Quaternary Science Reviews 220 (2019) 359–371

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

Introduction

Inception of a global atlas of sea levels since the Last Glacial Maximum

Nicole S. Khan [a, b, *], Benjamin P. Horton [a, c], Simon Engelhart [d], Alessio Rovere [e], Matteo Vacchi [f], Erica L. Ashe [g], Torbjörn E. Törnqvist [h], Andrea Dutton [i], Marc P. Hijma [j], Ian Shennan [k], , and the HOLSEA working group

[a] Asian School of the Environment, Nanyang Technological University, Singapore
[b] Department of Earth Sciences, University of Hong Kong, Hong Kong
[c] Earth Observatory of Singapore, Nanyang Technological University, Singapore
[d] Department of Geosciences, University of Rhode Island, Kingston, RI, USA
[e] MARUM, ZMT, University of Bremen, Germany
[f] Department of Earth Sciences, University of Pisa, Italy
[g] Department of Earth and Planetary Sciences, Rutgers University, Piscataway, NJ, United States
[h] Department of Earth and Environmental Sciences, Tulane University, New Orleans, LA, USA
[i] Department of Geological Sciences, University of Florida, Gainesville, FL, USA
[j] Department of Applied Geology and Geophysics, Deltares, Utrecht, the Netherlands
[k] Department of Geography, Durham University, Durham, UK

ARTICLE INFO

Article history:
Received 20 June 2019
Accepted 8 July 2019
Available online 20 August 2019

ABSTRACT

Determining the rates, mechanisms, and geographic variability of relative sea-level (RSL) change following the Last Glacial Maximum (LGM) provides insight into the sensitivity of ice sheets to climate change, the response of the solid Earth and gravity field to ice-mass redistribution, and constrains statistical and physical models used to project future sea-level rise. To do so in a scientifically robust way requires standardized datasets that enable broad spatial comparisons that minimize bias. As part of a larger goal to develop a unified, spatially-comprehensive post-LGM global RSL database, in this special issue we provide a standardized global synthesis of regional RSL data that resulted from the first 'Geographic variability of HOLocene relative SEA level (HOLSEA)' meetings in Mt Hood, Oregon (2016) and St Lucia, South Africa (2017). The HOLSEA meetings brought together sea-level researchers to agree upon a consistent protocol to standardize, interpret, and incorporate realistic uncertainties of RSL data. This special issue provides RSL data from ten geographical regions including new databases from Atlantic Europe and the Russian Arctic and revised/expanded databases from Atlantic Canada, the British Isles, the Netherlands, the western Mediterranean, the Adriatic, Israel, Peninsular Malaysia, Southeast Asia, and the Indian Ocean. In total, the database derived from this special issue includes 5634 (5290 validated) index (n = 3202) and limiting points (n = 2088) that span from ~20,000 years ago to present. Progress in improving the standardization of sea-level databases has also been accompanied by advancements in statistical and analytical methods used to infer spatial patterns and rates of RSL change from geological data that have a spatially and temporally sparse distribution and geochronological and elevational uncertainties. This special issue marks the inception of a unified, spatially-comprehensive post-LGM global RSL database.

1. Relative sea level since the Last Glacial Maximum

Sea-level rise poses one of the most immediate societal threats associated with present-day and future climate change (Nicholls et al., 2011; Mimura, 2013; Neumann et al., 2015; Hauer et al., 2016; Hauer, 2017; Mengel et al., 2018; Steffen et al., 2018). Therefore, determining the rates, mechanisms, and geographic variability of relative sea-level (RSL) change is an urgent priority for the next decade of ocean, climate, and hazards research (NRC, 2015). Changes in RSL — the height of local mean sea level relative to the local solid Earth surface, but excluding the dynamic

---

* Corresponding author. Department of Earth Sciences, University of Hong Kong, Hong Kong.
E-mail address: nskhan@hku.hk (N.S. Khan).

https://doi.org/10.1016/j.quascirev.2019.07.016

sediment surface (Gregory et al., 2019) – vary in time and space. RSL records spanning the Last Glacial Maximum (LGM) to present exhibit temporal and spatial variability that arises mainly from the interaction of eustatic (land ice volume and thermal expansion) and isostatic (ice and water loading and unloading) factors (Clark et al., 1978; Peltier, 2004; Milne et al., 2009; Khan et al., 2015). Conceptually, RSL change at a specific location is the sum of several processes that act over a variety of spatial and temporal scales (e.g., Shennan and Horton, 2002; Kopp et al., 2015a, 2015b; Rovere et al., 2016):

$$\mathrm{RSL} = \mathrm{ESL} + \mathrm{GIA} + \text{Static equilibrium} + \text{Tectonics} + \text{Local} \tag{1}$$

The **eustatic** or ESL term refers to melting (or growth) of land-based ice (barysteric contribution) and ocean water density changes from temperature and salinity variations (steric contribution) (see Gregory et al., 2019 for further discussion of terminology). Outstanding questions remain regarding ESL change since the LGM (Carlson and Clark, 2012), including a) the timing and magnitude of LGM ESL (e.g., (Peltier and Fairbanks, 2006; Austermann et al., 2013; Hughes et al., 2013; Clark and Tarasov, 2014; Yokoyama et al., 2018; Simms et al., 2019); b) the ESL trajectory during Heinrich Event 1 and the 'Mystery Period' (Broecker et al., 1992; Grousset et al., 2001; Carlson and Clark, 2012; Lambeck et al., 2014; Peltier and Vettoretti, 2014); c) the rates, sources and, in some cases, the existence of rapid periods of ESL rise such as Meltwater Pulse (MWP) 1A (Shennan, 1999; Clark et al., 2002; Peltier, 2005; Stanford et al., 2011; Gomez et al., 2015; Shennan et al., 2018, this issue), MWP 1B (Peltier and Fairbanks, 2006; Bard et al., 2010; Abdul et al., 2016), and early Holocene ESL changes (Yu et al., 2007; Hijma and Cohen, 2010, 2019, this issue; Bird et al., 2010; Törnqvist and Hijma, 2012); and d) the timing, magnitude and sources of the mid-to late-Holocene 'melting tail' (Tarasov and Peltier, 2002; Simpson et al., 2009; Lambeck et al., 2014; Lecavalier et al., 2014; Peltier et al., 2015; Bradley et al., 2016; Ullman et al., 2016).

Glacial isostatic adjustment (GIA) is the response of the solid Earth and gravity field to ice mass redistribution during a glacial cycle (e.g., Walcott, 1972; Farrell and Clark, 1976). Geophysical models of the GIA process are needed to correct past and present RSL records (e.g., Cazenave et al., 2009; Church and White, 2011), test hypotheses about sources of ice melt (Dutton et al., 2015a, 2015b; Piecuch et al., 2018), and provide regional predictions of RSL rise to managers and stakeholders (Slangen et al., 2012; Kopp et al., 2014; Horton et al., 2018). RSL data from the LGM to present provide vital constraints for parameters of Earth and ice (total ESL signal) components of GIA models, which cannot be estimated from direct measurements (Fig. 1; Peltier and Jiang, 1996; Davis and Mitrovica, 1996; Milne et al., 2005). For example, Fig. 1 illustrates how critical frequently-updated, high-quality sea-level databases are to accurately constrain models of the GIA process (Vacchi et al., 2018a, this issue). Twenty years ago, the available data from Hudson Bay provided far less precise constraints on the past position of RSL and thus the quality of fit of a GIA model to the data. The updated dataset (Vacchi et al., 2018a, this issue) includes data published in the last twenty years, as well as updated interpretations of older data and recalibration of radiocarbon ages. Furthermore, the inclusion of index points in the dataset permits statistical evaluation of the RSL evolution in the region (e.g., Ashe et al., 2019, this issue), providing more robust and quantitative constraints for GIA models, and also enables probabilistic assessments of rates of RSL change (Fig. 1d).

Interrelated to GIA are regional '**static equilibrium**' RSL changes associated with gravitational, deformational, and rotational processes in response to exchanges of mass between the cryosphere and the ocean (e.g., Milne et al., 2009; Kopp et al., 2010; Mitrovica et al., 2011). Together, these processes lead to sea-level 'fingerprints,' or associated spatial patterns in RSL changes whereby RSL falls in the near-field and exhibits a proportionally greater RSL rise than the global average in the far-field of the ice melt source (Clark, 1976; Conrad and Hager, 1997). It may be possible to take advantage of these spatial patterns by bringing together sea-level records distributed across the globe to provide clues about sources of ice melt following the LGM (Clark et al., 2002). One such example includes sea-level fingerprints associated with the catastrophic drainage of proglacial lakes Ojibway and Agassiz and associated climatic response in the early to mid Holocene (Kendall et al., 2008; Hijma and Cohen, 2010; Li et al., 2012; Törnqvist and Hijma, 2012; Lawrence et al., 2016; Hijma and Cohen, 2019, this issue).

Vertical land motion caused by **tectonics** can contribute significantly to RSL change on some coastlines (Nelson, 2007). On passive margins, such as the Russian Arctic or Atlantic coast of North America, some areas may have low rates of uplift or subsidence induced by tectonic compression and gliding, faulting, and folding or tilting of crustal blocks (e.g., Baranskaya et al., 2018, this issue; van de Plassche et al., 2014). On active margins, such as some coastlines of the Mediterranean and Southeast Asia, seismicity, volcanism, or mountain building may contribute substantially to local-to regional- RSL changes (e.g., Shaw et al., 2018, this issue; Mann et al., 2019, accepted, this issue). Atwater (1987) and later Nelson et al. (1996) demonstrated the utility of coastal wetlands in recording Holocene seismic activity and associated sea-level change along the Cascadian subduction zone. These early studies influenced the development of modern coastal wetland-based paleoseismology and its application to earthquake and tsunami hazards along active plate-boundaries across the Earth. Compilations of dated transgressive contacts from paleoseismic studies have contributed to numerous iterations of regional RSL databases (e.g., Hutchinson, 1992; Shugar et al., 2014; McLaren et al., 2014; Engelhart et al., 2015). Where regional compilations of RSL reconstructions that share common ESL, static equilibrium, and GIA contributions have been compiled, these data can be used to estimate the presence and rate of vertical land motion caused by tectonics at regional scales (e.g., van de Plassche et al., 2014; Shaw et al., 2018, this issue).

Local (to regional) scale factors include subsidence due to the compaction of shallow sediments (van Veen, 1945; Bennema, 1954; Kaye and Barghoorn, 1964; Törnqvist et al., 2008; Tam et al., 2018, this issue), deltaic sediment loading (Yu et al., 2012; Wolstencroft et al., 2014; Kuchar et al., 2018), and groundwater and hydrocarbon extraction (Kolker et al., 2011; Allison et al., 2016; Karegar et al., 2016), which may contribute to high rates of RSL rise. In areas underlain by limestone, karstification may cause isostatic uplift and tilting of carbonate platforms (e.g., Opdyke et al., 1984; Adams et al., 2010; Woo et al., 2017). Non-stationary tides may also contribute to apparent RSL changes (e.g., Shennan et al., 2018, this issue). The regional magnitude of this variation in tides is reduced in the mid to late Holocene (e.g., Uehara et al., 2006; Hill et al., 2011), although high-resolution bathymetric models are necessary to estimate the influence of local-scale variations (e.g., Hall et al., 2013). Ocean-atmosphere dynamics and river-discharge variability driven by changes in regional hydroclimate may also influence RSL (e.g., Enfield and Allen, 1980; Kopp et al., 2010; Piecuch et al., 2018); however, improved understanding of how these climate-driven processes manifest in proxy records is needed and it is likely that the resolution of most post-LGM archives is insufficient to detect the magnitude of RSL changes due to these processes (e.g., Woodworth et al., 2017, 2019; Kemp et al., 2018).

