

# Rising Sea Levels as an Indicator of Global Change

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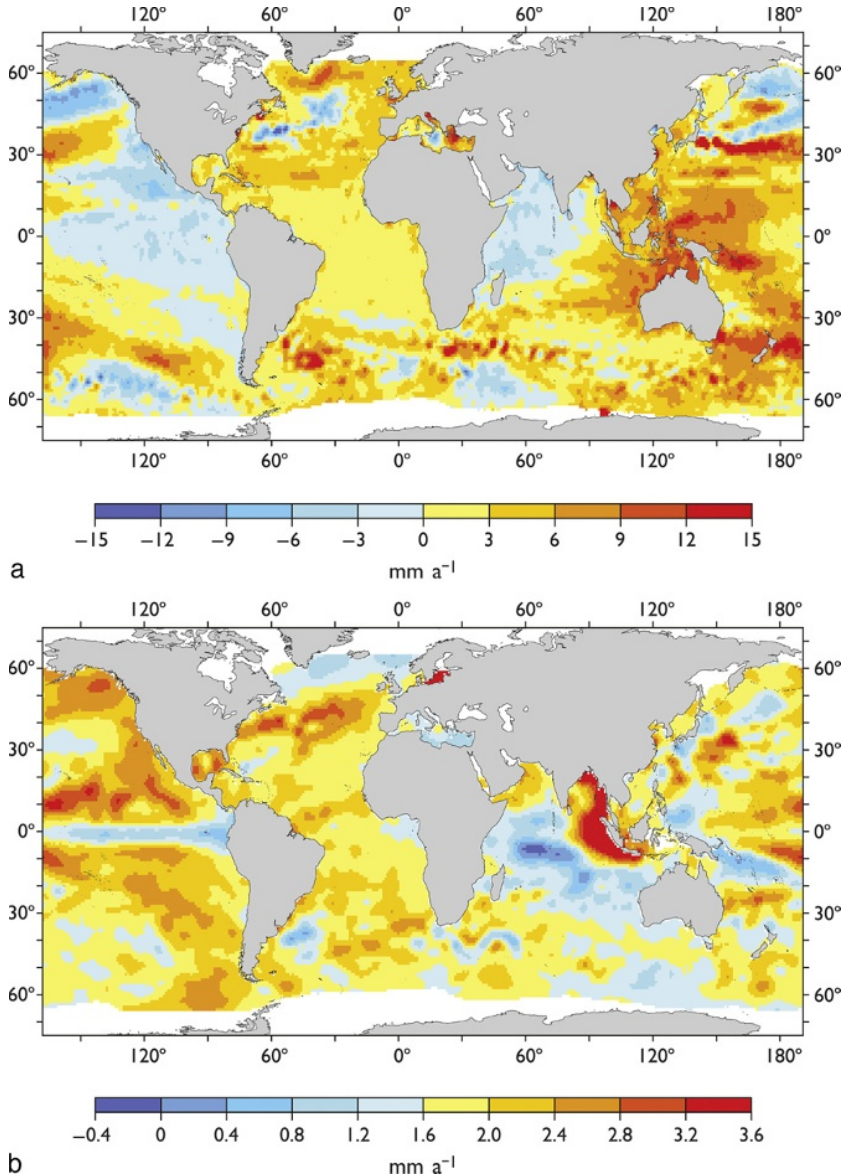
## 1. INTRODUCTION

The release of the fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC) in 2007 was followed by much debate, both in the media and in the scientific community, on the sea-level rise predictions it contained [1]. This was partly because sea-level rise is an effect of global climate change that will have far-reaching consequences for a majority of the world's population. However, attention also focussed on the predictions themselves – how accurate were they? The 2007 predictions contained similar uncertainties as the previous IPCC report from 2001 – so what was new? Despite perceived shortcomings, however, the last IPCC volume contains a wealth of new data on recent sea-level changes, in particular from the last 50 years, a period when oceanographic data collection underwent a true revolution. Collectively, the data summarised by the IPCC reflect our improved understanding of the causes of sea-level rise and they identify rising sea levels as one of the major indicators of ongoing global change.

