Geogr. Fis. Dinam. Quat.
32 (2009), 45-48, 2 figg.

PAOLO ANTONIO PIRAZZOLI (*)

LONG TERM, RECENT AND NEAR-FUTURE SEA-LEVEL EVOLUTION (**)

ABSTRACT: PIRAZZOLI P.A., *Long term, recent and near-future sea-level evolution*. (IT ISSN 0391-9838, 2009).

Past sea-level positions deduced from field observations are generally only of local value, while estimations of global (eustatic) sea-level changes can be obtained with assumptions only in a very few cases, or attempted with limited accuracy by using proxy data. Since 1993, satellite altimetry is providing global sea-level estimations every ten days, showing that coastal sea-level trends may differ from trends offshore. Evidence of an acceleration in the global sea-level rise since the last century has recently been provided by both satellites and tide-gauges, and confirmed by oceanographic and glaciological studies.

KEY WORDS: Global sea level, Relative sea level, Tide gauge, Satellite altimetry.

INTRODUCTION

A close relationship exists between the present sea level, the vertical biological zonation, and some geomorphological features that may result from erosion or sedimentation processes. Wave erosion may produce recognizable features and can be especially rapid on soft rocks. Bioerosion is active especially on limestone rocks, where it produces typical intertidal notches. Sedimentation processes near sea level may also produce recognizable features, e.g. favour the development of tidal flats and tidal marshes in estuaries or lagoons. Storm deposits may produce typical beach ridges that testify to wave height at high tide. On exposed coasts, strong wave action can be a very effective geomorphological tool, creating spectacular abrasion platforms.

When working in the field, it is frequent to observe sea-level marks that cannot be associated with the present sea-level position. Elevated marine platforms often indicate a former altitude where wave action was active. Marine terraces can be spectacular geomorphological features and often contain stratigraphic evidence that makes it possible to date former shorelines. Biological sea-level indicators still preserved in growth position are often of paramount importance to specify and date former sea-level positions. A good knowledge of the marine features related to the present sea level is therefore essential to identify and interpret marks related to former sea levels (Pirazzoli, 2007). However, if local identification and measurement of former sea levels can be essential to demonstrate and date relative sea-level changes at a certain site, very little information is generally available for an estimation of the global sea level elevation at the same time.

In this paper it will be shown that the contribution of data from other disciplines, like oceanography, geophysical modelling and satellite altimetry, can be essential to reach conclusions on a global scale that would not have been possible using only sparse geomorphological, biological or tide-gauge observations.

LONG-TERM SEA-LEVEL CHANGES

Climate change, which modifies the quantity of ocean water, has been during the Quaternary period the main cause of sea-level change on a global and regional scale. The development of an ice sheet has not only deprived the oceans of important quantities of water (glacio-eustasy) but has also produced, with its load, subsidence beneath the ice mass (glacio-isostasy). In this case deeper earth material will have to flow away and build a peripheral bulge around the ice margin. When the ice sheet melts, unloading occurs, resulting in glacio-isostatic uplift beneath the melted ice. The marginal peripheral rim will consequently tend to subside and move towards the centre of the vanishing load. In addition, the melt water will produce a load on the ocean floor, which will tend to subside (hydro-isostasy).

(*) *CNRS - Laboratoire de Géographie Physique, 1 Place Aristide Briand, 92195 Meudon cedex, France*. E-mail: pirazzol@cnrs-bellevue.fr

(**) *12th Belgium-France-Italy-Romania Geomorphological Meeting - IAG. «Climatic Change and Related Landscapes», Savona 26-29 September 2007.*

The various processes above have been used by geophysicists to produce global isostatic models which have demonstrated that relative sea-level changes may vary from place to place and that no region can be considered as vertically stable. The main results of isostatic models have also been confirmed by field data.

