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Identifying the causes of sea-level change

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Global mean sea-level change has increased from a few centimetres per century over recent millennia to a few tens of centimetres per century in recent decades. This tenfold increase in the rate of rise can be attributed to climate change through the melting of land ice and the thermal expansion of ocean water. As the present warming trend is expected to continue, global mean sea level will continue to rise. Here we review recent insights into past sea-level changes on decadal to millennial timescales and how they may help constrain future changes. We find that most studies constrain global mean sea-level rise to less than one metre over the twenty-first century, but departures from this global mean could reach several decimetres in many areas. We conclude that improving estimates of the spatial variability in future sea-level change is an important research target in coming years.

With about 200 million people living within coastal floodplains, and with two million square kilometres of land and one trillion dollars worth of assets lying less than 1 m above current sea level, sea-level rise is one of the major socio-economic hazards associated with global warming[1]. The expected rate is, however, extremely uncertain. Although the latest Intergovernmental Panel on Climate Change (IPCC) report[2] suggests a range of 0.18–0.59 m of sea-level rise between 1980–1999 and 2090–2099, it emphasizes that the contribution from changes in ice dynamics is highly uncertain, and provides three "illustrative" scenarios suggesting a possible addition of up to 0.17 m from this source. Since then, several studies[3,4] have suggested that a rise larger than 1 m cannot be ruled out. Sea-level rates of this magnitude (metres per century) are not uncommon in reconstructions of past sea-level change using geological evidence, and it has recently been suggested that similar rates occurred during the previous interglacial warm period 120,000 years ago[5,6] when the volume of land ice was similar to that at present.

A 'headline' figure of 1 m during the twenty-first century represents only the global average sea-level rise. Many different physical processes contribute to sea-level change (see Box 1) and none of these produce a spatially uniform signal. Indeed, one of the few statements that can be made with certainty is that future sea-level change will not be the same everywhere. Thus, the development of regional and local estimates of future sea-level rise — required for effective risk assessment — is one of the primary challenges for the coming years[2]. Prediction relies on models, and the veracity of model output is based on verification against observations. However, interpretation of these observations requires great care in light of the large spatial and temporal variability in sea-level change. In this article we summarize recent progress in understanding the variability in a suite of sea-level related observations at timescales ranging from decades to millennia. We conclude with an estimate of our current ability to predict future sea-level rise, and highlight outstanding problems to address in the coming years to achieve greater accuracy and confidence in such predictions.

The satellite era

The most comprehensive sea-level observations are the most recent ones. Since 1992, precise satellite altimeter missions have provided near-global maps of absolute sea level (Box 1) every ten days, permitting the sea-level trend to be determined for the majority of the world ocean (Fig. 1).The measurements highlight the non-uniform nature of the change over more than 14 years. Although the average is around 3 mm yr^{-1}, there are regions showing trends of over 10 mm yr^{-1} and larger areas (notably the northeastern Pacific) where sea level has fallen over this period. The small spatial scale of some of these differences draws attention to the issue of spatial sampling.

Recently, two observing systems that complement the altimetric data have been put into operation. The first — the Argo network — is a series of autonomous floats that sink and ascend, monitoring temperature and salinity in the top 1–2 km of the ocean. Since 2000, the Argo network has increased to more than 3,000 floats. The second — the Gravity Recovery and Climate Experiment (GRACE) satellite mission, launched in 2002 — measures the global gravity field every month. Resulting maps can be used to monitor month-to-month gravity changes, which are dominated by the motion of water around the Earth. Together, the Argo and GRACE measurement systems can, in principle, separate out the contributions to sea-level change from changes in ocean-water density and changes in ocean mass. With the GRACE system, it is also possible to determine the transfer of land-based water to the ocean.

Initial comparison of all three data sets[7] highlighted an inconsistency due to apparent ocean cooling[8]. This has since been identified as a result of the differing biases in the instruments observing ocean temperature[9–12], while geodetic constraints from observations of the Earth's dynamic oblateness confirmed that this apparent cooling was not being offset by a large increase in melting land ice[13]. After applying corrections for these biases, several studies[14–16] have shown greatly improved consistency, in one case[14] finding a tightly closed sea-level budget for interannual and seasonal cycles, but a significant imbalance of over 3 mm yr^{-1} in the trend. In a second case[15], a smaller net imbalance of about 1 mm yr^{-1} was found (this is within the estimated error bars). In a third study[16] GRACE data were used in two different ways: using a larger geodetic correction over the oceans than in other studies; and using it only to estimate Antarctic and Greenland mass loss, combining with other datasets to estimate the total mass entering the ocean. These two methods both result in a balance to within a small fraction of 1 mm yr^{-1}. However, in these three studies, there are differences of about 1 mm yr^{-1} in the results obtained from