To determine rates, mechanisms, and geographic variability will

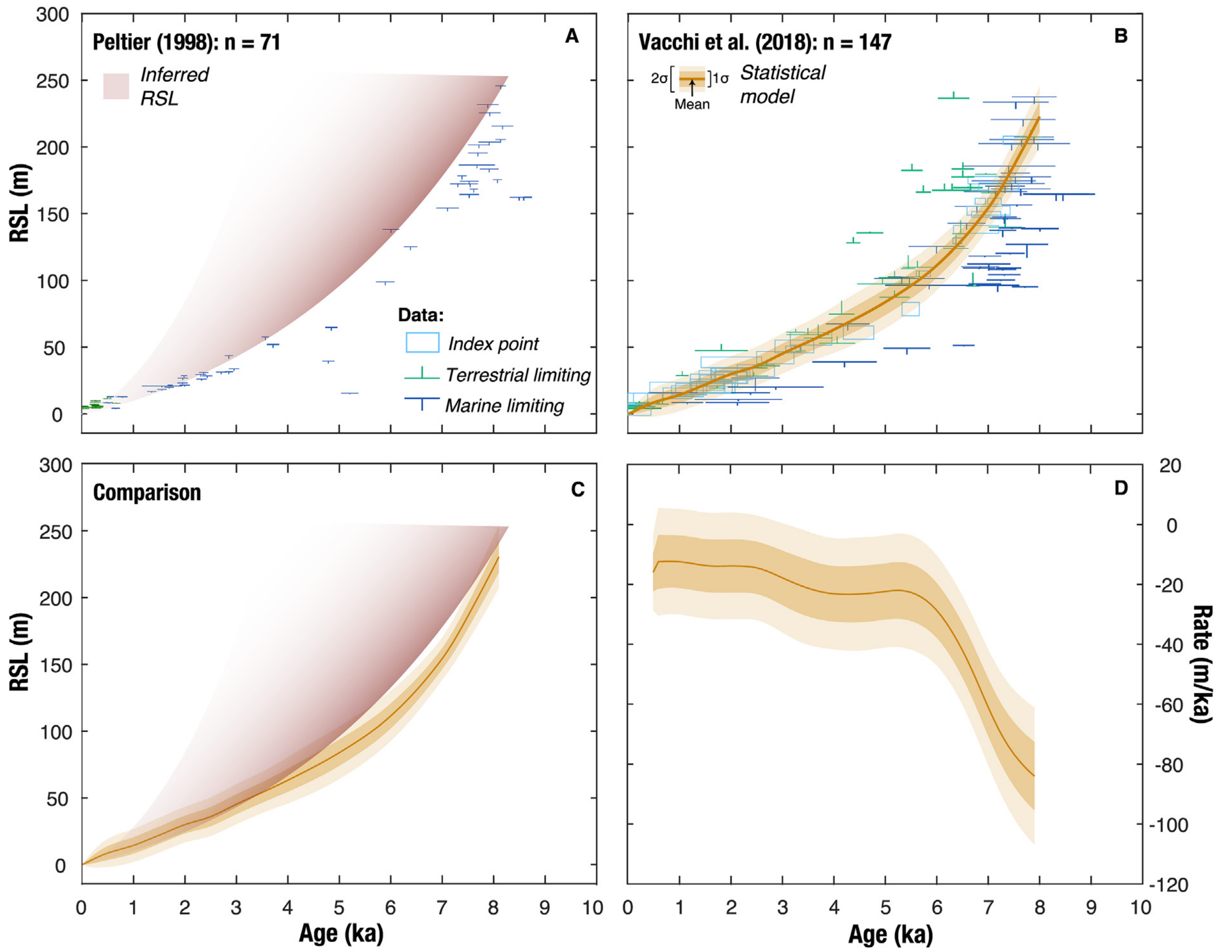

Fig. 1. Comparison of old (A) and new, validated data (B) from the Hudson Bay region from Peltier (1998) and Vacchi et al. (2018a, this issue), respectively. In (A), the red shading represents the possible inference on the RSL evolution given the previous dataset, where darker shading represents more likely positions of past RSL. The updated dataset (B) permitted statistical evaluation of the data using a hierarchical empirical temporal Gaussian process statistical model (see Ashe et al., 2019; this issue, for more details). The two datasets provide different inferences on the RSL evolution of Hudson Bay (C), which has important implications for the constraints the data provide on GIA models. (D) Implementation of the statistical model also allows for calculation of probabilistic rates of RSL change in the region. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

require a spatially-comprehensive, standardized global compilation of geological RSL reconstructions since the LGM. Building on efforts led by the sea-level community through the IGCP (International Geological Correlation Programme, now known as the International Geoscience Programme) projects 61, 200, 495, 588, and 639 (e.g., Tooley, 1974; Preuss, 1979; van de Plassche, 1982; Shennan, 1987a, 1987b; Gehrels and Long, 2007; Horton et al., 2009; Switzer et al., 2012; Padgett et al., 2018) and best practices outlined in the Handbook for Sea-level Research (Shennan et al., 2015; Hijma et al., 2015; Törnqvist et al., 2015; Dutton, 2015), we have developed a comprehensive framework for the standardization, reinterpretation, validation, and incorporation of accurate uncertainties of regional RSL databases.

Here we review the long legacy of efforts to establish a global atlas of RSL data and key advancements made in our understanding of past RSL and uncertainties inherent in the data we use to infer these changes (Section 2). We describe the characteristics of RSL data and the database framework, leveraged from lessons learned through previous efforts (Section 3). Finally, we describe the composition of the global database (Section 4) and discuss future work and challenges that remain in its completion and long-term maintenance (Section 5).

2. Legacy efforts to establish a global atlas

Scientists have long recognized that the relative positions of the land and sea have not remained stable through time due to a variety of different mechanisms (see reviews by Woodroffe and Murray-Wallace, 2012; Gehrels and Shennan, 2015). Early observations were related to volcanic or tectonic processes. More than 2000 years ago, Phythagoras identified changes in RSL due to the emergence or submergence of land or the presence of shells found far inland from the sea (Ovid, XV 259-306). The Greek philosopher Strabo linked volcanic activity in the Mediterranean to relative land-level changes and periodic marine inundations (Devoy, 2012; Goiran et al., 2011). Also related to volcanic processes, marine borings from bivalves on pillars standing within the Roman market at Pozzuoli in central Italy indicated that the columns must have sunk into and re-emerged from the sea at least once since their construction (e.g. Forbes, 1829; Niccolini, 1845; Babbage, 1847; Lyell, 1872; Flemming, 1969; Morhange et al., 2006). Darwin (1839) also witnessed and noted rapid uplift following the Concepción earthquake on the coastline of Chile during the voyage of the Beagle. In areas near LGM ice sheets, scientists were quick to recognize RSL changes due to isostatic rebound. In 1731, Celsius first observed uplift of a ‘seal rock,’ a formerly submerged rock on which seals would often lie, due to GIA in Lövgrund, Sweden (Celsius, 1743). Later, Huxley (1878) recognized the significance of submerged forests in recording the submergence of southern Britain.

The concept of ‘eustasy’ was first termed by Suess in 1888 and explains the transfer of water between the oceans and ice sheets during the Quaternary as ice sheets grew and melted during successive glaciations, which in turn had a first-order control on ocean volume and sea level (Suess, 1888; Dott, 1992; Rovere et al., 2016; Otvos, 2018). With the advent of radiocarbon dating in the 1950s (Libby, 1952), widespread investigations into post-LGM sea levels on local, regional and global scales were enabled, and a concerted effort was made to compile a global ‘eustatic’ sea-level curve. While Godwin (1940) produced the first RSL plot using pollen chronostratigraphy, expressing the vertical and age uncertainties (and coining the term ‘index point’) locally for the coasts of Britain, later Godwin et al. (1958), along with Shepard and Suess (1956) produced the first ‘eustatic’ Holocene sea-level curves from a variety of locations across the globe (Gehrels and Shennan, 2015).

Two schools of thought emerged regarding the nature of RSL rise since the LGM (Kidson, 1982, 1986). Some researchers accepted the ideas promoted by Fairbridge (1961), who suggested RSL rise featured fluctuations expressed by a series of transgressions separated by regressive phases (Morner, 1969; Tooley, 1974, 1978). Researchers from the second school of thought suggested that RSL rise took the form of a smooth exponential decay curve (Jelgersma, 1961; Shepard, 1963; Kidson and Heyworth, 1973, 1979; Kidson, 1977). They interpreted alternations of marine and terrestrial sediments in terms of local geomorphic changes and as consequences of the interplay between small-scale variations in rates of local RSL rise and sedimentation. Conflicts between the two schools of thought amounted to choosing what Kuhn (1962) termed a ‘paradigm,’ whereby one school may regard the explanation offered by another as unacceptable and unreasonable (Harvey, 1969). Two developments contributed to a step change in the understanding of past sea levels, promoted by collaboration among scientists gathering under the auspices of the International Quaternary Association (INQUA) and through successive IGCP projects (e.g., van de Plassche, 1986a).

The first was the development of geophysical models of the GIA process (e.g. Peltier, 1974; Farrell and Clark, 1976; Clark et al., 1978) and the understanding that gravitational effects were an important control on RSL (e.g., Clark and Lingle, 1977; Clark et al., 1978). Compiling an atlas of Holocene sea-level curves was a focus of the initial IGCP sea-level projects, with atlases following from both projects 61 and 200 (Bloom, 1977; Pirazzoli, 1991). Early analyses of RSL data confirmed that the eustatic curve was an immeasurable factor at any one point on Earth (Kidson, 1982, 1986) and that it could only ever be inferred from sea-level data at multiple locations (e.g., Bassett et al., 2005). Further analyses revealed that areas most sensitive for recording the eustatic signal vary both spatially and temporally and are extremely rare (Milne and Mitrovica, 2008).

The second development was a more rigorous recognition of uncertainties inherent in RSL reconstructions (van de Plassche, 1986a, 1986b). Many early reconstructions were presented as continuous hand-drawn lines fitted through the elevation of radiocarbon samples, with little regard for the errors that likely affected them (e.g., Pirazzoli, 1991). Chappell et al. (1987, p. 313) recognized that “data can be placed on a common footing by duly estimating error sources. Only when this is done consistently can the real differences between different sites be perceived and measured”. Shennan (1982, 1986), Shennan et al., 1983 and van de Plassche (1986a) advocated for the development of standard methodologies for litho- and bio-stratigraphical analyses, where RSL data plotted on an age/elevation graph should be shown with an uncertainty range that demonstrates the range of the indicative meaning and a full assessment of elevation and age uncertainties (e.g., van Straaten, 1954; Kidson and Heyworth, 1979; Streif, 1979; Shennan, 1982; Tooley, 1982).

The approach of Shennan (1982, 1986, 1989) and Shennan et al., 1983 forms the basis of the methodology used by IGCP projects and more recently the PALeo constraints on SEA level rise (PALSEA) PAGES and INQUA focus group (e.g., Düsterhus et al., 2016). We build on this approach to incorporate methodological advancements (e.g., accelerator mass spectrometer [AMS] dating, new proxies) to produce the global atlas in this special issue (Fig. 2).

3. Standard approach to reconstructing relative sea level

Geological RSL reconstructions are developed using sea-level indicators, which formed in relationship to the past position of sea level, and in this special issue, include sedimentary,

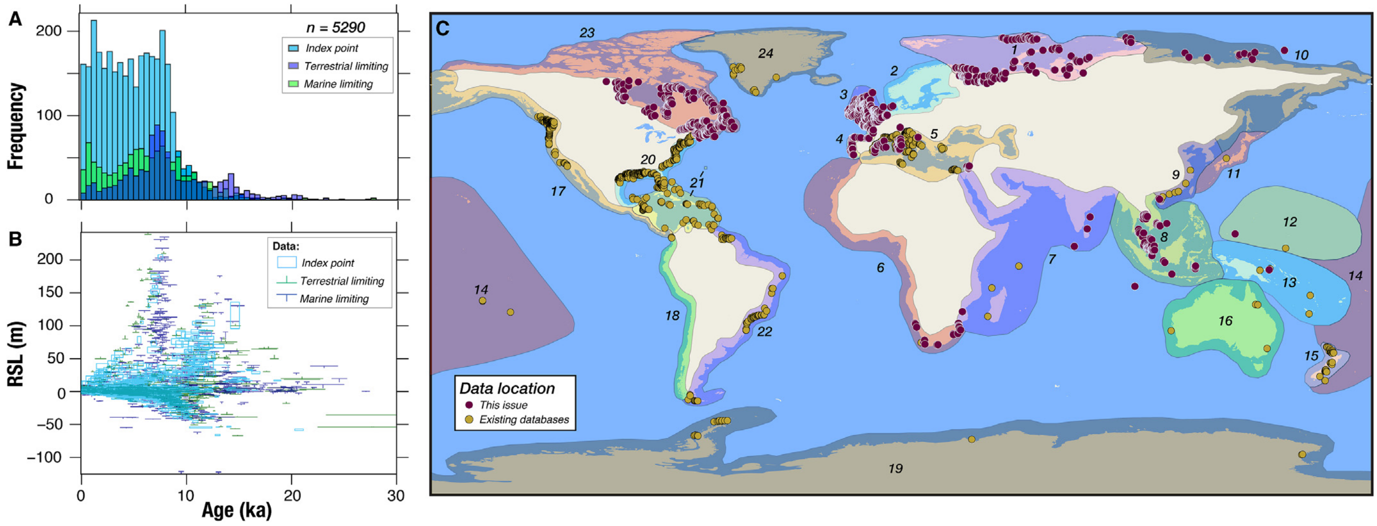

Fig. 2. Temporal and spatial distribution of the current dataset amassed by the HOLSEA working group. (A) Histogram showing the temporal distribution of the number of index points and limiting data since the LGM. (B) RSL variability exhibited in the global dataset since the LGM. (C) Spatial distribution of the global dataset presented in this special issue across 24 regions, modified from those identified by Pirazzoli (1991).

geomorphic, archaeological and fixed biological proxies, in addition to coral reefs, microatolls, and wetland flora and fauna (Fig. 3). The past position of RSL over space and time is defined by sea-level index or limiting points. Sea-level index points (or SLIPs) define the discrete position of past RSL in space and time, whereas limiting data provide an upper (terrestrial or upper limiting data points) or lower (marine or lower limiting data points) bound on the past position of RSL at a given point in space and time. Sea-level index points and limiting data are characterized by the following four fundamental attributes:

- Geographic location;
- Age of formation, traditionally determined by radiometric methods (e.g. radiocarbon or U-series dating) and/or by archaeological attribution;
- Elevation of the sample with respect to a contemporary tidal datum; and
- Relationship of the proxy to sea level. This relationship is known as the ‘indicative meaning’, which describes the central tendency (reference water level) and 2σ vertical range (indicative range) of the indicator's distribution relative to tidal levels (van de Plassche, 1986a, 1986b; Shennan et al., 2015).

