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A Review of Some Concepts Involved in the Sea-Level Rise Problem

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ABSTRACT

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This paper discusses the following items affecting the comprehension and evaluation of the "sea-level rise" phenomenon and an accurate determination of real present values and trends: (1) the question of the carbon dioxide increasing production rate related to its predictable atmospheric accumulation rate; (2) the question of the incidence of this further rate in the "greenhouse effect"; (3) the question of suitably discerning its real singular impact in the present climatic change and, consequently, of accurately predicting future trends, and (4) the question of relating the "sea-level rise" trend to short and long term trends of the "climate change". It discusses the subsidence factor in sea-level changes and its time-spatial variability and the different phenomena usually included in it, as a major element of confusion; the general and local factors and the different conditions between the Mediterranean and North-Atlantic (East-North America and Northwest Continental-European, where most of the surveys have been developed and issued) coasts. The paper also considers different impacts attributed to sea-level rise on coastal and shoreline evolution, critically analyzing some conclusions on coastal engineering and management.

INTRODUCTION

Since the beginning of the 1960's, there has been increasing alarm concerning erosion problems in many of the world's coastal areas. Some of these problems seem to be related to a long-term trend of rising sea level. The previous and well documented effects of transitory and more of less limited (in time and in surface extension) "sea-level rise" from storm surges, tides and tsunamis, on the stability of sandy and even pebble beaches called for a large scale analysis of this widely generalized problem.

An increasing consciousness of the escalation of both the greenhouse effect and the more significant temperature parameters of the planet as a whole led to the apparent correlation of the three phenomena: sea level rise (as a large scale trend), greenhouse effect evolution, and warming global climatic change. Although the two latter factors were studies in the last century by ARRHENIUS and CHAMBERLIN (cited in REVELLE, 1982), only in the middle of this century did they evoke general concern. Former works by REVELLE had special meaning in this sense; he discussed the impact of these three elements on mean sea level. However, it was the inception of the Brunn Rule (1961) that attracted general attention to the problem of "sea-level rise", particularly among oceanographers and coastal engineers. The principal appeal of this rule is the link between shoreline movements, related coastal erosion and accretion, and mean sea level change; this link introduced a new and powerful factor in the diagnosis of beach and coastal problems on a general scale.

Recent sea level gauge data has validated and expanded the scope of our understanding of coastal problems. It was not until the middle of this century that the geographical extension and length of time of the gauges began to permit a general analysis of mean sea level evolution. This analysis led to a general alarm created panic that led to risky conclusions and reckless efforts to remedy the surmised problems. This opinion is shared by other analyst who question the statistical meaning and the geographical representation of the available data, taking into consideration the distance between geographical locations, the great difference in the time span between the data, and the continuity and quality of the gauges (EMERY and AUBREY, 1991; ACINAS, 1993; LISLE and DOLAN, 1993).

POST-WÜRM SEA-LEVEL CHANGES

The last marine transgression process followed climatic evolution with its minor fluctuations but was modified by other isostatic and sedimentary factors; to date, sea-level data has been the primary predictor used to approximate quaternary climatic changes. The transgression attenuated (SIVAN, 1990) in the Calcolithic (~10000–7000BP) and the

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Flandrian period probably reached its peak between 3000–5000 years ago, between 2 and 4 m above PSL, subsiding to 1 m below PSL about 2000 years ago. Soon after the first millennium, the Frisian Netherlands required some dike shore protection, probably indicative of a new marine transgression (corresponding to the "little climatic optimum"); the last episodic "little climatic optimum" was one of the more comprehensive Flandrian transgressions, the Dunkerkian, and began in the 13th Century. To the contrary, a very important generation of "polders" (Beemster, Purmer, Vermer, Shermer . . .) appeared in the Netherlands during the 16th and 17th Centuries, due to the strong "regression" of the "Little Ice Age". The average temperature must have decreased somewhat more than 1°C in that period; volumetric changes were induced by this change in temperature (similar to the 1°C temperature change in the late Holocene) and important eustatic changes also occurred. Setting aside all other factors and taking into account only the relative sea levels corresponding at both the early stages of the last glaciation (80–130 m, depending on authors and locations) and the late Holocene (2–7 m), the last regression had to be very important, receding lower than the generally accepted 3 m (approximate) in coastal areas with a high rate of subsidence. We must consider that in long term thermic changes, only eustatic and volumetric variations can be hidden/amplified by tectonic and primarily isostatic effects; while in shorter thermic changes, even deferred processes of subsidence (glacier and sedimentary) and consolidation (sedimentary) can interfere significantly. Thus, a strong depuration factor must be taken into consideration with reference to the variations of the last century.

