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Gauging Quaternary Sea Level Changes Through Scientific Ocean Drilling

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Mining-type drill bit used on Expedition 325, Great Barrier Reef Environmental Changes. *Photo credit: D.S. Smith, ECORD-IODP*

ABSTRACT. Indicators of past sea level play a key role in tracking the history of global climate. Variations in global sea level are controlled mainly by growth and decay of continental glaciers and temperatures that are closely correlated with the mean global climate state (glacial and interglacial cycles). Our understanding of global climate and sea level has benefited significantly from improvements in ocean floor sampling achieved by the Ocean Drilling Program (ODP) and the Integrated Ocean Drilling and International Ocean Discovery Programs (IODP), as well as from the application of new analytical techniques and isotope mass spectrometry. This paper presents an overview of recent advances in paleo-sea level studies based on analysis of samples and data from deep-sea sediment cores and drowned coral reefs obtained through ODP and IODP. Future scientific ocean drilling will contribute further to studies of ice sheet dynamics under different climatic boundary conditions.

INTRODUCTION

Relative sea level change—the change in the sea surface relative to land—is determined by a combination of global and local environmental and geophysical factors, such as glacial ice volume, tectonic uplift and subsidence, and geoid adjustment (Lambeck, 1989). The advance and retreat of ice sheets over timescales of 10^3–10^5 years has dominated Quaternary sea level variations. During the Last Glacial Maximum (LGM, ~20,000–27,000 years before present), large ice sheets covered North America and Northern Europe (Figure 1). Between 20,000 and 6,000 years before present, melting of these ice sheets raised global mean sea level (GMSL) by more than 100 m (CLIMAP, 1981; Lambeck et al., 2014; Yokoyama et al., 2018). The Antarctic Ice Sheet, currently the largest ice sheet on Earth, was even larger at maximum extent, storing an additional 10–30 m GMSL equivalent above its present volume. These ice sheets play a key role in global climate because of their impact on albedo and ocean salinity and, hence, thermohaline circulation.

Past changes in global ice volume can be studied through the direct connection between ice volume and oxygen isotopes in the global hydrological cycle. This connection has been instrumental in providing a detailed and continuous picture of climate and sea level change over time (Shackleton, 1967; Hays et al., 1976). When water evaporates from the ocean, the heavier oxygen and hydrogen isotopes are preferentially left behind. Thus, the snow that builds glaciers will be relatively enriched in the lighter oxygen isotope ^{16}O while the ocean will have relatively more of the heavier oxygen isotope ^{18}O. Consequently, as ice sheets grow, the oxygen isotope ratio within the ocean changes. Deep-sea sediments contain an oxygen isotope record of seawater within the carbonate shells of foraminifera, a major class of marine microfossils (Shackleton, 1967). The relative amounts of the oxygen isotopes in the carbonate skeletons reflect temperature and the isotope ratio of the water when they formed, potentially providing information on ice volume changes. Thus, large-scale changes in GMSL can be broadly reconstructed from foraminiferal oxygen isotope records if temperature is known or assumed (Figure 2). This sensitive proxy has proven to be a game changer in understanding global sea level change over long periods of geological time.

In addition to oxygen isotope records, other indicators are used to determine past sea levels, including geological and biological samples dated through a variety of geochemical methods. A basic principle in determining sea level change