Although these four fundamental pieces of information are necessary to characterize sea-level index points and limiting data, in practice many more fields are required to appropriately archive information related to geological samples (e.g. stratigraphic context, sample collection method, laboratory processing, etc.). Distinction is made in the database between fields that represent direct measurements/observations and interpretations (often based on models, such as a radiocarbon calibration). This important distinction allows for re-interpretation as new advancements (e.g., new radiocarbon calibration datasets) arise (Hijma et al., 2015; Düsterhus et al., 2016; Hibbert et al., 2016). We also designate fields that relate to the quality of the constraint the sample provides on the past position of RSL at a given time. A sample may be excluded from further analysis (i.e., ‘rejected’) if any of the fundamental criteria of a sea-level index point or limiting data point (location, age, elevation related to former sea level) cannot be measured or estimated within reasonable uncertainty. The database template used in all publications in this special issue contains 77 fields to archive the geographic location, age, and vertical attributes of each sample (Hijma et al., 2015), 18 fields to house information related to radiocarbon dating (Törnqvist et al., 2015), and 18 fields to store Uranium-series metadata (Dutton, 2015). We are also currently developing formats to archive other dating methods (e.g., optically stimulated luminescence [OSL] or electron spin resonance [ESR]) that are less common in the current database. The relatively high number of fields of metadata related to each sample may seem daunting to a potential user; however, the structure of the database

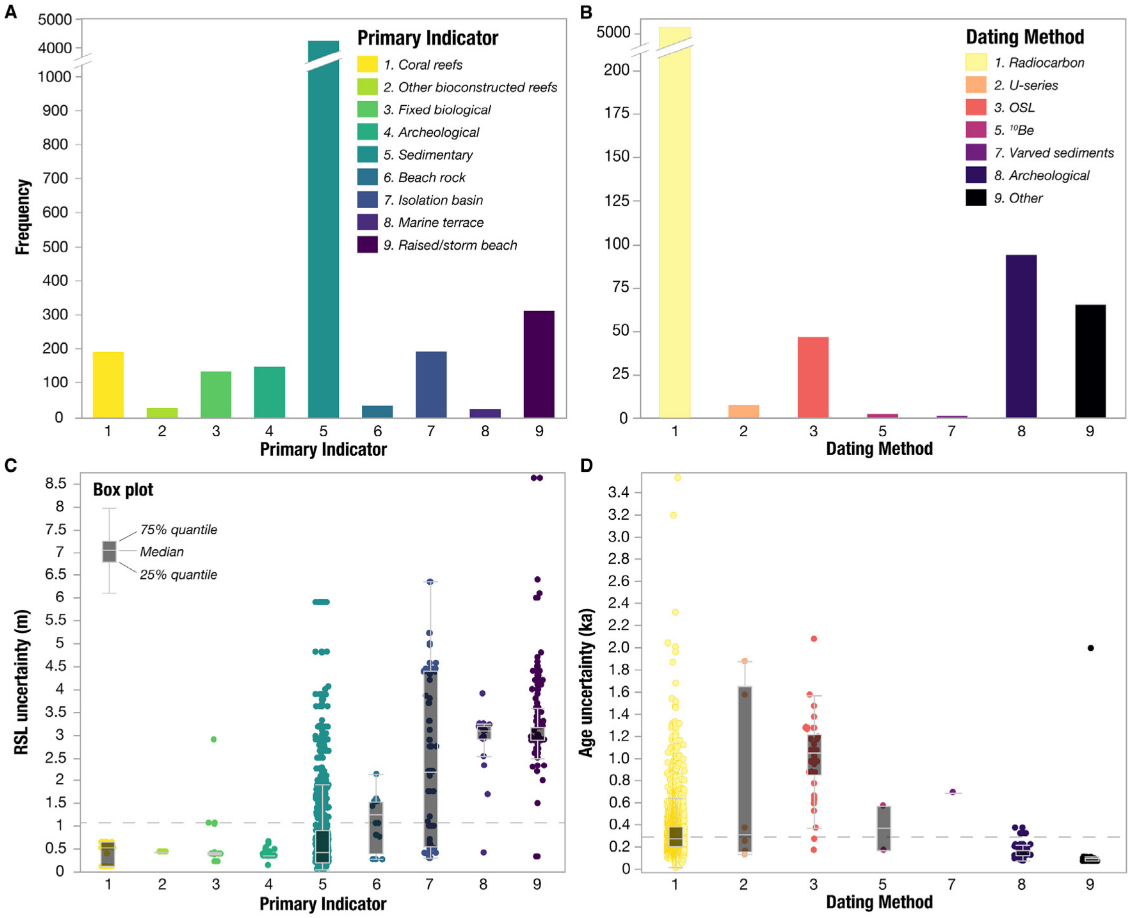

Fig. 3. Frequency of sea-level indicators (A), dating methods (B) and their uncertainties (C, D) in the global atlas presented in this special issue. RSL and age uncertainties are $\pm 2\sigma$ (i.e., half the 2σ uncertainty range). ‘Other’ dating methods in B and D include electron spin resonance (ESR) dating (Baranskaya et al., 2018, this issue), age-depth model estimates developed from composite chronologies derived from radiocarbon ages and fallout radionuclides (e.g., ^{210}Pb and ^{137}Cs) (Shaw et al., 2018, this issue), and annual growth bands between dated coral microatoll die-downs (Meltzner et al., 2017; Mann et al., 2019, accepted, this issue). The horizontal dashed lines in C and D represent the overall mean of all uncertainties.

was designed to be comprehensive and flexible to accommodate RSL data from a wide range of indicators or proxies. For many indicators, far fewer than the total number of fields are necessary to complete. The database template and detailed instructions describing its use are included as an Appendix to this introduction.

4. The global atlas

This special issue includes papers that present regional sea-level databases that span near-, intermediate-, and far-field locations (Table 1; Fig. 2). In near-field regions (i.e., areas located beneath continental ice sheets during the LGM), the rate of GIA uplift during deglaciation exceeded the rate of ESL rise, thus RSL records from these regions are characterized by continuous RSL fall. Comparisons between the near-field databases and GIA model predictions provide critical constraints on various parameters of GIA models (Shennan et al., 2018, this issue; Vacchi et al., 2018a, 2018b, this issue; Baranskaya et al., 2018, this issue). Vacchi et al. (2018a, this issue) revise the RSL history for Hudson Bay, an area relatively insensitive to ice loading histories and from which data can be used to estimate postglacial decay times that provide powerful constraints on Earth's viscous structure (e.g., Andrews, 1970; Mitrovica and Peltier, 1995; Han and Gomez, 2018). Shennan et al. (2018, this issue) offer important near-field insights into the magnitude of MWP-1A, the final deglaciation of the Laurentide Ice Sheet, and the continued melting of the Antarctic Ice Sheet after 7 ka. In addition, Shennan et al. (2018, this issue) show no coincident patterns of consistent coastal advance and retreat across different regions (~100–500 km in scale), implying that within-estuary processes produce major controls on the temporal pattern of horizontal shifts in coastal sedimentary environments. Baranskaya et al. (2018, this issue) present the first quality-controlled RSL database from the Russian Arctic spanning the Barents to Laptev Sea coastlines. Much of this region was formerly covered by the Barents Sea portion of the Eurasian Ice Sheet, although estimates vary on its thickness and spatial extent (e.g., Patton et al., 2015), which this database may help to address.

Table 1
Standardized, publicly-available, post-LGM sea-level databases.

This issue	
Atlantic Canada	Vacchi et al. (2018a)
Russian Arctic	Baranskaya et al. (2018)
British Isles	Shennan et al. (2018)
Northwest Europe	Hijma and Cohen (2019)
Atlantic Europe	García-Artola et al. (2018)
Mediterranean	Vacchi et al. (2018b)
	Shaw et al. (2018)
	Dean et al. (2019)
South Africa	Cooper et al. (2018)
Southeast Asia, India, Sri Lanka and the Maldives	Mann et al. (2019)
	Tam et al. (2018)
Existing	
Greenland	Long et al. (2011)
Antarctica	Briggs and Tarasov (2013)
Northwest Europe	Hijma and Cohen (2010)
	Meijles et al. (2018)
	Vink et al. (2007) (data available in Steffan, 2006)
Mediterranean	Vacchi et al. (2014, 2016)
US Atlantic	Engelhart and Horton (2012)
	Hawkes et al. (2016)
US Pacific	Engelhart et al. (2015)
	Reynolds and Simms (2015)
US Gulf	Hijma et al. (2015)
	Love et al. (2016)
Circum-Caribbean	Khan et al. (2017)
	Milne and Peros (2013)
Atlantic South America	Milne et al. (2005)
China	Zong (2004)
New Zealand	Clement et al. (2016)
Australia	Belperio et al. (2002)
	Woodroffe (2009)
Mid- to low-latitude locations	Hibbert et al. (2016, 2018)

Moving to intermediate-field locations on the periphery of LGM ice margins, RSL databases show continuously rising RSL due to ESL contributions and GIA forebulge subsidence, which are modulated by other local- to regional-scale processes. Hijma and Cohen (2019, this issue) provide the first evidence for a possible two-phase jump in RSL in the early to mid Holocene in the Rhine-Meuse Delta, and suggest important insights into the ESL and RSL response to rapid climate forcing. Garcia-Artola et al. (2018, this issue) show the spatial and temporal variability of rates of RSL change across the Atlantic coast of Europe in response to deglaciation of the British-Irish and Fennoscandian sectors of the Eurasian Ice Sheet, which suggests a potential migration of the peripheral forebulge from the northeast to the northwest after ~4 ka. In the western Mediterranean, Vacchi et al. (2018b, this issue) reveal a pattern of RSL variability driven by GIA that shows a significant departure from available GIA models, notably in the center of the basin. Further east in the Mediterranean, Shaw et al. (2018, this issue) and Dean et al. (2019, this issue) consider processes that cause RSL histories to deviate from those predicted by GIA models. Shaw et al. (2018, this issue) note deviations between GIA model predictions and the late Holocene RSL history of Croatia, which suggests a subsidence rate of 0.45 ± 0.6 mm/yr that they attribute to the Adriatic tectonic framework. In Israel, Dean et al. (2019, this issue) find centennial-scale fluctuations in the RSL history that correspond in timing with variations in regional climate proxies, including periods of increased storminess and/or precipitation.

Far-field locations distal to former ice sheets are sensitive to ice-equivalent contributions to RSL change, and many locations are characterized by a mid-Holocene sea-level highstand, approximately around the time meltwater production decreased (e.g., Pirazzoli, 1991). The fall in RSL to its present position is due to hydro-isostatic loading (also termed continental levering) (e.g., Clark et al., 1978; Nakada and Lambeck, 1989), a global fall in the ocean surface due to both hydro-and glacio-isostatic loading of the Earth's surface (termed equatorial ocean syphoning) (e.g., Mitrovica and Milne, 2002), and rotational feedback (e.g., Mitrovica et al., 2001). Cooper et al. (2018, this issue) review sea-level data from southern Namibia, South Africa, and southern Mozambique and conclude that existing sea-level data have insufficient resolution to accurately define the Holocene highstand or previously inferred oscillations during the mid to late Holocene. Mann et al. (2019, this issue) bring together sea-level data from across South and Southeast Asia and demonstrate how the spatial variability of GIA, tectonics, and local scale processes, such as compaction, contribute to Holocene RSL in the regions. Tam et al. (2018, this issue) raise the possibility of RSL below present during the last ~2 ka in the Malay-Thai peninsula, an area previously expected to be subject to a RSL highstand during this time. Barring significant local-scale effects, this RSL trend would require a substantial meltwater input in the last several thousand years.

Together, the papers from this special issue combine to create a database of 5634 samples that span ~20,000 years ago to present. Of the 5634 samples, 5290 of them could be validated (i.e., meet the criteria to define or reasonably estimate the fundamental attributes described in section 3.3) as index (n = 3202) and limiting points (n = 2088). The global atlas presented in this special issue predominantly consists of sedimentary indicators (n = 4224) in all locations (Fig. 3a). In high latitudes, there is a greater occurrence of raised/storm beaches (n = 310), isolation basins (n = 192), and marine terraces (n = 25), whereas in low-latitudes, coral reefs (including microatolls) occur in greater numbers (n = 191). Fixed biological indicators (n = 134), beach rock (n = 35), and other bio-constructed reefs (n = 28) are found on rocky or high-energy coastlines, and archaeological indicators (n = 149) appear in locations with a long history of human occupation (e.g., the Mediterranean Sea and the British Isles). The vertical uncertainty of RSL reconstructions is primarily related to the indicative range of the sea-level proxy, which for most sedimentary, fixed biological, and geomorphic indicators is a function of the magnitude of the local tidal range from which the sample was collected (Fig. 3c). However, especially in the case of older studies where precise leveling or geodetic techniques were unavailable, elevation uncertainties contribute significantly to the total RSL uncertainty. For example, in the Russian Arctic, although isolation basins provide relatively well-constrained indicative meanings, often times the elevation of the sill that separated the basin from the sea in the past is estimated using imprecise means (e.g., topographic map or altimeter; Baranskaya et al., 2018, this issue), which contributes to the relatively high uncertainties of indicators on uplifting coastlines that occur well above present-day RSL (Fig. 3c). Finally, RSL uncertainties are not systematically larger for older reconstructions (Fig. 4a); however, paleo-tidal range and coastal paleoceanography changes (e.g., Shennan et al., 2018, this issue; Hill et al., 2011; Hijma et al., 2015; Khan et al., 2017) or variations in the relationship of a proxy to sea level over time may add unquantified uncertainties that are difficult to estimate.