In summary, the current trend of global warming seems to be persistent, though fluctuating, since the last glaciation (−5°C; +130 m; 20,000 yBP) until well into the European Neolithic (+1°C; +3–6 m; 6,000 yBP) (GIEGENGACK, 1991; RABAN GALILI—cited by SIVAN, 1990). The warm period has continued until the present with two major cooler "ages": the "subboreal" (−1°C; −1m;?2,100 yBP) and the "Little Ice Age" (−1.5°C; 400 yBP).

The sea level wave that developed during the 15th Century influenced significantly the fact that there were few relative sea level changes during that historic period; this verifies the importance of the extreme cold temperatures of the "Little Ice Age". The present day statistics appear to be paralleling the expanding curve of the wave. This factor must be considered in all studies of sea level rise, climatic changes, greenhouse effect and atmospheric dioxide rates.

PROBLEMS OF MEAN-SEA-LEVEL DATA

This is not the principal group of concepts that will be considered in this paper. The mean sea level data used herein are taken from statistics evolved through the study of this phenomenon in sea level rise. A paper presented in Hilton Head by LISLE and DOLAN (1993) illustrates, as a general review, the suitability of the available recorded data, "to accurately forecast the implications of changes 100 years, or even 50 years, into the future"; proper consideration is given in this forecast to the known processes that control the system, the very complex one formed by the earth and the atmosphere and the planet as a whole.

Global sea level changes are primarily due to or observed as a consequence of eustatism. Eustatism affects the global relative mean sea level through several mechanisms: (a) sea floor spreading and the geologic time scale affect the volume of the ocean basins and the total amount of water at any given time; the rate affects sea level also through their influence on the density and subsidence of the ocean bottoms; (b) temperature and salinity affect water density and, consequently, the volume of liquid water; (c) temperature and other parameters of the global climate affect the distribution and amount of ice and the total volume of water. Eustatism can intensely affect regional sea level through: (a) changes in the geoidal surface caused by changes in ice volumes and distribution and (b) isostatism caused by ice sheets appearing and disappearing. Thus, the two principal factors of the processes with the most meaningful effect on mean sea level during the Pleistocene were eustasy due to ice/water transferences and isostasy (LISLE and DOLAN, 1993).

The isostasy or "adjustment of crustal material" floating on the earth's mantle to maintain gravitational equilibrium may have several causes or origins based on region. In the initial observation of sea level changes, the "positive" isostasy due to the unloading of massive ice-sheets with its dramatic effect on northern latitudes was the most apparent; as a matter of fact, it is only the "positive" sign of the glacio-isostasy which can be negative in the periods of glaciation. Later on, other forms of isostasy were observed: hydro-isostasy caused by changes in the weight of the water column covering a land plate and the isostasy caused by the weight of sediments. All of these have been aptly and simply outlines by LISLE and DOLAN (1993).

LISLE and DOLAN (1993) have accurately distinguished a second way in which sediments in coastal areas affect the relative mean sea level; it is through the subsidence (and pseudo-subsidence) caused by compression and other consolidative processes following the sedimentation. The most significant characteristic of these factors, isostatic and consolidative, is that they are deferred holding over for a meaningful time after the end of the movements; and they play a regional or local role in the phenomenon, introducing a great variability.