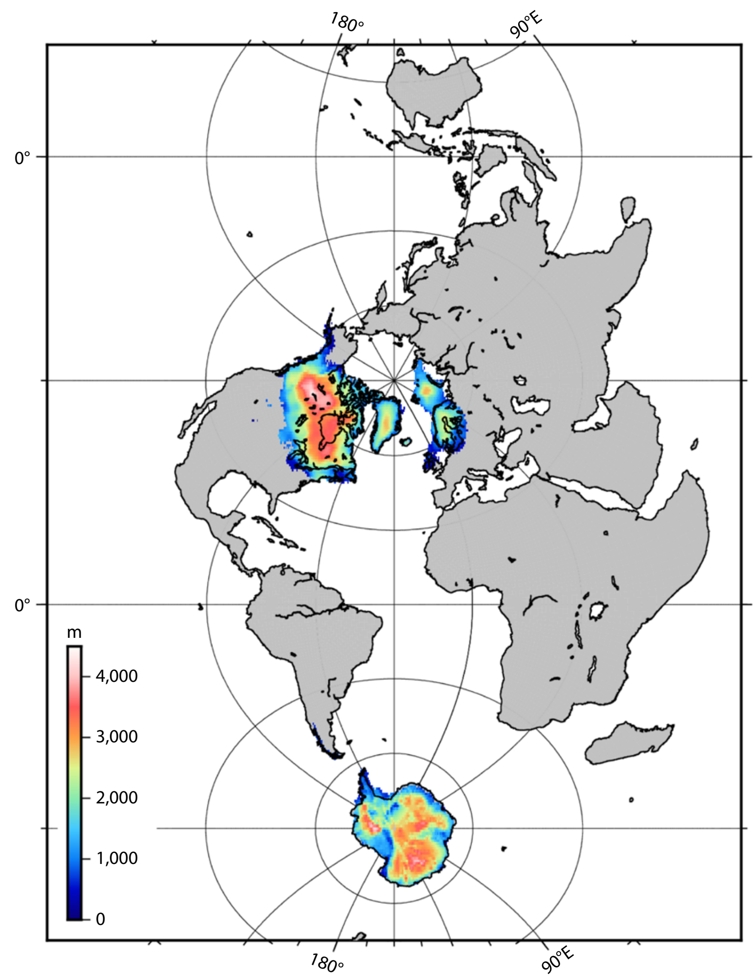

FIGURE 1. Global ice sheet distribution during the Last Glacial Maximum centered around 21,000 years ago according to ice model ICE6G (Peltier et al., 2015). The color bar indicates ice thickness in meters.

is to ensure that the collected sample was formed in situ and is thus indicative of sea level height, within a known uncertainty, and that a reliable age of formation can be determined. Biological carbonate samples, in particular from reef-building corals and coralline algae, are among the best sea level indicators because these organisms are sensitive to sea level and their carbonate skeletons are useful for both ^{14}C and U-series dating (e.g., Camoin et al., 2001; Woodroffe, 2002; Bard et al., 2010; Yokoyama and Esat, 2015).

Although cores collected during Ocean Drilling Program (ODP) and Integrated Ocean Drilling and International Ocean Discovery Programs (IODP) expeditions from the far-field can constrain GMSL, they do not provide information about the meltwater sources that caused sea level to rise. To capture the signals of melting events, scientific ocean drilling collected cores from around Greenland and Antarctica (Figure 3); the magnitude of changes can be deduced by comparing the results of core analyses with global data (e.g., Kanfoush et al., 2000; de Vernal and Hillaire-Marcel, 2008). Sediment cores obtained off East Antarctica provide evidence of the long-term stability of Antarctic ice sheets (e.g., Theissen et al., 2003), whereas cores obtained from Indian sector of the Southern Ocean record millennial-scale fluctuations of the Antarctic ice sheets during the last glacial period (e.g., Hodell et al., 2001).

An alternative approach to identifying meltwater sources that is particularly valuable for determining past ice sheet mass losses is to use modeled sea level signals from individual sources to derive a "sea level fingerprint" for each source. Matching the modeled fingerprints against observed sea level variations allows determination of the sea level contribution from each source (e.g., Clark et al., 2002). More generally, comparing modeled sea level contributions from past melting sourced from different ice sheets with intermediate- and far-field sea level observations from cores could potentially be used to identify past meltwater sources. This methodology requires both high-precision far-field sea level observations and the accurate modeling of the effects of glacial isostatic adjustment (GIA).

In addition to GIA, a factor that complicates determination of GMSL is that sea level is likely also influenced by solid Earth deformation on timescales >100,000 years (Austerman et al., 2013). This deformation can result from uplift (or subsidence) of a continental plate as it moves over upwelling (or downwelling) mantle or surface mass redistribution due to erosion and sediment deposition. The effect of these processes on sea level is negligible on shorter timescales but can amount to two to five meters over 100,000 years. From the geological record it is known that in the Pliocene and Miocene, sea levels were heavily influenced by dynamic topography, with amplitudes of on the order of tens of meters (Rovere et al., 2015). Observations of these effects gained through analysis of cores collected through scientific ocean drilling would provide information against which models of dynamic topography may be validated.