## 2. IS SEA LEVEL RISING?

Although this question appears almost rhetorical and can at first glance be answered with a resounding 'yes', the direction of sea-level changes, positive or negative, depends on the time scale of observations and the spatial scale under

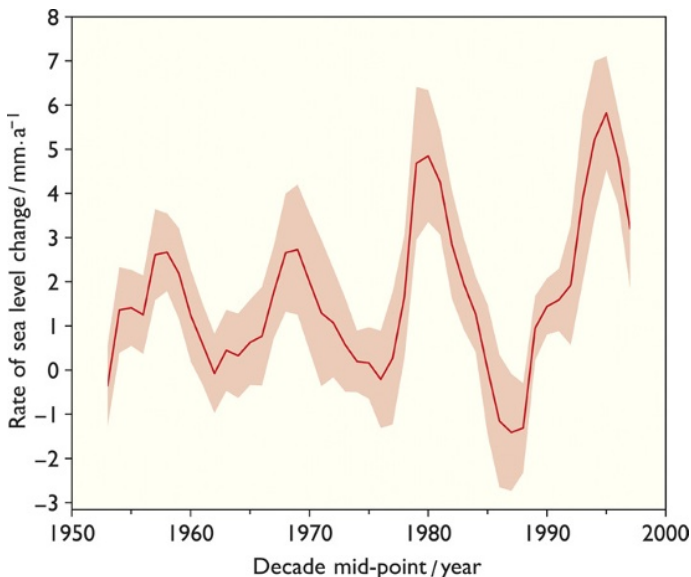
consideration. This is obvious on very short timescales, for example in the case of tidal fluctuations. However, sea-level changes are also highly variable in time and space on decadal timescales. Satellite observations since the early 1990s have revealed the complex regional patterns of sea-level changes (Fig. 1a). Linear trends over the decade 1993–2003 show that some parts of the world’s oceans have experienced high rates of sea-level rise ( $>10 \text{ mm}\cdot\text{a}^{-1}$  in places), while in other places



**FIGURE 1** Geographic patterns of sea-level change from (a) 1993 to 2003 (from Ref. [6], updated from Ref. [40]) and (b) 1955 to 2003 (from Ref. [6], updated from Ref. [41]).

sea level has fallen by similar amounts. When averaged over the past 50 years (Fig. 1b), linear rates are an order of magnitude smaller, but the pattern, which is derived from tide-gauge and satellite measurements, is still complex. Most areas have been subjected to sea-level rise, but, again, there are places, most notably in the Indian Ocean and the tropical Pacific, where sea level has fallen, albeit by a small amount. This picture does not take account of land-level movements which in many coastal locations need to be added to, or subtracted from, the mean sea-level change to derive a figure that represents the relative change at a coastline. This is, after all, the number that is of most practical value for coastal management.

To answer the question adequately it is clear that sea-level observations need to be averaged in some way, and, indeed, since the first attempt by Gutenberg [2] many scientists have derived a global value of average sea-level rise by using a range of statistical techniques and various datasets of measurements, many of which have been corrected for vertical movements of the coastlines to which tide gauges are attached. The IPCC consensus is that global sea level has risen during the twentieth century by about 17 cm [1]. An updated estimate is  $1.6 \pm 0.2 \text{ mm}\cdot\text{a}^{-1}$  for the period 1961–2003 [3]. Since the early 1990s, the rate of sea-level rise has been about  $3 \text{ mm}\cdot\text{a}^{-1}$  [1], but it is too early to conclude that this change represents a true deviation of the twentieth century global trend. This becomes evident when the global rate is analysed at decadal timescales (Fig. 2). Rates of sea-level rise, similar to those of the past few years, have occurred in previous decades. However, the maximum rates have increased from  $\sim 2.5 \text{ mm}\cdot\text{a}^{-1}$  in the decade centred on 1970, to  $\sim 6 \text{ mm}\cdot\text{a}^{-1}$  in the



**FIGURE 2** Global rates of sea-level change since 1950s, averaged over a decade, based on 177 tide-gauge stations [42,43].

late 1990s. The question is, of course, whether the lengths of the records limit us in the conclusions we can draw. Are measurements during three decadal cycles sufficient to conclude that the rates of sea-level rise are on the increase (i.e. that sea-level rise is accelerating)? Longer timescales of observations are necessary to provide the appropriate context to identify possible accelerations in the rate of sea-level rise. Long tide-gauge records and reconstructions based on proxy data are therefore crucial to inform the climate change debate (see [Section 4](#)).

