Setting the Frames of Expected Future Sea Level Changes by Exploring Past Geological Sea Level Records

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Chapter Outline

1. Introduction 185
2. Sea Level Changes by Year 2100 186
3. Frames of Glacial Eustatic Rise in Sea Level 186
4. Frames of Steric Expansion of the Water Column 189
5. Setting the Frames of Future Sea Level Changes 190
6. Solar Cycles in the Near Future 192
7. The State of Fear 192
8. Conclusions 194
Acknowledgments 194

1. INTRODUCTION

Eustasy was once defined as “simultaneous changes in global sea level” (e.g., Fairbridge, 1961). With the concept of geoid changes (Mörner, 1976), global loading adjustment (e.g., Clark, 1980; Peltier 1998), and global redistribution of the ocean water masses (Mörner, 1984, 1988), this definition had to be changed. Hence, Mörner (1986) redefined eustasy simply as “changes in ocean level” (contrary to changes in land level) and regardless of causation factor.

Many variables control the changes in ocean level (Mörner, 1996a, 2000, 2005). The most significant parameters to drive a possible sea level rise today are the redistribution of water to the oceans by glacial melting (a process known
as glacial eustasy) and the expansion of the water column by heating up the water (a process known as steric expansion). Both these parameters can be quantified as to maximum rates and amplitudes (Mörner, 1989, 1996a,b). Those values may even be used to define the frames, inside which we have values of possible changes and outside which we have values that are not anchored in physics of sea level variability. This is the topic of the present paper, initiated by the fairly careless dropping of values of assumed sea level rise by year 2100 that often seem, by far, to exceed the frames of possible changes.

2. SEA LEVEL CHANGES BY YEAR 2100

The first predictions by the IPCC (Intergovernmental Panel on Climate Change) did not hesitate to claim a sea level rise as high as 2–3 m by the year 2100 (Hoffman et al., 1983; Kaplin, 1989; IGBP, 1992). The values presented in the IPCC reports have diminished successively to +47 cm ± 39 cm in the 2001 report and to +37 cm ± 19 cm in the 2007 report (IGCP, 2001, 2007). The INQUA Commission on Sea Level Changes and Coastal Evolution, on the other hand, objected to values exceeding +20 cm with the expected value set at +10 cm ± 10 cm (INQUA, 2000), a value later updated at +5 cm ± 15 cm (Mörner, 2004). Recently, a sea level rise of 2 m, or even more by 2100, has again been claimed due to exceptional melting of the ice cap in Greenland (ACID, 2004) or Antarctica (e.g., Rapley, 2007). It is significant, however, that the Antarctic ice cap has expanded, not decreased, in the last 20 years (D’Aleo, 2007) and that the Greenland ice cap was roughly the same dimension during the Holocene Climatic Optimum and probably even during the Last Interglacial when climate was about 4–5° warmer than today (Willerslev et al., 2007). Despite all this, Rahmstorf (2007) proposed a sea level rise of 50–120 cm by 2100.

3. FRAMES OF GLACIAL EUSTATIC RISE IN SEA LEVEL

For more than 25 years, I have been engaged in the quantification of the various eustatic variables. The maximum glacial eustatic rate has been established at 10 mm year⁻¹ or 1.0 m in a century (Mörner, 1983). Subsequent studies confirmed this value (Mörner, 1987, 1989, 1996a,b). The relations among rates and amplitudes of different eustatic variables are given in Fig. 1. This value is primarily obtained from the rates recorded at the glacial eustatic rise after the last glaciation maximum (LGM) of the Last Ice Age at around 20 ka with a sea level low-stand in the order of −120 m.

The mean rate of glacial eustatic rise was 120 m in about 13,000 years from 18 to 5 ka or 9.2 mm year⁻¹. The rise from 18 to 12 ka was about 60 m or 10.0 mm year⁻¹. The Holocene rise from 10 to 5 ka was 50 ± 10 m or 10.0 mm year⁻¹ ± 2.0 mm year⁻¹. Therefore, a round figure of 10.0 mm year⁻¹ can be held as a quite good estimate of the maximum rate of sea level rise after the last glaciation maximum.
The predominant contribution to the post-LGM rise in sea level came from the huge continental ice caps over North America and Northwest Europe. In America, the ice cap reached down to about Latitude 40° N and in Europe down to about Latitude 53° N; i.e., mid-latitudes, which would be impossible under present-day climate conditions. The post-LGM rise in temperature was significant and the ice melted as fast as possible — still, sea level did not rise faster than 10 mm year$^{-1}$ (1.0 m in a century). Therefore, this value seems to set a natural frame for possible maximum rates of sea level rise.