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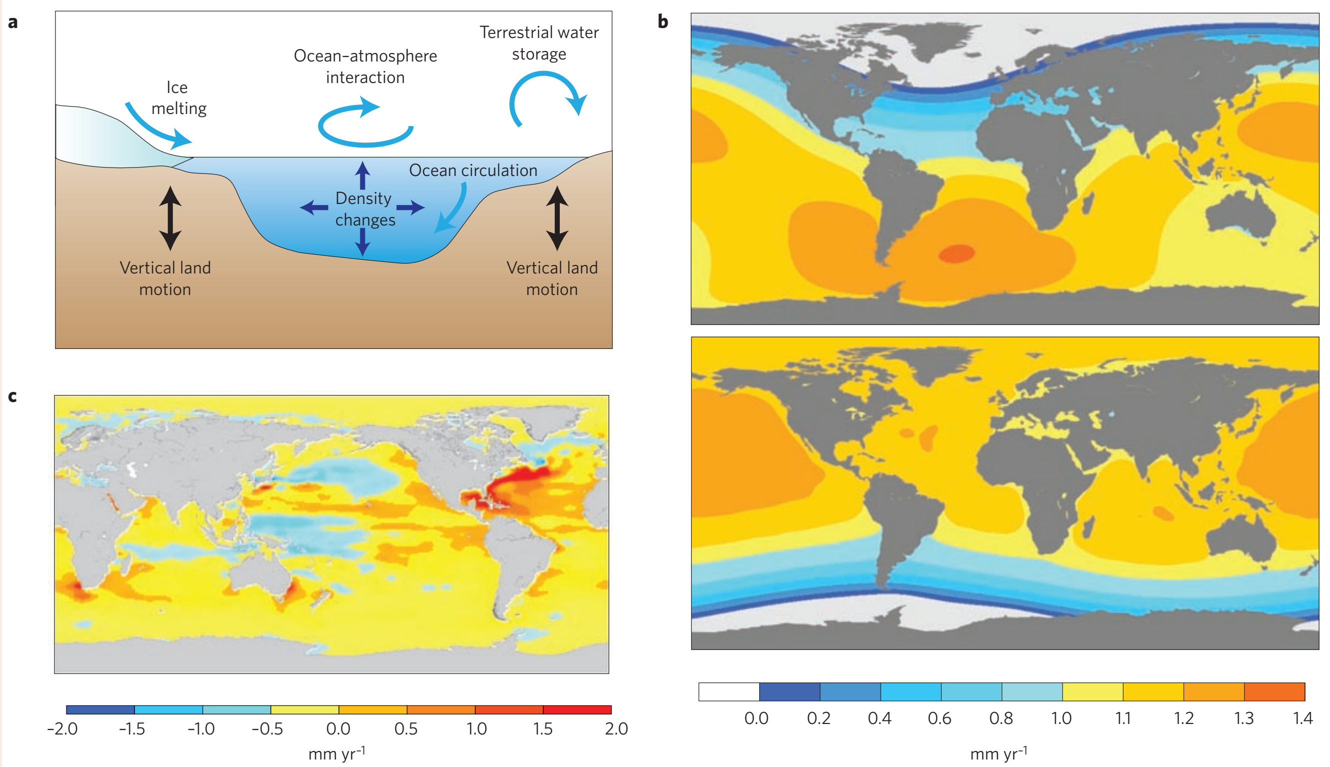
Box 1 | Processes affecting sea level.

Sea level is measured in one of two ways: relative to the ocean floor (known as 'relative sea level') or relative to the Earth's centre of mass (known as 'absolute sea level'). Satellite altimetry is the only method that provides a measure of absolute sea level. Both relative and absolute sea level are affected by a wide variety of processes (panel **a**). Note that absolute sea level is affected indirectly by deformation of the solid Earth owing to the corresponding changes to the gravity field and volume of the global ocean basin. All of the processes depicted in **a** result in a spatially variable sea-level response.

Two climate-related processes that will have central roles in governing sea-level changes over the coming decades to centuries are land-ice melting (mass contribution; **b**) and ocean-water density change owing to temperature and salinity changes (steric contribution; **c**). The spatial variability associated with these processes is depicted in **b** and **c**.

