Special Issue: The Impact of Upper Pleistocene Climatic and Environmental Change on Hominin Occupations and Landscape Use, Part 1

Changing Tidal Dynamics and the Role of the Marine Environment in the Maritime Migration to Sahul

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ABSTRACT

The marine environment plays a central role in the migration of *Homo sapiens* to Sahul c. 65,000 years ago. Despite the lower mean sea level at this time, humans must have made a maritime crossing from Sunda to Sahul. While tidal dynamics greatly affect the coastal environment, models of changing paleotidal conditions are frequently missing from reconstructions of coastal landscapes and maritime conditions in the deep past. At present, northern Australia is known for its high tidal range and strong current velocity, but tidal dynamics are sensitive to coastal geometry and water depths that were very different in the past. This paper presents a barotropic hydrodynamic model of the Australian coast to explore how past tidal dynamics would have caused variations in coastal environments north of Australia, and how tidal currents could have affected seafaring. The results indicate profound but complex changes in tidal dynamics along the northern Australian coast throughout the Upper Pleistocene, linked to mean sea level fluctuations, which inform the debate about the peopling of Sahul.

This special issue is guest-edited by William Davies (Centre for the Archaeology of Human Origins, University of Southampton) and Philip R. Nigst (Department of Prehistoric and Historical Archaeology, University of Vienna).

INTRODUCTION

The peopling of Sahul represents some of the earliest evidence for seafaring in global history. Even at the greatest sea level lowstand of the Last Glacial Maximum, movement between Sunda (the exposed shelf of Southeast Asia) and Sahul (Australasia) involved a series of water crossings through the Wallacean archipelago into New Guinea, and or, into Timor and south across to Sahul (Birdsell 1977; Figures 1 and 2).

While many Indigenous Aboriginal and Torres Strait Islander communities know they have *always* been on Country (Uluru Statement of the Heart 2017), within western science the timing of these earliest arrivals into Sahul is debated. A conservative estimate of 47,000 years ago was proposed (O'Connell and Allen 2015; O'Connell et al. 2018), but a growing body of evidence from new sites and re-dating of known sites using different dating methods continues to extend this chronology (see Figure 1). Several archaeological sites in Australia have been dated to between 60,000 and 50,000 years ago (Clarkson et al. 2015; Roberts 1997; Roberts et al. 1990, 1993, 1998). Recently, the site of Madjedbebe in Australia's Northern Territory has been re-

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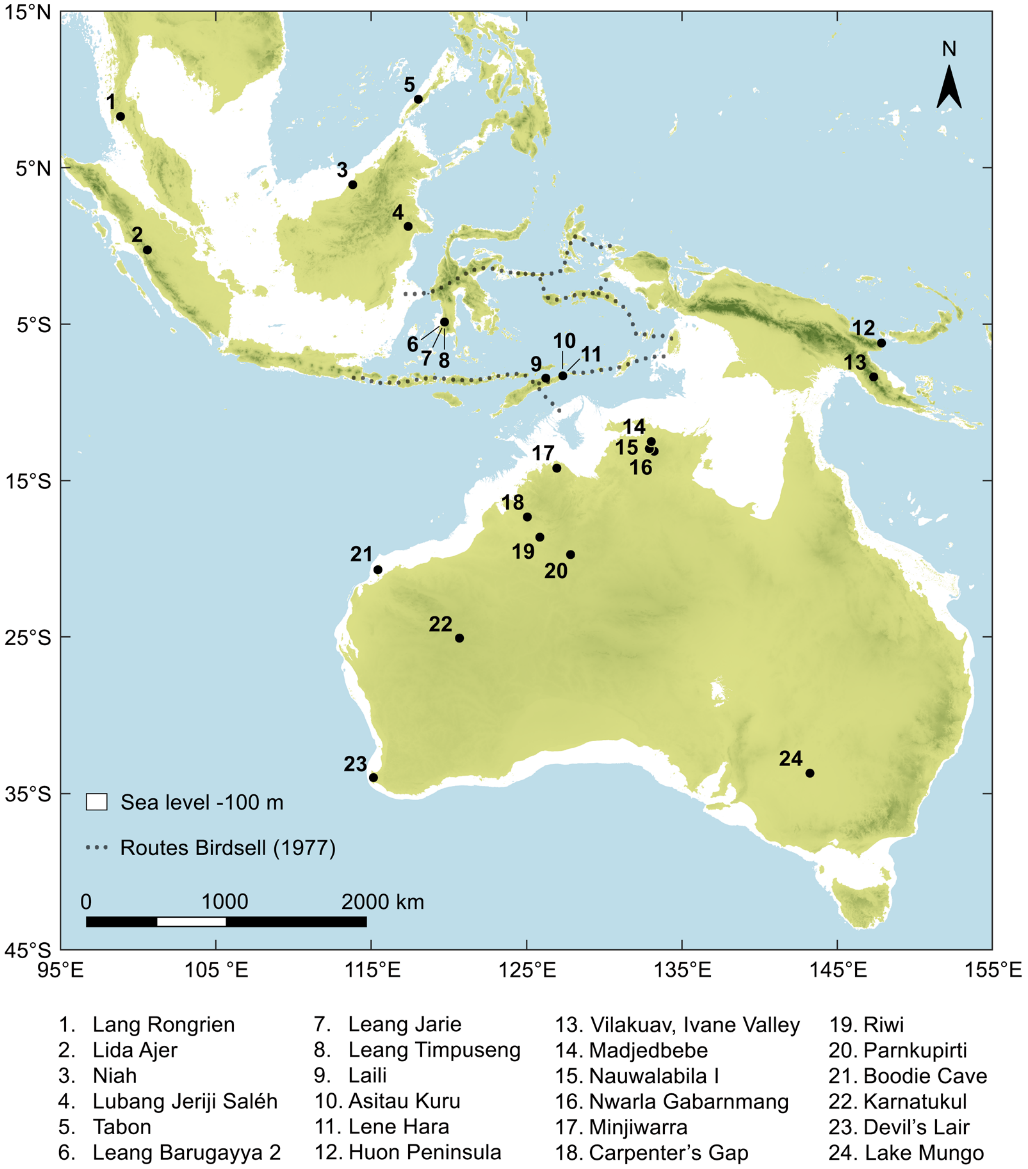

Figure 1. The earliest archaeological sites associated with Homo sapiens *in Sunda, Wallacea, and Sahul. For Sahul, only sites of which the earliest layers were dated to 45,000 years ago and earlier are included. The map, made using the GEBCO 30 arc-second global grid of elevations (GEBCO_2014, version 20150318, www.gebco.net; Weatherall et al. 2015), also shows the depth over the continental shelf at 100m, and migration routes proposed by Birdsell (1977).*

dated to ca. 65,000 years ago (Clarkson et al. 2017), significantly pushing back the date for human arrival in Sahul.

SEA LEVEL CHANGE

Climatic changes during the Upper Pleistocene caused fluctuations in mean sea level that exposed continental shelves to various degrees over time, changing the paleogeography of coastal regions. Figure 2 shows a mean sea level curve for the past 150,000 years, made using a relative mean sea level record from the Red Sea that reflects changes in the global mean sea level (Grant et al. 2012). This record shows that 65,000 years ago, mean sea level was ca. 100m lower than it is at present (De Deckker et al. 2019; Grant et al. 2012). At 50,000 years ago, it was probably around 75m lower than at present. The relative sea level between Sunda and Sahul differed from the global mean sea level due to glacio-hydro-isostacy and local tectonic changes. Whereas Australia is tectonically relatively stable, Wallacea has been subject to uplift over time (Kealy et al. 2017). Uplift rates differ throughout the region on a local scale, and more research is needed to constrain changes in the relative sea level between Sunda and Sahul. Paleogeographic reconstructions based on seismic survey of the Bonaparte Gulf in northern Australia indicate that sea levels were ca. 80m below present during MIS4 (Fogg et al. 2019).

SEAFARING

Early watercraft are rarely preserved in the archaeological

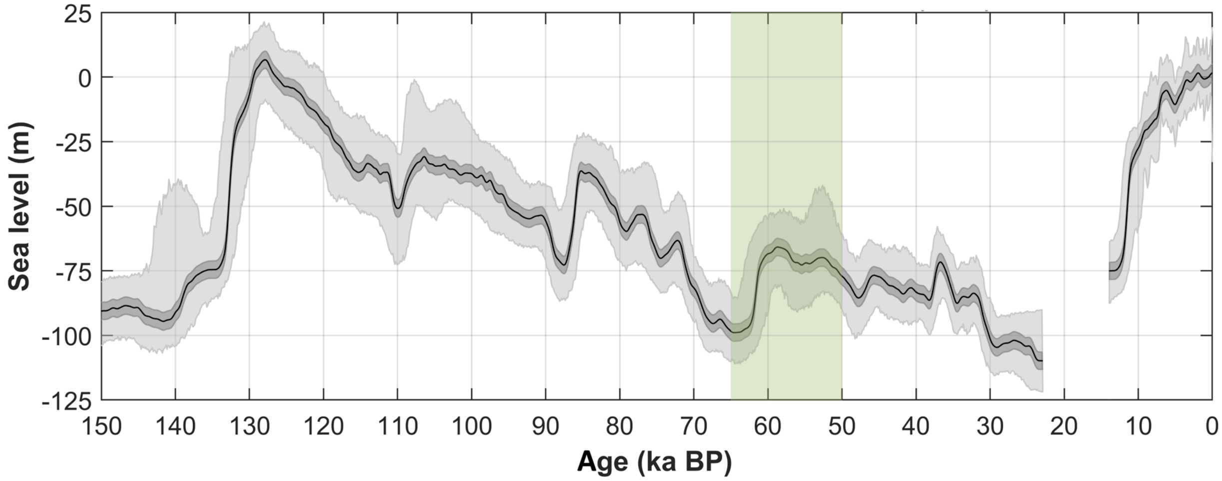

Figure 2. Sea level curve for the last 150,000 years, based on relative sea level data from the Red Sea (after Grant et al. 2012). The figure shows the maximum probability for relative sea level (black) within 2 standard errors (dark grey), and confidence intervals of 95% (light grey).