On a local or regional scale, tectonic effects may also be superimposed upon isostatic effects. As a result, it is extremely difficult to deduce global sea-level changes from sparse field observations. Reliable global estimates may be attempted in only a very few cases, e.g. when the coring of continuous sea-level indicators, covering a full glacial-interglacial hemicycle, has been possible (e.g. Bard & *alii*, 1996). According to the best estimates, the global sea-level rise since the last glacial peak must have been on the order of about 120 m.

It would be almost impossible to reach a similar result by using sparse field observations. This difficulty has been shown clearly by Newman (1986) in fig. 1, where it is almost impossible to trace a reliable curve of global sea-level change through the field data; formerly glaciated areas reveal late-glacial sea levels more than 200 m above the present datum, while zones on the margins of these glaciated areas show earlier sea levels as much as 160 m below the same datum. Thus the sea-level geoid of the late glacial age shows a relief of >360 m and therefore exceeds the estimated glacio-eustatic rise by a factor of 2. These vertical displacements are mainly of climatic origin and tend to exceed the strongest known tectonic rates observed during the same period even in the most tectonically active areas.

For longer periods of the past, the changes in the quantity of oceanic water can be estimated by analysing the oxygen isotope record in foraminifera shells cored from the ocean floor. Changes in oxygen isotopes depend mainly on salinity and temperature. Benthonic foraminifera are most useful because they were living at depth, where changes in temperature have been very limited. The changes in the oxygen isotope record of benthonic foraminifera depends therefore mainly upon changes in the salinity of the ocean, which reflect ice sheet development or melting. The curve of fig. 2 represents therefore the approximate changes in the global sea level during the last 2.6 million years. The temporal scale is adjusted by determination in the cores of the geomagnetic reversal of ~700 ka, by identification of the isotope 5e peak of 125 ka, and by biostratigraphy. The vertical scale is calibrated by the last post-glacial sea-level rise between isotope peaks 2 and 1 (~120 m).

To summarize, during all the Quaternary period there has been a repetition of sea-level oscillations of ~100 m between glacial and interglacial periods occurring about every 100 ka. The accuracy of the determinations in the global sea level with this method is however limited at best to ~±10 m (with assumptions). Anyway, the terms of Würm, Riss, Mindel and Gunz, often found in glacial geomorphological literature, are far from sufficient to describe all the Quaternary glacial periods.

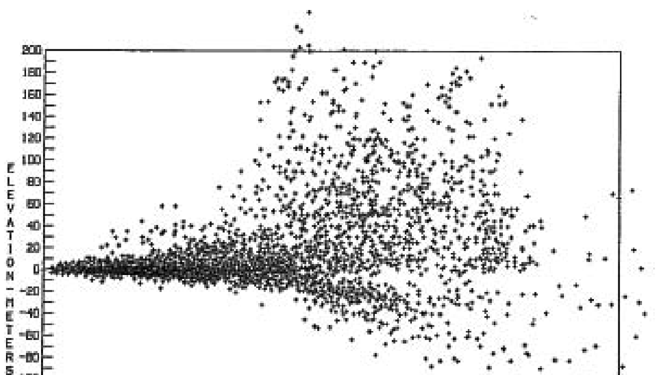

FIG. 1 - Elevation versus time compilation of more than 4000 radiocarbon-dated indicators of sea-level for the past 16,000 years from the coastal areas of many of the world's major land masses, as well as from oceanic islands (from Newman, 1986).

RECENT SEA-LEVEL CHANGES

Similar difficulties in estimating global sea-level changes from local measurements are found for the last century when local measurements are deduced from tide gauges. Several authors (see Pirazzoli, 1996, table 4, for references) have attempted an estimation of recent global sea-level rise from tide-gauge records, in spite of the very uneven geographical distribution of tide gauges in the world, of the limited number of sufficiently long records available, and of the difficulty in separating sea-surface movements from land movements. The results have been very variable, a sea-level rise from +0.5 to +3.0 mm/yr, with some authors even concluding that it was not possible to obtain a reliable accurate estimate from the tide gauges alone. These difficulties were recognized by the IPCC (2001), which proposed in 2001 the vague range of +1.0 to +2.0 mm/yr as an average global sea-level rise for the 20th century.