It is generally assumed that when land ice melts, the associated sea-level rise is globally uniform and proportional to the volume of ice loss. For example, it is often stated that the Greenland ice sheet holds about 7 m of global sea-level rise. In reality, the situation is more complex because of the isostatic deformation of the solid Earth along with gravitational and rotational changes driven by the ice–ocean mass exchange[27,85,98]. Panel **b** shows model predictions of the change in global sea level if the Greenland (top) or West Antarctic (bottom) ice sheets were to lose mass at 1 mm yr^{-1} (10 cm per century) of global mean sea-level equivalent. The predicted response departs significantly from the mean with a reduced rise and even fall in areas close to the ablating ice mass and an amplified rise in areas far removed from the melt source[99].

Ocean temperature and salinity changes have also been regionally variable in the past, and estimates of the resulting sea-level change reflect this variability. Panel **c** shows the mean rates of sea-level change over the period 1950–2003 estimated from observations of ocean temperature (taken from ref. 100).



each observing system (altimetry, Argo and GRACE), suggesting that this is the true error bound on trend estimates for these short (4 yr) time series. Variations may be partly a result of the slightly different time spans chosen and the dominant role of interannual variability over periods of only a few years, but there are also issues with each of the observing systems.

Problems with calibration of the temperature measurements were noted above, but a significant part of the imbalance arises from the incomplete temperature sampling of the ocean, particularly the Southern Ocean[14], which may be insufficient before 2004 (refs 15 and 16). The development of innovative ways to reduce sampling bias[17] is important. The GRACE mass estimates have a number of complications that contribute to their uncertainty. Because of the small signal over the oceans, compared with those over land, the analysis must reduce both the sampling of the nearby land signal along the coasts[18] and the presence of correlated errors in the GRACE solutions[19,20]. In addition, the GRACE mission is insensitive to geocentre motion, that is, the motion of the Earth's centre of figure relative to the centre of mass of the whole Earth (including cryosphere, hydrosphere and atmosphere). Ignoring this contribution can introduce an underestimate of up to 30% in sea-level rise caused by Greenland ice melting[18]. Estimates of geocentre motion derived from GRACE products or satellite laser ranging can be used in these analyses, but the accuracy of the trend in these estimates is difficult to obtain[21]. Finally, vertical motion of the ocean floor — due to glacial isostatic adjustment (the isostatic response of the solid Earth to past ice–ocean mass exchange) — makes a particularly large contribution to the measured gravity changes, with values used in recent analyses[7,14,15] ranging from -1 to -2 mm yr^{-1} (water-equivalent mass change).

Altimetry is not a perfect measurement system either. Although comparison with tide gauges shows that an accuracy of 0.4 mm yr^{-1} should be attainable[22,23], two of the above analyses[14,15] give estimates of 3.6 and 2.4 mm yr^{-1} respectively (both corrected for glacial isostatic adjustment in the same way). Much of this difference seems to result from the fact that the two four-year periods of analysis are offset by six months, but it should not be forgotten that there is a continual need to check for errors in the various corrections applied to altimetric data.

Since the most recent IPCC report, there have been two main advances: the correction of biases in ocean temperature observations[9,11], which greatly reduces the apparent cooling seen over the last few years[10,12], as well as reducing the apparent interdecadal variability in steric sea level[24]; and the ability to use three observing systems (altimetry, GRACE and Argo) to check the degree of closure of the mass flux and steric budget. However, given the short (4 yr) and differing time periods for the calculation of trends, it is not surprising that results vary between different studies, with central estimates of 2.4 to 3.6 mm yr^{-1} for the mean rate of absolute sea-level rise[15,16], -0.5 to 0.8 mm yr^{-1} for the steric component[14,15] and 2.4 to 3.6 mm yr^{-1} for the mass flux component[14,15].

Despite these uncertainties, progress is rapid and it is becoming clear that the combination of observing systems is very powerful. But the greatest dividends will come with longer time series, as interannual variability becomes less dominant and it becomes possible to isolate the causes of decadal and regional variability.