In this paper, we present an overview of sea level studies that have benefited from analysis of scientific ocean drilling cores of sediment and corals from drowned reefs collected by the Ocean Drilling Program, Integrated Ocean Drilling Program, and International Ocean Discovery Program from the 1990s to present.

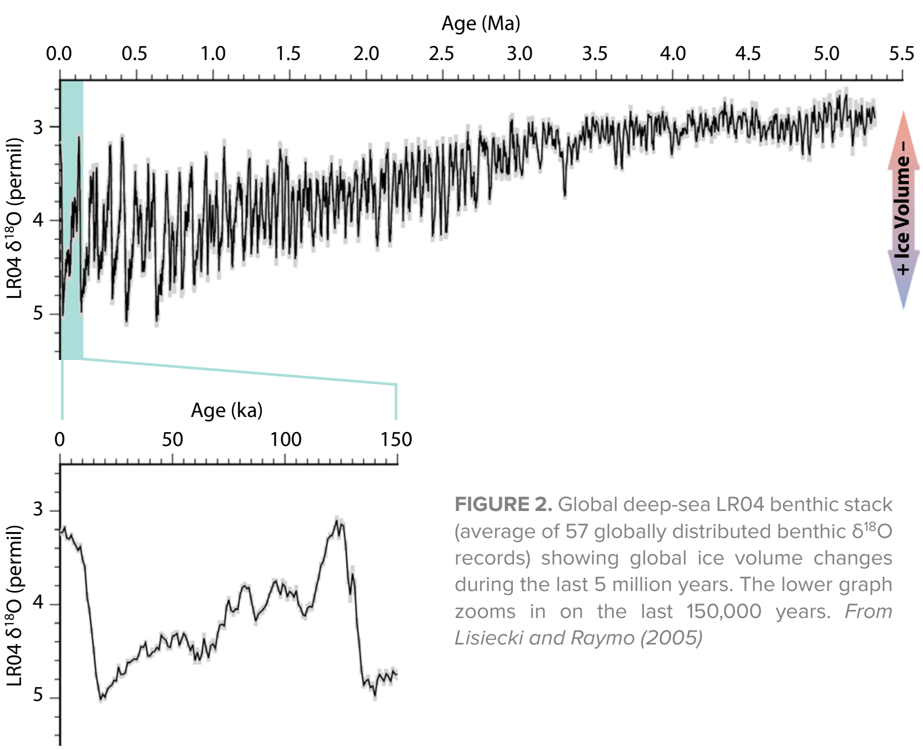

FIGURE 2. Global deep-sea LR04 benthic stack (average of 57 globally distributed benthic δ^{18}O records) showing global ice volume changes during the last 5 million years. The lower graph zooms in on the last 150,000 years. *From Lisiecki and Raymo (2005)*

PRE-QUATERNARY SEA LEVEL CHANGE FROM THE DEEP-SEA SEDIMENT RECORD

Global ice volumes for the last nine million years have been reconstructed from seawater oxygen isotope fluctuations (as δ^{18}O, a measure of the ratio of ^{18}O to ^{16}O) recorded in the foraminiferal skeletons recovered from deep-sea sediment cores (Lisiecki and Raymo, 2005; Miller et al., 2011; Figure 2). Sea level records obtained from oxygen isotope data reveal that glacial and interglacial ice volume fluctuations shifted in cyclicity from 40,000 years to 100,000 years at around 0.8 million years ago (Lisiecki and Raymo, 2005).

However, extension of the δ^{18}O data to the pre-Quaternary is complicated by changes in global temperature.

Uncertainties arise in the oxygen isotope-sea level correspondence because oxygen isotope fractionation depends on ambient temperatures, resulting in ice volume errors of more than 20% (Raymo et al., 2018). Various attempts have been made to overcome these difficulties, including compiling oxygen isotope data from deep-sea cores drilled in different ocean basins and statistically processing the combined data (e.g., Ahn et al., 2017), combining oxygen isotope with other temperature proxies (such as trace element abundances; e.g., Rosenthal et al., 2011), and correlating deep-sea core derived oxygen isotope records with uranium-series-dated speleothem climate records (e.g., Cheng et al., 2009; Rohling et al., 2014).