record, the earliest direct evidence is a Mesolithic logboat from the northern hemisphere (i.e., the Pesse logboat; Farr 2010; van Zeist 1935), although it is likely that simple rafts or boats made of logs, reed bundles, skin, or bark were used throughout human history. The earliest evidence for seafaring is indirect and comes from presence or absence of people on islands or isolated landmasses (Farr 2010; McGrail 2003: 183). The archaeological evidence from Sahul and the evidence for its paleogeographic isolation represents the first uncontested indirect evidence for seafaring in global history. While there are many unknowns that surround this early evidence of maritime activity, such as routing, technology, and skill, the question of *intentionality* of these early voyagers is much debated.

Suggestions that migration to Sahul was unintentional (e.g., Smith 2001; Thiel 1987) are not widely accepted. Unintentional arrival is judged to be highly unlikely based on the distances that had to be covered at sea, the direction of open ocean currents in the region (Bird et al. 2018; Bird et al. 2019; Sprintall et al. 2014), the distinct faunas of Southeast Asia and Australasia (other than humans, no large mammals have crossed to Australasia in the past; O'Connell et al. 2010), and the number of people involved in the migration (Bird et al. 2018: 437; Williams 2013). Today, the generally accepted view is that the migration was deliberate and staged, and that people used some type of early marine-capable watercraft such as a bamboo raft or log boat (Balme 2013; Birdsell 1977; Bulbeck 2007; Davidson and Noble 1992; Irwin 1992; O'Connell and Allen 2015; O'Connell et al. 2010).

Northern and southern migration routes across Wallacea have been suggested, based on the distances between islands, the number of water crossings necessary to reach Sahul, and island intervisibility (Birdsell 1977; see Figure 1). The routes have been widely discussed, and arguments have been presented in favor of both pathways (Allen and O'Connell 2008; Balme 2013; Balme et al. 2009; Bulbeck 2007; Butlin 1993; Davidson 2013; Field and Mirazón Lahr 2005; Kealy et al. 2017; Kealy et al. 2016; Mulvaney and Kamminga 1999; O'Connell and Allen 2015; O'Connor 2007; O'Connor et al. 2002; O'Connor et al. 2010). Recently, Kealy et al. (2018) conducted least-cost pathway analysis and found support for the northern pathway to Sahul. Support for this pathway was also found recently by Norman et al. (2018) based on visual connectivity network analysis, agent-based simulations, and ocean modelling where the authors used an ocean circulation model to create maps of mean current speeds between Sunda and Sahul. Norman et al. (2018) also indicate a good probability of reaching Sahul from Timor between 70,000 and 60,000 years ago, during the mean sea level lowstand of MIS 4.

Detailed discussion of the dynamic nature of maritime space and the experiences of early seafarers has only recently become the focus of research in this region (Bird et al. 2018; Bird et al. 2019; Norman et al. 2018), with the availability of high-resolution numerical models to study ocean dynamics. Yet the role of tidal dynamics within these models, and its effect on regional seafaring in the past, has not been explored.

TIDAL DYNAMICS

Tidal currents influence a range of processes, such as coastal flooding and erosion, the vertical zonation of species in coastal inter-tidal ecosystems, and sediment transport (Haigh et al. 2020). Tidal currents can be especially strong in coastal waters, reaching speeds of up to 5m/s or almost 10 knots (Stewart 2008). As such, tidal currents could have been utilized in early navigation and migration allowing for rapid movement towards, or away from coastlines. However, variations in current velocities over the course of the day can create a challenging environment for navigation. By studying tidal dynamics, we can further question the process of seafaring, necessary technology and skill, and contribute to discussions on intentionality and routing.

In addition, the tidal range (the vertical difference between the high and low tide during a day) has been linked to coastal resource availability (e.g., Fa 2008; Veth et al. 2017a). Coastal zones provide resource-rich and diverse environments offering a variety of subsistence options (e.g., Erlandson and Braje 2015). Humans have been systematically exploiting marine resources for 160,000 years (Jerardino and Marean 2010; Marean et al. 2007), and coastlines played an important role in the human migration out of Africa (Bailey and Flemming 2008; Bailey et al. 2007; Bailey and King 2011; Bulbeck 2007; Erlandson and Braje 2015; Erlandson et al. 2007; Macaulay et al. 2005; Mellars 2006; Mellars et al. 2013; Oppenheimer 2009; Stringer 2000; Walter et al. 2000). Evidence for pelagic fishing from the site Asitau Kuru (formerly known as Jerimalai; see Figure 1) in Wallacea dates back 44,000 years (O'Connor and Ono 2013; O'Connor et al. 2011; Shipton et al. 2019), while maritime skills facilitated the occupation of Wallacean islands (O'Connor et al. 2011). In Australia, evidence from Barrow Island and the Montebello Islands indicates coastal exploitation during the Upper Pleistocene and Early Holocene, prior to sea level stabilization in the mid-Holocene (Manne and Veth 2015). The oldest evidence for marine exploitation in Australia, from Barrow Island, dates back 42,500 years (Veth et al. 2017a; Veth et al. 2017b). The coastal foragers at Barrow Island gathered taxa from mangrove, mudflat, and rocky substrate environments. People arriving in Sahul are likely to have encountered and exploited similar environments.

Mean sea level fluctuations and associated changes in tidal regimes, coastal configuration, and sedimentation affect coastal productivity, however, these changes are not necessarily linear (Ward et al. 2013; 2015). Together with archaeological and ecological research into the use of coastal resources, information on past tidal amplitudes can be used to explore changes in the coastal zone through time. Today, the northern coast of Australia has a macrotidal regime, with a mean spring tidal range exceeding 9m at King Sound (Porter-Smith et al. 2004). However, present-day tide and current data cannot be used as a proxy for the past as the tides are subject to change over time (Haigh et al. 2020). During the Upper Pleistocene, changes in tides were dominated by changes in water depth associated with mean sea level fluctuations. In order to gain insight into the influence of the tides on seafaring to Sahul and coastal conditions on arrival, it is important to establish how Upper Pleistocene tidal conditions differed from present-day conditions. This paper models these tidal regimes with reference to the question of seafaring.

TIDAL MODELLING

The astronomical forces that regulate the tides are regular and entirely predictable. With increased availability of scientific data, including high-resolution bathymetric data, and computational power, computer models can now be used to make highly reliable predictions of the tides in both the future and the past. As such, recent decades have seen an increase in global studies of Pleistocene tidal dynamics that mainly focus on the Last Glacial Maximum (Arbic et al. 2008; Egbert et al. 2004; Green et al. 2009; Griffiths and Peltier 2009; Montenegro et al. 2007; Thomas and Sündermann 1999; Tojo et al. 1999; Uehara et al. 2006; Ward et al. 2013; Wilmes and Green 2014). This paper presents a regional model implemented with mean sea levels corresponding to the period between 65,000 and 50,000 years ago in order to consider seafaring to Sahul in deep time.

Here, a depth-averaged barotropic hydrodynamic model of the Australian coast is used to simulate tidal dynamics over the northern Australian continental shelf, for different mean sea level scenarios. The study focuses on the Timor Sea, a region identified as likely to have been traversed in a migration to Sahul. This route constitutes the 'southern' dispersal route as identified by Birdsell (1977) and human activity within this region is evidenced by known sites on Timor and the Northern Territory in Sahul, i.e., Asitau Kuru and Madjedbebe (Clarkson et al. 2017; Clarkson et al. 2015; Langley et al. 2016; O'Connor 2007; O'Connor et al. 2011; Shipton et al. 2019). A comparison of these tidal scenarios gives insight into the coastal changes that took place and is used to examine the effects of tides on early seafaring during the migration to Sahul.

METHODS

The depth-averaged barotropic hydrodynamic model of the Australian coast used here was previously developed to estimate extreme water level exceedance probabilities around Australia (Haigh et al. 2014a; 2014b). The model was configured using the MIKE 21 FM coastal modelling tool by the Danish Hydraulic Institute (Danish Hydraulic Institute 2016). Validation of the model output against measurements from 30 tide gauge sites around the coast demonstrated its reliability to accurately predict the present-day tides around Australia (for details, see Haigh et al. 2014b).