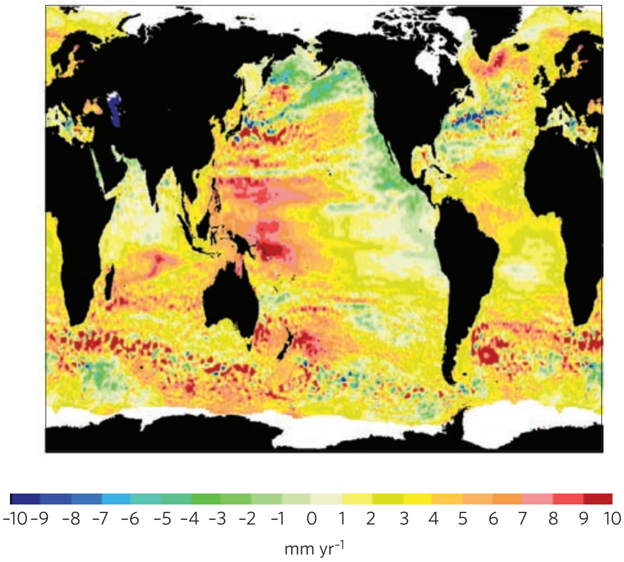


Figure 1 | Mean rate of sea-surface height change during October 1992 to May 2007, determined from satellite altimetry measurements. Measurements were corrected for the inverted barometer effect. The large spatial variability reflects the dominance of dynamical ocean processes over this period. The measurement error at a given point is difficult to assess, but is probably less than 2 mm yr^{-1}. Variations also occur on many different timescales, such that a linear trend is not a statistically significant fit to the time series at most locations; the trend is merely indicative of the kind of variability to be found.

The twentieth century

The large spatial variability in sea-level change, as well as honest assessment of error sources, must also be considered carefully when interpreting older measurements. These necessarily rely on a highly incomplete observing system: the global tide-gauge network[25]. From these records (Fig. 2) it is clear that spatial variation is still an important contributor to the measured changes even at the century timescale. Various processes (such as, atmosphere-driven and internal ocean dynamical modes, and unmodelled vertical land movement) probably contribute to this variability. In some cases, these processes are likely to produce highly localized signals, bringing into question how representative the tide-gauge record is of ocean-basin-scale averages. More work is needed to resolve the roles of these various processes.

For the globally integrated budget, the new temperature calibrations cited above improve the balance for 1961–2003 (ref. 24), but complete closure contains many uncertainties, including the human influence on land-based water storage[26], and relies on a significant (0.2 mm yr^{-1}) unmeasured deep-ocean temperature component[24]. It may never be possible to determine the steric contribution to twentieth century sea-level change to the same accuracy as can be achieved with the measurement system now in place, but it remains important to understand better the magnitudes and error budgets of the various processes that contributed to sea-level change during this period.

Few direct observations of ice-mass flux into the oceans exist for the pre-satellite era. One indirect method of estimating the polar mass contributions is to use regional variations in the sea-level response to ice-mass change ('fingerprinting'; see Box 1). Initial applications of this method inferred a sea-level trend from Greenland water flux of 0.35 to 0.6 mm yr^{-1} (refs 27, 28). Unfortunately, steric and dynamical ocean-level changes are significantly larger than the ice-induced signal in most areas[29] and so should be removed using a combination of ocean models and available data. Such a combination is available for the satellite altimeter period[30], but for earlier periods this procedure is more speculative. Although, the improved ocean-temperature time series produces less decadal variability in sea level owing to the thermosteric process[11,24] (thus reducing the discrepancy between observations and climate models[31,32]), there are still significant unexplained signals in total sea-level variability. There is a need to assess how much of the dynamical signal can be explained by realistically forced ocean models, beyond the regional analysis of simplified models[33,34], and to consider the dynamical as well as the gravitational and isostatic response to melting ice[35].

An influential paper by Munk[36] reviewed the status of closure in the sea-level budget for the twentieth century and reached a number of conclusions. One of these, based on observations and model predictions of changes in Earth's rotation, limited the melt contribution from the two ice sheets. The lack of closure led Munk to coin the term 'sea-level enigma' as there was no clear solution at that time. The identification of an error in the standard theory of polar motion of the Earth, together with a reassessment of the error bounds on constraints placed by measurements going back to 1979, has shown that geodetic constraints on ice melt over the pre-GRACE period are weaker than previously thought[37]. This result provides a solution to the 'enigma' by broadening the uncertainty on the contribution of ice melt to twentieth century global mean sea-level rise.

Vertical land motion can introduce highly localized signals to tide-gauge records (tide gauges measure motion of the sea surface relative to the land). One way to reduce the impact of land motion on estimates of global mean sea-level rise in the twentieth century is to measure directly the land motion component using the global positioning system and remove it to isolate the sea-surface height variation. A recent application of this method resulted in a decreased standard deviation of the corrected tide-gauge rates by 35% (ref. 38). The reduced estimate of global mean sea-level rise (1.3 mm yr^{-1}) offers another solution to the 'enigma'. The rates of land motion from the global positioning system are obtained from a relatively short times series (< 10 yr in general) and so this correction procedure may be less applicable in regions where the recent land motion might not represent that for the past 50–100 years (for example, those affected by frequent and large earthquakes, sediment compaction, large-scale mining and land reclamation).