SEA LEVEL SINCE THE LAST ICE AGE

One of the major outstanding scientific questions for both glaciology and climatology of the last glacial cycle is the so-called "missing ice problem," as presented in Andrews (1992). Estimates of the combined volume of the Northern Hemisphere ice sheets during the LGM using evidence from glaciological and geological studies predict a change in GMSL of 102 m (Denton and Hughes, 1981), while estimates of global ice volume deduced from sea level observations predict a change in GMSL of around 130–140 m from the LGM to present (CLIMAP, 1981; Andrews, 1992; Yokoyama et al., 2000; Lambeck et al., 2014). Thus, to match the global ice volume estimate requires placing more than 25 m of GMSL in the Southern Hemisphere, most likely in Antarctica. Yet, recent glaciological reconstructions seem to cluster toward smaller estimates of Antarctic ice sheet volume (typically 10–15 m of GMSL; e.g., Whitehouse et al., 2012). Determining whether the change in global ice volume during the LGM amounts to 130 m GMSL or not is key to understanding global climate boundary conditions during the last glacial period.

Samples of reef-building corals recovered through scientific ocean drilling provide information about relative sea level during the LGM and the subsequent period of deglaciation. Some of the first systematic sea level data were from radiocarbon dates and habitat depth information obtained from submerged corals recovered from drilling offshore Barbados (Fairbanks et al., 1989). Core sample analysis indicated that sea level was ~120 m lower than present during the LGM and that sea level rose in a sequence of rapid meltwater pulses (MWP) during deglaciation (Fairbanks et al., 1989). Later studies of coral and sediment cores confirmed and reinforced these initial findings (Hanebuth et al., 2000; Yokoyama et al., 2000; Bard et al., 2010; Camoin et al., 2012; recent work of author Ishiwa and colleagues). Comparison of these results with other climate archives such as ice cores not only produced refined sea level curves but also showed the need for higher temporal and spatial resolutions to better understand the relationship between global climate and polar ice sheets at millennial to centennial scales (e.g., Rovere et al., 2018). While it was hoped that systematic coral-based sea level reconstructions would solve various paleoceanographic issues, including the missing ice problem, there are also some uncertainties associated with using corals, including the role of tectonic uplift (e.g., Barbados), age conversion from radiocarbon to calendar age (e.g., silicic sediment-based reconstructions; Hanebuth et al., 2000; Yokoyama et al., 2000), and robustness of depth uncertainties that rely on a particular coral (e.g., Barbados).