Tectonism is the last of the general, global and long term factors affecting the measurements of mean sea level, locally or regionally. Tectonism directly affects land levels and movements, and the suitability of sources for natural nourishment and accretion of shorelands, *i.e.,* through volcanism and fraturations; it also affects the size and shape of the ocean basins as a whole. Mean sea level is affected by all of these factors. Tectonism as it relates to our planet is well known since the development of the plate tectonic theory; however, it is obvious that many long term and large scale processes have not been accurately estimated to appropriately correct relative sea level measurements, specifically for local gauges. The effects of tectonism is generally estimated over the long term; however, the effect is less clear due to the variety and hodge-podge dispersion of local gauges, a meaningful source of error. A much longer period of gauging and an even more extensive and homogenous network of gauge-points is necessary to arrive at an accurate determination of both local and global sea-level change.

All these factors have a great local and/or regional variability, suggesting modifications are required in current gauges to determine accurately the actual value of global sea level change. No allowance has been made to date for the difference in local circumstances; in gauge-tool location, apparent local factors such as the consolidation of dikes and other maritime structures and their placement have been largely ignored in determining mean sea level (ACINAS, 1993). Other analogous anthropic circumstances affecting local sea level have also been ignored, *i.e.,* the removal of oil and natural gas causing "unusual high" sea-level rise below Long Beach, California, (EMERY and AUBREY, 1991).

In the collection of data, no corrections have been made for short term natural processes such as ENSO, storm surges, tides and tsunamis (EMERY and AUBREY, 1991; PARKER, 1992; LISLE and DOLAN, 1993). The consideration of all these sources of possible inaccuracies in the gauge data system firmly undermines the principal support for the present quantitative prediction and current and future sea level rise trends; it can, however, be accepted that sea level is currently rising.

Where abundant and long standing gauges exist, circumstances differ from one geographical zone to another, even within the same regions of the planet. In the North Atlantic and Mediterranean information to correct the direct gauge data is readily available and provides a high probability of relative accuracy; however, a comparison of the data from these different regions indicates a large degree of dissimilarity. It seems that the effects of subsidence and consolidative processes with their strongly deferred component are far more significant than previously realized.

THE CONCEPTS INVOLVED AND THE HYPOTHESES

It is obvious from recent registered data that our planet has become warmer over the last century; however, future warming trends are uncertain due to the lack of sufficient long-term data (JONES and WIGLEY, 1990).

Climatic data during the "human era" are reasonably well known but not totally defined. Until recently, only "long term changes" have been taken into consideration, assuming that climate could be considered a constant in the short term. Other minor climatic changes are receiving increasing attention, particularly those having affected both pre-historic and historic eras. The widely accepted thesis of the relationship between carbon dioxide emission rates and present climatic changes brought about through the "greenhouse effect" has led to the present day perception of climate variability and its impact on the environment and human life. The Little Ice Ages and genial warm periods in pre-historic times are described in literary and artistic descriptions (LAMB, 1982), but are presently being comprehensively analyzed and quantified.

The principal hypothesis used to explain the present sea-level process is based on an increasing "greenhouse effect", unleashed by the growing rates in atmospheric carbon dioxide. The remainder of the hypothesis is obvious: (1) an increasingly warmer environment with a consequence of positive eustatism and (2) a general subsidence of sea level would accentuate these changes except in a case of glacio-isostasy (LISLE and DOLAN, 1993). All of these lines of reasoning deserve consideration.

The capability of these models to assist in the determination of the progression of our climatic system is obvious (KASTING and others, 1988; WHITE, 1990); but the necessary simplicity of their structure leads to conclusions with only a relative accuracy. Most models have completely refused to consider the possibility that the world's oceans may be capable of completely eradicating carbon dioxide from the atmospheric-lithospheric system; some have even completely ignored or underestimated the oceanic solubility of CO_2. Some models are introducing new anthropic greenhouse factors (SCHNEIDER, 1987) enforcing the CO_2 role before correcting it in accordance with the oceanic capability to modify the foreseeable evolution of its atmospheric presence.

