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Ice Volume and Sea Level During the Last Interglacial

A. Dutton[1,2]* and K. Lambeck[1,3]

During the last interglacial period, ~125,000 years ago, sea level was at least several meters higher than at present, with substantial variability observed for peak sea level at geographically diverse sites. Speculation that the West Antarctic ice sheet collapsed during the last interglacial period has drawn particular interest to understanding climate and ice-sheet dynamics during this time interval. We provide an internally consistent database of coral U-Th ages to assess last interglacial sea-level observations in the context of isostatic modeling and stratigraphic evidence. These data indicate that global (eustatic) sea level peaked 5.5 to 9 meters above present sea level, requiring smaller ice sheets in both Greenland and Antarctica relative to today and indicating strong sea-level sensitivity to small changes in radiative forcing.

Forecasting the nature of future sea-level rise requires an understanding of potential ice-sheet instability under sustained global warming conditions. One approach to elucidate ice-sheet behavior during warm climate periods is to investigate geologic records during periods when the size and configuration of the cryosphere was largely analogous to that of today (*1*).

The last interglacial period (LIG)—also known as marine isotope stage (MIS) 5e, MIS 5.5, or the Eemian stage in Western Europe (*2*)—is a clear choice for such a study because there are more empirical data than for any prior interglacial period. The LIG is usually described as having a eustatic sea level (ESL) some +4 to 6 m higher than today (*3*, *4*) and with a global mean temperature that was similar or perhaps slightly warmer than the preindustrial state (*5*–*7*). In contrast, a recent study suggested that ESL was in fact significantly higher, peaking between +6.6 and 9.4 m (*8*). The difference between ESL at +4 and ESL at +9 m higher than present is important: The former can be largely accounted for through thermal expansion of seawater, loss of mountain glaciers, and partial loss of the Greenland ice sheet, but higher levels require a contribution from Antarctica (*9*, *10*).

The focus of this Report is twofold: one, to present a new global database of U-Th ages and elevations of fossil LIG corals and, two, by correcting this record for contributions from the glacio-hydro-isostatic process during glacial cycles, to establish an independent estimate of ice volumes during the LIG compared with the present. We have compiled and normalized age-elevation data of LIG fossil corals into a database containing 711 U-Th measurements from 16 sites around the globe, six of which are considered tectonically stable (Fig. 1) (database S1) (*11*). To interpret these data, we provide insight into how deformations of Earth's solid surface and gravity field in glacial-interglacial cycles influence the position of the LIG shorelines that are observed today. This analysis highlights the difference in observed sea level at field sites around the globe versus the eustatic sea-level signal that primarily reflects changes in the volume of land-based ice. We argue that glacial isostatic adjustment is a critical element in assessing field observations of LIG sea level and cannot be ignored when discussing the observed differences reported between sites.

Resolving the magnitude and timing of maximum sea level during the LIG requires well-dated sea-level markers and an appreciation of the processes that produce changes in sea level relative to land. One common approach is to use elevations of LIG corals that grow near the sea surface, which can potentially be extremely accurately and precisely dated by using U-series geochronometry (*12*, *13*).

The primary strength of coral-based sea-level reconstructions is their potential to deliver an extremely well-resolved record with respect to both time and elevation, whereas the principal weakness lies in paleodepth uncertainties of the corals and in the geochemical alteration of skeletal aragonite. Thus, coral age-elevation data provide a minimum estimate of sea-level position, with some uncertainty in absolute age that is related to ambiguous effects of diagenesis or variability in seawater uranium isotope composition (δ^{234}U) through time (*13*).

Coral U-Th data from uplifting sites are valuable because multiple oscillations in sea-level rise are expressed geomorphically as different terraces, whereas in tectonically stable areas overprinting and reworking during prolonged sea-level highstands will often mask oscillations. However, it is not possible to reconstruct the precise absolute elevation of LIG sea level by using coral U-Th data from uplifting sites, because assumptions about the magnitude and constancy of uplift rates become a substantial source of uncertainty when extrapolating back in time. An additional confounding factor is that tectonically active sites have uplift or subsidence rates that are calculated on the basis of assumptions about LIG sea-level timing and position—hence, the argument can become circular. However, rapid oscillations in ESL can be inferred from geographically widespread observations including uplifted sites, and in fact global prevalence of sea-level oscillations is a prerequisite before "real" ESL or ice-volume oscillations are invoked.