The model grid (Figure 3) has a spatial resolution of 1/12° (~10km) near the coastline. Away from the coast, the resolution drops to between 1/3° and 1/5° at the open tidal boundaries. The grid was configured using the medium resolution coastline by the National Oceanic and Atmospheric Administration (NOAA). Modern bathymetric data from the Geoscience Australia 9 arc second dataset (Webster and Petkovic 2005) was interpolated onto the grid. The open model boundaries were forced with output from the TOPEX/Poseidon Global Inverse Solution 7.2 (TPX07.2) global tidal model (Egbert and Erofeeva 2002; Egbert et al. 1994). Eight primary tidal constituents (M_2, S_2, N_2, K_2, K_1, O_1, P_1, Q_1), two long period constituents (M_f, M_m), and three compound constituents (M_4, MS_4, MN_4) were included. Tidal forcing is not only provided at the open boundaries; direct gravitational tidal forcing in the coastal areas themselves are accounted for through selection of the 'tidal potential' option in MIKE 21. Further details on the model configuration can be found in Haigh et al. (2014b).

To explore the effects of the changing mean sea level on tides north of Australia, simulations were run for a series of mean sea level scenarios at 25m intervals, ranging

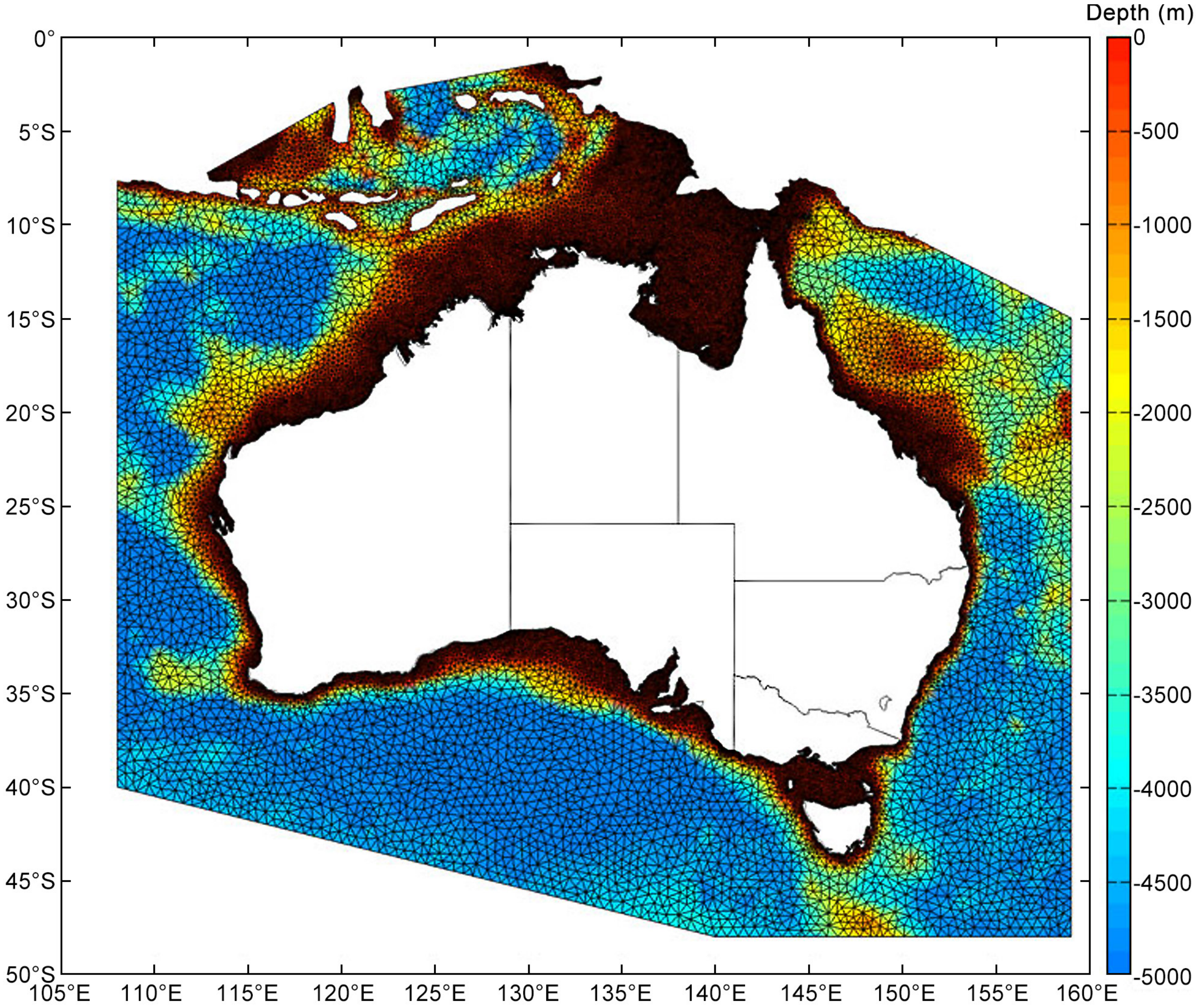

Figure 3. The model domain, grid, and bathymetry (after Haigh et al. 2014b).

from 0m (the present-day scenario) to -150m. By doing so, broad-scale changes that occur in the tide with mean sea level change could be discerned. The 75m scenario corresponds approximately to 65 ka BP. The model uses modern data, and a full month in a recent year (2010) was simulated for each mean sea level scenario. Each simulation starts on the 26th of December 2009 and spans 37 days. The first six days were not included in the results as they correspond to a spin-up period of the model. The largest tidal range in semi-diurnal regions (regions that experience two high and two low tides a day, such as the Timor Sea) occurs during spring tides, when the Moon, Earth and Sun align. The tidal range is smallest during neap tides, when the moon and sun are at right angles to each other. The spring-neap cycle takes 14.76 days (Pugh and Woodworth 2014), so two spring-neap cycles were included in the results.

The model results (hourly predicted water levels and current velocities) were loaded into MATLAB using the DHI MATLAB toolbox 2014 and graphs of water levels and current velocities were generated. Note that the scenarios modelled assume that that there is no change in the bathymetry over time and that tides remain unchanged in the deep waters along the model boundary.

RESULTS

Figure 4 shows maps of the bathymetry over the Timor Sea for four mean sea level scenarios (0m, 50m, 75m, 100m). Cross-sections of the shelf at 124°E and 126°E (see Figure 4E-F) show the contrast in depth between the shallow continental shelf and the deep Timor Strait. The model results are shown in Figures 5 to 7. Figure 5 shows the modelled variability in tidal levels and current speeds over one spring-neap cycle, along two transects (1: 124°E, and 2: 126°E). The locations for which tidal levels and current speeds are shown are marked with crosses in Figure 4. The locations were selected to lie close to the Australian shoreline, where tidal amplitudes and currents are the greatest. Figures 6 and 7 display maps of the maximum tidal range and current speeds, over the simulated period, for the 0m, 50m, 75m, and 100m scenarios. Maps of current speeds and directions during flood, high water, ebb, and low water have been included for the same scenarios in the Supple-

