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Two Millennia of Sea Level Data: The Key to Predicting Change

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Sea level reconstructions spanning the late Holocene (the past 2000 years) provide a preindustrial context for understanding the patterns and causes of contemporary and future change. The Intergovernmental Panel on Climate Change (IPCC) assumed that global sea level change during the past two millennia (prior to the middle of the nineteenth century) was close to zero [*Bindoff et al.*, 2007], but understanding of late Holocene sea level variability is limited. Glaciers and ice sheets changed significantly in size during this period, and therefore sea level likely oscillated on the order of several decimeters. In addition, ocean dynamics, solid Earth movements, steric (density) changes, and gravitational effects contributed to complex regional patterns of sea level change.

Unraveling this regional variability and determining the various contributing sources to past global sea level change will help to improve contemporary understanding and future predictions of sea level change and ice-ocean mass flux. Thus, a close look at the past 2000 years of sea level history may help reveal useful lessons for improving future sea level predictions.

Causes of Sea Level Change During the Past 2000 Years

On any given coastline, relative sea level changes occur as a result of local, regional, and global processes. Examples of local processes are tidal range changes and sediment compaction. Regional processes are dominated by vertical land motion (isostatic and tectonic). Global processes include ocean basin volume change and exchange of mass between oceans and continental ice sheets and glaciers. A slow increase in ocean basin volume due to glacial isostatic adjustment (GIA), a process triggered by the rebound of the Earth following the melting of ice sheets that covered much of North America and Europe during the last glaciation, causes sea level to fall around most of the globe at a rate of about 0.3 millimeter per year [*Gehrels*, 2010]. The contribution of global ice melt during the past 2000 years is less well constrained but is assumed to be close to zero by GIA models [*Milne et al.*, 2009] and 0.0–0.2 millimeter per year by the IPCC's fourth assessment report [*Bindoff et al.*, 2007]. Accurately estimating this rate has far-reaching implications because it provides a benchmark against which rates of sea level rise measured by tide gauges and satellites can be compared.

Proxy-based reconstructions of late Holocene climate show considerable regional and temporal variability. It is likely that global sea level (through ice melt) and regional sea level (through steric processes) varied around the zero long-term baseline in response to climate changes, for example, during the Medieval Warm Period (~900–1300 C.E.) and the

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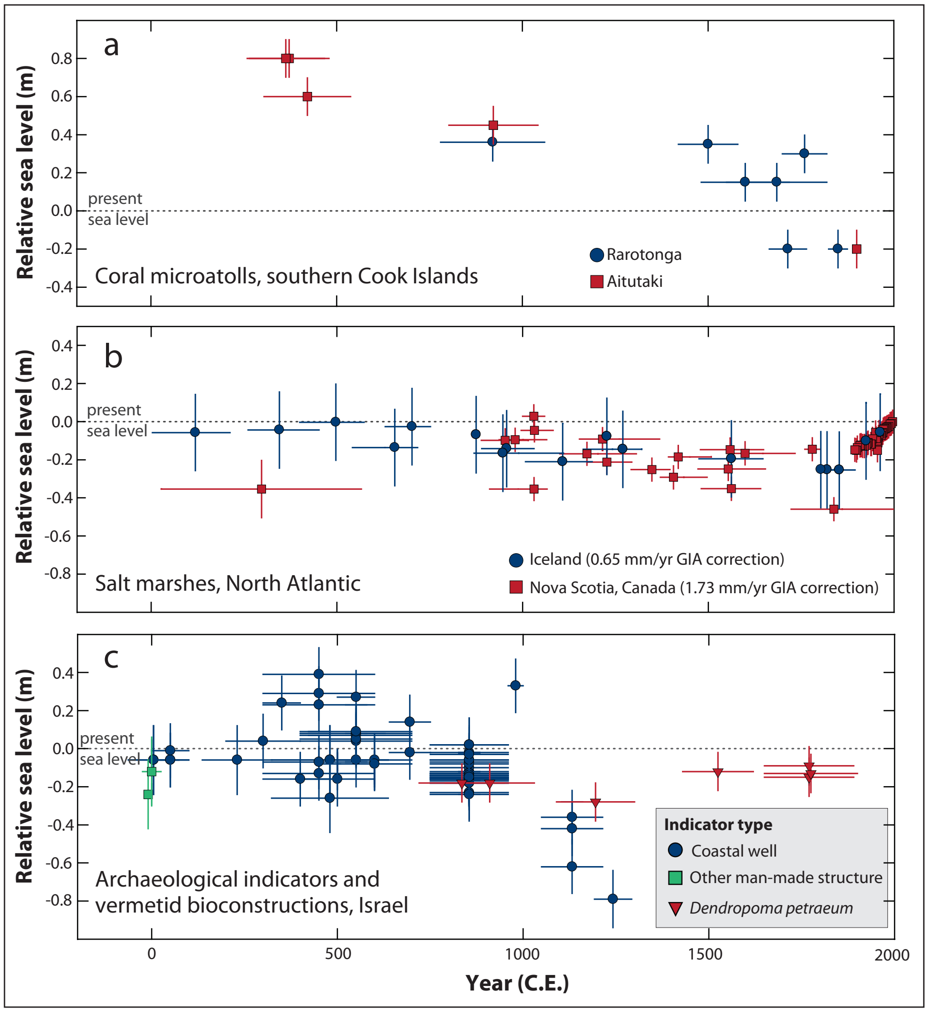