In 1992, with the advent of satellite altimetry, a quality jump in the accuracy of sea-level measurements became possible. The satellite TOPEX/Poseidon, followed in 2001 by Jason-1, refers altimetric measurements to an absolute, geocentric datum. The groundtrack of these satellites repeats every 10 days, providing almost global (from 66°N to 66°S) maps of sea-level change with this temporal sampling. When averaged globally, these maps provide 10-day estimates of global mean sea level with an accuracy of about 4-5 mm.

It appears immediately, when looking at such maps (e.g. fig. 2 in Nerem & *alii*, 2006) that, sea-level change is not uniform, but that there are oceanic regions where the sea level is rising and other regions where it is dropping. It appears also that the sea-level change measured along a coast may differ from the sea-level change in the nearby deep sea.

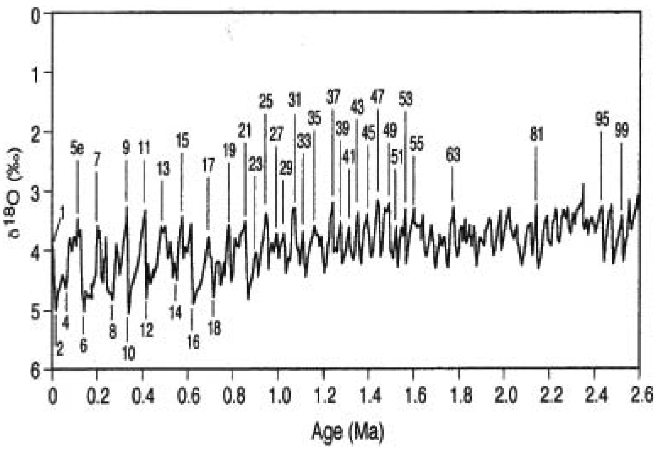

FIG. 2 - Benthonic oxygen isotope data for ODP677 for the past 2.6 Ma (from Shackleton & *alii*, 1990, adapted). Labels of selected isotope stages have been added for orientation.

A close correlation has been found between thermal expansion (caused by the warming of oceanic water, measured by oceanographic surveys) and regional sea-level changes observed by satellites. Thermal expansion may however vary with the period considered**.** In the Pacific, as well as in the Atlantic, the trends of the period 1993-2003 are almost opposite to those of the longer period 1950-2003 (Berge-Nguyen & *alii*, 2008, fig. 1).

The global sea-level rise obtained by satellite altimetry since 1992 appears to be much faster, according to Nerem & *alii* (2006) (+3.1±0.4 mm/yr, to which a +0.3 mm/yr of glacial isostatic adjustment should be added), than what had been deduced from tide gauges during the 20th century. In a recent study, Holgate & Woodworth (2004) have analysed in detail the tide-gauge data of the period 1950-2000: the global sea-level rise during this half a century deduced from tide gauges can be estimated at about +1.8±0.3 mm/yr. In addition, for the decade from 1993 to 2003, Holgate and Woodworth compared tide-gauge data from 13 selected regions to sea-level trends derived from altimetry in the same regions. They found with both methods a similar rate of sea-level rise, at a rate of ~+4 mm/yr, that was slightly faster than the global average sea level during the same period. They provided in this way a triple demonstration: 1) that the «global coastline» (where tide gauges are located) and the «global ocean» could follow different sea-level trends; 2) that there is a regional coherence between tide-gauge and satellite altimetry results in the same areas, and 3) that a recent acceleration in sea-level rise could be deduced also from tide-gauge records.