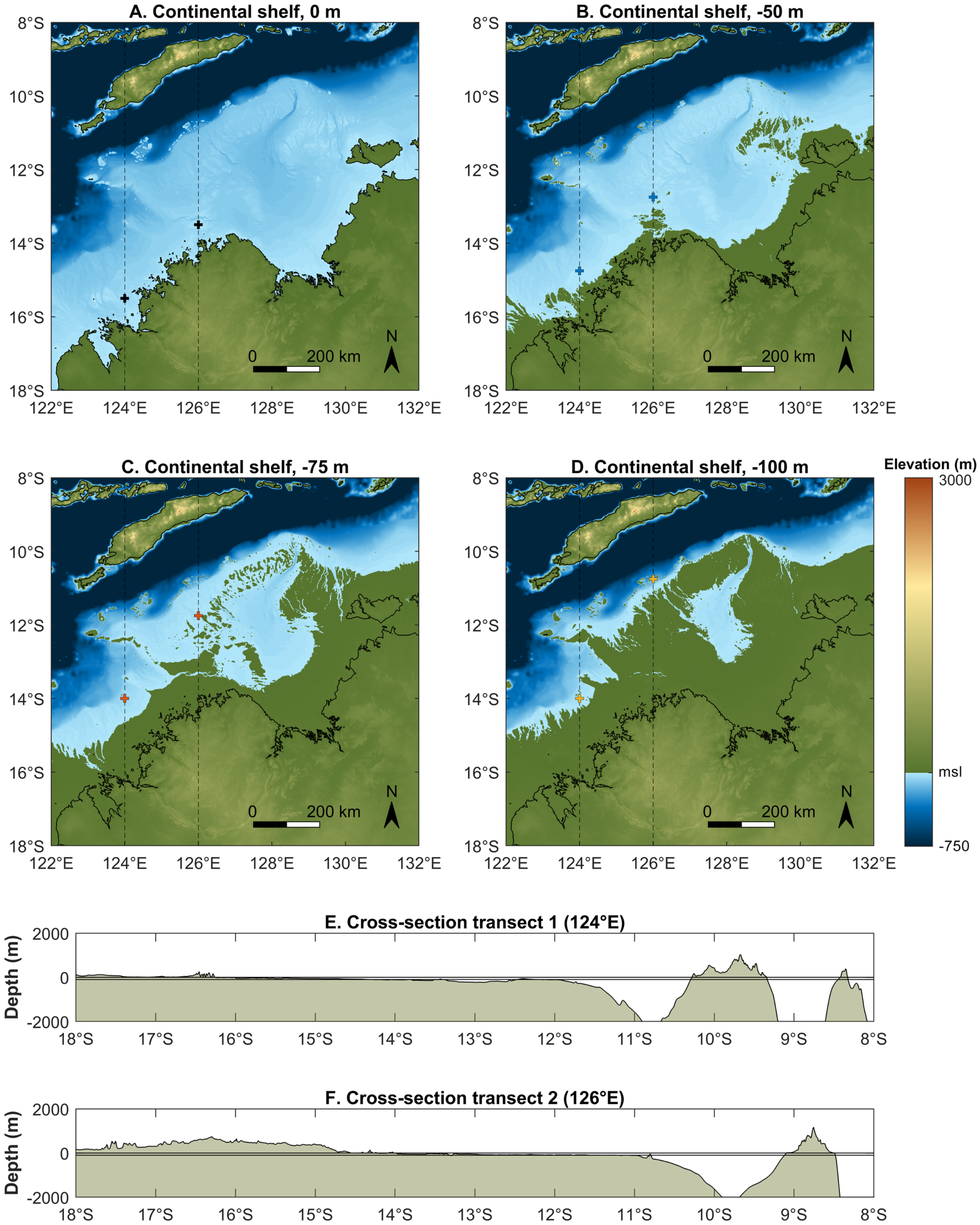

Figure 4. A–D: Maps of the Australian continental shelf between 122°E and 132°E, showing the position of the coastline for the 0m, 50m, 75m, and 100m scenarios. The dashed lines mark the transects described in the text. The crosses mark locations along the transects for which the tidal range and current speeds are described (see Figure 5). E–F: cross-sections of the continental shelf along Transect 1 (124°E) and 2 (126°E), with black horizontal lines marking the depth at 0m and 100m.

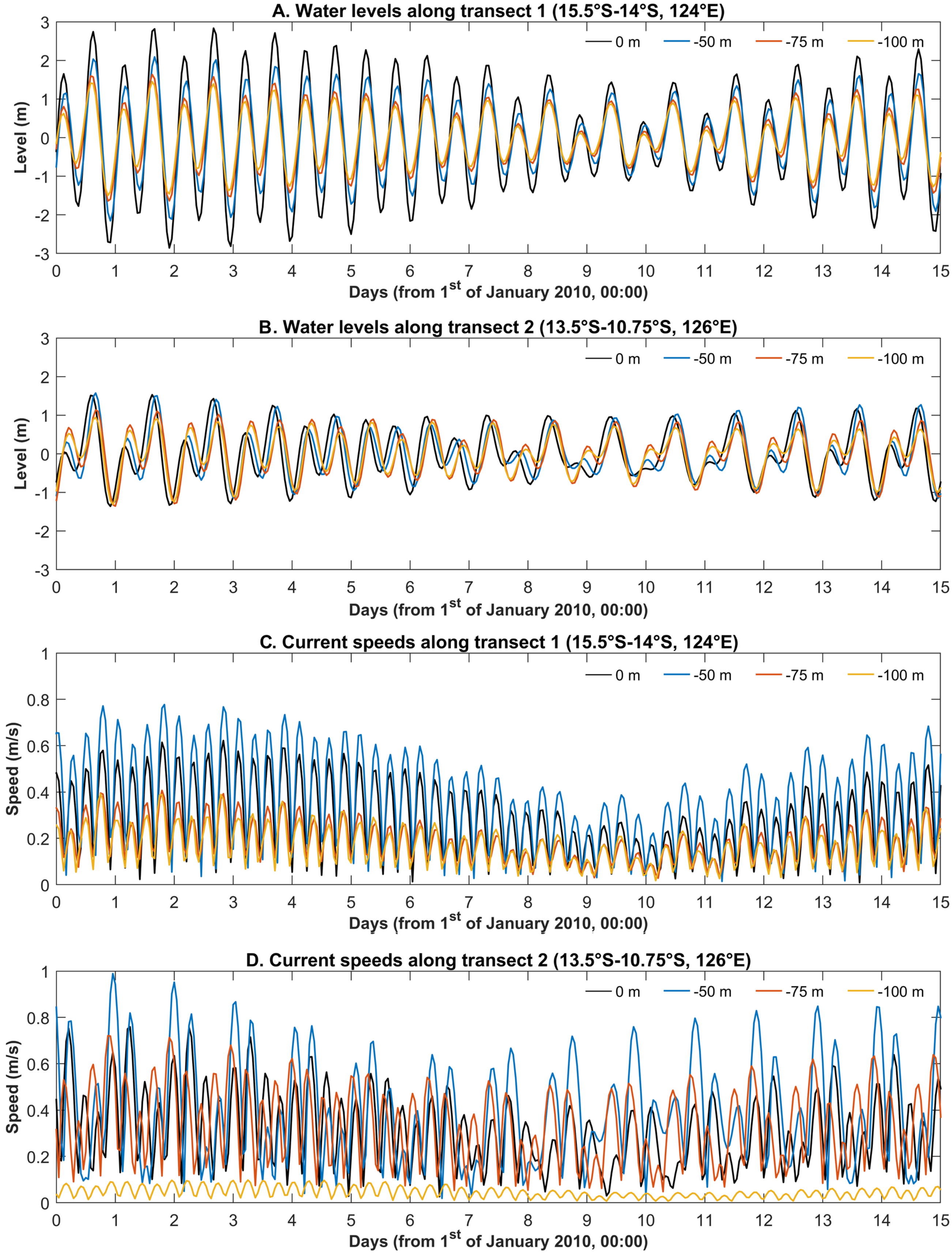

Figure 5. Tidal levels and current speeds over 15 days (1–15 January 2010) for four sea level scenarios (0m, 50m, 75m, 100m), at near-shore locations along two transects offshore northern Australia (see Figure 4). A: tidal levels along Transect 1. B: tidal levels along Transect 2. C: current speeds along Transect 1. D: current speed along Transect 2.

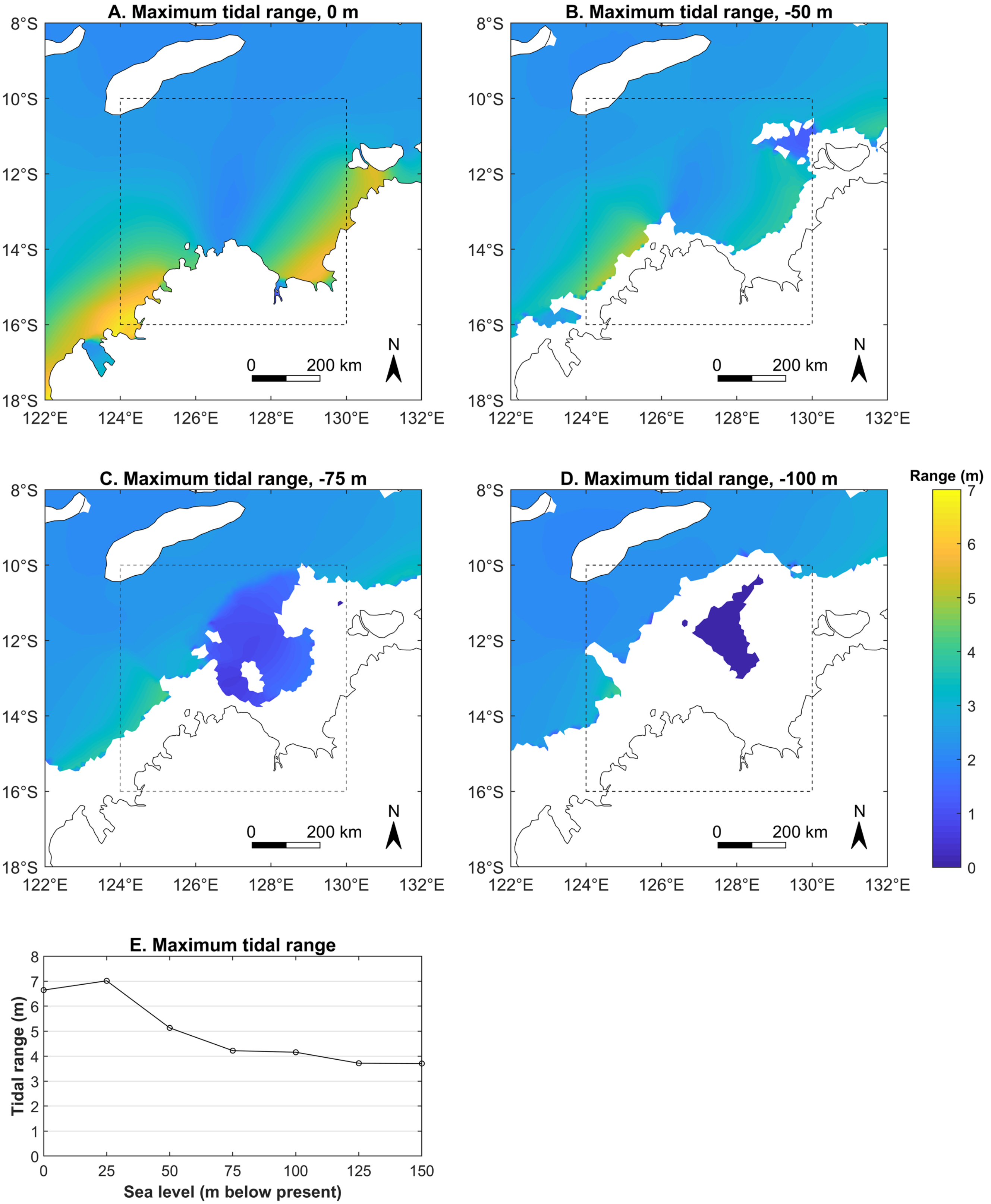

Figure 6. A–D: the maximum tidal range in the Timor Sea during January 2010, for the 0m, 50m, 75m, and 100m scenarios. E: the maximum tidal range within the region marked by a dashed box in Figures 6A–D, for each mean sea level scenario (0m to 150m).