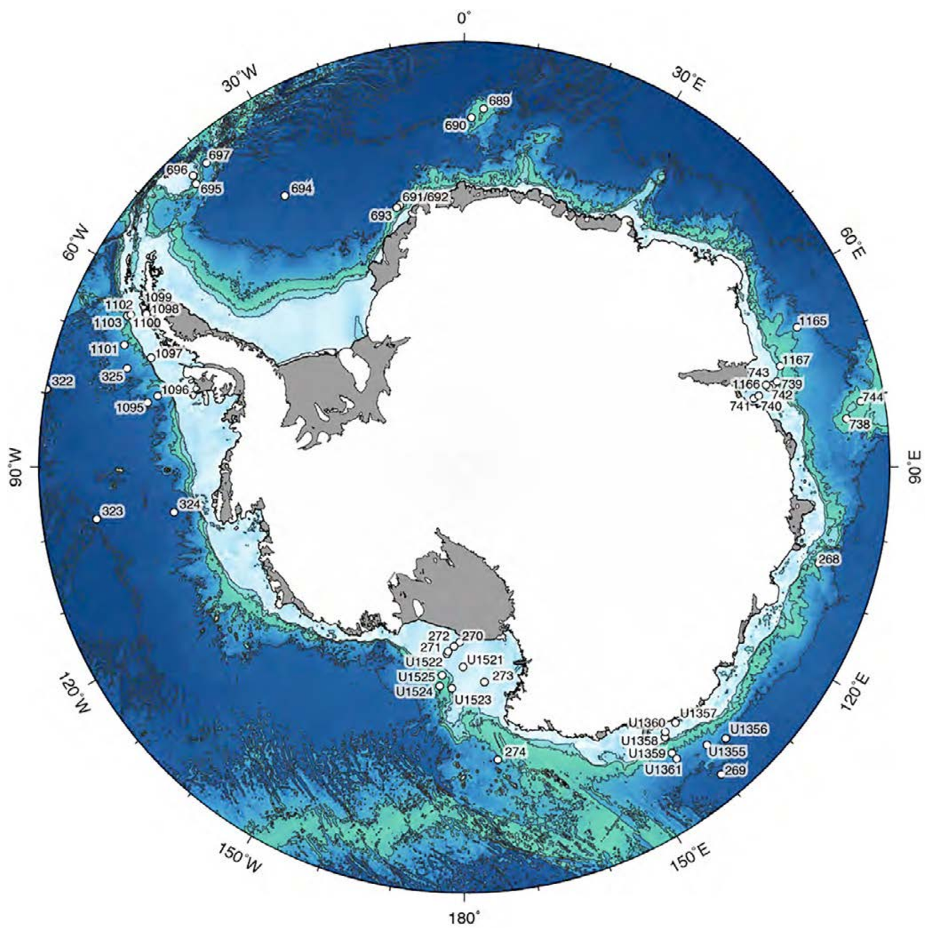

FIGURE 3. Locations of sites drilled around Antarctica during Deep Sea Drilling Project Legs 28 and 35; Ocean Drilling Program Legs 113, 119, and 178; Integrated Ocean Drilling Program Expedition 318; and International Ocean Discovery Program Expedition 374 to study meltwater sources that caused sea level to rise. Three sites (645, 646, 647) were also drilled off Greenland during Ocean Drilling Program Leg 105 for the same purpose.

SEA LEVELS DURING THE LATE PLEISTOCENE

Good localities for collecting samples are the carbonate platforms found in fringing reefs of volcanic islands and atolls as well as barrier reefs, as these structures retain long records through almost continuous reef building. Although many coral-based sea level studies have been conducted on uplifted coral terraces found on shore, at sites such as Tahiti and Huon Peninsula (Papua New Guinea), these land-based drilling projects could only sample corals back to 13,800 years ago (e.g., Edwards, et al., 1993; Bard et al., 2010; Camoin et al., 2012). Prior to the 2005 IODP Expedition 310 "Tahiti Sea Level" (Camoin et al., 2007a,b), the only corals available to the community for study of sea level during the LGM and subsequent deglaciation were from offshore of Barbados (Fairbanks, 1989). In 2010, IODP Expedition 325 (Webster et al., 2011; Yokoyama et al., 2011), using the same approach as the Tahiti drilling expedition, targeted the Great Barrier Reef in Australia (Webster et al., 2011; Yokoyama et al., 2011). The cores recovered by Expeditions 310 and 325 are providing an additional rich source of data to better understand sea level change during and after the LGM.

The three main scientific objectives of IODP Expeditions 310 to Tahiti and 325 to the Great Barrier Reef were (1) to establish the details of sea level rise, including pulses of rapid rise during the last deglaciation, such as MWP1a, MWP1b, and 19ka MWP (Figure 4; Fairbanks, 1989; Yokoyama et al., 2000), (2) to determine the nature and magnitude of seasonal to millennial-scale climate variability, and (3) to examine the biologic and geologic responses of Tahiti and the Great Barrier Reef to abrupt sea level and climate changes (Camoin et al., 2007a,b; Webster et al., 2011; Yokoyama et al., 2011).