The question of carbon dioxide and its influence on global climate was reopened at the beginning of the second half of this century by several authors, but most meaningfully by REVELLE. He has emphasized the more recent problems by taking new data about the content and distribution of CO_2 and the results of several new models to introduce a factor of softening due to the CO_2 oceanic solubility, ignored by most previous models. Many other authors (WOODWELL, 1978; HOUGHTON and WOODWELL, 1989: WHITE, 1990; and others) have contributed to Revelle's hypothesis; however, recent questions have arisen concerning the origin of the reasoning behind the hypothesis. The question concerning Revelle's findings is: may an undefined exponential growth of the atmospheric CO_2 rates be accepted. As is in true in all population dynamics governed by the Goldberg and Waage "Rule of Mass Action", the hypothesis in question cannot be accepted. However, we must acknowledge that the present statistics are still within the growth sector of the sigmoidal curve, the conclusion of the models; only recently have they included the softening factor of CO_2 solubility in the oceans.

It is possible that adequate consideration has not been given to the hypothesis; solubility has been restricted to a thin surface layer and when diffusion processes were considered, the supposition has been that the capability of vertical mixing is slight. No consideration has been given to the vertical capability derived from thermohaline currents and from turbidity linked to general and local oceanic currents. Usually, models do not factor in the atmospheric behavior of oceanic waters and their ability to daily regenerate CO_2 solubility through the processes included in the carbonates cycle. Even when authors consider the role of the CO_2, they usually adopt the less favorable hypothesis (BERNER and LASAGA, 1989) and do not take into account the biological apportionment to the global bio-geochemical cycle. The daily cycle of both the photosynthetic activity and solubility permits daily regeneration of the carbon dioxide rate deficit in the upper oceanic layer. A more in-depth discussion of this question might be very enlightening but is not within the scope of this paper.

The meaning of carbon dioxide rates on the greenhouse effect, on the other hand, has been under recent review (HOUGHTON and WOODWELL, 1989); the role of other components, *i.e.* methane, nitrogen oxides and carbon halides, are called to count. The temperature evolution since 1896 presents some inversions, as in the 1940–1965 period; they and other punctual distortions with respect to the CO_2 evolution rate seem to be explained by these components and by the feed-back complex mechanisms. This explanation is not sufficient to bring the reality in line with the model conclusions. Natural factors, *i.e.,* astronomic factors, are now being reviewed.

A natural factor closely related to the greenhouse effect and possibly mixed with anthropic factors is natural CO_2 production through both biological feedback processes and volcanism. Although the former may be partially or totally linked to anthropic activity, the latter is "strictly" natural and noticeably affects carbon dioxide rates, indicating a close relationship between those rates and the volcanic activity rates.

Other components governed by natural and anthropic activities may contribute to the global "greenhouse effect". One of these components, for instance, is methane and carbon halides which are produced from both volcanism and biological processes; these are also "strictly" natural which makes it more difficult to determine their real anthropic responsibility toward the increasing "greenhouse effect".

The introduction of astronomic factors in the models is based on the accuracy of the previous Milankovitch model, undoubtedly underestimated for many years, in relation to a general alarm over the "greenhouse effect". This more complete analysis may be inaccurate, leaving out or underestimating the activity of the sun.

The three mechanisms used by Milankovitch to explain the Pleistocene glacial cycles are extremely accurate with respect to the timing of the processes; although, it seems unable to demonstrate accurately the magnitude of the changes. An interesting present day condition is the narrow correlation of changes in the carbon dioxide rates and the glacial or interglacial situation.

The measurements in glacial ice cores and other analyses and considerations (BROCKER and DENTON, 1990) establish ⅔ as the relation between the carbon dioxide rates in glacial and interglacial periods, respectively, with no anthropic activity to justify these variations. This introduces the question as to whether or not both factors are connected by a causal relationship and whether the greenhouse effect (supposedly primarily produced by the CO_2) is causing the climatic changes or the climatic changes are producing, directly or indirectly, the carbon dioxide atmospheric presence. The natural production of CO_2 (mainly through volcanism) is also being considered.