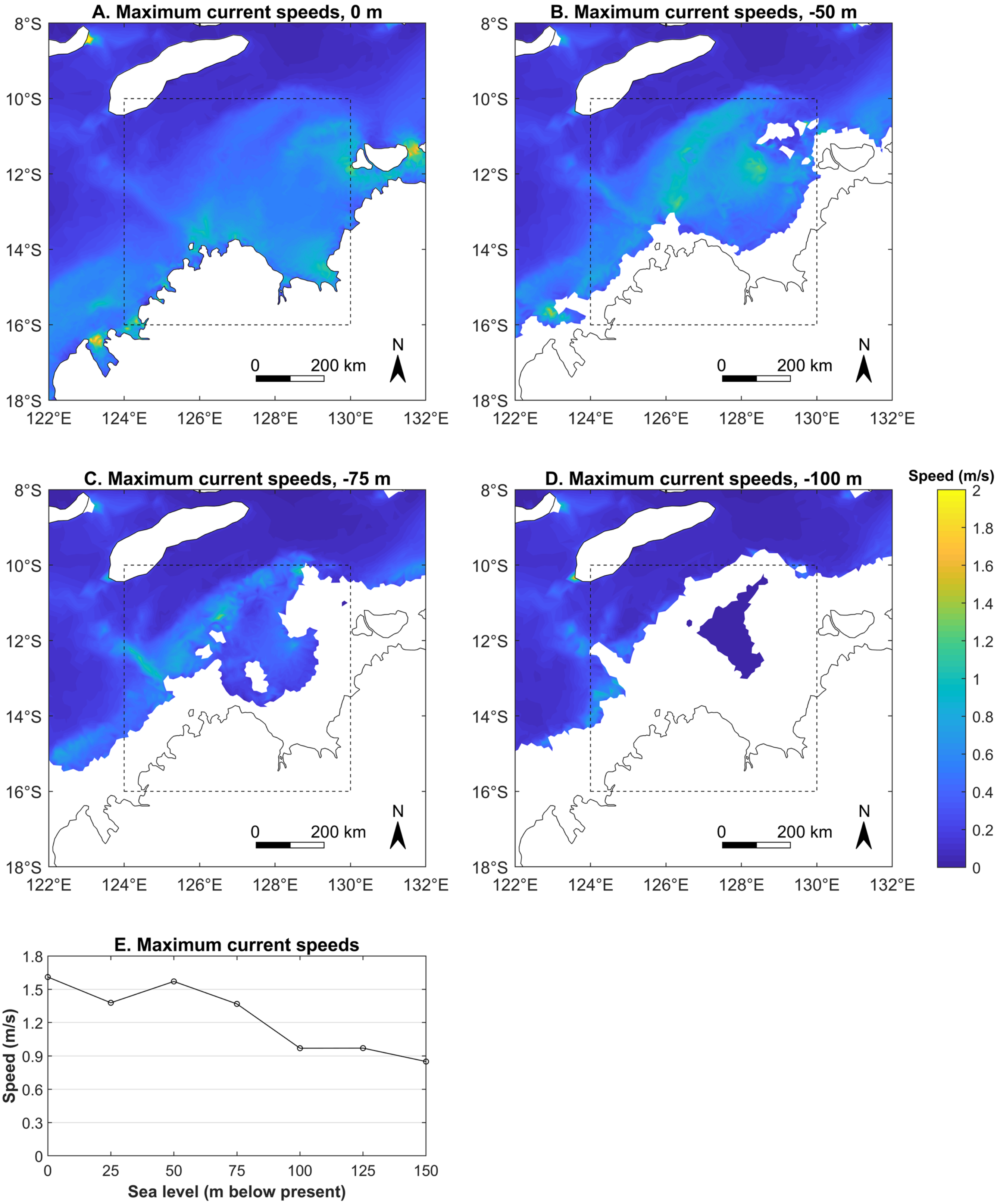

Figure 7. A–D: the maximum current speeds in the Timor Sea during January 2010, for the 0m, 50m, 75m, and 100m scenarios. E: the maximum current speeds within the region marked by a dashed box in Figures 7A–D, for each mean sea level scenario (0m to 150m).

mentary Material (Figures S1 to S4). These figures give an impression of how tidal currents change over the course of a day.

THE TIDAL RANGE

Tides along Transect 1 (see Figure 5A) are semi-diurnal, but there is a diurnal inequality (the two high and low tides that occur during the day differ in height). The spring tide occurs at the start of the month (1–2 January). The tidal range is greatest in the present-day scenario (5.65m), and smallest in the 100m scenario (2.91m). In the two intermediary scenarios (50m and 75m), the spring tidal range is 4.20m and 3.27m respectively. The difference between spring and neap tide is greatest in the present-day scenario, where the neap range (10–11 January) can be as low as 1.16m. The neap tidal range is 0.89m in the 50m scenario, 0.53m in the 75m scenario, and 0.41m in the 100m scenario.

Along Transect 2 (see Figure 5B), the tidal range is smaller than along Transect 1, and the diurnal inequality is more evident. During the latter half of the month (25–26 January, not shown here) the present-day neap tidal range is mainly diurnal. Again, the spring tidal range is largest in the present-day scenario (2.86m on 1 January; see Figure 4) and smallest in the 100m scenario (2.25m). The difference between the highest high water and the lowest low water around this time is 1.51m.

Figure 6 shows that the tidal range is highest near the Australian coast in all scenarios. At present, the maximum tidal range is 6.6m. In the -50m scenario, it is 5.1m, and in the -75m and -100m scenarios, it is 4.2m. In the -75m scenario (ca 65 ka BP), the tidal range is relatively low (up to ca. 1.5m) in the Bonaparte Gulf. Figure 4 shows that a series of islands would have existed near the edge of the continental shelf, sheltering this area. Further west, near the Australian coast, the spring tidal range in this scenario is around 4m, and in the Timor Strait it is around 2.5m. In the -100m scenario, most of the continental shelf is exposed, with the exception of the Bonaparte Depression, which is connected to the Timor Strait by a narrow channel. No tidal dynamics are seen in the Bonaparte Depression. Near the Australian coast, the spring tidal range is between 2m and 4m. In the Timor Strait, the spring range is around 2m to 2.5m. Figure 6E shows the maximum tidal range in the region between 124–126°E and 16–10°S (the dashed box on the maps in Figure 6), for all sea level scenarios. The tidal range is highest (7m) in the -25m scenario and lowest (3.7m) in the -150m scenario.

TIDAL CURRENT SPEEDS

The current speeds along Transect 1 over the first fifteen days of January (see Figure 5C) are highest in the 50m scenario, with a maximum of 0.78m/s occurring on the 2nd of January. In the present-day scenario, current speeds of up to 0.62m/s occur. In the 75m scenario, the maximum speed along Transect 1 is 0.41m/s, and in the 100m scenario, it is only 0.39m/s. The difference in current speeds over the spring-neap cycle is greatest in the present-day scenario and the 50m scenario. In the 75m and 100m scenarios, the variation over the spring-neap cycle is less profound. At present during neap tide on the 10th of January the maximum current speed is 0.27m/s. In the 50m scenario the maximum speed on this day is 0.39m/s. In the 75m scenario it is 0.19m/s, and in the 100m scenario it is 0.21m/s.

Along Transect 2 (see Figure 5D), the highest current speeds also occur in the 50m scenario (0.99m/s on the 1st of January). In the present-day scenario, the maximum current speed is 0.76m/s. Comparable current speeds (0.72m/s) are seen in the 75m scenario. The current speeds are much lower in the 100m scenario (up to 0.10m/s). This is related to the location for which results are shown—as seen in Figure 4E, this location (the yellow cross at 126°E) is not on the continental shelf but in the deep Timor Strait. At present, the highest current speed during neap tide, on the 10th of January, is 0.40m/s. In the 50m scenario, the current speeds are lowest earlier in the month, on the 7th of January (maximum 0.64m/s). The highest speed reached during neap tide in the 75m scenario is 0.51m/s (on the 9th of January), and in the 100m scenario it is 0.04m/s (on the 11th of January).

Figure 7 shows that the highest current speeds in the Timor Sea occur in areas where depths are shallow (and not necessarily in areas where the tidal range is greatest). The maximum current speeds in the Timor Strait are between 0.1m/s and 0.3m/s in both the -75m and the -100m scenarios. In the -75m scenario, the current speeds are strongest (up to 1.37m/s) around the islands in the Timor Sea (see Figure 4C). In the -100m scenario, the highest current speeds are found near the Australian coast (generally between 0.3m/s and 0.6m/s, and up to 0.97m/s). The current speeds are strongest (1.57m/s at maximum) in the 50m scenario, and weakest (0.49m/s at maximum) in the 150m scenario.