*Fig. 1. Examples of proxy sea level reconstructions spanning the past two millennia. (a) Coral microatoll records from the South Pacific [*Goodwin and Harvey, *2008]. (b) Salt marsh records from Iceland [*Gehrels et al., *2006] and Nova Scotia, Canada [*Gehrels et al., *2005]. The effects of glacial isostatic adjustment (GIA) have been removed from these records. (c) Sea level record from the Mediterranean coast of Israel [*Sivan et al., *2004, 2010;* Anzidei et al., *2011;* Toker et al., *2011] based on archaeological structures and analysis of vermetid (*Dendropoma petraeum, *a mollusk) colonies.*

Little Ice Age (LIA; ~1500–1850 C.E.). The Greenland Ice Sheet and many Northern Hemisphere glaciers grew during the late Holocene "Neoglacial," which lasted until the end of the LIA [*Alley et al.,* 2010]. Mountain glaciers in many regions advanced in the past 2000 years and reached their maximum extent during the LIA. Similarly, field evidence from Antarctica shows that the two most recent ice advances occurred around 2000 years ago and less than 700 years ago [*Hall,* 2009]. In contrast, the West Antarctic Ice Sheet thinned throughout the late Holocene—in Marie Byrd Land alone, thinning was equivalent to 0.2–0.3 meter of global sea level rise [*Stone et al.,* 2003].

Sea Level Reconstructions From the Past Two Millennia

Contemporary observations of changes in the sizes of glaciers and ice sheets made by the Gravity Recovery and Climate Experiment (GRACE) demonstrate the relevance of a late Holocene context and the importance of robust sea level reconstructions [*Bentley,* 2010]. GRACE measures the distribution of mass on Earth's surface. However, it is unable to distinguish directly between gravitational changes produced by changing ice volume and those caused by GIA. Corrections to compensate for GIA are therefore critical, but they can be as large as the ice-ocean mass flux signal itself [*Cazenave et al.,* 2009], making it difficult to isolate the meltwater contribution to sea level rise.

Late Holocene relative sea level reconstructions provide one of the few reliable means to infer GIA beyond the instrumental period, as seen in the three examples of sea level reconstructions spanning the past 2000 years shown in Figure 1. The records are from coasts that are tectonically stable and are based on the four types of proxy archives (coral microatolls, salt marsh sediments, archaeological indicators, and vermetid (mollusk) bioconstructions) that are best capable of capturing submeter-scale relative sea level changes.

Coral microatolls—colonies of corals with a raised rim surrounding a lower, dead surface—are accurate indicators of former sea level because the growth of living coral occurs close to mean low water. Analyses of South Pacific microatolls [*Goodwin and Harvey,* 2008] show slowly falling sea levels during much of the past 2000 years (Figure 1a). In addition, two lowstands of sea level in the past 400 years were separated by a highstand at around 1750 C.E., indicating centennial-scale sea level oscillations.