The method used to date a sea-level indicator dictates the age range over which it may be used and its age uncertainty. Given that the LGM falls well within the time span in which radiocarbon ages can be reliably obtained (the last ~40-50 ka), radiocarbon dating (n = 5058) is the primary method used to date sea-level indicators in this global atlas (Fig. 3b). However, datable, *in-situ* carbonaceous material may not accumulate in some (typically high-energy) settings, and in marine and estuarine environments, the influence of the local marine reservoir effect and diagenetic processes introduces significant uncertainties into radiocarbon ages (e.g., Törnqvist et al., 2015; Bush et al., 2013). These factors necessitate alternative dating methods, such as U-series (n = 6), OSL (n = 47), or archaeological (n = 91) methods (Fig. 1b), some of which offer comparable precision to radiocarbon dating (Fig. 1d), although they have their own associated caveats and considerations (e.g., Dutton, 2015; Bateman, 2015; Morhange and Marriner, 2015). In contrast to the RSL uncertainty of reconstructions, the age uncertainty does increase over time (Fig. 4b).

The new contributions in this special issue will be combined with databases compiled in recent years following a similar standard from the Atlantic (Engelhart and Horton, 2012), Pacific (Engelhart et al., 2015), Gulf (Hijma et al., 2015; Love et al., 2016), and Caribbean (Khan et al., 2017) coasts of North America, Atlantic South America (Milne et al., 2005), Greenland (Long et al., 2011), Antarctica (Briggs and Tarasov, 2013), northwest Europe (Steffen, 2006; Vink et al., 2007), the Barents Sea (Auriac et al., 2016), the Mediterranean Sea (Vacchi et al., 2016, 2014), China (Zong, 2004), Australia (Belperio et al., 2002; Woodroffe, 2009), New Zealand (Clement et al., 2016), and other low-latitude locations (Hibbert et al., 2018, 2016) to produce a spatially-comprehensive global sea-level database (Table 1; Fig. 2).

5. Continued development of the global atlas

We publish this database with the intention that it may be used by the larger community to: 1) produce a data-driven reconstruction of global mean sea level (GMSL) from the LGM to present (e.g., Kopp et al., 2016, 2009; Lambeck et al., 2014); 2) examine regional variability of RSL, its rates, and its driving mechanisms (e.g., Engelhart et al., 2015; Khan et al., 2017; García-Artola et al., 2018); 3) make projections of spatial variability of RSL for regional scenarios of sea-level rise (e.g., Miller et al., 2013; Kopp et al., 2015b; Love et al., 2016); 4) provide a high-quality standard to the GIA modeling community for model tuning and optimization (e.g., Roy and Peltier, 2015, 2018; Yousefi et al., 2018; Clark et al., 2019); and 5) interface seamlessly with older (Plio-Pleistocene) archives and new data that become available after this special issue is published. However, the regional databases presented in this special issue only represent a first step in developing a standardized, high-quality, spatially-comprehensive global atlas. Further work is required to update the databases published prior to the special issue with new studies since their publication, and further standardization may be required to fully integrate these regional databases with the global atlas presented here. Moreover, key spatial gaps remain in Fennoscandia, the Baltic Sea, Arctic Canada, Pacific Central and South America, Africa, and the Pacific Islands, and there is limited data spanning the deglacial period (i.e., older than 9 ka). These spatial gaps may be due to a variety of reasons. In some cases, data are available but they have yet to be archived in the standardized format presented here (e.g., Scandinavia). In other cases, data are sparse due to inaccessibility of the field area (e.g., remote polar locations) or poor preservation potential of sea-level indicators in given regions or time periods (e.g., highstand coastlines or locations

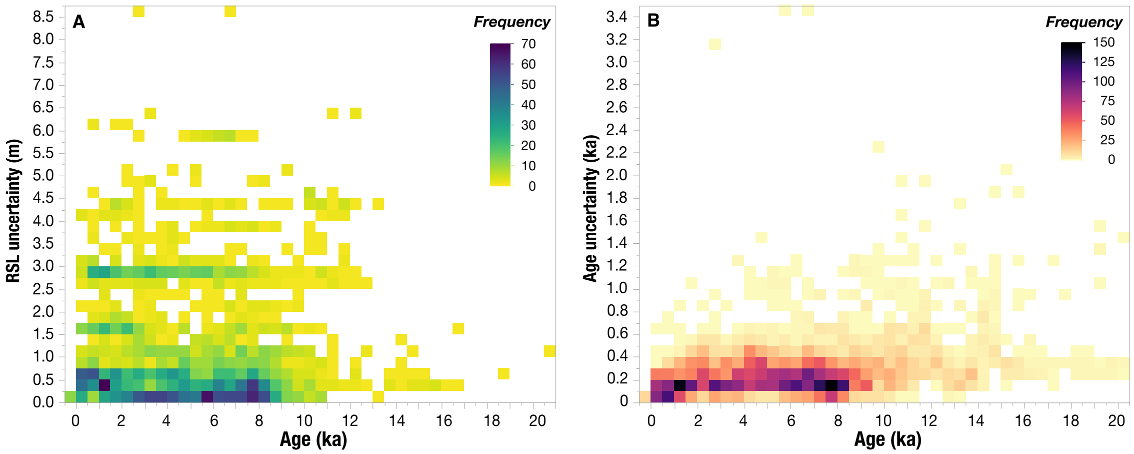

Fig. 4. Variation of RSL (A) and age (B) uncertainties of the data presented in this special issue as a function of time. RSL and age uncertainties are ± 2σ (i.e., half the 2σ uncertainty range).

where human activities, coastal erosion or sea-level rise have destroyed late Holocene archives). Any future research efforts targeting these locations should ask the question whether data from these regions are useful to the scientific question at hand (e.g., constraining solid Earth properties, ice-equivalent meltwater input, or fingerprinting sources of ice melt). Further scrutiny and debate regarding the remaining scientific challenges in understanding post-LGM sea levels and defining where and for what time periods data are needed to address these questions is an important avenue of future work.

Significant challenges remain in continued database development, maintenance and longevity. Addressing gaps in the database requires continued participation and support from the wider paleo sea-level community. This includes finding incentives for data scientists who have previously produced paleo sea-level data to directly or indirectly cooperate to include their data in this global atlas, as well as data scientists who are actively producing new sea-level records to publish their data in the format we outline. For example, use of this data template may be one avenue to simplify data management plans that are increasingly being required for grant proposals. In addition, developments such as journals directly dedicated to publishing datasets (e.g., *Open Quaternary, Nature Scientific Data, Earth System Science Data, Mendeley*) and the consideration of datasets as equivalent to publications for processes of tenure and promotion will likely improve the chances of datasets being updated on a regular basis (Düsterhus et al., 2016).

To improve the longevity of the database management, we will integrate it with established, online archives that are used by the wider community, such as the NOAA World Data Center for Paleoclimatology, PANGAEA, and the Interdisciplinary Earth Data Alliance (IEDA), and maintain a website (www.holsea.org) to access and provide updates regarding the database. Both raw and reinterpreted data will be made available to satisfy the needs of end users that may not have the expertise to re-evaluate raw data. However, questions remain about oversight of quality control and accommodating differing interpretations of data. To illustrate this point, we draw on an example from this special issue where two studies (Tam et al., 2018, this issue; Mann et al., 2019, this issue) compiled the same original data from the region of Peninsular Malaysia (Fig. 5). It is evident that there are some small differences in how samples are interpreted (e.g., index point vs. limiting data), and the midpoints and uncertainties of the index points vary. The differences in ages primarily come from the choice by Mann et al. (2019, this issue) to add an additional 'bulk uncertainty' of ±100 years to dated peat samples (after Törnqvist et al., 2015; Hijma et al., 2015) to account for heterogeneity in the ages of material incorporated in bulk peat samples. The primary difference in RSL and vertical uncertainties is the choice of indicative meanings, where a) a more conservative approach is taken by Mann et al. (2019, this issue), which is appropriate for the broad spatial scale of their study across South and Southeast Asia, and b) a more detailed approach is taken in Tam et al. (2018, this issue), where they try to refine the indicative meanings for a smaller region based on modern surveys. In addition, Mann et al. (2019, this issue) consider limiting data and include additional samples in their analysis that Tam et al. (2018, this issue) exclude. Importantly, both interpretations provide broadly consistent accounts of the RSL evolution in this region (Fig. 5). Further, because both studies used the database template, it is possible to quickly assess why there are differences between the two datasets. To account for differing interpretations of overlapping datasets, we will flag instances where the same sample has multiple interpretations, and leave the decision to the end user of the database to choose which interpretation to use given the objectives of their study. Moreover, in the current database template, a binary accept-reject system is used for data quality considerations. Future work should consider different rankings of data quality that are clearly outlined.

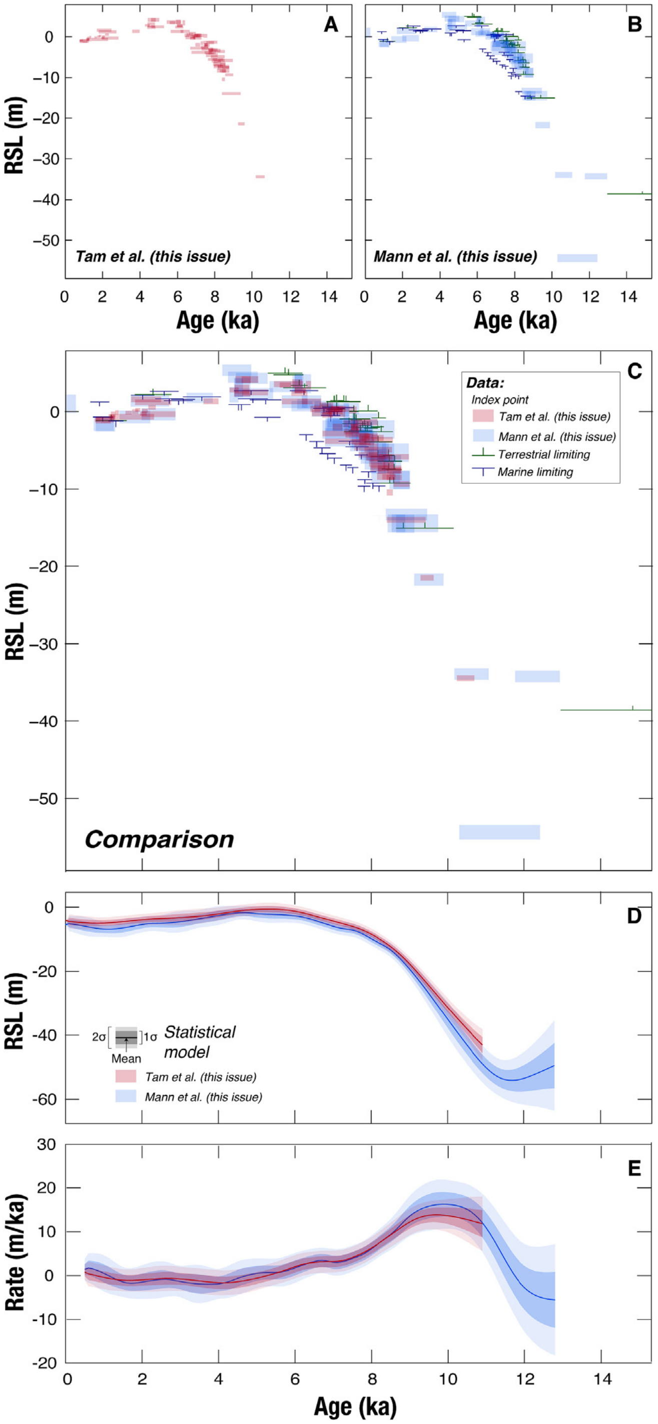

Fig. 5. Comparison of overlapping datasets in Peninsular Malaysia compiled by Tam et al. (2018, this issue) (A) and Mann et al. (2019, this issue) (B). Both datasets (C) show a largely similar RSL history, although some differences exist in the interpretation of the data. A statistical model applied to both datasets shows indistinguishable RSL (D) and rates of RSL change (E) at the 2σ level. See section 5 for further discussion.

This special issue provides an important step forward towards a unified, spatially-comprehensive post-LGM global RSL database. Improved understanding of the mechanisms driving RSL variability will be achieved through the standardization of sea-level databases, which will enhance the comparability and accessibility of information to improve both geophysical models and statistical reconstructions. This not only applies to post-LGM timescales, but also to communities working on deciphering mechanisms of Plio-Pleistocene RSL that have only more recently adopted the methodology developed through IGCP projects. We conclude with the same sentiment expressed over 30 years ago (Shennan, 1987a, 1987b, p. 227) near the conclusion of the second IGCP project aimed at establishing a global atlas of Holocene sea levels, which continues to hold true today: “IGCP Project 200 aims to initiate a move towards global analyses and applied science, both based in the first instance on high-quality local sea-level data. Whether or not the ‘C’ [in IGCP] stands for correlation or co-operation, a number of aims and advances will be thwarted without the unselfish contribution of every sea-level research worker contributing to the exchange of data, especially the compilation of the data banks.”

Acknowledgements

First and foremost, we want to thank and acknowledge all the authors whose work contributed to the global atlas, in particular those whose original studies contributed to the regional databases presented in this special issue. We also thank the participants who attended the HOLSEA meetings in Mt Hood, Oregon and St Lucia, South Africa, whose support and guidance contributed to this special issue being published, and the INQUA Coastal and Marine Processes (CMP) Commission, which provided financial support for the meetings.