DISCUSSION

The results presented here show that the northern Australian coast experienced great variations, through the last glacial cycle, in tidal levels and current speeds over the course of a day, and over the spring-neap cycle. Spatially, the phase and amplitude of the tides change along the vast northern Australian coastline (see Figure 5). Temporally, over the course of the Upper Pleistocene, tides change markedly with fluctuations in mean sea level over the Australian continental shelf.

Two key assumptions were made in this study. The first assumption is that the tides remain unchanged in the deep waters along the model boundary. This seems reasonable based on results from previous global studies (Arbic et al. 2008; Egbert et al. 2004; Green et al. 2009; Griffiths and Peltier 2009; Montenegro et al. 2007; Thomas and Sündermann 1999; Wilmes and Green 2014), but future work could consider driving the regional model with predictions from global models. The second assumption is that the bathymetry remains unchanged over time. Future work addressing this is taking place through the ERC funded ACROSS project, which is developing the hydrodynamic modelling approach to address changing conditions in deep time.

The high tidal range of up to 6.6m seen in the Timor Sea at present (see Figure 6E) is the result of tidal resonance. On continental shelves in areas with semi-diurnal tides, such as the northern Australian continental shelf, resonance occurs when the width of the shelf width is about one quarter of the tidal wavelength (Clarke 1991; Clarke and Battisti 1981; Godin 1993). At 65,000 years ago, when mean sea level was lower than today, the shelf was shallower and less wide, resulting in a lower tidal range than at present. Although there is no one-to-one correlation between tidal range and current speeds (the highest current speeds occur in areas with shallow bathymetry, and not necessarily in areas with the highest tidal range; compare Figures 6 and 7), the results show that from 65,000 to 50,000 years ago, both tidal current speeds and tidal range would have increased (compare the -75m and -50m scenarios). The processes are causally opposed: higher current speeds may have hindered migration, but higher tidal range leads to increased productivity and is therefore favorable for migration. Below, the effects of both processes on maritime migration will be discussed in detail.

TIDAL CURRENT SPEEDS

In consideration of distance and potential speeds of simple boats and rafts (Farr 2006), the crossing from Timor or Roti to Sahul probably took several days (Bird et al. 2018). Every six hours, the direction of tidal currents would have changed (see Supplementary Figures S1 to S4). Early seafarers are unlikely to have been able to paddle at more than 1m/s (2 knots) for any length of time (Farr 2006). Seafarers departing from Timor or Roti would not have been strongly affected by tidal currents in the Timor Strait, where the maximum tidal current speed would have only been up to 0.3m/s (ca. 0.5 knot; see Figure 7C and D), nor, potentially would they have been familiar with such tidal currents. However, on the continental shelf of Sahul, tidal currents would have strongly affected navigation and sea state, especially during periods with the wind direction countering the tide creating rough seas. Even in the -100m scenario, tidal current with speeds of up to ca. 0.3–0.6m/s (ca. 0.5–1 knot) are seen near the coast. In the -75m scenario, current speeds of ca. 1m/s (and above, in some areas) occur near islands during spring tide. In the -50m scenario, current speeds are even higher. Given the strength of tidal currents and the relative proximity of mainland Sahul, it was potentially easier to reach Sahul around 65,000 years ago, during the MIS 4 sea level lowstand, than around 50,000 years ago.

The results from the -75m simulation shows that during part of the day, especially during spring tides, early seafarers were unlikely to have been able to make headway while paddling against the currents. However, even during neap tides, tidal currents would have affected seafaring, as shown by the current speeds of 0.41m/s and 0.51m/s near the Australian coast at 124°E and 126°E (see Figure 5). Timing and planning would have been key to the success of these voyages. Tides could have hindered early seafarers, but also could have been used to expedite journeys. As such, early seafarers would have benefitted from long-term planning abilities to make safe, successful voyages to the islands on the Sahul shelf, aided by an understanding of tidal dynamics, and daily and monthly patterns in the tides. With a world view that incorporated an understanding of the temporality of the marine environment and good planning abilities, simple watercraft (e.g., rafts and log-boats) with low paddling speeds (1–2 knots) would have been sufficient to successfully voyage to Sahul. In the case of this southern route presented, once seafarers reached the Bonaparte Gulf, where currents were weak, navigation would have been easier.

Tidal currents may have had less of an impact on return journeys to Timor and Roti—the model results show that in the Timor Strait and near Timor and Roti (which have steep coastlines), tidal currents are less strong than near Sahul. This may lead us to question whether peopling travelling from Wallacea would have experienced tidal conditions like those on the Sahul shelf. In terms of seafaring along coastal Sahul shelf, people could have used the strong currents to great effect.

TIDAL RANGE

The modelled tidal range gives a first insight into the potential productivity of the coastline in the Timor Sea area. In the -75m scenario (65 ka BP) and even the -100m scenario, a tidal range of 4m is seen along parts of the Australian coastline. Fa (2008) compared the tidal range and resource availability on the Atlantic and Mediterranean side of the Gibraltar Strait, and found that the Atlantic side is characterized by high tidal amplitudes (3m) and high species densities, whereas the Mediterranean side is characterized by low tidal amplitudes (15–30cm) and low species densities. While the southern hemisphere has different ecozones and tropical and sub-tropical coastal habitats, this does raise the question about links between tidal range and resource availability. In Australia, the evidence for early consistent use of marine resources from 42.5 ka BP and throughout the terminal Pleistocene (Veth et al. 2017a; 2017b) demonstrates the productivity of the coastal zone. The coastal zone contained rich marine environments, including reef flats, rocky foreshore substrates, intertidal mudflats, and mangrove communities. A correlation between the tidal range and coastal productivity is also discussed—the greater the tidal range, and the lower the gradient of the shoreline, the greater the carrying capacity for marine resource exploitation (Veth et al. 2017a).

Despite a smaller tidal range than at present, the maximum tidal range of 4m 65,000 years ago may also indicate a productive coastline. However, coastal ecozones would have differed locally and more paleoenvironmental research is needed. What can be concluded, however, is that throughout the Upper Pleistocene, the global mean sea level fluctuated, causing tidal amplitudes to change, affecting the productivity of the coastal zone. As mean sea level rose after 65,000 years ago (see Figure 2), resource availability along the Australian coastline may have increased, making the environment more favorable for habitation (but potentially less favorable for navigation); 50,000 years ago, the coastal gradient would have been less steep, and the tidal range greater. Although preliminary, this work supports other studies (Erlandson and Braje 2015; Manne and Veth 2015; Ulm 2011; Veth et al. 2017a; 2017b; Ward et al. 2015) that indicate that Upper Pleistocene coastlines were not homogenous in space and time, and that they provided relatively resource-rich environments supporting coastal habitation.

CONCLUDING REMARKS

Past fluctuations in climatic conditions do not only affect terrestrial landscapes, they also strongly affect the marine environment. It is important to take this into account when thinking about Upper Pleistocene environmental transitions and changes in hominin occupation and behavior. Coastal environments play an important role in the past, with people living in changing coastal landscapes and engaging in seafaring at least as early as 65,000 years ago in Sahul.

The findings presented here suggest a productive coastline, but as sea level fluctuations occurred over the past 65,000 years, the nature of the coastline changed. As sea levels rose from 65,000 years ago, the coast may have become more productive. Specific areas would have been more suitable for habitation than others at different times, and people living in coastal areas would have had to adapt to changing conditions at various scales, from those of the daily and monthly tidal cycles, to seasonal cyclones, monsoon, and long term changes to sea level and climate. Early seafarers would have been strongly affected by local conditions including tidal currents in coastal areas, and an understanding of tidal dynamics would have been essential to safely navigate to, and along, the Sahul coast.

Tides would have been important, encountered marine phenomenon, however, they only make up part of the maritime environment. In the Timor Strait, open ocean currents would have strongly affected navigation. The strait forms one of the major outflow passages of the Indonesian Throughflow, a current system that flows from the Pacific Ocean to the Indian Ocean (Sprintall et al. 2009; 2014). In addition, prevailing winds and weather conditions, including cyclones, would have affected seafaring (e.g., Farr 2006; Irwin 1992). Cyclones in this region (Eliot and Pattiaratchi 2010; Fandry and Steedman 1989; Haigh et al. 2014a) are regular and may have had a major impact on water circulation; frequency of cyclones in deep time needs further analysis. Prevailing winds may have aided seafarers migrating to Sahul during parts of the year. However, the possibility of bad weather conditions would have added an element of risk to voyages. The dynamic nature of the maritime environment strongly affects the duration of journeys as well as potential migration routes, and the shortest distance between islands may not reflect an optimal route at any time (Bird et al. 2018). The work on tides presented here forms part of a wider study modelling paleotides and open ocean currents throughout Wallacea (ERC ACROSS) in order to gain a better understanding of the changing nature of the complexity of the marine environment through Wallacea and into Sahul in deep time.

As demonstrated in this study, a greater understanding of the environmental context for this early seafaring can shed light on past human behavior, seafaring skills, and social organization (Farr 2006). When the potential speeds of simple watercraft are considered, a good understanding of the marine environment (including daily, seasonal, and annual patterns in the weather and the tides) would have been essential for these early voyages to be successful. Watercraft must have been strong enough to stay intact for days, and seafarers must have had access to freshwater, or at least, been able to collect rainwater. Such voyages would have required particular maritime skills, long-term planning, knowledge of marine environmental conditions, and adaptability to those encountered if they were to be successful.