Rates of sea-level change varied both spatially and temporally during the twentieth century (Fig. 2), and decadal rates of global sea-level rise show large variations throughout this period[39]. A number of recent analyses have studied sea-level accelerations and regional patterns of sea-level change[29,40,41], and have shown that regional differences, at least partly associated with ocean dynamical response to changes in atmospheric forcing, persist on multidecadal timescales. Thus, in certain locations, dynamical processes may have contributed significantly to the observed twentieth-century trend. The influence of these dynamical signals complicates the determination of a global mean acceleration from sea-level records longer than 100 yr. For this application, supplementing the tide-gauge data with sea-level data reconstructed from the geological record is highly beneficial. There is strong evidence that global mean sea-level rise has accelerated from a rate of centimetres per century in the past few millennia to decimetres per century in the twentieth century[42,43], but this acceleration does not appear to have been synchronous. High-resolution sea-level records from salt marshes in the North Atlantic[44,45] and New Zealand[46] (Fig. 2c) date this acceleration between 1880 and 1920. However, instrumental records[41] and other proxy records[47] demonstrate a regional non-synchronoeity of sea-level accelerations during the past two centuries. This non-synchroneity probably reflects the spatial variability of sea-level change owing to the influence of land-ice changes, ocean-temperature change and long-term ocean dynamics.

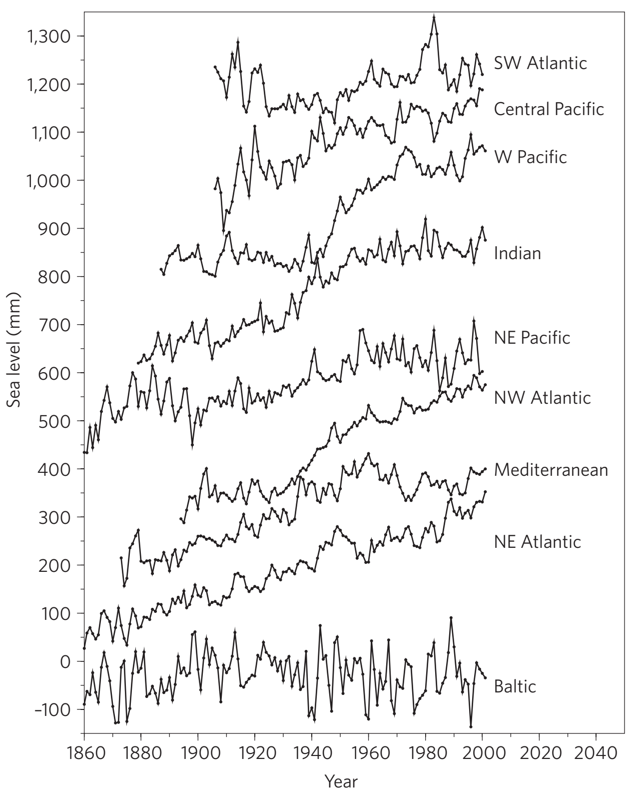


Figure 2 | Sea-level curves derived from tide-gauge data using the 'virtual station' method[95]. The robustness of each of the regional estimates varies both spatially, owing to the geographic distribution of the stations (with an inherent Northern Hemisphere bias present in the network), and temporally, owing to the changing number of stations (with a very limited number of records spanning the entire twentieth century). Each time series has been offset along the *y* axis by an arbitrary amount to avoid overlap. Adapted from ref. 41.

The past decade has seen the proposal and solution of an attribution problem in explaining the observed global mean sea-level rise for the twentieth century. At present, uncertainties in the observed global mean trend, as well as in the magnitudes of various contributing processes are large enough to account for any remaining imbalance. An important focus for future research is to understand better the observed temporal and spatial variability in sea-level change with respect to the underlying oceanographic and climatic processes.

The geological record

Observations of sea-level change during the past few hundreds to thousands of years are determined through the use of palaeoecological or morphological information in the geological record (see Table 1). Height and time precision of these records lie in the ranges of tens of metres to decimetres, and thousands of years to a few years, respectively. Spatial sampling is, in general, poor compared with the distribution of tide gauges, and the majority of the data span parts of the Holocene period only (10,000 yr ago to present), with a distinct paucity of data before the Last Glacial Maximum around 25,000 yr ago.