The best ESL indicators are from tectonically stable localities that are geographically distant, or far field, from former ice-sheet margins (*14*). Although it has been common practice to equate sea-level observations from far-field sites to glacio-eustatic changes in sea level, even far-field sites are sensitive to glacio-isostatic processes that cause local, or relative sea level (RSL), observations to depart significantly from the ESL curve during both the Holocene (*14*, *15*) and the LIG (*16*). In the following discussion, we first examine how RSL differs from ESL because of the glacio-hydro-isostatic process and then combine this knowledge with the observational record to interpret maximum ESL during the LIG (*11*).

LIG and earlier interglacial shorelines above or below present sea level have been attributed to differences in polar ice volumes compared with

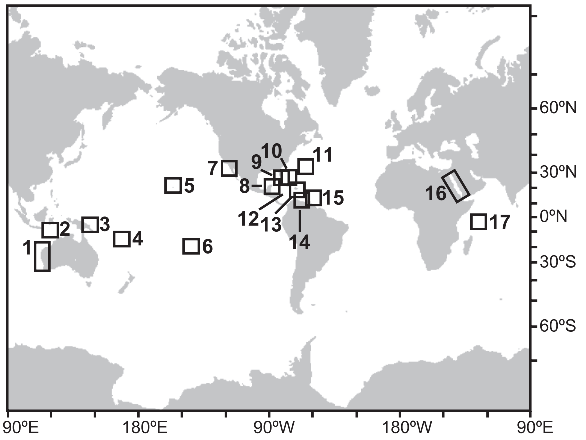

Fig. 1. Geographic distribution of LIG reefs in our coral U-Th database. Localities are as follows: 1, Western Australia; 2, Sumba Island, Indonesia; 3, Huon Peninsula, Papua New Guinea; 4, Vanuatu; 5, Oahu; 6, Mururoa Atoll, French Polynesia; 7, California/Mexico coast and islands; 8, XCaret, Yucatan; 9, Florida Keys; 10, Bahamas; 11, Bermuda; 12, Jamaica; 13, Haiti; 14, Curaçao; 15, Barbados; 16, Red Sea coast; 17, Seychelles (granitic islands). Coral U-Th data sources are listed in database S1.

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today, vertical tectonic movement, residual isostatic response to previous and subsequent ice loads, or a combination of these processes depending on the locality. The +4- to 6-m benchmark for LIG sea level has been widely held as a de facto ESL and used as an indicator for establishing tectonic stability at sites around the globe (e.g., *3, 17, 18*). This approach is not valid because LIG sea-level position and timing, like their Holocene counterparts, can be expected to vary between locations depending on the position relative to former and subsequent ice sheets and the response to isostatic adjustments to ice and water loading and gravitational effects (*16*, *19*). In other words, the elevation of peak LIG sea level seen today is not expected to be the same across Earth's surface, nor will the timing of peak sea level be synchronous.

Glacio-hydro-isostatic effects include the deformation and gravitational and rotational responses of the solid earth and ocean surfaces to changes in ice and water loads. In regions proximal to large ice sheets (near- to intermediate-field sites), changes in ice loading dominate the isostatic signal. For example, along much of the United States. Atlantic coast and across the Caribbean, the unloading of the North American ice sheet results in a slowly rising sea level, superimposed on the eustatic change, throughout the interglacial until the onset of the next phase of glaciation, mainly because of subsidence of a broad peripheral bulge in Earth's surface that developed around the ice sheet during the preceding glacial period (Fig. 2B).

At far-field sites, the change in water load dominates the shorter wavelengths of the spatial pattern of sea-level change because, in a first approximation, the ocean floor loading during the deglaciation phase depresses the sea floor relative to the continent. Therefore, in the absence of any changes in ice volume during an interglacial period, far-field, continental coastal sea levels will fall. In this instance, a small-amplitude highstand develops at the time melting ceased and decays by a few meters during the interglacial period (Fig. 2A).