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REFERENCES

Allen, J. and O'Connell, J.F. 2008. Getting from Sunda to Sahul. In Clark, G.R., Leach, B.F., and O'Connor, S. (eds.), *Islands of Inquiry: Colonisation, Seafaring and the Archaeology of Maritime Landscapes*. ANU E Press, Canberra, pp. 31–46.

Arbic, B.K., Mitrovica, J.X., MacAyeal, D.R., and Milne, G.A. 2008. On the factors behind large Labrador Sea tides during the last glacial cycle and the potential implications for Heinrich events. *Paleoceanography* 23, PA3211.

Bailey, G.N. and Flemming, N.C. 2008. Archaeology of the continental shelf: marine resources, submerged landscapes and underwater archaeology. *Quaternary Science Reviews* 27, 2153–2165.

Bailey, G.N., Flemming, N.C., King, G.C.P., Lambeck, K., Momber, G., Moran, L.J., Al-Sharekh, A., and Vita-Finzi, C. 2007. Coastlines, submerged landscapes, and human evolution: the Red Sea Basin and the Farasan Islands. *The Journal of Island and Coastal Archaeology* 2, 127–160.

Bailey, G.N. and King, G.C.P. 2011. Dynamic landscapes and human dispersal patterns: tectonics, coastlines, and the reconstruction of human habitats. *Quaternary Science Reviews* 30, 1533–1553.

Balme, J. 2013. Of boats and string: the maritime colonisation of Australia. *Quaternary International* 285, 68–75.

Balme, J., Davidson, I., McDonald, J., Stern, N., and Veth, P. 2009. Symbolic behaviour and the peopling of the southern arc route to Australia. *Quaternary International* 202, 59–68.

Bird, M.I., Beaman, R.J., Condie, S.A., Cooper, A., Ulm, S., and Veth, P. 2018. Palaeogeography and voyage modeling indicates early human colonization of Australia was likely from Timor-Roti. *Quaternary Science Reviews* 191, 431–439.

Bird, M.I., Condie, S.A., O'Connor, S., O'Grady, D., Reepmeyer, C., Ulm, S., Zega, M., Saltré, F., and Bradshaw, C.J.A. 2019. Early human settlement of Sahul was not an accident. *Scientific Reports* 9, 8220–8220.

Birdsell, J.B. 1977. The recalibration of a paradigm for the first peopling of greater Australia. In Allen, J., Golson, G., and Jones, R. (eds.), *Sunda and Sahul: Prehistoric Studies in Southeast Asia, Melanesia and Australia*. Academic Press, New York, pp. 113–167.

Bulbeck, D. 2007. Where river meets sea: a parsimonious model for *Homo sapiens* colonization of the Indian Ocean rim and Sahul. *Current Anthropology* 48, 315–321.

Butlin, N.G. 1993. *Economics and the Dreamtime: A Hypothetical History*. Cambridge Uiversity Press, Cambridge.

Clarke, A.J. 1991. The dynamics of barotropic tides over the continental shelf and slope (Review). In Parker, B.B. (ed.), *Tidal Hydrodynamics*. John Wiley and Sons, New York, pp. 79–108.

Clarke, A.J. and Battisti, D.S. 1981. The effect of continental shelves on tides. *Deep Sea Research Part A, Oceanographic Research Papers* 28, 665–682.

Clarkson, C., Jacobs, Z., Marwick, B., Fullagar, R., Wallis, L., Smith, M., Roberts, R.G., Hayes, E., Lowe, K., Carah, X., Florin, S.A., McNeil, J., Cox, D., Arnold, L.J., Hua, Q., Huntley, J., Brand, H.E.A., Manne, T., Fairbairn, A., Shulmeister, J., Lyle, L., Salinas, M., Page, M., Connell, K., Park, G., Norman, K., Murphy, T., and Pardoe, C. 2017. Human occupation of northern Australia by 65,000 years ago. *Nature* 547, 306–310.

Clarkson, C., Smith, M., Marwick, B., Fullagar, R., Wallis, L.A., Faulkner, P., Manne, T., Hayes, E., Roberts, R.G., Jacobs, Z., Carah, X., Lowe, K.M., Matthews, J., and Florin, S.A. 2015. The archaeology, chronology and stratigraphy of Madjedbebe (Malakunanja II): a site in northern Australia with early occupation. *Journal of Human Evolution* 83, 46–64.

Danish Hydraulic Institute. 2016. *MIKE 21 & MIKE 3 Flow Model FM, Hydrodynamic and Transport Module*, scientific documentation.

Davidson, I. 2013. Peopling the last new worlds: the first colonisation of Sahul and the Americas. *Quaternary International* 285, 1–29.

Davidson, I. and Noble, W. 1992. Why the first colonisation of the Australian region is the earliest evidence of modern human behaviour. *Archaeology in Oceania* 27, 135–142.

De Deckker, P., Arnold, L.J., van der Kaars, S., Bayon, G., Stuut, J.-B.W., Perner, K., Lopes dos Santos, R., Uemura, R., and Demuro, M. 2019. Marine Isotope Stage 4 in Australasia: a full glacial culminating 65,000 years ago – Global connections and implications for human dispersal. *Quaternary Science Reviews* 204, 187–207.

Egbert, G.D., Bennett, A.F., and Foreman, M.G.G. 1994. TOPEX/POSEIDON tides estimated using a global inverse model. *Journal of Geophysical Research: Oceans* 99, 24821–24852.

Egbert, G.D. and Erofeeva, S.Y. 2002. Efficient inverse modeling of barotropic ocean tides. *Journal of Atmospheric and Oceanic Technology* 19, 183–204.

Egbert, G.D., Ray, R.D., and Bills, B.G. 2004. Numerical modeling of the global semidiurnal tide in the present day and in the last glacial maximum. *Journal of Geophysical Research: Oceans* 109, C03003.

Eliot, M. and Pattiaratchi, C. 2010. Remote forcing of water levels by tropical cyclones in southwest Australia. *Continental Shelf Research* 30, 1549–1561.

Erlandson, J.M. and Braje, T.J. 2015. Coasting out of Africa: the potential of mangrove forests and marine habitats to facilitate human coastal expansion via the Southern Dispersal Route. *Quaternary International* 382, 31–41.

Erlandson, J.M., Graham, M.H., Bourque, B.J., Corbett, D., Estes, J.A., and Steneck, R.S. 2007. The kelp highway hypothesis: marine ecology, the coastal migration theory, and the peopling of the Americas. *The Journal of Island and Coastal Archaeology* 2, 161–174.

Fa, D.A. 2008. Effects of tidal amplitude on intertidal resource availability and dispersal pressure in prehistoric human coastal populations: the Mediterranean–Atlantic transition. *Quaternary Science Reviews* 27, 2194–2209.

Fandry, C.B. and Steedman, R.K. 1989. An investigation of tropical cyclone-generated circulation on the North-West Shelf of Australia using a three-dimensional model. *Deutsche Hydrografische Zeitschrift* 42, 307–341.

Farr, H. 2006. Seafaring as social action. *Journal of Maritime Archaeology* 1, 81–99.

Farr, R.H. 2010. Island colonization and trade in the Mediterranean. In Anderson, A., Barrett, J.H., and Boyle, K.V. (eds.), *The Global Origins and Development of Seafaring*. McDonald Institute for Archaeological Research, Cambridge, pp. 179–189.

Field, J.S. and Mirazón Lahr, M. 2005. Assessment of the southern dispersal: GIS-based analyses of potential routes at Oxygen Isotopic Stage 4. *Journal of World Prehistory* 19, 1–45.

Fogg, A., Dix, J., and Farr, R.H. 2019. Late Pleistocene palaeo environment reconstruction from 3D seismic data, NW Australia. The ACROSS project - Australasian Research: Origins of Seafaring to Sahul, AGU Fall Meeting 2019. *Earth and Space Science Open Archive*.

Godin, G. 1993. On tidal resonance. *Continental Shelf Research* 13, 89–107.

Grant, K.M., Rohling, E.J., Bar-Matthews, M., Ayalon, A., Medina-Elizalde, M., Ramsey, C.B., Satow, C., and Roberts, A.P. 2012. Rapid coupling between ice volume and polar temperature over the past 150,000 years. *Nature* 491, 744–747.

Green, J.A.M., Green, C.L., Bigg, G.R., Rippeth, T.P., Scourse, J.D., and Uehara, K. 2009. Tidal mixing and the meridional overturning circulation from the Last Glacial Maximum. *Geophysical Research Letters* 36, L15603.

Griffiths, S.D. and Peltier, W.R. 2009. Modeling of polar ocean Ttides at the Last Glacial Maximum: amplification, sensitivity, and climatological implications. *Journal of Climate* 22, 2905-2924.

Haigh, I.D., MacPherson, L.R., Mason, M.S., Wijeratne, E.M.S., Pattiaratchi, C.B., Crompton, R.P., and George, S. 2014a. Estimating present day extreme water level exceedance probabilities around the coastline of Australia: tropical cyclone-induced storm surges. *Climate Dynamics* 42, 139–157.

Haigh, I.D., Pickering, M.D., Green, J.A.M., Arbic, B.K., Arns, A., Dangendorf, S., Hill, D., Horsburgh, K., Howard, T., Idier, D., Jay, D.A., Jänicke, L., Lee, S.B., Müller, M., Schindelegger, M., Talke, S.A., Wilmes, S.-B., and Woodworth, P.L. 2020. The tides they are a-changin': a comprehensive review of past and future non-astronomical changes in tides, their driving mechanisms and future implications. *Reviews of Geophysics* 58, e2018RG000636.