### 3. WHY IS SEA LEVEL RISING?

Many factors contribute to the changes in sea level that the globe is experiencing today. Some cause sea levels to rise, others make a negative contribution. Not all factors are well constrained and herein lies one of the bigger challenges of sea-level science: can we explain the sea-level rise we are observing?

According to the IPCC, the main contributors to sea-level rise since 1961 are thermal expansion ( $0.4 \text{ mm}\cdot\text{a}^{-1}$ ) and melting ice from small glaciers and ice caps ( $0.5 \text{ mm}\cdot\text{a}^{-1}$ ), with small amounts (that carry relatively large uncertainties) from the Greenland Ice Sheet ( $0.1 \text{ mm}\cdot\text{a}^{-1}$ ) and the Antarctic Ice Sheet ( $0.1 \text{ mm}\cdot\text{a}^{-1}$ ). In the IPCC assessment for the latter half of the twentieth century, these known sources of sea-level rise do not match the measurements and only add up to a little over half of the observed rise. This issue has been called the ‘sea-level enigma’ [4] or the ‘attribution problem’ [5]. The discrepancy implies one of three things: either the measurements produce a global value that is too high, or the contributions are underestimated, or there are sources of sea-level rise that are not accounted for.

Could the ‘enigma’ be due to the various ways in which sea-level rise has been measured? The measurements for the twentieth century are based on tide-gauge records, which are limited in spatial and temporal extent. For the past decade, the period for which satellite measurements are available, the sea-level budget is almost closed [6]. At face value this could highlight that satellites produce more accurate measurements of global sea-level rise than tide gauges. However, satellite and tide-gauge measurements agree well in the 1990s. They diverge from 1999 onwards [3], but this mismatch could be due to records in the tide-gauge dataset being a few years out of date. It seems therefore more likely that a possible source of sea-level rise has been left out of the equation or that a source has been underestimated.

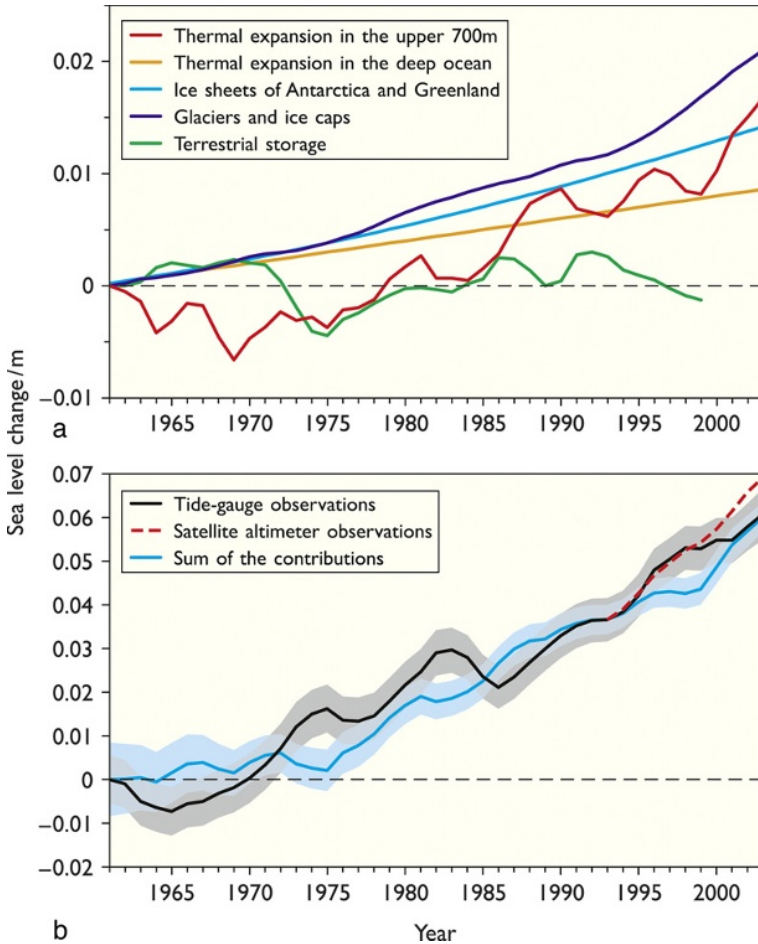
One of the most uncertain terms in the sea-level budget is the contribution of terrestrial water sources. Although the filling of reservoirs extracts water from the hydrological cycle and causes sea level to drop [7], other human interference with hydrological processes (e.g. wetland drainage, sedimentation in reservoirs, groundwater mining, surface water consumption, deforestation)