During the most recent glacial–interglacial transition (~20,000–7,000 yr BP) the rates and patterns of sea-level changes were dominated by the mass exchange between ice sheets and oceans, and its influence on the solid Earth and gravity field[48–50]. We note that, although there were large ocean-temperature changes during the most recent glacial–interglacial transition[51], the steric effect is likely to have been within data uncertainty in most regions (but this remains to be demonstrated). Figure 3 shows a selection of data that illustrates some of the spatial and temporal variability of the sea-level response to the ice–ocean mass exchange. At sites distant from major glaciation centres (Fig. 3a–c), sea-level change is dominated by the rate of global ice melt. The observed fall in sea level following the end of major melting (~7,000 yr BP; Fig. 3b) is due to isostatic processes[52]. A growing number of high-resolution records (Fig. 3c) detect an acceleration in sea level around AD 1850–1900 (refs 43–45). In regions once covered by large ice sheets (for example, Fennoscandinavia, Canada) crustal uplift dominates the response, leading to a monotonic sea-level fall (Fig. 3d). This signal can become relatively complex in adjacent areas (Fig. 3e) owing to the interplay between local isostatic and global meltwater signals.

Sea levels in mid-to-low latitudes rose, on average, at a rate of ~1 m per century (Fig. 3a), with this rate increasing to ~4 m per century during periods of exceptionally rapid melting that lasted only a few centuries[53,54] (Table 1). Of course, these rates must be interpreted carefully when attempting to place a bound on possible rates of future rise as they occurred when there was 70% more grounded ice on Earth, a significant portion of which was located on continental shelves and therefore inherently unstable. A recent study combining field evidence of ice-margin retreat, palaeoclimate observations and modelling has argued that mass loss from the Laurentide ice sheet dominated global melting in the early Holocene and that the rates of low-latitude sea-level rise measured during this period (about 1 m per century) are plausible in the twenty-first century owing to the response of the Greenland ice sheet to predicted warming[55].

More direct analogues for the response of the present ice sheets to future warming can be found by considering past and present interglacial periods when ice extent was similar to that at present. During the previous interglacial, global mean sea level is estimated to have been about 4 to 6 m higher than at present in response to elevated temperatures sustained over a few millennia[56]. Studies have indicated that significant volume reductions of both the Greenland[57,58] and West Antarctic ice sheets[59,60] were largely responsible, and that rates of sea-level change during this period may have