Perhaps the sun's activity, not yet fully introduced in the numerical models nor sufficiently considered in other descriptive behavior, may be an underlying factor in all of these questions. Recent proposals suggest that 50% or better of the current climatic changes can be attributed to natural factors; additional research is needed in this area. The conclusions surrounding these questions are not trivial; the development and stability of the planet may depend on the application of the data that they produce.

The correlation between the sea level/climate/carbon dioxide rates has to be finally questioned with reference to both long and short term trends. The mantle origin of oceanic water is generally accepted. The volume of the oceans has evolved in relation to crustal formation and successive ocean floor spreading processes; rates of water generation may have evolved in correlation to the nature of the mantle, crust and ocean floor as well. This is a scientific question that is very difficult to answer. However, it can be assumed that a convex (decreasing) curve symbolizes the evolution of the total amount of oceanic waters on the planet during the last geologic periods. The present day position and slope of this curve is more difficult to determine. Nearly stationary conditions can probably be assumed for the Holocene, but this would be a dangerous assumption for the whole of the Pleistocene; stationary conditions can also be assumed for the entire Kainozoic and/or Mesozoic periods. Similar conditions may be assumed with respect to the evolution of the shape and cubic content of the oceanic basins; with reference to shape and cubic content, there was a great disparity in the Mesozoic which makes it necessary to avoid any anterior predictions with reference to same. There may have been much more variability in the generation rate of CO_2; these rates vary greatly in the present day, *i.e.,* from 1.5 ppm over the last 15 years up to 2.4 ppm over the last 18 months in Mauna Loa, Hawaii (HOUGHTON and WOODWELL, 1989). These considerations imply that the past carbon dioxide rates/climate (even supposing that the other components of the greenhouse effects remain stable) and climate/sea level relationship cannot be used in current evaluations and predictions. The hypothesis of this analogy has to be restricted to the Holocene or an even shorter period. DIEZ (1992) estimates a sea level low on the eastern coast of the United States of 3–7 m, corresponding to the "Little Ice Age"; subsidence has not been evaluated.

Research providing an accurate determination of the three parameters at that point in time would be of vital importance, but historical and geological knowledge is clearly insufficient to establish any analogy at present. Proposal of climatic evolution since the Würm (DIEZ, 1992) is in final consideration based on proposals concerning mean sea-level evolution and avoids using it for scientific sea-level rise predictions (Figure 1).

THE CONCEPTS "EVOLVED" AND APPLICATIONS

One of the most important contributions of Brunn's Rule has been the information it has provided concerning sea level rise and coastal erosion. The study of the stability of barrier islands led the rules second important contribution, the landward barrier migration. Following this line of reasoning, it could be suggested that any attempt at shore protection is useless. It is clear that in this series of assertions and propositions several sophisms have been introduced. In any case, Bruun's Rule deserves cursory discussion.

First of all, Brunn's Rule provides an accurate mean of a particular beach profile to sea level rise which can be extended to other beach profiles. It is not clear whether or not it can be extended to all beach profiles at any rising term or temporal scale is not clear, and the rule assumes a natural