contribute positively to sea-level rise. In fact, it has been argued that the transfer of terrestrial water sources to the ocean could represent the ‘missing’ term in the sea-level budget of the twentieth century [8].

Others have argued that the ice-melt term has been underestimated [5]. The contribution of small glaciers and ice caps is reasonably well constrained, but monitoring of mass-balance changes in land-based ice sheets is a relatively new activity so that the volumes of discharge of the polar ice sheets are not well known before the 1970s. It is now clear that dynamical changes in the outlet glaciers of the Greenland and Antarctic Ice Sheets can lead to large sea-level contributions. Outlet glaciers in Greenland, including the Jakobshavn Glacier, have contributed about  $0.1 \text{ mm}\cdot\text{a}^{-1}$  of sea-level rise since the mid 1990s [9]. The Amundsen Sea glaciers in West Antarctica, including the Pine Island Glacier, produced sea-level rise contributions of  $0.15 \text{ mm}\cdot\text{a}^{-1}$  in the 1990s [10], and possibly as much as  $0.24 \text{ mm}\cdot\text{a}^{-1}$  between 2002 and 2005 [11]. Is it possible that a hitherto unknown ice shelf disappeared, for example somewhere in West Antarctica, which led to a rapid discharge of parts of the interior of the West Antarctic Ice Sheet? Seemingly, one can only speculate, but there are indirect methods by which this question may be addressed.

One method by which the ice-mass term in the sea-level budget can be tackled is by determining the rates at which the ocean has freshened as a result of melting ice [5,12]. However, this method is, again, limited by the record length of hydrographic data. An arguably more intriguing route of investigation is to map the ‘sea-level fingerprint’ that would have been left by a melting ice mass. A shrinking ice mass produces a diminishing gravitational pull on the ocean surface and perturbs the sea surface as far as thousands of kilometres away, so that sea-level rise near the melt source is less than the sea-level rise in the far field [13,14]. In theory, therefore, it should be possible to determine from the patterns of sea-level change measured by tide gauges the ice-mass contribution to sea-level rise. For example, this method has been used to estimate a  $1.0 \pm 0.6 \text{ mm}\cdot\text{a}^{-1}$  contribution of melting of the Greenland Ice Sheet to global sea-level rise since 1960 [15]. Although other attempts to find a systematic pattern in tide-gauge measurements have been less successful [16], possibly due to steric (density) and isostatic overprints, it is clear that sea-level fingerprinting has wide ranging applications in sea-level research [17,18].