Sea-level observations from geologic archives measure past positions of sea level relative to present sea level. However, the elevations of paleoshorelines—including those of the LIG—will continue to evolve because the relaxation of the mantle to the last glacial cycle is not yet complete (*19*). At sites near field to the last glacial maximum ice sheets, for example, sea levels will continue to rise into the future, so that at some later time the LIG shorelines seen today will be seen at a lower elevation. At far-field sites, present sea level will continue to fall (in the absence of other processes), and presently raised LIG reefs will appear at higher elevations even though no additional water has been removed from the oceans. Thus at neither near- nor far-field sites is there a simple relation between observed sea levels and ice volumes during interglacials: The actual relation requires knowledge of the ice sheets before, during, and after the interglacial; of Earth's rheological response to the ice-water loads; and of the evolution of the ocean basin shape during the glacial cycles (*19–21*).

To approximate the magnitude of the isostatic and gravitational effects, we used a reference ice model in which grounded ice volumes during the LIG are set constant and equal to present ice volume for the duration of the period (*11*, *22*). The predicted LIG RSL curves have several notable characteristics (Fig. 2). The first relates to the different character of sea-level response at different sites. In particular, for the reference ice model (see ESL curve in Fig. 2, A to C) a highstand is predicted to occur early in the interglacial at far-field localities, whereas in the near field it occurs at the end of the interglacial. Thus, if observational data from the Yucatan and Western Australia (WA) were plotted on the same diagram without correcting for the differences in isostatic response, the resulting curve would show two peaks (Fig. 2C). Therefore, if RSL data from multiple sites have not been corrected for isostatic contributions, their superposition can result in synthetic sea-level oscillations that misrepresent the ESL history.

The second notable feature relates to the timing when sea levels first reach present-day sea level. At the far-field sites, this occurs earlier, by 3 to 4 thousand years, than at sites in the near field, and considerable variation can also occur between far-field sites depending on their positions relative to the principal ice sources and on the coastline geometry.

A third characteristic illustrated by the forward model is the gradient of the LIG highstand across the Caribbean (Fig. 2B), which is similar in behavior to the observationally better-constrained Holocene sea-level rise along the United States. Atlantic coast (*23*). The amplitude and gradient of this sea-level pattern are critically dependent on the adopted North American ice sheet for the two glacial cycles, with the average