The volume of the post-LGM ice melting was in the order of 50.7 million km$^3$ (Flint, 1971), and most of these masses were melting under strong climate forcing in mid-latitude positions. Still, it took about 12,000–13,000 years to melt the main continental ice caps of the Last Ice Age.

Today, there are two major continental ice caps left—Antarctica (~21.5 million km$^3$) and Greenland (~2.4 million km$^3$), both in high-latitude positions. In case of a hypothetical melting, the rate of melting must be significantly lower than that of the big mid-latitude ice caps at LGM.

The ice cap in Antarctica was assumed even by the IPCC to increase rather than decrease in the near future (IGCP, 2001). The recent claim of a rapid

**FIGURE 1** Rates and amplitudes of different sea level variables. (A) Estimates of 1983 and 1989 (Mörner, 1983, 1989) with GL (yellow field) denoting glacial eustasy peaking at a rate of 10 mm year$^{-1}$. (B) Improved estimates of 1996 (Mörner, 1996b) with variables from seconds up to a million years. Glacial eustasy (red line) is still peaking at a rate of 10 mm year$^{-1}$ or 1.0 m in a century (red dots).
ongoing melting (e.g., Rapley, 2007) is strongly contradicted by the observed increase in ice cover during the last 20 years (D’Aleo, 2007).

The Greenland ice cap was recently claimed to be under rapid melting (ACID, 2004). However, the Greenland ice cap seems to have been roughly the same size in mid-Holocene time when temperature was about 2.5 °C warmer than today in the northern hemisphere. Recent studies (Willerslev et al., 2007) also record a persisting ice cap during the Last Interglacial when temperature was some 4–5 °C warmer than today. Therefore, a rapid down-melting of the whole ice cap seems highly unlikely.

Physically, the melting of ice is a function of the calories available in the process. The heat (calorie) input comes from the air, the sea, and the underground (Fig. 2). All of these three sources of energy are significantly larger in the mid-latitude positions than in the polar to high-latitude areas. Therefore, any melting of the ice caps in Antarctica and Greenland (totally or partly) must be significantly slower than that of the huge mid-latitude ice caps at LGM.

Even in the earliest part of the Holocene, when temperature rose very rapidly and the rate of ice retreat was fast, the glacial eustatic rise did not exceed 10 mm year$^{-1}$. So, for example, the ice recession in the Stockholm area (in the early Holocene some 400 years after the end of the Younger Dryas period) was about 300 m year$^{-1}$, which is a very rapid recession, especially if one considers that the outward ice-flow at the same time was in the order of 500 m year$^{-1}$, implying a total ice-front recession in the order of 800 m year$^{-1}$ (Fig. 3).

In conclusion, the observed rate of post-LGM glacial eustatic rise in sea level—10 mm year$^{-1}$ or 1.0 m in a century—appears to be a very good value of the maximum possible rate of sea level rise from glacial melting.

It might be appropriate to stress that any melting of the Arctic summer ice has insignificant effects on global sea level, because the ice cover is thin and is already floating in the sea. Similarly, in view of present melting of some alpine
glaciers, one should also remember that the extensive expansion of alpine glaciers during the so-called Little Ice Ages of the last 600 years had seemingly little to insignificant effects on global sea level.

4. FRAMES OF STERIC EXPANSION OF THE WATER COLUMN

The amount of expansion of a water column that is heated can fairly easily be calculated (Fig. 4.). In the oceans, only the upper couple of hundred meters are likely to become heated. Such a heating is hardly likely to amount to more than a degree or two. Figure 4 gives the expansion effects (i.e., sea level rise) with respect to different amount of heating and height of the water column affected. An expansion (sea level rise) of more than some 5–10 cm seems hardly likely (Mörner, 1996a; Nakibogul and Lambeck, 1991).