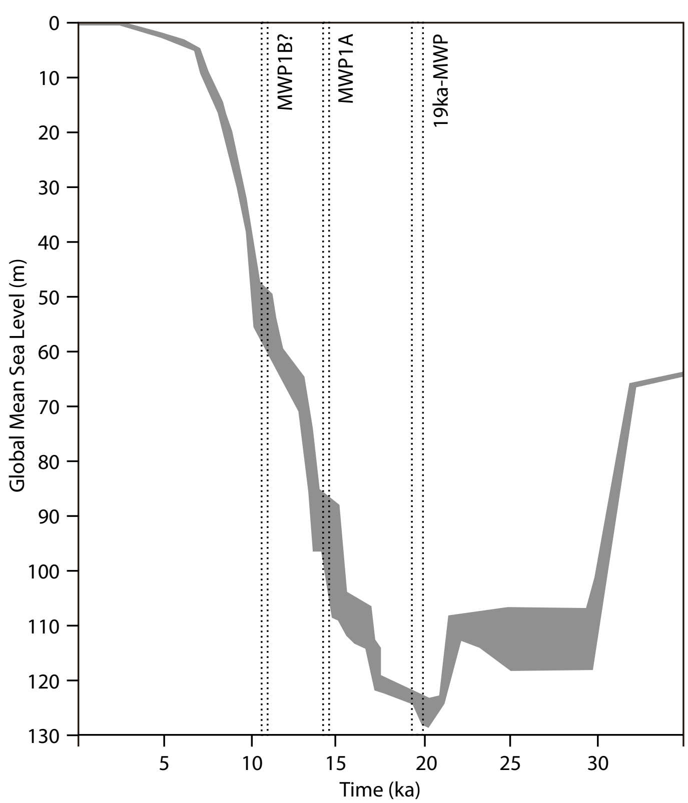

FIGURE 4. Newly obtained global mean sea level from fossil coral reef materials obtained from the Great Barrier Reef during Integrated Ocean Drilling Program Expedition 325 combined with data from a glacio hydro isostatic adjustment model. Dotted lines are previously proposed rapid melting events since the Last Glacial Maximum discussed in the text. MWP = Meltwater Pulse. *Figure modified from Yokoyama et al. (2018)*

IODP Expedition 310 marked the first IODP coring of coral reef materials from the Pleistocene. The recovered samples provided sea level records for both the Last Glacial Termination (Termination I or TI; Deschamps et al., 2012) and the deglaciation that followed the penultimate glacial maximum, Termination II in the Pleistocene (TII; Thomas et al., 2009). Termination is the term used for the relatively rapid transitions (≤10,000 years) from glacial to interglacial conditions, with T1 being the most recent termination. Analysis of uranium series nuclides from Tahitian corals that grew during TII suggests that ice volume reductions preceded atmospheric CO_2 increase, but postdate increased insolation at Northern Hemisphere high latitudes—confirming the Milankovitch hypothesis, which says that glacial terminations were initiated by changes in high-latitude insolation (Thomas et al., 2009). The large magnitude of sea level changes during TI and TII were also recorded in assemblages of large benthic foraminifera in the reef materials, suggesting that those specimens can be used to identify deglaciations and independently validate U-series ages obtained from coral samples, even though foraminifera shells may be susceptible to diagenetic changes after deposition (Fujita et al., 2010).

The sea level reconstruction for TI made possible by the Tahiti cores identified the timing and magnitude of MWP-1A, which had not been tightly constrained in previous studies. Debate continues about whether the Northern Hemisphere ice sheet is the sole source of meltwater for MWP-1A. The answer is important because it will help us understand the stability of Antarctic ice sheets against global warming as well as solve the missing ice problem. A sequence of U-series dates obtained from shallow-water corals drilled during Expedition 310 yielded a date for MWP-1A of ~14,600 years ago with a sea level change magnitude of about 16 ± 2 m at a rate of about 40 mm yr^{-1} (Deschamps et al., 2012). Using sea level fingerprinting techniques (Clark et al., 2002), these results have been compared to the Barbados sea level reconstructions of Fairbanks (1989) in an effort to identify the source of the meltwater that drove this event. This analysis found that the source of meltwater was likely not restricted to the Northern Hemisphere ice sheets, and must include a contribution from Antarctica. However, no cores older than 16,000 years old were recovered by the Tahiti drilling, so the magnitude of LGM sea level minimum and its source remained unknown.

In 2010, IODP Expedition 325 to the Great Barrier Reef recovered fossil reef materials from two transects separated by more than 500 km. Detailed investigations of the different reef facies contained in the cores, together with more than 1,000 dates obtained from radiocarbon and U-series dating of coral samples, show almost identical relative sea level histories in both transects (Yokoyama et al., 2018). These analyses were enabled by the use of new core sampling equipment, including HQ-size wireline core barrels used in the mining industry, and resulted in better recovery of reef materials (35%–40%) than previously possible, allowing construction of more accurate sea level curves.