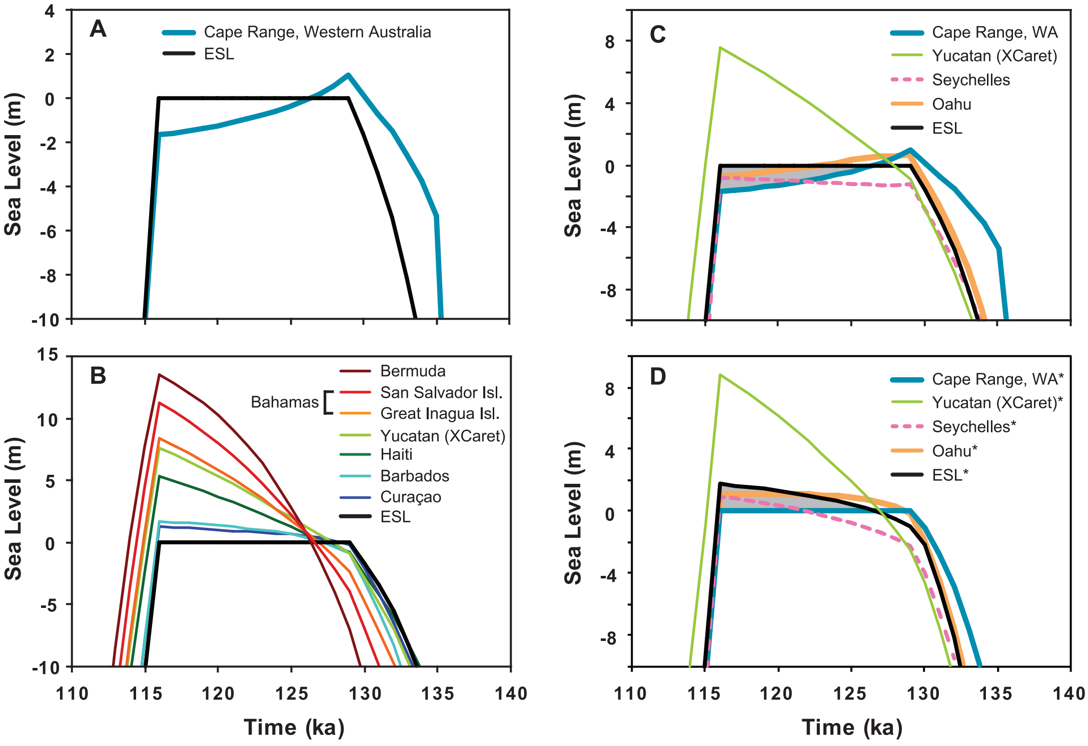


Fig. 2. RSL predictions during the LIG for (**A**) Cape Range, Western Australia, (**B**) several sites across the Caribbean-Atlantic region, and (**C** and **D**) several disparate sites display the differences in timing and magnitude of RSL (colored lines) compared with ESL (heavy black line). ESL is set equal to zero (present sea level) for the duration of the LIG in this forward model in all cases except (D), where the ESL function is defined to have a gradual increase during the LIG (denoted by asterisks), similar to the pattern seen in the Holocene. Gray shaded areas in (C) and (D) are the magnitude of the sum of the isostatic and gravitational effects at Cape Range that cause RSL to depart from the ESL curve. ka, thousand years ago.

elevation of LIG sea level at any site providing primarily a constraint on the last glacial maximum ice volume and the rate of RSL change providing a constraint on the MIS 6 ice sheet. The latter remains poorly understood; hence, data from this area do little to constrain LIG ESL unless the knowledge of the ice-sheet history can first be improved. The present disparity between the maximum predicted RSL in our forward model and maximum LIG observations in this region indicates that modification of the MIS 2 and/or MIS 6 ice sheet will be required to bring the model in line with the observations. Fortunately, the far-field sites are not sensitive to the distribution of ice volume between the various ice sheets, allowing us to place reasonable constraints on maximum LIG ESL by using the existing ice model.

The nature of these predicted RSL patterns provides the necessary context to evaluate the geochronological data. Synthesis of U-Th data for fossil corals is complicated by a number of factors, including (i) the use of different screening criteria to accept or reject data, (ii) different decay constants used to calculate ages, (iii) inconsistent application of open-system models, (iv) uncertainty in the past uranium-isotope composition of seawater, (v) lack of stratigraphic information paired with geochronological data to interpret sea-level position, and (vi) the use of different sea-level benchmarks for elevation measurements. We have normalized our database for all these factors with the exception of (iv) and (v), the first of which remains ambiguous and the second we consider where enough information is provided.

Coral age-elevation data confirm the isostatic modeling predictions in that different sites display a variety of behaviors during the LIG sea-level highstand, including both stable and rising sea-level patterns (*24*) (Fig. 3). A pattern of rising RSL is expected in the Bahamas and the Yucatan even for the nominal scenario where ESL remains constant throughout the LIG (Fig. 2B). In fact, a progression toward younger ages with increasing elevation is observed in reef growth at both of these sites (*25*, *26*).

Evidence for rapid sea-level rise occurring late in the LIG rests largely on high notches observed in the Bahamas and Bermuda (*27*) and the presence of a second, higher LIG terrace that defines a back-stepping reef architecture in the Yucatan (*26*). The model results show that, even with no change in LIG ESL, a late peak is expected at these localities and that there is no need to invoke a rapid change in ESL or ice volume to explain these field observations (Fig. 2).

To determine the magnitude of peak LIG ESL, we combined model-derived corrections for the noneustatic component with observational data from tectonically stable, far-field localities where RSL is dominantly a function of ESL (*11*). Maximum elevations of in situ LIG corals at (assumed) tectonically stable sites indicate local sea-level positions ranging from +2 to 8 m above present (*28*) (Fig. 4). Consideration of elevation data from the only two sites in our database that are both far field and stable (WA and the Seychelles) along with the expected isostatic corrections translates to maximum ESLs of +5 and 9 m, respectively. These predicted ESL values have an associated