Another factor of fundamental importance is the available water depth. In the littoral zone, the water depth is so small that any heating expansion will be more or less negligible (Fig. 4). At the shore (the land/sea interface), the effect will always remain zero. Therefore, thermal expansion will not affect coastal sea level. There seems to exist a misunderstanding that a water expansion at sea will flood landwards. What is deformed, is the dynamic sea
level, which is a highly irregular surface due to all interacting dynamic variables.

The warming at the Younger Dryas to early Holocene transition was both rapid and drastic (e.g., Alley, 2000). Still we are unable to identify any sea level effect driven by steric expansion of the water masses.

The Holocene sea level oscillations observed have sometimes been proposed to be the steric effects of changes in ocean surface temperature and/or salinity (Schofield, 1980). Nowadays, it seems quite clear, however, that such sea level oscillations are the function of dynamic redistribution of the water masses (Mörner, 1996a, 2005, 2007).

During the ENSO-year 1998, the Maldives were affected by a strong coral bleaching due to over-heating of the water. The sea level effect was in the order of 3 cm (Mörner, 2011).

5. SETTING THE FRAMES OF FUTURE SEA LEVEL CHANGES

In view of the data presented, it seems justifiable to apply physical frames of possible sea level changes in the near future. In Fig. 5, the value 10 mm year$^{-1}$ is used as the frame value. Possible future changes in sea level should lie inside (probably well inside) this box (blue). Values falling outside the frame should be discarded as unrealistic.

**FIGURE 4** Thermal expansion of a water column of different size (depth) with respect to various degrees’ of heating (Mörner, 1996a). In the oceans, the water column is never heated uniformly with depth due to its stratification and slow vertical mixing. At the base, a schematic depth zonation is added, illustrating the decreasing effect towards the coast and the absence of any effect at the very shoreline.
The sea level changes observed over the last 300 years have oscillated within a range of about 1.1 mm year\(^{-1}\) lacking sign of any long-term trend (Mörner, 2004, 2005, 2008). For the last half a century, the situation has remained highly controversial, however (Mörner, 2010a). The excellent northwest European tide gauge records give little or no rise (Woodworth, 1990; Mörner, 1996a, 2004, 2010a). Selected Pacific and Indian Ocean tide gauges (Church et al., 2007) give 1.4 mm year\(^{-1}\). Proposed global mean tide gauges (Holgate, 2007) give 1.45 mm year\(^{-1}\) with the actual rate for the last 40 years being only 1.2 mm year\(^{-1}\). All values lie well within the lower half of the blue square set by the frames in Fig. 5.

Satellite altimetry is an important new tool because it does no longer limit our records to the shores of the world but covers the whole ocean surface below Latitude 60° N and S. Whilst the satellite altimetry groups themselves (Cazenave and Llovel, 2010; Nicholls and Casenave, 2010; NOAA, 2008) give rates of +3.1 to 3.4 mm year\(^{-1}\), Mörner (2004) gives a value of ±0 mm year\(^{-1}\). The difference in interpretation is illustrated in Fig. 6 (Mörner, 2008, 2010a). The satellite readings need some technical adjustment. This gives an ongoing rate of sea level change of ±0 mm year\(^{-1}\) (Mörner, 2008, 2010a; Aviso, 2000) or a slight rise of <0.5 mm year\(^{-1}\) (Mörner, 2005). I term this as “the instrumental record” (Mörner, 2008). Other persons seeking a rise in sea level add “personal calibrations” (primarily a tide gauge factor), by that arriving at an “interpretational record” of about +3.0 mm year\(^{-1}\) (Cazenave and Llovel, 2010; Nicholls and Casenave, 2010; Aviso, 2003, 2008). Even the “calibrated records” lie well within the lower half of the square set by the frames in Fig. 5.