NSK and BPH were funded by the Singapore Ministry of Education Academic Research Fund MOE2018-T2-1-030, the National Research Foundation Singapore, and the Singapore Ministry of Education, under the Research Centres of Excellence initiative. This work is Earth Observatory of Singapore contribution 252. AR acknowledges the Institutional Strategy of the University of Bremen, funded by the German Excellence Initiative (ABPZuK-03/2014) and the SEASCHANGE (RO-5245/1-1) from the Deutsche Forschungsgemeinschaft (DFG) as part of the Special Priority Program (SPP)-1889 ″Regional Sea Level Change and Society”. TET acknowledges support from the Paleo Perspectives on Climate Change program of the US National Science Foundation (OCE-1502588). We thank Maren Bender for her help in preparing the comparison of data from Southeast Asia. This article is a contribution to PALSEA (Palaeo-Constraints on Sea-Level Rise) and International Geoscience Program (IGCP) Project 639, “Sea Level Change from Minutes to Millennia”.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.quascirev.2019.07.016.

References

Abdul, N.A., Mortlock, R.A., Wright, J.D., Fairbanks, R.G., 2016. Younger Dryas sea level and meltwater pulse 1B recorded in Barbados reef crest coral Acropora palmata. Paleoceanography 31, 2015PA002847. https://doi.org/10.1002/2015PA002847.

Adams, P.N., Opdyke, N.D., Jaeger, J.M., 2010. Isostatic uplift driven by karstification and sea-level oscillation: modeling landscape evolution in north Florida. Geology 38, 531–534. https://doi.org/10.1130/G30592.1.

Allison, M., Yuill, B., Törnqvist, T., Amelung, F., Dixon, T., Erkens, G., Stuurman, R., Jones, C., Milne, G., Steckler, M., Syvitski, J., Teatini, P., 2016. Global risks and research priorities for coastal subsidence. EOS 97. https://doi.org/10.1029/2016EO055013.

Andrews, J.T., 1970. A Geomorphological Study of Post-glacial Uplift: with Particular Reference to Arctic Canada, No. 2. Institute of British Geographers, London.

Ashe, E.L., Cahill, N., Hay, C., Khan, N.S., Kemp, A., Engelhart, S.E., Horton, B.P., Parnell, A.C., Kopp, R.E., 2019. Statistical modeling of rates and trends in Holocene relative sea level. Quat. Sci. Rev. 204, 58–77. https://doi.org/10.1016/j.quascirev.2018.10.032.

Atwater, B.F., 1987. Evidence for great Holocene earthquakes along the outer coast of Washington state. Science 236, 942–944. https://doi.org/10.1126/science.236.4804.942.

Auriac, A., Whitehouse, P.L., Bentley, M.J., Patton, H., Lloyd, J.M., Hubbard, A., 2016. Glacial isostatic adjustment associated with the Barents Sea ice sheet: a modelling inter-comparison. Quat. Sci. Rev. 147, 122–135. https://doi.org/10.1016/j.quascirev.2016.02.011.

Austermann, J., Mitrovica, J.X., Latychev, K., Milne, G.A., 2013. Barbados-based estimate of ice volume at Last Glacial Maximum affected by subducted plate. Nat. Geosci. 6, 553–557. https://doi.org/10.1038/ngeo1859.

Babbage, C., 1847. Observation on the Temple of Serapis at Pozzuoli Near Naples with remarks on certain causes which may produce geological cycles of great extent. Quar. J. Geol. Soc. 3, 186–217. https://doi.org/10.1144/GSL.JGS.1847.003.01-02.22.

Baranskaya, A.V., Khan, N.S., Romanenko, F.A., Roy, K., Peltier, W.R., Horton, B.P., 2018. A postglacial relative sea-level database for the Russian Arctic coast. Quat. Sci. Rev. 199, 188–205. https://doi.org/10.1016/j.quascirev.2018.07.033.

Bard, E., Hamelin, B., Delanghe-Sabatier, D., 2010. Deglacial meltwater pulse 1B and Younger Dryas sea levels revisited with boreholes at Tahiti. Science 327, 1235–1237. https://doi.org/10.1126/science.1180557.

Bassett, S.E., Milne, G.A., Mitrovica, J.X., Clark, P.U., 2005. Ice sheet and solid earth influences on far-field sea-level histories. Science 309, 925–928. https://doi.org/10.1126/science.1111575.

Bateman, M.D., 2015. The application of luminescence dating in sea-level studies. In: Shennan, I., Long, A.J., Horton, B.P. (Eds.), Handbook of Sea-Level Research. John Wiley & Sons, pp. 404–418.

Belperio, A.P., Harvey, N., Bourman, R.P., 2002. Spatial and temporal variability in the Holocene sea-level record of the South Australian coastline. Sedimentary Geology, Coastal Environment Change During Sea-Level Highstands 150, 153–169. https://doi.org/10.1016/S0037-0738(01)00273-1.

Bennema, J., 1954. Bodem- en zeespiegelbewegingen in het Nederlandse kustgebied (Doctoral dissertation, Veenman).

Bird, M.I., Austin, W.E.N., Wurster, C.M., Fifield, L.K., Mojtahid, M., Sargeant, C., 2010. Punctuated eustatic sea-level rise in the early mid-Holocene. Geology 38, 803–806. https://doi.org/10.1130/G31066.1.

Bloom, A.L., 1977. Atlas of sea-level curves. IGCP Project 61.

Bradley, S.L., Milne, G.A., Horton, B.P., Zong, Y., 2016. Modelling sea level data from China and Malay-Thailand to estimate Holocene ice-volume equivalent sea level change. Quat. Sci. Rev. 137, 54–68. https://doi.org/10.1016/j.quascirev.2016.02.002.

Briggs, R.D., Tarasov, L., 2013. How to evaluate model-derived deglaciation chronologies: a case study using Antarctica. Quat. Sci. Rev. 63, 109–127. https://doi.org/10.1016/j.quascirev.2012.11.021.

Broecker, W., Bond, G., Klas, M., Clark, E., McManus, J., 1992. Origin of the northern Atlantic's Heinrich events. Clim. Dyn. 6, 265–273. https://doi.org/10.1007/BF00193540.

Bush, S.L., Santos, G.M., Xu, X., Southon, J.R., Thiagarajan, N., Hines, S.K., Adkins, J.F., 2013. Simple, rapid, and cost effective: a screening method for 14C analysis of small carbonate samples. Radiocarbon 55 (2), 631–640. https://doi.org/10.1017/S0033822200057787.

Carlson, A.E., Clark, P.U., 2012. Ice sheet sources of sea level rise and freshwater discharge during the last deglaciation. Rev. Geophys. 50, RG4007. https://doi.org/10.1029/2011RG000371.

Cazenave, A., Dominh, K., Guinehut, S., Berthier, E., Llovel, W., Ramillien, G., Ablain, M., Larnicol, G., 2009. Sea level budget over 2003–2008: a reevaluation from GRACE space gravimetry, satellite altimetry and Argo. Glob. Planet. Chang. 65, 83–88. https://doi.org/10.1016/j.gloplacha.2008.10.004.

Celsius, A., 1743. Anmärkning Om Vatnets Förminskande Så I Östersiön Som Vesterhafvet. Kongl. Swenska Wetenskaps Academiens Handlingar 4, 33–50.

Chappell, J., Tooley, M.J., Shennan, I., 1987. Late Quaternary sea-level changes in the Australian region. In: Sea-Level Changes. Basil Blackwell, Oxford.

Church, J.A., White, N.J., 2011. Sea-level rise from the late 19th to the early 21st century. Surv. Geophys. 32, 585–602. https://doi.org/10.1007/s10712-011-9119-1.

Clark, J., Mitrovica, J.X., Latychev, K., 2019. Glacial isostatic adjustment in central Cascadia: insights from three-dimensional Earth modeling. Geology 47, 295–298. https://doi.org/10.1130/G45566.1.

Clark, J.A., 1976. Greenland's rapid postglacial emergence: a result of ice-water gravitational attraction. Geology 4, 310–312. https://doi.org/10.1130/0091-7613(1976)4<310:GRPEAR>2.0.CO;2.

Clark, J.A., Farrell, W.E., Peltier, W.R., 1978. Global changes in postglacial sea level: a numerical calculation. Quat. Res. 9, 265–287. https://doi.org/10.1016/0033-5894(78)90033-9.

Clark, J.A., Lingle, C.S., 1977. Future sea-level changes due to West Antarctic ice sheet fluctuations. Nature 269, 206. https://doi.org/10.1038/269206a0.

Clark, P.U., Mitrovica, J.X., Milne, G.A., Tamisiea, M.E., 2002. Sea-level fingerprinting as a direct test for the source of global meltwater pulse IA. Science 295, 2438–2441. https://doi.org/10.1126/science.1069017.

Clark, P.U., Tarasov, L., 2014. Closing the sea level budget at the Last Glacial Maximum. Proc. Natl. Acad. Sci. 111, 15861–15862. https://doi.org/10.1073/pnas.1418970111.

Clement, A.J.H., Whitehouse, P.L., Sloss, C.R., 2016. An examination of spatial variability in the timing and magnitude of Holocene relative sea-level changes in the New Zealand archipelago. Quat. Sci. Rev. 131 (Part A), 73–101. https://doi.org/10.1016/j.quascirev.2015.09.025.

Conrad, C.P., Hager, B.H., 1997. Spatial variations in the rate of sea level rise caused by the present-day melting of glaciers and ice sheets. Geophys. Res. Lett. 24, 1503–1506. https://doi.org/10.1029/97GL01338.

Cooper, J.A.G., Green, A.N., Compton, J.S., 2018. sea-Level change in southern Africa since the Last Glacial Maximum. Quat. Sci. Rev. 201, 303–318. https://doi.org/10.1016/j.quascirev.2018.10.013.

Darwin, C., 1839. Journal of Researches into the Geology and Natural History of the Varoius Countries Visited by H.M.S. Beagle, under the Command of Captain Fitzroy from 1832 to 1836 by Charles Darwin (Colburn).

Davis, J.L., Mitrovica, J.X., 1996. Glacial isostatic adjustment and the anomalous tide gauge record of eastern North America. Nature 379, 331–333. https://doi.org/10.1038/379331a0.

Dean, S., Horton, B.P., Evelpidou, N., Cahill, N., Spada, G., Sivan, D., 2019. Can we detect centennial sea-level variations over the last three thousand years in Israeli archaeological records? Quat. Sci. Rev. 210, 125–135. https://doi.org/10.1016/j.quascirev.2019.02.021.

Devoy, R.J., 2012. Sea Surface Studies: A Global View. Springer Science & Business Media.

Dott, R.H., 1992. An introduction to the ups and downs of eustasy. In: Dott, R.H. (Ed.), Eustasy: the Historical Ups and Downs of a Major Geological Concept, GSA Memoir. Geological Society of America.

Düsterhus, A., Rovere, A., Carlson, A.E., Horton, B.P., Klemann, V., Tarasov, L., Barlow, N.L.M., Bradwell, T., Clark, J., Dutton, A., Gehrels, W.R., Hibbert, F.D., Hijma, M.P., Khan, N., Kopp, R.E., Sivan, D., Törnqvist, T.E., 2016. Palaeo-sea-level and palaeo-ice-sheet databases: problems, strategies, and perspectives. Clim. Past 12, 911–921. https://doi.org/10.5194/cp-12-911-2016.

Dutton, A., 2015. Uranium-thorium dating. In: Shennan, I., Long, A.J., Horton, B.P. (Eds.), Handbook of Sea-Level Research. John Wiley & Sons, Ltd, pp. 386–403.

Dutton, A., Carlson, A.E., Long, A.J., Milne, G.A., Clark, P.U., DeConto, R., Horton, B.P., Rahmstorf, S., Raymo, M.E., 2015a. Sea-level rise due to polar ice-sheet mass loss during past warm periods. Science 349, aaa4019. https://doi.org/10.1126/science.aaa4019.

Dutton, A., Webster, J.M., Zwartz, D., Lambeck, K., Wohlfarth, B., 2015b. Tropical tales of polar ice: evidence of Last Interglacial polar ice sheet retreat recorded by fossil reefs of the granitic Seychelles islands. Quat. Sci. Rev. 107, 182–196. https://doi.org/10.1016/j.quascirev.2014.10.025.

Enfield, D.B., Allen, J.S., 1980. On the structure and dynamics of monthly mean sea level anomalies along the Pacific coast of North and South America. J. Phys. Oceanogr. 10 (4), 557–578.

Engelhart, S.E., Horton, B.P., 2012. Holocene sea level database for the Atlantic coast of the United States. Quat. Sci. Rev. 54, 12–25. https://doi.org/10.1016/j.quascirev.2011.09.013.

Engelhart, S.E., Vacchi, M., Horton, B.P., Nelson, A.R., Kopp, R.E., 2015. A sea-level database for the Pacific coast of central North America. Quat. Sci. Rev. 113, 78–92. https://doi.org/10.1016/j.quascirev.2014.12.001.

Fairbridge, R.W., 1961. Eustatic changes in sea level. Phys. Chem. Earth 4, 99–185. https://doi.org/10.1016/0079-1946(61)90004-0.

Farrell, W.E., Clark, J.A., 1976. On postglacial sea level. Geophys. J. Int. 46, 647–667. https://doi.org/10.1111/j.1365-246X.1976.tb01252.x.

Flemming, N.C., 1969. Archaeological evidence for eustatic change of sea level and earth movements in the western Mediterranean during the last 2,000 years. Geol. Soc. Am. Spec. Pap. 1–98. https://doi.org/10.1130/spe109-p1.

Forbes, J.D., 1829. Physical notice in the Bay of naples; number 5, on the temple of jupiter serapis at Pozzuoli and the phenomena which it exhibits. Edinb. J. Sci. 1, 260–286.