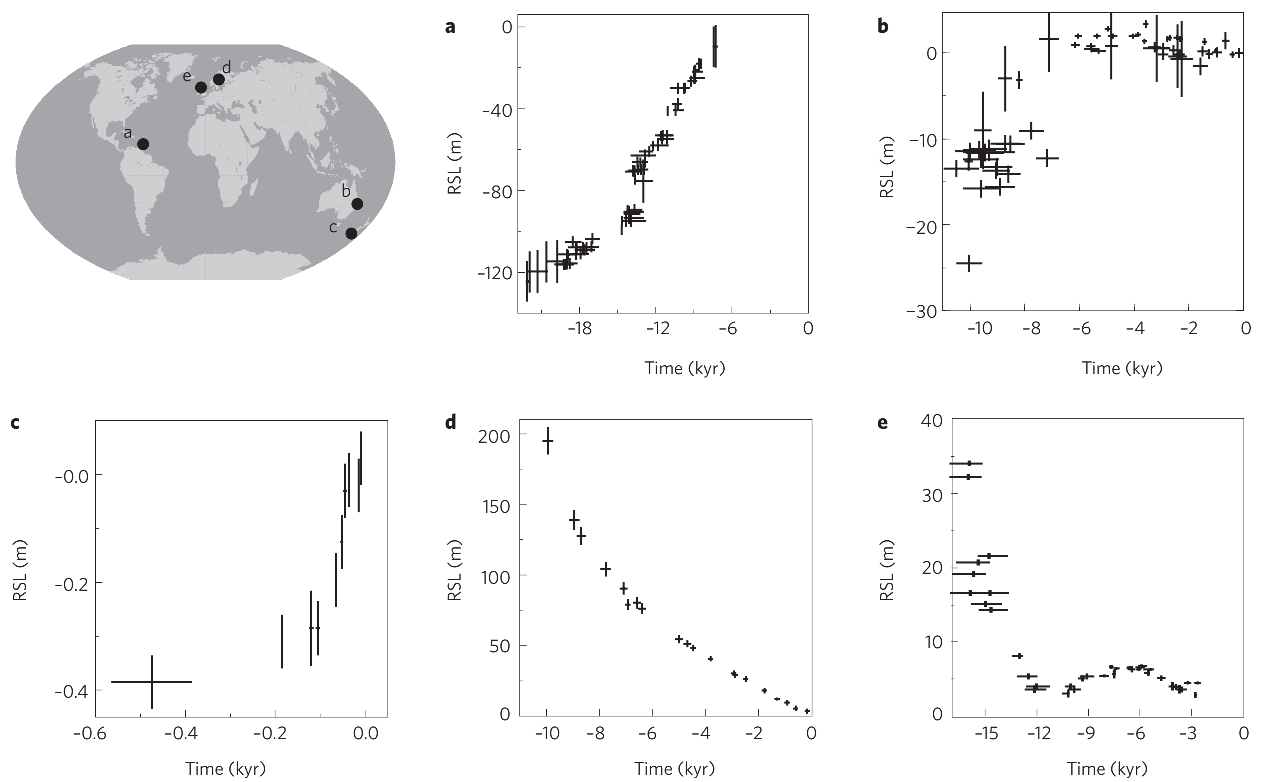


Figure 3 | Relative sea level (RSL) reconstructed from the geological record at the five localities shown in the inset. a, Barbados[53,91]; **b**, Cleveland Bay, Australia[96]; **c**, Pounawea, New Zealand[46]; **d**, Angerman River, Sweden[97]; **e**, Arisaig, Scotland[93]. These data were chosen to illustrate the spatial and temporal variation in sea-level change during and following the most recent glacial–interglacial transition and the typical time and height precision obtained using the most common reconstruction methods. Note that, at most sites, the data span different time periods.

reached values exceeding 1 m per century[6,60]. During the early to mid-Holocene, the Greenland ice sheet was subjected to temperatures about 2 °C higher than present values[61] (compared with ~5 °C during the previous interglacial[58]). The response of the ice sheet to this more modest forcing appears to have been a few decimetres of ice-equivalent sea-level change[62,63] with rates of melt on the order of 1 cm per century.

During the mid- to late Holocene, subsequent to the complete disintegration of ice sheets in North America and Eurasia by ~7,000 yr BP, the magnitude and rates of ice melting have been relatively small. Sea-level records from mid-to-low-latitude locations (for example, Fig. 3b), when corrected for isostatic effects, indicate about 3 m of ice-equivalent sea-level change between approximately 7,000 and 3,000 yr BP. There is some disagreement on the timing of the end of ice melting[64,65], which probably reflects differences in model parameterization and data precision. The IPCC[65] allows for up to 0.4 m of ice-equivalent sea-level rise since 2,000 yr BP, but considers it more likely that this value has been zero (within data error bounds) from this time until the acceleration to modern rates. This is corroborated by archaeological data from the Mediterranean region[66].

Much of the melt in the mid- to late Holocene has been attributed to the Antarctic ice sheet[67]. This proposal is supported by evidence for contributions of only a few decimetres from the Greenland ice sheet[68–71] and small glaciers[56] during this period, and is also consistent with a growing body of data from Antarctica. Das and Alley[72] documented a change towards a more maritime climate in West Antarctica in the late Holocene, which led to considerable ice retreat in Marie Byrd Land[73] and the Amundsen Sea embayment[74]. Using an ice-load model of the Antarctic ice sheet constrained by field evidence of past ice extent and contemporary mass-balance measurements, Ivins and James[75] estimated that the ice sheet has contributed ~4 m to global mean sea-level rise since ~7,000 yr ago, with the majority of this delivered by ~3,000 yr ago.

Sea-level observations for the mid- to late Holocene provide constraints on the natural variability of sea-level change immediately preceding the industrial revolution. These data indicate that local rates were generally at the 1–10 cm per century level (see Table 1). For example, high-resolution records based on salt-marsh stratigraphy[76] and microatolls[77] show that regional short-term fluctuations did not exceed 0.2 m per century during the middle and late Holocene, including the Medieval Climatic Optimum[78,79]. (We note that these rates are an order of magnitude lower than rates of ice-equivalent sea-level change inferred for some previous interglacial periods using oxygen isotope records[5,6].) In most studies, the observations have been interpreted in terms of vertical land motion and/or land-ice contributions to sea-level change. However, the contributions from steric changes and long-term ocean dynamics may be significant in some areas. For example, during the past 8,000 years, sea surface temperatures determined from proxy records indicate changes of several °C in magnitude — with some regions experiencing a distinct warming and others a cooling[80].

Reconstructions of past sea-level changes demonstrate that the sea-level response to changes in ice sheets has a high degree of spatial and temporal variability over century to millennial timescales. Rates of rise on the order of metres per century sustained over several centuries have occurred in the past during major deglaciation events. Whether such rates can be achieved with the current configuration of ice sheets, as suggested by oxygen isotope data from the last interglacial[6], remains an important question for future research.