Modeled GMSL from IODP Expedition 325 results suggests that the maximum sea level drop during the LGM was 118 m at the Great Barrier Reef. This is larger than the 102 m drop estimated for the Northern Hemisphere ice sheets during the LGM, suggesting that Antarctic excess ice volume during the LGM was at least 11 m of GMSL. After correcting for GIA, the GMSL drop during the LGM becomes −125 m to −130 m based on the Great Barrier Reef record, and accordingly, the excess LGM Antarctic ice volume must have been even higher (e.g., 23–28 m GMSL from Antarctica; Yokoyama et al., 2018). Because the GIA contributions at these and other far-field sites are dominated by hydro-isostatic effects, the uncertainties in crustal rheology have only a small impact, and the GIA signal depends mostly on the magnitude of the local water load (Figure 5). The new sea level data revealed previously unknown rapid drops and rises in sea levels during the last 30,000 years (Yokoyama et al., 2018).

In addition, almost 3°–5°C cooling was recorded in the core samples as $\delta^{18}O$ and Sr/Ca excursions during the LGM (Felis et al., 2014). These large temperature changes severely impacted the Great Barrier Reef, and together with rapid sea level changes resulted in at least five "near death events" during the last 30,000 years (Webster et al., 2018). The Great Barrier Reef's survival of these significant environmental changes may provide a key to understanding the ecological resilience of reef systems (Webster et al., 2018).

In summary, analyses of cores collected globally and in a range of settings by scientific ocean drilling have revealed unexpected behavior of the major ice sheets and their responses to climate forcing. A rapid melting, so-called MWP-1A, occurred at around 14,600 years ago according to corals obtained from IODP Expedition 310 to