At this point it is useful to verify whether a recent acceleration occurred also in the two main potential causes of recent sea-level rise: thermal expansion of sea water due to ocean warming, and ocean mass increase due to water addition from land ice melt. From 1950 to 2000, when the observed sea-level rise along the global coastline was ~+1.8 mm/yr, the thermal expansion component computed by oceanographic studies was ~+0.4 mm/yr (Ishii & *alii*, 2006). From 1993 to 2003, when a global sea-level rise +3,1±0,4 mm/yr was measured by satellite altimetry, several independent oceanographic studies have found that the thermal expansion component was 3 to 4 times stronger than a few decades earlier (e.g. Ishii & *alii*, 2006: +1.2 mm/yr; Willis & *alii*, 2004: +1.6 mm/yr). As concerns the acceleration in the mass loss of glaciers and ice caps in sea level equivalent, it is estimated by Lemke & *alii* (2007) at +0.50±0.18 mm/yr between 1961 and 2004 and +0.77±0.22 mm/yr between 1991 and 2004.

NEAR-FUTURE SEA-LEVEL CHANGES

For the near-future, according to IPCC (2001) projections, based on several emission scenarios, the global sea level in the year 2100 is expected to be between 9 and 88 cm above present. For IPCC (2007) projections the range is narrower: 18 to 59 cm, because of improved information. The latter range, however, is suspected to represent an under-estimation, because it does not take into account further accelerations in ice flow, of the kind recently observed in some Greenland outlet glaciers and West Antarctic ice streams. These accelerations, if continued, could substantially increase the contribution from the ice sheets and the possible contribution of such increased discharge is estimated at 10 to 20 cm by Meeh & *alii* (2007).

In addition, the model projections producing the 18-59 cm range are essentially independent from the observed climate data since 1990. They have been deduced from physics-based models developed over many years that are not «tuned» to reproduce the most recent temperature and global sea-level data. From 1990 to 2006, sea level has been rising close to the upper boundary of the IPCC (2001) uncertainty range, that was expected to reach a rise of 88 cm in 2100, rather than in the central range of the projections (Rahmstorf & *alii*, 2007).

If the more plausible global sea-level rise during this century can be expected to be of about 0.8 m (Pfeffer & *alii*, 2008), the regional variability around the global mean should also be taken into account. According to various models, the sea-level rise is expected to increase at high latitudes of the Northern Hemisphere and even to be 5 to 15 cm higher than the global mean around western Europe. In addition, local factors, like land subsidence, may also contribute to increase the sea-level rise at certain sites.

A last question could be: what are the areas most vulnerable to a rising sea level? They are low coastal plains, deltas, lagoons, estuaries, atolls, salt marshes. Most of these areas already have problems with the present sea level and the risks of flooding will be greatly increased by a sea-level rise.

CONCLUSIONS

As already noted in a previous paper (Pirazzoli, 1993), the absence of a stable datum has been the major source of uncertainty in past estimations of global sea-level changes.

For the middle and late Quaternary, correlation of well-studied uplifted marine terraces, with assumptions on the local tectonic rates and correlation with isotope stages, have produced acceptable estimations of global sea-level changes, at least at the time of oxygen isotope peaks (e.g. Chappell & Shackleton, 1986; Pirazzoli & *alii*, 1991). For the global sea-level changes during the last hemicycle, the best solution (again with assumptions) remains the ability to core a continuous series of sea-level indicators, possibly in the same place (Fairbanks, 1989; Bard & *alii*, 1996). Finally for the most recent period, satellite altimetry, which is based on an absolute datum, is still the most promising method for global sea-level estimations. The problem remains however completely open for near-future global estimations, since extrapolations depend not only from the validity of the assumptions used by models, but also on assumptions on greenhouse gas emissions which can be modified by international agreements not yet reached for this century.

REFERENCES

BARD E., HAMELIN B., ARNOLD M., MONTAGGIONI L., CABIOCH G., FAURE G. & ROUGERIE F. (1996) - *Deglacial sea level record from Tahiti corals and the timing of global meltwater discharge*. Nature, 382, 241-244.

BERGE-NGUYEN M., CAZENAVE A., LOMBARD A., LLOVEL W., VIARRE J. & CRETAUX J.F. (2008) - *Reconstruction of past decades sea level using thermosteric sea level, tide gauge, satellite altimetry and ocean reanalysis data*. Global and Planetary Change, 62, 1-13.