FIGURE 5 Rates and amplitudes of expected future changes in sea level with the frame of physically possible changes set at 10 ± 1 mm year\(^{-1}\) or 1.0 ± 0.1 m in a century, and with the observed rate of changes in the last 300 years of 1 mm year\(^{-1}\) or 10 cm in a century (Mörner, 1996a, 2004) marked in lower right corner. For reasons discussed in the text, reliable estimates of sea level changes by year 2100 must lie well within the frame given. Values falling outside should simply be considered unreliable or exaggerated. At the same time, however, even a possible rise in the order of half a meter or so by year 2100 would pose serious threats to some low-lying coasts and islands around the globe.
6. SOLAR CYCLES IN THE NEAR FUTURE

Finally, discussing the next centennial changes in sea level, one should, at least, consider the long-term changes in solar activity. From the cyclic repetition between solar maxima and minima, one can infer that there will be a future solar minimum in the middle of this century (Mörner, 2006, 2010b; Easterbrook, 2007).

During the previous solar minima—the Dalton, Maunder, and Spörer Minima—climate was cold and known as “Little Ice Age”. In analogy, by about 2040–2050 similar climatic conditions might reappear. This might even lead to a minor, decadal, lowering in sea level. Therefore, my estimate of the possible changes in sea level by years 2100 is $+5\, \text{cm} \pm 15\, \text{cm}$ (Mörner, 2004).

7. THE STATE OF FEAR

A rise in sea level will always pose a threat to low-lying coastal areas. This is also something that coastal dwellers through time seem to have learned to cope with (e.g., the changes in sea level affecting the Maldives in the last 4000 years; Mörner, 2007, 2011). There are, of course, limits of the capacity of “adaptation”. The more reasons there are to be realistic in our predictions and estimates. Exaggerations just feed a “state of fear”, to borrow the title of Crichton’s book (Crichton, 2004).

The main purpose of this paper is to provide a tool of discrimination between reasonable and unreasonable sea level predictions for this century (up to 2100). Using the frames set in Fig. 5, one should exclude all claims exceeding 1 m rise in a century or 10 mm year$^{-1}$ (for example, the recent claim by Black (2008) of a rise by 2100 of 1.5 m). Even values in the order of...
0.5–1.0 m (5–10 mm year\(^{-1}\)) seem less probable (in view of what is said above about the rate of melting).

Hansen and Sato (2011) have recently claimed that global sea level will rise to +5 m by year 2100. They even proposed an exponential increase in the glacier melting giving a 4 m rise in sea level in 20 years from 2080 to 2100, which is a rate of 200 mm year\(^{-1}\) (Fig. 7). This rate far exceeds the “ultimate frame of possible sea level rise” as given in Fig. 5. Their claim violates geology (it does not concur with our experience and observations), physics (ice can simply not melt that fast), and scientific ethics (one should know what one is talking about and not drop idle talk just for the sake of promoting a view). Hence, this contribution has only one message to offer; it provides a shocking example of disinformation and should be immediately dismissed as such.

Values ranging between 0 m and 0.5 m (0–5 mm year\(^{-1}\)) must be classified as possible, though our best estimate is +5 cm ± 15 cm by year 2100 (Mörner, 2004).

Figure 8 shows coastal problems plotted against the possible future sea level rise. The scale is, of course, arbitrary. A rise from 0 cm to +25 cm by the year 2100 seems “OK”, from +25 cm to +75 cm “bad”, and above +75 cm “disastrous”. A rise of up to +1 m may be theoretically possible (Fig. 4), but is quite unlikely to exceed about 0.5 m.

By the frames set in Fig. 5, there seems little reason for the expectation of a sea level rise causing disastrous effects (Fig. 8). Still, even a minor rise may cause problems in low areas where the balance between sea and land remains delicate. In general, however, we seem to be exposed to extensive exaggerations (Mörner, 2010a).
8. CONCLUSIONS

The rate of post-glacial melting of the big continental ice caps in mid-latitude position provides an excellent maximum value for all talk of what will happen in the next 100 years. This value provides us with a tool of discriminating between realistic proposals and unrealistic claims that should be discarded or, at least, be taken with great care. The following conclusions are drawn:

1. The prediction of sea level changes within this century (i.e., up to year 2100) must be well within the frames set by the post-LGM rates of sea level rise; that is \( \leq 1.0 \) m (or \(< 10 \) mm year\(^{-1}\)).
2. Any rate of melting of the Greenland and/or Antarctic ice caps must be well below that of the melting of the major LGM ice caps.
3. The effect of thermal expansion must be well below that of the major post-LGM warming pulse at the “terminations” and especially at the rapid warming of the early Holocene. At the coast, the effect is negligible to zero.

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