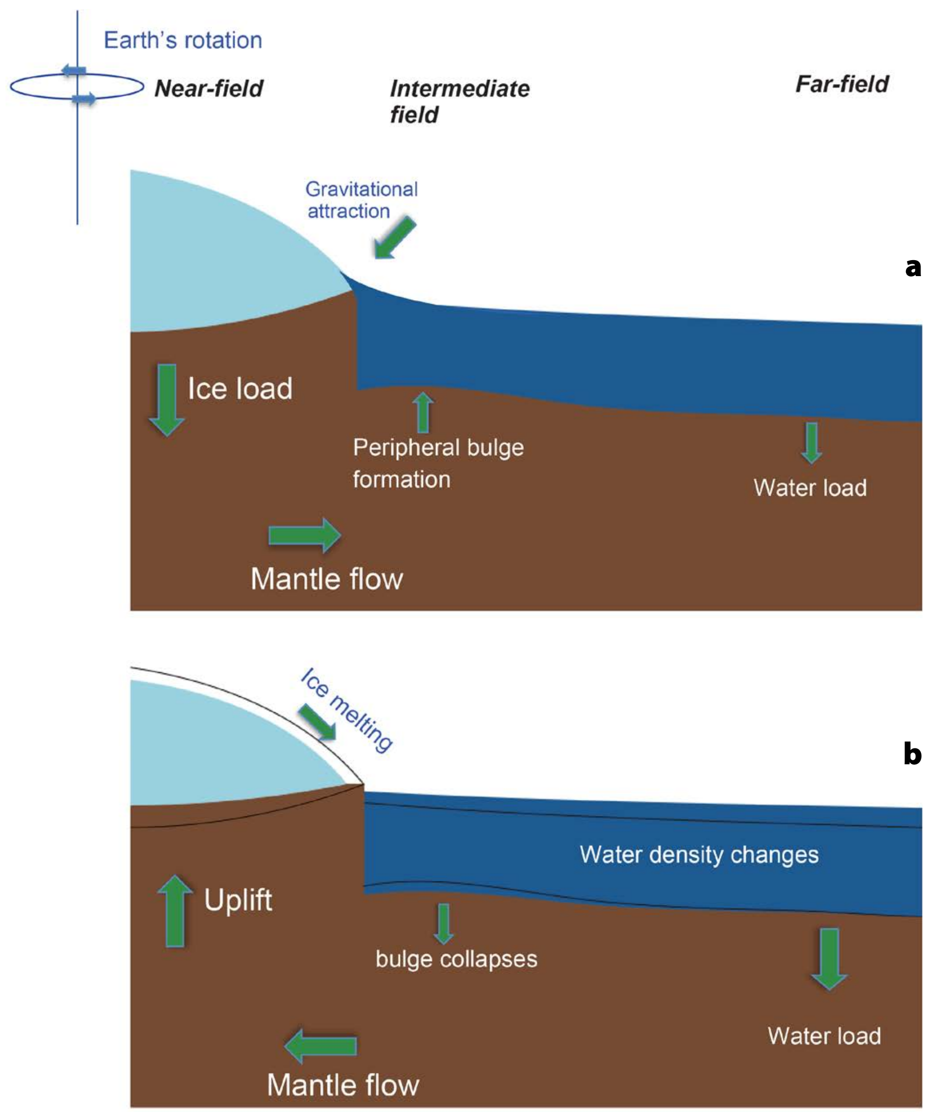

FIGURE 5. Schematic diagram of physical processes and their impacts associated with changes in ice sheets. (a) During the growth stage, these include local crustal loading and an intermediate crustal bulge due to mantle flow, gravitational attraction of seawater adjacent to and toward the ice margin, and perturbation of Earth's rotational axis. (b) During the melting stage, there is local uplift, bulge collapse, and a decrease in rotational disturbances and local gravitational effects on seawater. *From Yokoyama and Esat (2011)*

Tahiti. The conventional picture of ice sheets is that growth is slow but disintegration is rapid. However, cores from the Great Barrier Reef collected during IODP Expedition 325 clearly captured a rapid, two-step buildup of global ice sheet volume, reflected as two rapid sea level falls at about 30,000 years ago and 21,000 years ago, before culmination at the LGM. Because current glaciological models do not have the capacity to reproduce these rapid changes identified through scientific ocean drilling, it is important to incorporate this dynamic behavior into models in order to better predict future changes.

CONCLUSIONS

Scientific ocean drilling has provided the Earth and ocean sciences communities with valuable data that have allowed reconstructions of past global mean sea level and ice sheet volumes. These data provide some of the most immediate large-scale constraints on climate and ice sheet interactions, the rate and magnitude of ice sheet and climate adjustments, and local environmental conditions from previous epochs, particularly during and since the last glacial maximum.

Our understanding of the extent and magnitude of the major ice sheets since the LGM has been greatly enhanced by scientific ocean drilling core data, which have shown that sea level is highly variable and very dynamic, contradicting the results of ice sheet modeling efforts. However, this variability points out that more data are needed to fully understand sea level changes that occurred before and during the LGM at a resolution sufficient to more tightly constrain the GMSL curve.

The responses of the Antarctic Ice Sheet to past climate forcings are a critical, but poorly constrained, component of our understanding of potential contributions of the Antarctic Ice Sheet to present and future sea level changes. Given that many formerly glaciated regions of Antarctica are now submerged, seafloor surveys and scientific ocean drilling will continue to play a vital role in more tightly constraining the history of the Antarctic Ice Sheet and regional sea level change.

Our estimates of the magnitude of the fall in sea level during the Last Glacial Maximum and the late glacial period also rely heavily on IODP results. These estimates of roughly −130 m GMSL, in combination with reconstructions of the Northern Hemisphere ice sheets, allow us to infer that the Antarctic Ice Sheet was much larger than its present maximum extent (30 m GMSL) and larger than suggested by glaciological modeling. Further sampling of the Antarctic continental shelf by scientific ocean drilling is required to better constrain the evolution of the Antarctic Ice Sheet and to distinguish between different possible ice history scenarios.

On longer timescales (e.g., pre-Quaternary), the effects of other geological processes become increasingly significant. In particular, sea level changes resulting from dynamic topography can reach amplitudes of tens of meters. Robust paleo-sea level data are required to validate numerical models of this process. This makes the interpretation of sea level data from the last interglacial particularly difficult because dynamic topography and GMSL effects are of comparable magnitude in this epoch and not readily disentangled.

Although today models of GIA are more mature and have been repeatedly tested against large data sets, there remain significant uncertainties associated with the rheological parameters and the trade-off between ice and Earth models. These uncertainties have generally not been well explained by the GIA community, but must be considered when these models are applied to observational data, such as those collected during Deep Sea Drilling Project, ODP, and IODP expeditions.

Improvements in numerical models of geophysical processes and in seafloor sampling techniques and refinements in analytical methodology will produce more accurate data and a more comprehensive understanding of paleo-environments. These advancements will expand the range of scientific questions that can be addressed and lead to further refinements in our understanding of past and present sea level and climate. The value of IODP's contribution to this process cannot be overstated.

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