will provide an analog basis for understanding list (a).

(c) Preparation of recommendations for monitoring and integration of predictable or probalistic recurrence of geophysical and extraterrestrial forcing events that may affect the coastline.

We would, of course, insist on "Warning Labels" that such predictions are for guidance only. Much more in-depth research is called for.

Conclusion

To recapitulate then, this editorial essay urges that, regardless of the CO_2-greenhouse effect, almost all of the world's coastlines are subject to episodic catastrophic events at one time or another, at irregular intervals. To some extent these events are predictable and we propose to investigate them.

Coastal authorities, engineers, planners, or just ordinary householders, should not be lulled into a false sense of security by saying that a secular trend of only millimeters per year will not worry them within the life-expectancy of their investment. In high subsidence-rate areas, that secular trend is irreversible, and may, with increasing CO_2, become catastrophically exacerbated. People are not drowned , however, by a millimeter rise, but by discrete crescendo events.

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