Towards improved predictions of future sea-level change

A tightly constrained prediction of sea-level change in the coming decades to millennia requires knowledge of the climate forcing and

Table 1 | Methods of sea-level reconstruction over various timescales, and the time and height precision associated with each. The maximum rate of sea-level rise is given for each time period and reconstruction method (note that rates have been corrected for land motion).

Time period (kyr BP)	Sea-level indicator	Chronology	Maximum resolution (yr)	Estimated vertical precision (± m)	Maximum rate (m per century)	Example studies
0–470	Oxygen isotopes	AMS ^{14}C, palaeomagnetism, tuning	200	12	2.5	Refs 6, 88-90
0–30	Corals	U/Th	400	5	4	Refs 53, 91
0–20	Sediment facies, microfossils	AMS ^{14}C	200	3	4	Refs 54, 92
0–16	Isolation basin stratigraphy	AMS ^{14}C	200	0.2–1.0*	n/a	Ref. 93
0–10	Basal peat	AMS ^{14}C	200	0.2–0.5*	0.2	Ref. 76
0–7	Microatolls	^{14}C	200	0.1–0.2*	0.2	Ref. 77
0–7	Biological indicators on rocky coasts	^{14}C	200	0.05–0.5*	0.1	Ref. 94
0–2	Archaeology	Historical documentation	100	0.1–0.5*	0.1	Ref. 66
0–0.5	Salt-marsh microfossils	AMS ^{14}C, ^{210}Pb, ^{137}Cs, Pb isotopes, pollen, chemostratigraphy	20	0.05–0.3*	0.2	Ref. 46

* indicates uncertainties that are tidal-range dependent. Some methods quantify the error on inferred past sea levels by analysing the distribution of flora and fauna within the tidal zone and so the estimated uncertainty is less in areas with a smaller tidal range. AMS, accelerator mass spectrometry.

an ability to calculate accurately the sea-level response to this forcing. The uncertainties in both of these elements are reflected in the spread of global mean sea-level projections offered in the most recent IPCC report[2]: 0.18–0.59 cm between 1980–1999 and 2090–2099.

Although 70–75% of the IPCC projected rise is due to ocean-temperature change, the influence of ice dynamical changes is identified as a major source of uncertainty. Ongoing and future efforts to improve understanding of the processes that control ice discharge in the large ice sheets and marine-terminating glaciers will have a central role in constraining better the land-ice contribution to sea level over the twenty-first century. Sea-level changes reconstructed from the geological record can provide useful constraints on upper limits of ice melt, particularly when combined with additional observational and modelling constraints to isolate the climatic conditions and ice sheet(s) responsible for a given rate of rise[55,81]. Sea-level and climate records for previous interglacial periods are of particular interest given the similar ice extent and temperatures of present-day conditions (although forcing factors, such as insolation and CO_2, may differ). The high rates of sea-level change interpreted from oxygen isotope records[5,6] are certainly troubling and warrant further investigation, particularly through the use of more precise proxy methods.

If spatial variability in sea level were to be included in sea-level projections for the twenty-first century, the spread in possible values, which would be defined for a specific region or locality, would probably be significantly different than that for the global mean. For example, a recent study concluded on a sea-level rise of 30–80 cm by 2100 in northwest Europe[82]. It is possible that in specific areas, the upper bound could be significantly higher owing to, for example, land subsidence[83], ocean dynamics[84], and gravitational and rotational changes due to ice melting[85]. Even though producing regional projections of sea-level change is considerably more challenging, it must be a focus of future research given the large spatial variability in past changes.

It has become clear from satellite altimetry that steric and dynamic changes have dominated spatial variability in the past few decades and so will probably continue to do so in the twenty-first century. Although future projections of this component are converging, there remains significant discrepancy at the regional scale[2]. It is critical to maintain the current level of observational control (both satellite and *in situ* systems) to test and calibrate the models over decadal and longer periods. In addition, devising more sophisticated combinations of geodetic and oceanographic data, as well as correctly accounting for temperature sampling errors, will result in more rigorous testing of current models.

Advances in our understanding of the causes of past and present sea-level change have been remarkable in the past decade and this progress continues unabated[86,87]. The rich observational database made available through satellite monitoring has had a central role in the rate of progress. Our understanding of the causes of sea-level changes in the late 1900s and early 2000s will continue to grow as time series lengthen and methods of analysis improve. Observations of the sea-level response before the satellite era from both tide gauges and proxy methods provide the length of time series necessary to isolate and interpret the climate component and place the more recent changes in context. Even though current uncertainty on global mean and regional sea-level change for the twenty-first century is at the metre level, this will no doubt improve in the coming years assuming that observational initiatives are supported.

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