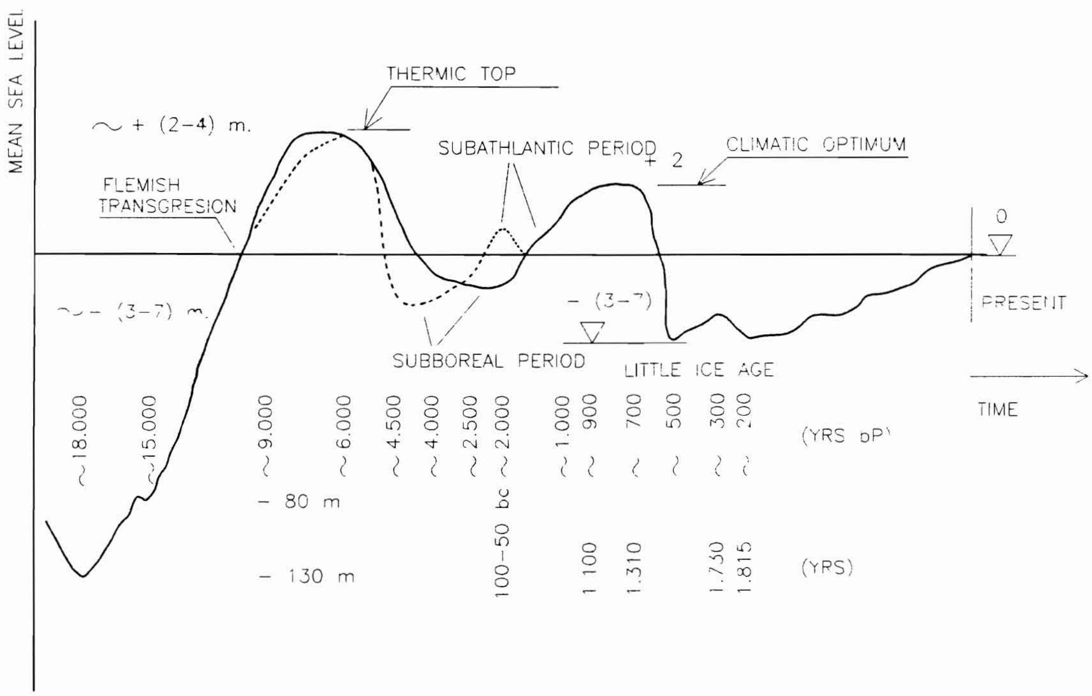

Figure 1. Curve of sea-level change for the last 18,000 years. (For transgresion read transgression; for subathlantic read subatlantic.)

as opposed to constricted beach. In fact, the parabolic profile indicates erosive conditions, because this unstable profile requires the existence of at least one permanent bar. It is in agreement with experience and the behavior of the theoretical wave theory (DIEZ, 1982, 1986, 1988).

Even for bar profiled beaches, Bruun's Rule may be assumed with permanent bar conditions, if longshore equilibrium exists so that erosion does not exist. Barrier migration would be an accurate prediction as is shoreline regression except that erosion is linked with a lack of equilibrium of beach materials.

The genesis and evolution of barrier islands cannot be considered to be unique. It depends on the nature of coastal topology (SCHWARTZ, 1971) and littoral dynamics (BORES, 1975). In accordance with WILLIAMS and BUILDING (1982) (and individual referee DE BEAUMONT, 1845; and JOHNSON, 1919) assumed a bar origin and evolution emerged barrier islands through a combination of morphodynamic mechanisms governed by wind waves, tides and storm surges; GILBERT (1885) proposed a genesis like spit and HOYT (1960) a formation by marine and flooding of a coastal dune plain. All of these theories have been confirmed in nature and have a basic hypothesis of hyperstability. Landward migration under sea level rise conditions is restricted to the first group of barriers as successfully shown by LEATHERMAN *et al.* (1982).

Intensification of the erosive processes in sea-walled beaches is generally expected; erosion can be estimated when the renourished beach is raised so that the waves do not reach the wall. These considerations and the failure of much hard coastal work has led to the assumption that beach nourishment under sea level rise conditions is the only solution to erosion. The high cost (economical and environmental) of permanent nourishment has made questionable the efficacy and common sense of fighting against erosive problems "caused" by "unavoidable" and "predicted" sea level rise, especially in migrating barrier islands (PILKEY, 1992). The hard work involved in reducing wind and wave power does not have to necessarily be inefficient; our predictions of unusually high rates of sea level rise cannot be verified.

These predictions simply verify the need for a better understanding of all of the factors surrounding the current sea level problem.

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