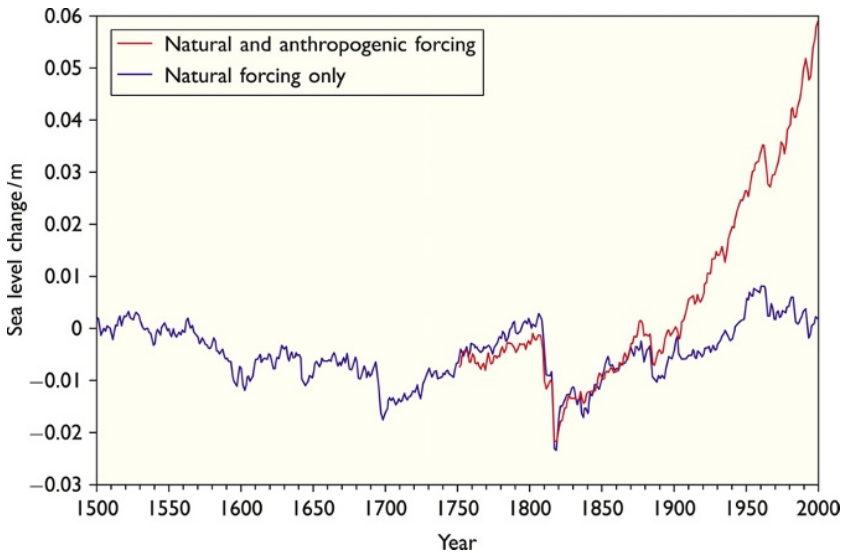
In a potentially highly significant study, a new suggestion has recently been made which can resolve the enigma [3]. This study concludes that the contribution of thermal expansion in past assessments has been underestimated, because of biases in the way the expansion was calculated from observational data. This appears to be a convincing explanation and it is satisfying to see that the sea-level budget since 1961 now appears to be closed (Fig. 3). With the revised steric estimates, the sum of the contributions is  $1.5 \pm 0.4 \text{ mm}\cdot\text{a}^{-1}$  for the period 1961–2003, very close to what has been measured. It is probably too early to tell whether this is the final word on the enigma debate, but the



**FIGURE 3** (a) Contributions to global sea-level change since 1960, including thermal expansion in the upper 700 m of the oceans, thermal expansion in the deep ocean, polar ice sheets, glaciers and ice caps, and terrestrial water storage. (b) Sea-level change estimated from global measurements and the sum of the contributions in (a). One standard deviation errors are also shown. From Ref. [3].

advances made are of some significance. A better understanding of the past contributions to sea-level rise will enable modellers to improve their predictions of future sea-level rise.

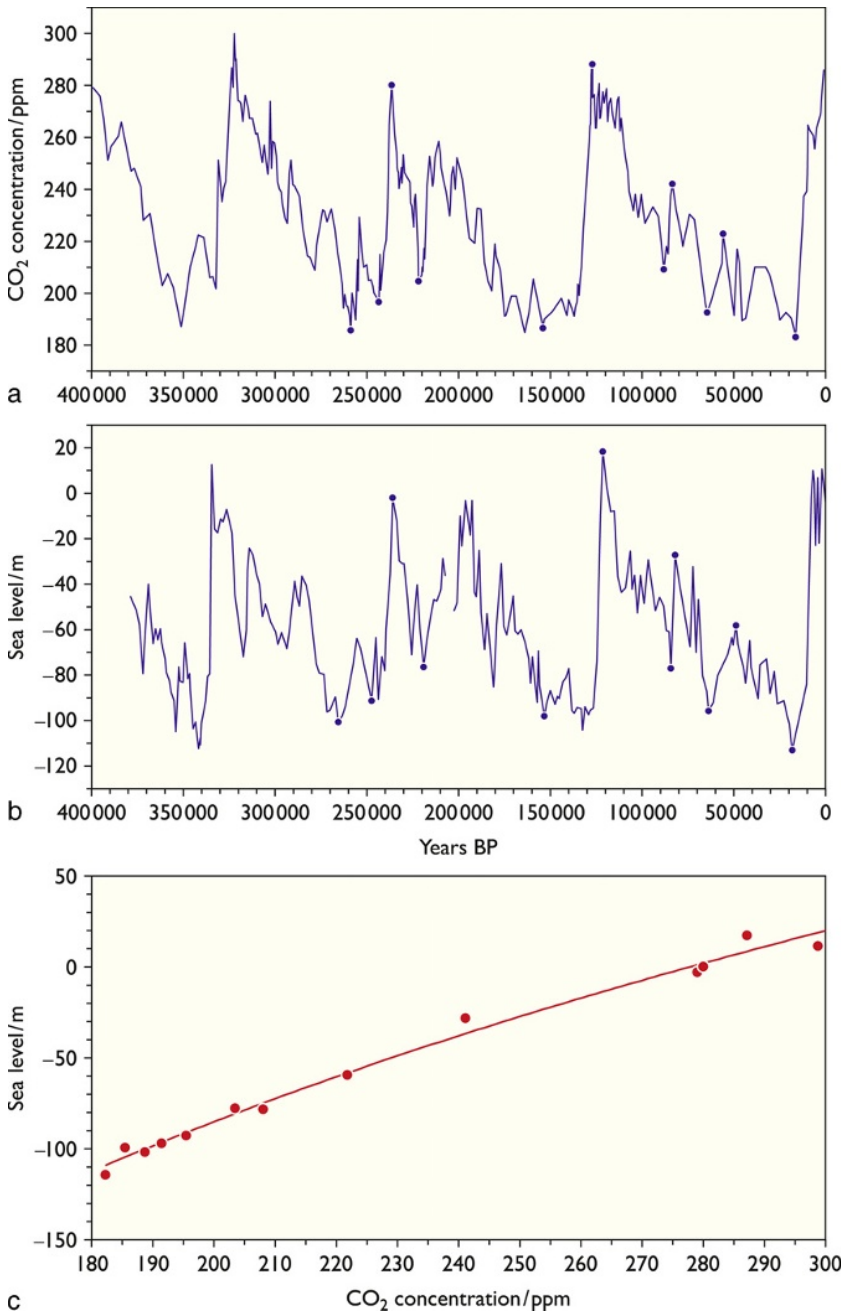
Humans have had a measurable impact on sea-level rise since about 1900 (Fig. 4). Model experiments demonstrate the influence of greenhouse gas emissions, producing increased thermal expansion and greater glacier melt [19]. Volcanic eruptions have slowed down sea-level rise, and some of the twentieth century rise in sea level was delayed by the eruptions of