García-Artola, A., Stéphan, P., Cearreta, A., Kopp, R.E., Khan, N.S., Horton, B.P., 2018. Holocene sea-level database from the Atlantic coast of Europe. Quat. Sci. Rev. 196, 177–192. https://doi.org/10.1016/j.quascirev.2018.07.031.

Gehrels, W.R., Long, A., 2007. Quaternary land–ocean interactions: sea-level change, sediments and tsunami. Mar. Geol. 242, 1–4. https://doi.org/10.1016/j.margeo.2007.05.005.

Gehrels, W.R., Shennan, I., 2015. Sea level in time and space: revolutions and inconvenient truths. J. Quat. Sci. 30, 131–143. https://doi.org/10.1002/jqs.2771.

Godwin, H., 1940. Studies in the post-glacial history of British vegetation. III. Fenland pollen diagrams. IV. Post-glacial changes in relative land- and sea-level in the English Fenland. Philos. Trans. R. Soc. Lond. B Biol. Sci. 230, 239–303.

Godwin, H., Suggate, R.P., Willis, E.H., 1958. Radiocarbon dating of the eustatic rise in ocean level. Nature 181, 1518–1519.

Goiran, J.P., Pavlopoulos, K.P., Fouache, E., Triantaphyllou, M., Etienne, R., 2011. Piraeus, The ancient island of Athens: evidence from Holocene sediments and historical archives. Geology 39 (6), 531–534. https://doi.org/10.1130/G31818.1.

Gomez, N., Gregoire, L.J., Mitrovica, J.X., Payne, A.J., 2015. Laurentide-Cordilleran Ice Sheet saddle collapse as a contribution to meltwater pulse 1A. Geophys. Res. Lett. 42, 3954–3962. https://doi.org/10.1002/2015GL063960.

Gregory, J.M., Griffies, S.M., Hughes, C.W., Lowe, J.A., Church, J.A., Fukimori, I., Gomez, N., Kopp, R.E., Landerer, F., Cozannet, G.L., Ponte, R.M., Stammer, D., Tamisiea, M.E., van de Wal, R.S.W., 2019. Concepts and terminology for Sea level: mean, variability and change, both local and global. Surv. Geophys. https://doi.org/10.1007/s10712-019-09525-z.

Grousset, F.E., Cortijo, E., Huon, S., Hervé, L., Richter, T., Burdloff, D., Duprat, J., Weber, O., 2001. Zooming in on Heinrich layers. Paleoceanography 16, 240–259. https://doi.org/10.1029/2000PA000559.

Hall, G.F., Hill, D.F., Horton, B.P., Engelhart, S.E., Peltier, W.R., 2013. A high-resolution study of tides in the Delaware Bay: past conditions and future scenarios. Geophys. Res. Lett. 40, 338–342. https://doi.org/10.1029/2012GL054675.

Han, H.K., Gomez, N., 2018. The impact of water loading on postglacial decay times in Hudson Bay. Earth Planet. Sci. Lett. 489, 156–165. https://doi.org/10.1016/j.epsl.2018.02.043.

Harvey, D., 1969. Explanation in Geography. Edward Arnold, London.

Hauer, M.E., 2017. Migration induced by sea-level rise could reshape the US population landscape. Nat. Clim. Chang. 7, 321–325. https://doi.org/10.1038/nclimate3271.

Hauer, M.E., Evans, J.M., Mishra, D.R., 2016. Millions projected to be at risk from sea-level rise in the continental United States. Nat. Clim. Chang. 6, 691–695. https://doi.org/10.1038/nclimate2961.

Hawkes, A.D., Kemp, A.C., Donnelly, J.P., Horton, B.P., Peltier, W.R., Cahill, N., Hill, D.F., Ashe, E., Alexander, C.R., 2016. Relative sea-level change in northeastern Florida (USA) during the last~ 8.0 ka. Quat. Sci. Rev. 142 (2016), 90–101.

Hibbert, F.D., Rohling, E.J., Dutton, A., Williams, F.H., Chutcharavan, P.M., Zhao, C., Tamisiea, M.E., 2016. Coral indicators of past sea-level change: a global repository of U-series dated benchmarks. Quat. Sci. Rev. 145, 1–56. https://doi.org/10.1016/j.quascirev.2016.04.019.

Hibbert, F.D., Williams, F.H., Fallon, S.J., Rohling, E.J., 2018. A database of biological and geomorphological sea-level markers from the Last Glacial Maximum to present. Sci. Data 5, 180088. https://doi.org/10.1038/sdata.2018.88.

Hijma, M., Engelhart, S., Törnqvist, T., Horton, B., Hu, P., Hill, D., 2015. A protocol for a geological sea-level database. In: Shennan, I., Long, A.J., Horton, B.P. (Eds.), Handbook of Sea-Level Research. John Wiley & Sons, pp. 536–553.

Hijma, M.P., Cohen, K.M., 2010. Timing and magnitude of the sea-level jump preluding the 8200 yr event. Geology 38, 275–278. https://doi.org/10.1130/g30439.1.

Hijma, M.P., Cohen, K.M., 2019. Holocene sea-level database for the Rhine-Meuse Delta, The Netherlands: implications for the pre-8.2 sea-level jump. Quat. Sci. Rev. 214, 68–86. https://doi.org/10.1016/j.quascirev.2019.05.001.

Hill, D.F., Griffiths, S.D., Peltier, W.R., Horton, B.P., Törnqvist, T.E., 2011. High-resolution numerical modeling of tides in the western Atlantic, Gulf of Mexico, and Caribbean Sea during the Holocene. J. Geophys. Res. 116. https://doi.org/10.1029/2010jc006896.

Horton, B.P., Kopp, R.E., Garner, A.J., Hay, C.C., Khan, N.S., Roy, K., Shaw, T.A., 2018. Mapping sea-level change in time, space, and probability. Annu. Rev. Environ. Resour. 43, 481–521. https://doi.org/10.1146/annurev-environ-102017-025826.

Horton, B.P., Long, A.J., Donnelly, J.P., 2009. Quaternary ice sheet–ocean interactions and landscape responses. Quat. Sci. Rev. 28, 1570–1572. https://doi.org/10.1016/j.quascirev.2009.06.014.

Hughes, P.D., Gibbard, P.L., Ehlers, J., 2013. Timing of glaciation during the last glacial cycle: evaluating the concept of a global 'Last Glacial Maximum' (LGM). Earth Sci. Rev. 125, 171–198. https://doi.org/10.1016/j.earscirev.2013.07.003.

Hutchinson, I., 1992. Holocene Sea Level Change in the Pacific Northwest: a Catalogue of Radiocarbon Dates and an Atlas of Regional Sea-Level Curves. Institute of Quaternary Research, Simon Fraser University.

Huxley, T.H., 1878. On the classification and the distribution of the crayfishes. Proc. Zool. Soc. Lond. 751–788.

Jelgersma, S., 1961. Holocene sea-level changes in The Netherlands. Meded. Geol. Sticht. 7, 1–100.

Karegar, M.A., Dixon, T.H., Engelhart, S.E., 2016. Subsidence along the atlantic coast of North America: insights from GPS and late Holocene relative sea level data. Geophys. Res. Lett. 43, 3126–3133. https://doi.org/10.1002/2016GL068015.

Kaye, C.A., Barghoorn, E.S., 1964. Late quaternary sea-level change and crustal rise at Boston, Massachusetts, with notes on the autocompaction of peat. Bull. Geol. Soc. Am. 75, 63–80. https://doi.org/10.1130/0016-7606(1964)75[63:LQSCAC]2.0.CO;2.

Kemp, A.C., Wright, A.J., Edwards, R.J., Barnett, R.L., Brain, M.J., Kopp, R.E., Cahill, N., Horton, B.P., Charman, D.J., Hawkes, A.D., Hill, T.D., van de Plassche, O., 2018. Relative sea-level change in Newfoundland, Canada during the past ~3000 years. Quat. Sci. Rev. 201, 89–110. https://doi.org/10.1016/j.quascirev.2018.10.012.

Kendall, R.A., Mitrovica, J.X., Milne, G.A., Törnqvist, T.E., Li, Y., 2008. The sea-level fingerprint of the 8.2 ka climate event. Geology 36, 423–426. https://doi.org/10.1130/G24550A.1.

Khan, N.S., Ashe, E., Horton, B.P., Dutton, A., Kopp, R.E., Brocard, G., Engelhart, S.E., Hill, D.F., Peltier, W.R., Vane, C.H., Scatena, F.N., 2017. Drivers of Holocene sea-level change in the Caribbean. Quat. Sci. Rev. 155, 13–36. https://doi.org/10.1016/j.quascirev.2016.08.032.

Khan, N.S., Ashe, E., Shaw, T.A., Vacchi, M., Walker, J., Peltier, W.R., Kopp, R.E., Horton, B.P., 2015. Holocene relative sea-level changes from near-, intermediate-, and far-field locations. Curr. Clim. Change Rep. 1, 247–262. https://doi.org/10.1007/s40641-015-0029-z.

Kidson, C., 1986. Sea level changes in the Holocene. In: Sea Level Research: A Manual for the Collection and Evaluation of Data. Geobooks, Norwich.

Kidson, C., 1982. Sea level changes in the Holocene. Quat. Sci. Rev. 1, 121–151. https://doi.org/10.1016/0277-3791(82)90002-6.

Kidson, C., 1977. In: Kidson, C., Tooley, M.J. (Eds.), The Quaternary History of the Irish Sea. Seel House, Liverpool, pp. 1–12.

Kidson, C., Heyworth, A., 1979. Sea "level. Proc. 1978 Int. Symp. Coast. Evol. Quat. São Paulo Braz. 1–28.

Kidson, C., Heyworth, A., 1973. The Flandrian sea-level rise in the Bristol Channel. Proc. Ussher Soc. 2, 565–584.

Kolker, A.S., Allison, M.A., Hameed, S., 2011. An evaluation of subsidence rates and sea-level variability in the northern Gulf of Mexico. Geophys. Res. Lett. 38. https://doi.org/10.1029/2011GL049458.

Kopp, R.E., Hay, C.C., Little, C.M., Mitrovica, J.X., 2015a. Geographic variability of sea-level change. Curr. Clim. Change Rep. 1, 192–204. https://doi.org/10.1007/s40641-015-0015-5.

Kopp, R.E., Horton, B.P., Kemp, A.C., Tebaldi, C., 2015b. Past and future sea-level rise along the coast of North Carolina, USA. Clim. Change 132, 693–707. https://doi.org/10.1007/s10584-015-1451-x.

Kopp, R.E., Horton, R.M., Little, C.M., Mitrovica, J.X., Oppenheimer, M., Rasmussen, D.J., Strauss, B.H., Tebaldi, C., 2014. Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites. Earths Future 2, 2014EF000239. https://doi.org/10.1002/2014EF000239.

Kopp, R.E., Kemp, A.C., Bittermann, K., Horton, B.P., Donnelly, J.P., Gehrels, W.R., Hay, C.C., Mitrovica, J.X., Morrow, E.D., Rahmstorf, S., 2016. Temperature-driven global sea-level variability in the Common Era. Proc. Natl. Acad. Sci. 201517056. https://doi.org/10.1073/pnas.1517056113.

Kopp, R.E., Simons, F.J., Mitrovica, J.X., Maloof, A.C., Oppenheimer, M., 2009. Probabilistic assessment of sea level during the last interglacial stage. Nature 462, 863–867. https://doi.org/10.1038/nature08686.

Kopp, R.E., Mitrovica, J.X., Griffies, S.M., Yin, J., Hay, C.C., Stouffer, R.J., 2010. The impact of Greenland melt on local sea levels: a partially coupled analysis of dynamic and static equilibrium effects in idealized water-hosing experiments. Clim. Change 103 (3–4), 619–625. https://doi.org/10.1007/s10584-010-9935-1.

Kuchar, J., Milne, G., Wolstencroft, M., Love, R., Tarasov, L., Hijma, M., 2018. The influence of sediment isostatic adjustment on sea level change and land motion along the U.S. Gulf coast. J. Geophys. Res. Solid Earth 123, 780–796. https://doi.org/10.1002/2017JB014695.

Kuhn, T.S., 1962. The Structure of Scientific Revolutions. University of Chicago Press.

Lambeck, K., Rouby, H., Purcell, A., Sun, Y., Sambridge, M., 2014. Sea level and global ice volumes from the Last Glacial Maximum to the Holocene. Proc. Natl. Acad. Sci.

Lawrence, T., Long, A.J., Gehrels, W.R., Jackson, L.P., Smith, D.E., 2016. Relative sea-level data from southwest Scotland constrain meltwater-driven sea-level jumps prior to the 8.2 kyr BP event. Quat. Sci. Rev. 151, 292–308. https://doi.org/10.1016/j.quascirev.2016.06.013.

Lecavalier, B.S., Milne, G.A., Simpson, M.J.R., Wake, L., Huybrechts, P., Tarasov, L., Kjeldsen, K.K., Funder, S., Long, A.J., Woodroffe, S., Dyke, A.S., Larsen, N.K., 2014. A model of Greenland ice sheet deglaciation constrained by observations of relative sea level and ice extent. Quat. Sci. Rev. 102, 54–84. https://doi.org/10.1016/j.quascirev.2014.07.018.