CHAPPELL J. & SHACKLETON N.J. (1986) - *Oxygen isotopes and sea level*. Nature, 324, 137-140.

FAIRBANKS R.G. (1989) - *A 17,000-year glacio-eustatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation*. Nature, 342, 637-642.

HOLGATE S.J. & WOODWORTH P.L. (2004) - *Evidence for enhanced coastal sea level rise during the 1990s*. Geophysical Research Letters, 31, L07305, doi:10.1029/2004GL019626.

IPCC 2001 - *Climate Change 2001 - The Scientific Basis*. Cambridge University Press, Cambridge.

IPCC 2007 - *Climate Change 2007: The Physical Science Basis. Contribution of the Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge.

ISHII M., KIMOTO M., SAKAMOTO K. & IWASAKI S.I. (2006) - *Steric sea level changes estimated from historical ocean subsurface temperature and salinity analyses*. Journal of Oceanography, 62 (2), 155-170.

LEMKE P., REN J., ALLEY R.B., ALLISON I., CARRASCO J., FLATO G., FUJII Y., KASER G., MOTE P., THOMAS R.H. & ZHANG T. (2007) - *Observations: changes in snow, ice and frozen ground*. In: «Climate Change 2007: the Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change». Cambridge University Press, Cambridge.

MEEHL G.A., STOCKER T.F., COLLINS W.D., FRIEDLINGSTEIN P., GAYE A.T., GREGORY J.M., KITOH A., KNUTTI R., MURPHY J.M., NODA A., RAPER S.C.B., WATTERSON I.G., WEAVER A.J. & ZHAO Z.C. (2007) - *Global Climate Projections*. In: «Climate Change 2007: The Physical Science Basis. Contribution of the Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change». Cambridge University Press, Cambridge.

NEREM R.S., LEULIETTE E. & CAZENAVE A. (2006) - *Present-day sea-level change: a review*. C.R. Geoscience, 338, 1077-1083.

NEWMAN W.S. (1986) - *Palaeogeodesy data bank and palaeogeodesy. IGCP 200 Newletter and Annual Report*. University of Durham, p. 41.

PFEFFER W.T., HARPER J.T. & O'NEEL S. (2008) - *Kinematic constraints on glacier contributions to the 21st-century sea-level rise*. Science, 321, 1340-1343.

PIRAZZOLI P.A. (1993) - *Global sea-level changes and their measurement.* Global and Planetary Change, 8, 135-48.

PIRAZZOLI P.A. (1996) - *Sea-Level Changes: The Last 20000 Years*. Wiley, Chichester.

PIRAZZOLI P.A. (2007) - *Geomorphological indicators*. In: «Sea Level Studies. Encyclopedia of Quaternary Science». Elsevier, Amsterdam, 2974-2983.

PIRAZZOLI P.A., RADTKE U., HANTORO W.S., JOUANNIC C., HOANG C.T., CAUSSE C. & BOREL BEST M. (1991) - *Quaternary raised coral-reef terraces on Sumba Island, Indonesia*. Science, 252, 1834-1836.

RAHMSTORF S., CAZENAVE A., CHURCH J.A., HANSEN J.E., KEELING R.F., PARKER D.E. & SOMERVILLE R.C.J. (2007) - *Recent climate observations compared to projections*. Sciencexpress / www.sciencexpress.org/ 1 February 2007/10.1126/ science. 1136843.

SHACKLETON N.J., BERGER A. & PELTIER W.R. (1990) - *An alternative astronomical calibration on the Lower Pleistocene time scale based on ODP Site 677*. Transactions of the Royal Society, London, B, 318, 679-688.

WILLIS J.K., ROEMMICH D. & CORNUELLE B. (2004) - *Interannual variability in upper ocean heat content, temperature, and thermosteric expansion on global scales*. Journal of Geophysical Research 109, C12036, doi:10.1029/2003JC002260.

(Ms. presented 30 September 2007; accepted 30 December 2008)