**FIGURE 4** A model simulation for the past 500 years of natural and anthropogenically forced sea-level change (red) and sea-level change forced by natural factors only (blue). Although the model simulations fail to reproduce the magnitude of both the observed long-term sea-level trend and interannual and decadal variability, the onset of twentieth century sea-level rise appears to be controlled by anthropogenic forcing. Sea-level rise in these model runs started after the eruption of Tambora in 1815, but was driven by natural factors during the nineteenth century. From Ref. [19].

Krakatoa in 1886 and Pinatubo in 1991 [20]. This is important, because these eruptions temporarily masked the impact of anthropogenic effects on sea-level rise.

The relationship between sea-level change and greenhouse gas concentrations is well known on geological timescales. For example, when  $\text{CO}_2$  concentrations were higher than 1000 ppm around 70 Ma, ice was absent from the planet and sea level was 73 m higher than today [9]. Figure 5 shows the Red Sea sea-level record during the past 400 000 years [21] and a comparison with  $\text{CO}_2$  concentrations measured in the Vostok ice core [22]. Although chronologies of both records have inherent uncertainties, and  $\text{CO}_2$  fluctuations may in fact lead temperature change by several centuries [23], the correlation between  $\text{CO}_2$  and sea-level change is obvious: higher  $\text{CO}_2$  levels correspond with increased sea levels. If the almost linear trend, shown in Fig. 5c, persists for  $\text{CO}_2$  concentrations in excess of 300 ppm, it implies that sea levels will continue to rise significantly in the future. Indeed, climate models predict that with stabilisation of  $\text{CO}_2$  levels by the year 2100 at 550 ppm [9] or 700 ppm [1], sea level will continue to rise for another 1000 years. If  $\text{CO}_2$  levels reach 1000 ppm, the Greenland Ice Sheet will disappear in 3000 years, raising sea level by about 7 m [9].



**FIGURE 5** (a) CO<sub>2</sub> concentrations during the past 400 ka as measured in the Vostok ice core from Antarctica [22]. (b) Sea-level changes in the Red Sea during the past 400 ka [21]. (c) Relationship between CO<sub>2</sub> concentrations and sea level, assuming minima and maxima in (a) and (b) are of similar age. Points in (c) correspond to dots on the curves in (a) and (b).