Li, Y.-X., Törnqvist, T.E., Nevitt, J.M., Kohl, B., 2012. Synchronizing a sea-level jump, final Lake Agassiz drainage, and abrupt cooling 8200 years ago. Earth Planet. Sci. Lett., Sea Level and Ice Sheet Evolution: A PALSEA Special Edition 315–316, 41–50. https://doi.org/10.1016/j.epsl.2011.05.034.

Libby, W.F., 1952. Radiocarbon Dating, first ed. University of Chicago Press, Chicago.

Long, A.J., Woodroffe, S.A., Roberts, D.H., Dawson, S., 2011. Isolation basins, sea-level changes and the Holocene history of the Greenland Ice Sheet. Quat. Sci. Rev. 30, 3748–3768. https://doi.org/10.1016/j.quascirev.2011.10.013.

Love, R., Milne, G.A., Tarasov, L., Engelhart, S.E., Hijma, M.P., Latychev, K., Horton, B.P., Törnqvist, T.E., 2016. The contribution of glacial isostatic adjustment to projections of sea-level change along the Atlantic and Gulf coasts of North America. Earths Future 4, 440–464. https://doi.org/10.1002/2016EF000363.

Lyell, C., 1872. Principles of Geology. John Murray, London.

Mann, T., Bender, M.M., Lorscheid, T., Stocchi, P., Vacchi, M., Switzer, A.D., Rovere, A., 2019. Holocene sea levels in Southeast Asia, Maldives, India and Sri Lanka: the SEAMIS database. Quat. Sci. Rev. 219, 112–125. https://doi.org/10.1016/j.quascirev.2019.07.007.

McLaren, D., Fedje, D., Hay, M.B., Mackie, Q., Walker, I.J., Shugar, D.H., Eamer, J.B.R., Lian, O.B., Neudorf, C., 2014. A post-glacial sea level hinge on the central Pacific coast of Canada. Quat. Sci. Rev. 97, 148–169. https://doi.org/10.1016/j.quascirev.2014.05.023.

Meijles, E.W., Kiden, P., Streurman, H.J., van der Plicht, J., Vos, P.C., Gehrels, W.R., Kopp, R.E., 2018. Holocene relative mean sea-level changes in the Wadden Sea area, northern Netherlands. J. Quat. Sci. 33, 905–923.

Meltzner, A.J., Switzer, A.D., Horton, B.P., Ashe, E., Qiu, Q., Hill, D.F., Bradley, S.L., Kopp, R.E., Hill, E.M., Majewski, J.M., Natawidjaja, D.H., Suwargadi, B.W., 2017. Half-metre sea-level fluctuations on centennial timescales from mid-Holocene corals of Southeast Asia. Nat. Commun. 8, 14387. https://doi.org/10.1038/ncomms14387.

Mengel, M., Nauels, A., Rogelj, J., Schleussner, C.-F., 2018. Committed sea-level rise under the Paris Agreement and the legacy of delayed mitigation action. Nat. Commun. 9, 601. https://doi.org/10.1038/s41467-018-02985-8.

Miller, K.G., Kopp, R.E., Horton, B.P., Browning, J.V., Kemp, A.C., 2013. A geological perspective on sea-level rise and its impacts along the U.S. mid-Atlantic coast. Earths Future 1, 3–18. https://doi.org/10.1002/2013EF000135.

Milne, G.A., Gehrels, W.R., Hughes, C.W., Tamisiea, M.E., 2009. Identifying the causes of sea-level change. Nat. Geosci. 2, 471–478. https://doi.org/10.1038/ngeo544.

Milne, G.A., Long, A.J., Bassett, S.E., 2005. Modelling holocene relative sea-level observations from the caribbean and south America. Quat. Sci. Rev. 24, 1183–1202. https://doi.org/10.1016/j.quascirev.2004.10.005.

Milne, G.A., Mitrovica, J.X., 2008. Searching for eustasy in deglacial sea-level histories. Quat. Sci. Rev. 27, 2292–2302. https://doi.org/10.1016/j.quascirev.2008.08.018.

Milne, G.A., Peros, M., 2013. Data–model comparison of Holocene sea-level change in the circum-Caribbean region. Global Planet. Change 107, 119–131.

Mimura, N., 2013. Sea-level rise caused by climate change and its implications for society. Proc. Jpn. Acad. Ser. B Phys. Biol. Sci. 89, 281–301. https://doi.org/10.2183/pjab.89.281.

Mitrovica, J.X., Gomez, N., Morrow, E., Hay, C., Latychev, K., Tamisiea, M.E., 2011. On the robustness of predictions of sea level fingerprints. Geophys. J. Int. 187, 729–742. https://doi.org/10.1111/j.1365-246X.2011.05090.x.

Mitrovica, J.X., Milne, G.A., 2002. On the origin of late Holocene sea-level highstands within equatorial ocean basins. Quat. Sci. Rev. 21, 2179–2190. https://doi.org/10.1016/S0277-3791(02)00080-X.

Mitrovica, J.X., Milne, G.A., Davis, J.L., 2001. Glacial isostatic adjustment on a rotating earth. Geophys. J. Int. 147, 562–578.

Mitrovica, J.X., Peltier, W.R., 1995. Constraints on mantle viscosity based upon the inversion of post-glacial uplift data from the Hudson Bay region. Geophys. J. Int. 122, 353–377. https://doi.org/10.1111/j.1365-246X.1995.tb07002.x.

Morhange, C., Marriner, N., 2015. Archeological and biological relative sea-level indicators. In: Shennan, I., Long, A.J., Horton, B.P. (Eds.), Handbook of Sea-Level Research. John Wiley & Sons, pp. 146–156.

Morhange, C., Pirazzoli, P.A., Marriner, N., Montaggioni, L.F., Nammour, T., 2006. Late Holocene relative sea-level changes in Lebanon. Eastern Mediterranean. Mar. Geol. 230, 99–114. https://doi.org/10.1016/j.margeo.2006.04.003.

Morner, N.A., 1969. Eustatic and climatic changes during the last 15,000 years. Geol. Mijnb.

Nakada, M., Lambeck, K., 1989. Late Pleistocene and Holocene sea-level change in the Australian region and mantle rheology. Geophys. J. Int. 96, 497–517. https://doi.org/10.1111/j.1365-246X.1989.tb06010.x.

Nelson, A.R., 2007. SEA-LEVELS, LATE QUATERNARY | Tectonic locations. In: Elias, S.A. (Ed.), Encyclopedia of Quaternary Science. Elsevier, Oxford, pp. 3072–3087. https://doi.org/10.1016/B0-44-452747-8/00150-2.

Nelson, A.R., Jennings, A.E., Kashima, K., 1996. An earthquake history derived from stratigraphic and microfossil evidence of relative sea-level change at Coos Bay, southern coastal Oregon. Geol. Soc. Am. Bull. 108, 141–154. https://doi.org/10.1130/0016-7606(1996)108<0141:aehdfs>2.3.co;2.

Neumann, B., Vafeidis, A.T., Zimmermann, J., Nicholls, R.J., 2015. Future coastal population growth and exposure to sea-level rise and coastal flooding - a global assessment. PLoS One 10, e0118571. https://doi.org/10.1371/journal.pone.0118571.

Niccolini, A., 1845. Descrizione della gran terma puteolana volgarmente detta Tempio di Serapide.

Nicholls, R.J., Marinova, N., Lowe, J.A., Brown, S., Vellinga, P., de Gusmão, D., Hinkel, J., Tol, R.S.J., 2011. Sea-level rise and its possible impacts given a “beyond 4°C world” in the twenty-first century. Philos. Transact. A Math. Phys. Eng. Sci. 369, 161–181. https://doi.org/10.1098/rsta.2010.0291.

NRC, 2015. Sea Change: 2015-2025 Decadal Survey of Ocean Sciences. National Academies Press, Washington, D.C, 2015.

Opdyke, N.D., Spangler, D.P., Smith, D.L., Jones, D.S., Lindquist, R.C., 1984. Origin of epeirogenic uplift of the Pliocene-Pleistocene beach ridges in Florida and development of the Florida karst. Geology 12, 226–228. https://doi.org/10.1130/0091-7613(1984)12<226:OOTEUO>2.0.CO;2.

Otvos, E.G., 2018. Eustasy and sea level. In: Finkl, C.W., Makowski, C. (Eds.), Encyclopedia of Coastal Science. Springer International Publishing, Cham, pp. 1–5. https://doi.org/10.1007/978-3-319-48657-4_364-2.

Ovid, Metamorphoses (Kline). XV: 259-306. Accessed from Ovid Collection, Univ. of Virginia E-Text Center.

Padgett, J.S., Engelhart, S.E., Hoffmann, G., Rosentau, A., Yu, F., 2018. Sea-level change from minutes to millennia: first meeting of IGCP Project 639 in Oman. Episodes 41, 115–118.

Patton, H., Andreassen, K., Bjarnadóttir, L.R., Dowdeswell, J.A., Winsborrow, M.C., Noormets, R., Polyak, L., Auriac, A., Hubbard, A., 2015. Geophysical constraints on the dynamics and retreat of the Barents Sea ice sheet as a paleobenchmark for models of marine ice sheet deglaciation. Rev. Geophys. 53, 1051–1098.

Peltier, W.R., 2005. On the hemispheric origins of meltwater pulse 1a. Quat. Sci. Rev., Quaternary Land-ocean Correlation 24, 1655–1671. https://doi.org/10.1016/j.quascirev.2004.06.023.

Peltier, W.R., 2004. Global glacial isostasy and the surface of the ice-age earth: the ICE-5G (VM2) model and GRACE. Annu. Rev. Earth Planet Sci. 32, 111. https://doi.org/10.1146/annurev.earth.32.082503.144359.

Peltier, W.R., 1998. Postglacial variations in the level of the sea: implications for climate dynamics and solid-Earth geophysics. Rev. Geophys. 36, 603. https://doi.org/10.1029/98RG02638.

Peltier, W.R., 1974. The impulse response of a Maxwell Earth. Rev. Geophys. 12, 649–669. https://doi.org/10.1029/RG012i004p00649.

Peltier, W.R., Argus, D.F., Drummond, R., 2015. Space geodesy constrains ice age terminal deglaciation: the global ICE-6G_C (VM5a) model. J. Geophys. Res. Solid Earth 120, 2014JB011176. https://doi.org/10.1002/2014JB011176.

Peltier, W.R., Fairbanks, R.G., 2006. Global glacial ice volume and Last Glacial Maximum duration from an extended Barbados sea level record. Quat. Sci. Rev. 25, 3322–3337. https://doi.org/10.1016/j.quascirev.2006.04.010.

Peltier, W.R., Jiang, X., 1996. Glacial isostatic adjustment and Earth rotation: refined constraints on the viscosity of the deepest mantle. J. Geophys. Res. Solid Earth 101, 3269–3290. https://doi.org/10.1029/95JB01963.

Peltier, W.R., Vettoretti, G., 2014. Dansgaard-Oeschger oscillations predicted in a comprehensive model of glacial climate: a “kicked” salt oscillator in the Atlantic. Geophys. Res. Lett. 41, 7306–7313. https://doi.org/10.1002/2014GL061413.

Piecuch, C.G., Huybers, P., Hay, C.C., Kemp, A.C., Little, C.M., Mitrovica, J.X., Ponte, R.M., Tingley, M.P., 2018. Origin of spatial variation in US East Coast sea-level trends during 1900–2017. Nature 564, 400. https://doi.org/10.1038/s41586-018-0787-6.

Pirazzoli, P.A., 1991. World Atlas of Holocene Sea-Level Changes. Elsevier.

Preuss, H., 1979. Progress in computer evaluation of sea level data within the IGCP Project no. 61. In: Presented at the 1978 International Symposium on Coastal Evolution in the Quaternary. Universidade Sao Paulo, Sao Paulo, pp. 104–134.

Reynolds, L.C., Simms, A.R., 2015. Late Quaternary relative sea level in southern California and Monterey Bay. Quat. Sci. Rev. 126, 57–66.

Rovere, A., Stocchi, P., Vacchi, M., 2016. Eustatic and relative sea level changes. Curr. Clim. Change Rep. 2, 221–231. https://doi.org/10.1007/s40641-016-0045-7.

Roy, K., Peltier, W.R., 2018. Relative sea level in the Western Mediterranean basin: a regional test of the ICE-7G_NA (VM7) model and a constraint on late Holocene Antarctic deglaciation. Quat. Sci. Rev. 183, 76–87. https://doi.org/10.1016/j.quascirev.2017.12.021.

Roy, K., Peltier, W.R., 2015. Glacial isostatic adjustment, relative sea level history and mantle viscosity: reconciling relative sea level model predictions for the U.S. East coast with geological constraints. Geophys. J. Int. 201, 1156–1181. https://doi.org/10.1093/gji/ggv066.

Shaw, T.A., Plater, A.J., Kirby, J.R., Roy, K., Holgate, S., Tutman, P., Cahill, N., Horton, B.P., 2018. Tectonic influences on late Holocene relative sea levels from the central-eastern Adriatic coast of Croatia. Quat. Sci. Rev. 200, 262–275. https://doi.org/10.1016/j.quascirev.2018.09.015.

Shennan, I., 1999. Global meltwater discharge and the deglacial sea-level record from northwest Scotland. J. Quat. Sci. 14, 715–719. https://doi.org/10.1002/(SICI)1099-1417(199912)14:7<715::AID-JQS511>3.0.CO;2-G.

Shennan, I., 1989. Holocene crustal movements and sea-level changes in Great Britain. J. Quat. Sci. 4, 77–89. https://doi.org/10.1002/jqs.3390040109.

Shennan, I., 1987a. Holocene sea-level changes in the North Sea region. In: Sea-Level Changes. Blackwell, pp. 109–151.