Salt marsh sediments record former sea levels because marsh surfaces accrete vertically in response to the frequency and duration of tidal inundation. The salt marsh–based sea level reconstructions are precise to within a tenth of a meter [*Milne et al.,* 2009]. Salt marsh data from western Iceland and Atlantic Canada [*Gehrels et al.,* 2005, 2006] are consistent when adjusted for GIA and show stable sea levels between 0 and 1000 C.E. (Figure 1b). During the past millennium, sea levels fell slowly, reaching a lowstand in the eighteenth or nineteenth century, before rapidly rising to present levels.

Archaeological indicators and vermetid bioconstructions (Figure 1c) have been used to reconstruct sea levels along the coast of Israel to within a tenth of a meter or better [*Sivan et al.,* 2004, 2010; *Anzidei et al.,* 2011; *Toker et al.,* 2011]. *Dendropoma petraeum* is a vermetid that constructs reef-like structures on rims of rocky abrasion shore platforms in the upper part of the subtidal zone. Data from Israel (mainly from archaeological sites) demonstrate that the sea rose to its present level about 2000 years ago, similar to other regions in the Mediterranean [*Lambeck et al.,* 2004]. A possible relative highstand (less than 0.5 meter above present sea level) between 300 and 600 C.E. was followed by sea levels lower than the present level (–0.3 to –0.8 meter) during the thirteenth century. Since the late eighteenth century, sea level on the Israeli coast has risen by at least 0.2 meter.

When the records are compared, they all show tendencies for falling sea level during much of the past millennium, in agreement with trend hindcasts by some semiempirical models [*Grinsted et al.,* 2010]. Differences on millennial timescales can be attributed to GIA. However, the records also show considerable differences when examined on centennial timescales. This is an important observation, which can be due to a number of factors. First, meltwater inputs from different sources create spatially variable patterns and magnitudes of sea level change caused by the decreasing gravitational pull that a melting ice mass exerts on the ocean surface, an effect less noticeable farther from the ice [*Mitrovica et al.,* 2001]. Second, regional variability is generated by steric effects and ocean dynamics [*Milne et al.,* 2009] including El Niño–Southern Oscillation (ENSO) processes in the South Pacific and changes in the strength of subtropical gyres in the North Atlantic. Steric effects are density changes associated with changing temperature and/or salinity of surface and intermediate waters, which are susceptible to decadal-scale climatic processes such as ENSO and the North Atlantic Oscillation. Third, like all paleoenvironmental studies, sea level reconstructions are subject to intrinsic uncertainties and limitations associated with the type of proxy and dating method used.

There is one late Holocene sea level "event" that appears to be global in character and that unequivocally represents a significant departure from late Holocene trends. This is the rapid rise that has characterized global sea level change in the 20th and 21st centuries [*Kemp et al.,* 2009; *Gehrels,* 2010]. It is best captured by salt marsh proxy records, due to their ability to provide continuous records up to the present day, but can be recognized elsewhere because of differences between rates estimated from late Holocene sea level reconstructions and rates measured by nearby tide gauges. The onset of the rapid rise has been dated to the end of the nineteenth or the beginning of the twentieth century. The latter is in agreement with long tide gauge records [*Woodworth et al.,* 2009], but variability is evident in both the magnitude and timing of the change, in proxy as well as instrumental data. More proxy sea level reconstructions are needed to bridge the gap between instrumental records and millennial-scale sea level reconstructions.

Lessons From Past Data

Several lessons can be drawn from global sea level patterns during the past two millennia. First, sea level change attributed to melting ice from 0 to 1000 C.E. was close to zero, but proxy sea level data from various regions appear to record a slowly falling sea level during much of the past millennium. Second, ongoing sea level rise represents a significant departure from late Holocene trends and began during the late nineteenth or early twentieth century. The preceding global sea level fall implies that the change to modern rates of sea level rise was greater in magnitude than assumed by the IPCC, which considered a rate of 0.0–0.2 millimeter per year for the past 2000 years and a rate of about 1.7 millimeters per year for the twentieth century. Third, proxy sea level observations can improve GIA models. These models are used to estimate rates of isostatic land motion and are critical in assessing contemporary and future changes of the cryosphere (through GRACE) and local relative sea level.

Finally, regional sea level variability must be captured by climate models if there is to be any expectation that these models can accurately predict future sea level change. Herein lies a big challenge for future work. Single values of the magnitude of future global sea level rise are of little practical use for agencies concerned with defending coasts against future flooding. To obtain a better understanding of future sea level change, projections must take into account all known processes that contribute to patterns of relative sea level change at local to regional scales.

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