#### 4. ARE CONTEMPORARY RATES OF SEA-LEVEL RISE UNUSUAL?

It is a well known fact that rates of sea-level rise in the past have been much higher than the ones we are experiencing today. For example, during the last deglaciation around 14 000 years ago, rapid melting of ice sheets during Meltwater Pulse 1A produced rates of sea-level rise in excess of  $40 \text{ mm}\cdot\text{a}^{-1}$  [24]. However, the world was then emerging from an ice age, and many ice sheets contained unstable marine components which have now largely disappeared. The only marine-based ice sheet left is in West Antarctica, and this ice sheet is situated in the coldest region of our planet. A comparison with the late glacial sea-level history, therefore, does not provide a suitable analogue for modern (or future) conditions. Instead, it is more instructive to examine periods in the Earth's history when the cryosphere contained roughly the same volume of ice as today (or slightly less) and temperatures were similar (or slightly higher) than today's. Periods often cited as useful analogues include the Last Interglacial, the middle Holocene and the Medieval Climatic Optimum.

The position of sea level during the Last Interglacial is generally estimated at 4–6 m above present [25], but the exact height is difficult to determine due to uncertainties about land movements that have occurred since the Last Interglacial. Most evidence points at sea levels close to the present level, or slightly higher, for the time interval 128–116 ka [26]. Only one study on sediment cores from the Red Sea provides a detailed assessment of the rates of sea-level rise during the Last Interglacial [25]. It is estimated that the 'full potential range' of rates of sea-level rise was between 0.6 and 2.5 m per century. It is interesting to note that this estimate is within the same ballpark as some predictions made for the twenty-first century [27], although it is higher than those provided by the IPCC. Most of the sea-level rise during the Last Interglacial is thought to have come from Greenland, with possibly a small contribution from Antarctica [28].

Evidence from many parts around the world suggests that temperatures in the current interglacial reached their maximum in the middle Holocene, although the Holocene 'thermal optimum' is spatially variable and not globally synchronous. There are many published sea-level studies that argue for sea-level fluctuations, some up to several meters in amplitude, during the Holocene, but these are almost always based on data with large vertical and age uncertainties and often use a 'connect-the dot' approach that ignores these uncertainties [29]. Many Holocene sea-level histories are only resolved on millennial time scales. The more robust sea-level reconstructions that contain evidence for century-scale sea-level oscillations are arguably from micro-atolls in Australia and have recorded rates of 0.1–0.2 m per century in the middle Holocene [30]. Even during the 8.2 ka event, which was caused by the final draining of a huge glacial lake (Lake Agassiz-Ojibway) and thus is not truly representative as a modern analogue, sea-level rise may not have been more than 0.4 m [31].

Sea-level changes during the Medieval Climatic Optimum were small, and have not been clearly resolved in palaeo-records. Salt marshes in eastern North America provide evidence that rates did not exceed 0.2 m per century during the past millennium before the twentieth century [32]. In the North Atlantic Ocean [33] and in the Southwest Pacific [34], the recent acceleration of sea-level rise started about 100 years ago, although there are also signs of an earlier sea-level acceleration in the beginning of the nineteenth century [35]. These findings are based on microfossil evidence and high-precision dating of salt-marsh sediments and are supported by some analyses of long tide-gauge records [36]. However, tide-gauge measurements that extend back into the eighteenth century are only available for a few stations in western Europe (Amsterdam since 1700, Stockholm since 1774, Liverpool since 1768 [37]). The earliest global acceleration of sea-level rise that can be clearly demonstrated in instrumental sea-level data [38] and in global reconstructions based on tide-gauge data [39] occurred in the 1930s.

## 5. CONCLUSION

Sea-level rise is a major indicator of ongoing global change. Sea level has been rising at rates of up to 0.06 m per decade in the twentieth century. Since the 1950s, every subsequent decade has experienced increased rates of sea-level rise. Model experiments show that twentieth century sea-level rise cannot be explained by natural processes alone. Anthropogenic forcing by greenhouse gasses has become a dominant cause for recent sea-level change. The geological record of the past three glacial-interglacial cycles shows a strong positive relationship between atmospheric CO<sub>2</sub> concentrations and sea level. Modern rates of sea-level rise started about 100 years ago and the rate of twentieth century sea-level rise appears to be faster than rates reconstructed for the warm intervals of the Medieval Climatic Optimum and the middle Holocene. However, during the Last Interglacial rates of sea-level rise were possibly higher and were similar to those predicted in some future climate-change scenarios.

## ACKNOWLEDGEMENT

I am grateful to Phil Woodworth for helpful comments which improved this chapter.

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