Shennan, I., 1987b. Global analysis and correlation of sea-level data. In: Devoy, R.J.N. (Ed.), Sea Surface Studies: A Global View. Springer Netherlands, Dordrecht, pp. 198–230. https://doi.org/10.1007/978-94-015-1146-9_7.

Shennan, I., 1986. Flandrian sea-level changes in the Fenland. I: the geographical setting and evidence of relative sea-level changes. J. Quat. Sci. 1, 119–153. https://doi.org/10.1002/jqs.3390010204.

Shennan, I., 1982. Interpretation of flandrian Sea-level data from the Fenland, England. Proc. Geol. Assoc. 93, 53–63. https://doi.org/10.1016/S0016-7878(82)80032-1.

Shennan, I., Bradley, S.L., Edwards, R., 2018. Relative sea-level changes and crustal movements in Britain and Ireland since the last glacial maximum. Quat. Sci. Rev. 188, 143–159. https://doi.org/10.1016/j.quascirev.2018.03.031.

Shennan, I., Horton, B., 2002. Holocene land- and sea-level changes in Great Britain. J. Quat. Sci. 17, 511–526. https://doi.org/10.1002/jqs.710.

Shennan, I., Long, A.J., Horton, B.P., 2015. Handbook of Sea-Level Research. John Wiley & Sons.

Shennan, I., Tooley, M.J., Davis, M.J., Haggart, B.A., 1983. Analysis and interpretation of Holocene sea-level data. Nature 302, 404. https://doi.org/10.1038/302404a0.

Shepard, F.P., 1963. Thirty-five thousand years of sea level. In: Clements, T. (Ed.), Essays in Marine Geology in Honour of K. O. Emery. University of Southern California Press, Los Angeles.

Shepard, F.P., Suess, H.E., 1956. Rate of postglacial rise of sea level. Science 123, 1082–1083. https://doi.org/10.1126/science.123.3207.1082-a.

Shugar, D.H., Walker, I.J., Lian, O.B., Eamer, J.B.R., Neudorf, C., McLaren, D., Fedje, D., 2014. Post-glacial sea-level change along the Pacific coast of North America. Quat. Sci. Rev. 97, 170–192. https://doi.org/10.1016/j.quascirev.2014.05.022.

Simms, A.R., Lisiecki, L., Gebbie, G., Whitehouse, P.L., Clark, J.F., 2019. Balancing the Last Glacial Maximum (LGM) sea-level budget. Quat. Sci. Rev. 205, 143–153. https://doi.org/10.1016/j.quascirev.2018.12.018.

Simpson, M.J.R., Milne, G.A., Huybrechts, P., Long, A.J., 2009. Calibrating a glaciological model of the Greenland ice sheet from the Last Glacial Maximum to present-day using field observations of relative sea level and ice extent. Quat. Sci. Rev. 28, 1631–1657. https://doi.org/10.1016/J.Quascirev.2009.03.004.

Slangen, A.B.A., Katsman, C.A., van de Wal, R.S.W., Vermeersen, L.L.A., Riva, R.E.M., 2012. Towards regional projections of twenty-first century sea-level change based on IPCC SRES scenarios. Clim. Dyn. 38, 1191–1209. https://doi.org/10.1007/s00382-011-1057-6.

Stanford, J.D., Hemingway, R., Rohling, E.J., Challenor, P.G., Medina-Elizalde, M., Lester, A.J., 2011. Sea-level probability for the last deglaciation: a statistical analysis of far-field records. Glob. Planet. Change 79, 193–203. https://doi.org/10.1016/j.gloplacha.2010.11.002.

Steffen, H., 2006. Determination of a Consistent Viscosity Distribution in the Earth's Mantle beneath Northern and Central Europe. https://doi.org/10.23689/fidgeo-339.

Steffen, W., Rockström, J., Richardson, K., Lenton, T.M., Folke, C., Liverman, D., Summerhayes, C.P., Barnosky, A.D., Cornell, S.E., Crucifix, M., Donges, J.F., Fetzer, I., Lade, S.J., Scheffer, M., Winkelmann, R., Schellnhuber, H.J., 2018. Trajectories of the earth system in the anthropocene. Proc. Natl. Acad. Sci. 115, 8252–8259. https://doi.org/10.1073/pnas.1810141115.

Streif, H., 1979. Cyclic formation of coastal deposits and their indications of vertical sea-level changes. Oceanus 5, 303–306.

Suess, E., 1888. The face of the earth:(Das antlitz der erde).

Switzer, A.D., Sloss, C.R., Horton, B.P., Zong, Y., 2012. Preparing for coastal change. Quat. Sci. Rev. 54, 1–3. https://doi.org/10.1016/j.quascirev.2012.09.005.

Tam, C.Y., Zong, Y., Hassan, K. bin, Bin Ismal, H., Binti Jamil, H., Xiong, H., Wu, P., Sun, Y., Huang, G., Zheng, Z., 2018. A below-the-present late Holocene relative sea level and the glacial isostatic adjustment during the Holocene in the Malay Peninsula. Quat. Sci. Rev. 201, 206–222. https://doi.org/10.1016/j.quascirev.2018.10.009.

Tarasov, L., Peltier, W.R., 2002. Greenland glacial history and local geodynamic consequences. Geophys. J. Int. 150, 198–229.

Tooley, M.J., 1982. Sea-level changes in northern England. Proc. Geol. Assoc. 93, 43–51. https://doi.org/10.1016/S0016-7878(82)80031-X.

Tooley, M.J., 1978. Sea-level Changes: North-West England during the Flandrian Stage. Clarendon Press.

Tooley, M.J., 1974. Sea-level changes during the last 9000 Years in north-west england. Geogr. J. 140, 18–42.

Törnqvist, T.E., Hijma, M.P., 2012. Links between early Holocene ice-sheet decay, sea-level rise and abrupt climate change. Nat. Geosci. 5, 601–606. https://doi.org/10.1038/ngeo1536.

Törnqvist, T.E., Rosenheim, B.E., Hu, P., Fernandez, A.B., 2015. Radiocarbon dating and calibration. In: Shennan, I., Long, A.J., Horton, B.P. (Eds.), Handbook of Sea-Level Research. John Wiley & Sons, Ltd, pp. 349–360.

Törnqvist, T.E., Wallace, D.J., Storms, J.E.A., Wallinga, J., van Dam, R.L., Blaauw, M., Derksen, M.S., Klerks, C.J.W., Meijneken, C., Snijders, E.M.A., 2008. Mississippi Delta subsidence primarily caused by compaction of Holocene strata. Nat. Geosci. 1, 173–176. https://doi.org/10.1038/ngeo129.

Uehara, K., Scourse, J.D., Horsburgh, K.J., Lambeck, K., Purcell, A.P., 2006. Tidal evolution of the northwest European shelf seas from the Last Glacial Maximum to the present. J. Geophys. Res.-Oceans 111. https://doi.org/10.1029/2006jc003531.

Ullman, D.J., Carlson, A.E., Hostetler, S.W., Clark, P.U., Cuzzone, J., Milne, G.A., Winsor, K., Caffee, M., 2016. Final Laurentide ice-sheet deglaciation and Holocene climate-sea level change. Quat. Sci. Rev. 152, 49–59. https://doi.org/10.1016/j.quascirev.2016.09.014.

Vacchi, M., Engelhart, S.E., Nikitina, D., Ashe, E.L., Peltier, W.R., Roy, K., Kopp, R.E., Horton, B.P., 2018a. Postglacial relative sea-level histories along the eastern Canadian coastline. Quat. Sci. Rev. 201, 124–146. https://doi.org/10.1016/j.quascirev.2018.09.043.

Vacchi, M., Ghilardi, M., Melis, R.T., Spada, G., Giaime, M., Marriner, N., Lorscheid, T., Morhange, C., Burjachs, F., Rovere, A., 2018b. New relative sea-level insights into the isostatic history of the Western Mediterranean. Quat. Sci. Rev. 201, 396–408. https://doi.org/10.1016/j.quascirev.2018.10.025.

Vacchi, M., Marriner, N., Morhange, C., Spada, G., Fontana, A., Rovere, A., 2016. Multiproxy assessment of Holocene relative sea-level changes in the western Mediterranean: sea-level variability and improvements in the definition of the isostatic signal. Earth Sci. Rev. 155, 172–197. https://doi.org/10.1016/j.earscirev.2016.02.002.

Vacchi, M., Rovere, A., Chatzipetros, A., Zouros, N., Firpo, M., 2014. An updated database of Holocene relative sea level changes in NE Aegean Sea. Quat. Int. 328, 301–310. https://doi.org/10.1016/j.quaint.2013.08.036.

van de Plassche, O., 1986a. Introduction. In: Sea-Level Research: A Manual for the Collection and Evaluation of Data. Geobooks, Norwich.

van de Plassche, O., 1986b. Sea-level Reasearch: A Manual for the Collection and Evaluation of Data. Geobooks, Norwich.

van de Plassche, O., 1982. Sea-level change and water-level movements in The Netherlands during the Holocene. Meded. Rijks Geol. Dienst 36, 1–93.

van de Plassche, O., Wright, A.J., Horton, B.P., Engelhart, S.E., Kemp, A.C., Mallinson, D., Kopp, R.E., 2014. Estimating tectonic uplift of the Cape Fear Arch (south-eastern United States) using reconstructions of Holocene relative sea level. J. Quat. Sci. 29, 749–759. https://doi.org/10.1002/jqs.2746.

van Straaten, L.M.J., 1954. Radiocarbon datings and changes of sea level at Velzen (Netherlands). Geol. Mijnb. 16, 247–253.

van Veen, J., 1945. Bestaat er een geologische bodemdaling teAmsterdam sedert 1700? Tijdschr Kon Ned Aardr Genootsch 62, 2–36.

Vink, A., Steffen, H., Reinhardt, L., Kaufmann, G., 2007. Holocene Relative Sea-Level Change. Isostatic Subsidence and the Radial Viscosity Structure of the Mantle of Northwest Europe (Belgium, the Netherlands, Germany, Southern North Sea).

Walcott, R.I., 1972. Past sea levels, eustasy and deformation of the earth. Quat. Res. 2, 1–14. https://doi.org/10.1016/0033-5894(72)90001-4.

Wolstencroft, M., Shen, Z., Törnqvist, T.E., Milne, G.A., Kulp, M., 2014. Understanding subsidence in the Mississippi Delta region due to sediment, ice, and ocean loading: insights from geophysical modeling: modeling load-induced subsidence. J. Geophys. Res. Solid Earth 119, 3838–3856. https://doi.org/10.1002/2013JB010928.

Woo, H.B., Panning, M.P., Adams, P.N., Dutton, A., 2017. Karst-driven flexural isostasy in North-Central Florida. Geochem. Geophys. Geosyst. 18, 3327–3339. https://doi.org/10.1002/2017GC006934.

Woodroffe, C.D., Murray-Wallace, C.V., 2012. Sea-level rise and coastal change: the past as a guide to the future. Quat. Sci. Rev. 54, 4–11. https://doi.org/10.1016/j.quascirev.2012.05.009.

Woodroffe, S.A., 2009. Testing models of mid to late Holocene sea-level change, North Queensland, Australia. Quat. Sci. Rev. 28, 2474–2488. https://doi.org/10.1016/j.quascirev.2009.05.004.

Woodworth, P.L., Melet, A., Marcos, M., Ray, R.D., Wöppelmann, G., Sasaki, Y.N., Cirano, M., Hibbert, A., Huthnance, J.M., Monserrat, S., Merrifield, M.A., 2019. Forcing factors affecting sea level changes at the coast. Surv. Geophys. https://doi.org/10.1007/s10712-019-09531-1.

Woodworth, P.L., Morales Maqueda, M.Á., Gehrels, W.R., Roussenov, V.M., Williams, R.G., Hughes, C.W., 2017. Variations in the difference between mean sea level measured either side of Cape Hatteras and their relation to the North Atlantic Oscillation. Clim. Dyn. 49, 2451–2469. https://doi.org/10.1007/s00382-016-3464-1.

Yokoyama, Y., Esat, T.M., Thompson, W.G., Thomas, A.L., Webster, J.M., Miyairi, Y., Sawada, C., Aze, T., Matsuzaki, H., Okuno, J., Fallon, S., Braga, J.-C., Humblet, M., Iryu, Y., Potts, D.C., Fujita, K., Suzuki, A., Kan, H., 2018. Rapid glaciation and a two-step sea level plunge into the Last Glacial Maximum. Nature 559, 603. https://doi.org/10.1038/s41586-018-0335-4.

Yousefi, M., Milne, G.A., Love, R., Tarasov, L., 2018. Glacial isostatic adjustment along the Pacific coast of central North America. Quat. Sci. Rev. 193, 288–311. https://doi.org/10.1016/j.quascirev.2018.06.017.

Yu, S.Y., Berglund, B.E., Sandgren, P., Lambeck, K., 2007. Evidence for a rapid sea-level rise 7600 yr ago. Geology.

Yu, S.-Y., Törnqvist, T.E., Hu, P., 2012. Quantifying Holocene lithospheric subsidence rates underneath the Mississippi Delta. Earth Planet. Sci. Lett. 331–332, 21–30. https://doi.org/10.1016/j.epsl.2012.02.021.

Zong, Y., 2004. Mid-Holocene sea-level highstand along the Southeast coast of China. In: Quat. Int., 117, pp. 55–67. https://doi.org/10.1016/S1040-6182(03)00116-2.