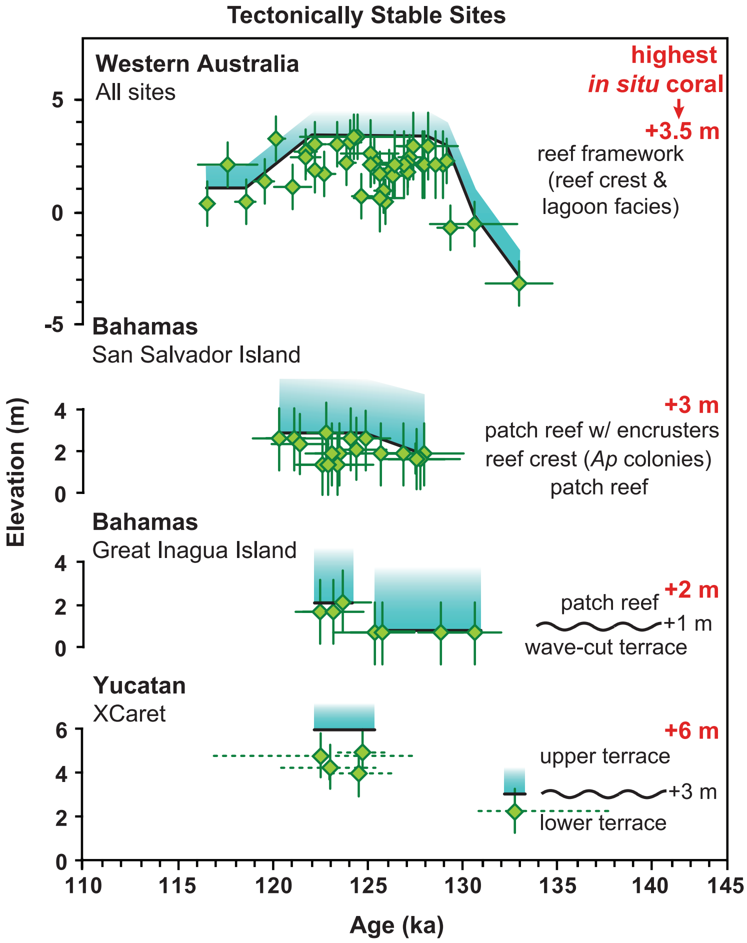
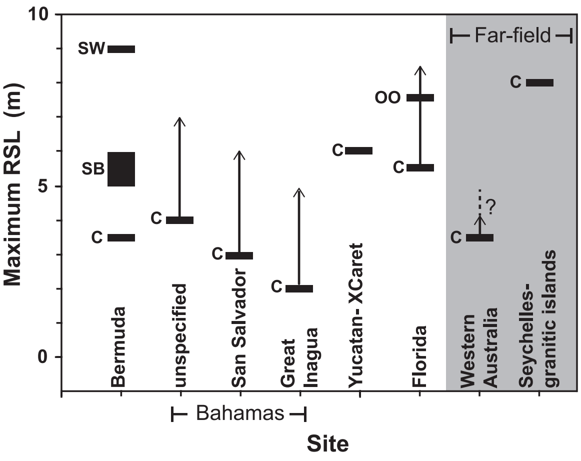


Fig. 3. RSL reconstruction based on coral elevations and U-Th ages (*16*). Closed-system ages for tectonically stable localities with five or more data points that pass the diagenetic screening process (*24*). Data are shown with 2σ errors except for the Yucatan data, which are plotted with error bars that span the range of ages on replicates from the same coral. Indicated sea-level curves (black line) reflect the simplest interpretations that are consistent with reef stratigraphy and existing geochronology. Blue shading indicates likely paleodepth of corals.

Fig. 4. Elevation of the highest in situ corals at all of the tectonically stable sites in our database along with associated sedimentary sea-level markers at these sites, where C indicates in situ coral; OO, oolite shoal; SB, subtidal facies; and SW, storm wash deposits. Arrows indicate paleodepth of corals as estimated in the original data sources; in Western Australia, we estimate a minimum paleodepth of 1 m because the modern reef crest remains unexposed at low tide. Gray shading highlights the only two sites far field from former Northern Hemisphere ice-sheet margins. Data sources are listed in database S1.



error of ±1.5 m that includes uncertainties associated with the ice and earth model parameters. The +5-m estimate from WA has its basis in LIG fossil reefs that outcrop discontinuously along some 1300 km of coastline at the same elevation, whereas it has not been independently established that the few closely spaced localities in the granitic Seychelles are indeed tectonically stable (*11*). We attribute part of the discrepancy in our maximum-elevation estimates from WA and the Seychelles to an underestimation in WA. The highest corals we surveyed there (+3.5 m) are planed off, implying that sea level may have easily reached +4.0 m (RSL), which translates to a +5.5 m ESL. In contrast, the highest in situ coral that we surveyed in the Seychelles was capped by an intertidal facies, suggesting that the coral grew right up to the sea surface and represents a maximum estimate of sea-level position. This result is remarkably similar to the +6.6- to 9.4-m range determined from a separate compilation of LIG sea-level markers by using a statistical analysis method to account for the role of isostatic effects (*8*) yet still leaves a considerable 3- to 4-m uncertainty on the elevation of peak sea level, highlighting the need for additional observations from far-field, tectonically stable sites.

The absolute timing of peak sea level during the LIG period remains uncertain because of the temporal resolution of the data as well as uncertainty in δ^{234}U of LIG seawater, which affects the interpretation of the U-Th ages regardless of whether closed-system ages or modeled open-system ages are used to define the chronology. Because the overall pattern in elevation for the closed-system U-Th data in Fig. 3 (i.e., relatively stable in WA and slightly increasing in the Bahamas and the Yucatan) will hold even if an open-system interpretation is invoked, we can infer that maximum sea level was more likely achieved during the latter portion of the sea-level highstand. This effect is apparent in Fig. 2D, where the isostatic effect is greater in WA at the end of the highstand, implying that a rising ESL is required to maintain or raise RSL at this site in the latter portion of the highstand.

Despite differences in the timing and elevation of LIG sea level at globally distributed fossil reefs, we have demonstrated that many of the different patterns observed in coral age-elevation data can provide a consistent interpretation of LIG sea level when the glacio-hydro-isostatic processes are quantitatively modeled. These latter processes are well understood and quantifiable for more recent times, but their magnitudes and rates are less certain for the LIG—particularly for the near-field sites under the influence of the North American ice sheet—because of the limited knowledge of the ice sheets during the preceding glacial maximum. Hence, to construct an ESL curve for the LIG, we suggest a strategy that uses the evidence from the far-field sites to estimate the ESL during the LIG and then uses the near-field sites as indicators of the MIS 6 ice-sheet parameters.

The two far-field locations for which accurately dated LIG information is available, WA and the Seychelles, indicate a discrepancy of up to 3 to 4 m in peak LIG ESL, similar to the range estimated independently (*8*). This large uncertainty in the current best estimate of the peak LIG ESL highlights the need for additional, stratigraphically controlled, data from additional far-field localities that are stable at a level better than 0.01 mm/year. Can either location be considered stable at this level? The other requirement is improvements in the isostatic modeling, particularly in the ice models for the penultimate glaciation, but also in some of the model assumptions made: For example, are the effective rheological parameters that describe the earth's deformation on time scales of 10^4 years also valid on the longer time scale? Lastly, we need to address outstanding issues surrounding the interpretation of absolute ages from coral U-Th data and in relating absolute chronologies of sea-level change to paleoclimate records from ice and deep-sea cores to better understand the temporal interplay between climate, ice sheets, and sea-level change.

The need to improve upon the uncertainty in the LIG ESL estimates is best seen in terms of its consequences on melting from both Greenland and Antarctica during the LIG. Current modeling and data-based estimates converge on a 2- to 4-m contribution to ESL from Greenland (*9*, *10*, *29*–*31*) and on a maximum contribution of +3.3 m from West Antarctica (*32*). Thus, the lower limit estimate of the peak LIG ESL (+5.5 m) is consistent with such contributions from both Greenland and West Antarctica, but the upper limit (+9 m) implies additional melt-water contribution from adjacent sectors in East Antarctica.

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Supplementary Materials

www.sciencemag.org/cgi/content/full/337/6091/216/DC1
Materials and Methods
Fig. S1
References (*33*–*71*)
Database S1

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