Haigh, I.D., Wijeratne, E.M.S., MacPherson, L.R., Pattiaratchi, C.B., Mason, M.S., Crompton, R.P., and George, S. 2014b. Estimating present day extreme water level exceedance probabilities around the coastline of Australia: tides, extra-tropical storm surges and mean sea level. *Climate Dynamics* 42, 121–138.

Irwin, G. 1992. *The Prehistoric Exploration and Colonisation of the Pacific*. Cambridge University Press, Cambridge.

Jerardino, A. and Marean, C.W. 2010. Shellfish gathering, marine paleoecology and modern human behavior: perspectives from cave PP13B, Pinnacle Point, South Africa. *Journal of Human Evolution* 59, 412–424.

Kealy, S., Louys, J., and O'Connor, S. 2017. Reconstructing palaeogeography and inter-island visibility in the Wallacean Archipelago during the likely period of Sahul colonization, 65–45000 years ago. Archaeological Prospection, 24, 259–272.

Kealy, S., Louys, J., and O'Connor, S. 2016. Islands under the sea: a review of early modern human dispersal routes and migration hypotheses through Wallacea. *The Journal of Island and Coastal Archaeology* 11, 364–384.

Langley, M.C., O'Connor, S., and Piotto, E. 2016. 42,000-year-old worked and pigment-stained *Nautilus* shell from Jerimalai (Timor-Leste): evidence for an early coastal adaptation in ISEA. *Journal of Human Evolution* 97, 1–16.

Macaulay, V., Hill, C., Achilli, A., Rengo, C., Clarke, D., Meehan, W., Blackburn, J., Semino, O., Scozzari, R., and Cruciani, F. 2005. Single, rapid coastal settlement of Asia revealed by analysis of complete mitochondrial genomes. *Science* 308, 1034–1036.

Manne, T. and Veth, P.M. 2015. Late Pleistocene and early Holocene exploitation of estuarine communities in northwestern Australia. *Quaternary International* 385, 112–123.

Marean, C.W., Bar-Matthews, M., Bernatchez, J., Fisher, E., Goldberg, P., Herries, A.I.R., Jacobs, Z., Jerardino, A., Karkanas, P., Minichillo, T., Nilssen, P.J., Thompson, E., Watts, I., and Williams, H.M. 2007. Early human use of marine resources and pigment in South Africa during the Middle Pleistocene. *Nature* 449, 905–908.

McGrail, S. 2003. The sea and archaeology. *Historical Research* 76, 1–17.

Mellars, P. 2006. Going east: new genetic and archaeological perspectives on the modern human colonization of Eurasia. *Science* 313, 796–800.

Mellars, P., Gori, K.C., Carr, M., Soares, P.A., and Richards, M.B. 2013. Genetic and archaeological perspectives on the initial modern human colonization of southern Asia. *Proceedings of the National Academy of Sciences USA* 110, 10699–10704.

Montenegro, Á., Eby, M., Weaver, A.J., and Jayne, S.R. 2007. Response of a climate model to tidal mixing parameterization under present day and last glacial maximum conditions. *Ocean Modelling* 19, 125–137.

Mulvaney, J. and Kamminga, J. 1999. *Prehistory of Australia*. Smithsonian Institution Press, in association with Allen & Unwin, St Leonards, Washington, D.C.

Norman, K., Inglis, J., Clarkson, C., Faith, J.T., Shulmeister, J., and Harris, D. 2018. An early colonisation pathway into northwest Australia 70-60,000 years ago. *Quaternary Science Reviews* 180, 229–239.

O'Connell, J.F. and Allen, J. 2015. The process, biotic impact, and global implications of the human colonization of Sahul about 47,000 years ago. *Journal of Archaeological Science* 56, 73–84.

O'Connell, J.F., Allen, J., and Hawkes, K. 2010. Pleistocene Sahul and the origins of seafaring. In Anderson, A., Barrett, J.H., and Boyle, K.V. (eds.), *The Global Origins and Development of Seafaring*. McDonald Institute for Archaeological Research, Cambridge, pp. 57–69.

O'Connor, S. 2007. New evidence from East Timor contributes to our understanding of earliest modern human colonisation east of the Sunda Shelf. *Antiquity* 81, 523–535.

O'Connor, S. and Ono, R. 2013. The case for complex fishing technologies: a response to Anderson. *Antiquity* 87, 885–888.

O'Connor, S., Spriggs, M., and Veth, P. 2002. Excavation at Lene Hara Cave establishes occupation in East Timor at least 30,000-35,000 years ago. *Antiquity* 76, 45–48.

O'Connell, J.F., Allen, J., Williams, M.A.J., Williams, A.N., Turney, C.S.M., Spooner, N.A., Kamminga, J., Brown, G., and Cooper, A. 2018. When did *Homo sapiens* first reach Southeast Asia and Sahul? *Proceedings of the National Academy of Sciences USA* 115, 8482–8490.

O'Connor, S., Barham, A., Spriggs, M., Veth, P., Aplin, K., and St Pierre, E. 2010. Cave archaeology and sampling issues in the tropics: a case study from Lene Hara Cave, a 42,000 year old occupation site in East Timor, Island Southeast Asia. *Australian Archaeology* 71, 29–40.

O'Connor, S., Ono, R., and Clarkson, C. 2011. Pelagic fishing at 42,000 years before the present and the maritime skills of modern humans. *Science* 334, 1117–1121.

Oppenheimer, S. 2009. The great arc of dispersal of modern humans: Africa to Australia. *Quaternary International* 202, 2–13.

Porter-Smith, R., Harris, P.T., Andersen, O.B., Coleman, R., Greenslade, D., and Jenkins, C.J. 2004. Classification of the Australian continental shelf based on predicted sediment threshold exceedance from tidal currents and swell waves. *Marine Geology* 211, 1–20.

Pugh, D. and Woodworth, P.L. 2014. *Sea-Level Science: Understanding Tides, Surges, Tsunamis and Mean Sea-Level Changes*. Cambridge University Press, Cambridge.

Roberts, R., Yoshida, H., Galbraith, R., Laslett, G., Jones, R., and Smith, M. 1998. Single-aliquot and single-grain optical dating confirm thermoluminescence age estimates at Malakunanja II rock shelter in northern Australia. *Ancient TL* 16, 19–24.

Roberts, R.G. 1997. Luminescence dating in archaeology: from origins to optical. *Radiation Measurements* 27, 819–892.

Roberts, R.G., Jones, R., and Smith, M.A. 1990. Thermoluminescence dating of a 50,000-year-old human occupation site in northern Australia. *Nature* 345, 153–156.

Roberts, R.G., Jones, R., and Smith, M.A. 1993. Optical dating at Deaf Adder Gorge, Northern Territory, indicates human occupation between 53,000 and 60,000 years ago. *Australian Archaeology* 37, 58–59.

Shipton, C., O'Connor, S., Jankowski, N., O'Connor-Veth, J., Maloney, T., Kealy, S., and Boulanger, C. 2019. A new 44,000-year sequence from Asitau Kuru (Jerimalai), Timor-Leste, indicates long-term continuity in human behaviour. *Archaeological and Anthropological Sciences* 11, 5717–5741.

Smith, J.M.B. 2001. Did early humans cross sea gaps on natural rafts? In Metcalfe, I., Smith, J.M.B., Morwood, M., and Davidson, I. (eds.), *Faunal and Floral Migrations and Evolution in Southeast Asia-Australasia*. A.A. Ballkema Publishers, Lisse, pp. 409–416.

Sprintall, J., Gordon, A.L., Koch-Larrouy, A., Lee, T., Potemra, J.T., Pujiana, K., and Wijffels, S.E. 2014. The Indonesian seas and their role in the coupled ocean-climate system. *Nature Geoscience* 7, 487–492.

Sprintall, J., Wijffels, S.E., Molcard, R., and Jaya, I. 2009. Direct estimates of the Indonesian Throughflow entering the Indian Ocean: 2004–2006. *Journal of Geophysical Research: Oceans* 114, C07001.

Stewart, R.H. 2008. Coastal processes and tides. In *Introduction to Physical Oceanography*. Orange Grove Texts Plus, Gainesville, FL, pp. 293–312.

Stringer, C.B. 2000. Coasting out of Africa. *Nature* 405, 24–27.

Thiel, B. 1987. Early settlement of the Philippines, Eastern Indonesia, and Australia-New Guinea: a new hypothesis. *Current Anthropology* 28, 236–241.

Thomas, M. and Sündermann, J. 1999. Tides and tidal torques of the world ocean since the last glacial maximum. *Journal of Geophysical Research: Oceans* 104, 3159–3183.

Tojo, B., Ohno, T., and Fujiwara, T. 1999. Late Pleistocene changes of tidal amplitude and phase in Osaka Bay, Japan, reconstructed from fossil records and numerical model calculations. *Marine Geology* 157, 241–248.

Uehara, K., Scourse, J.D., Horsburgh, K.J., Lambeck, K., and Purcell, A.P. 2006. Tidal evolution of the northwest European shelf seas from the Last Glacial Maximum to the present. *Journal of Geophysical Research: Oceans* 111, C09025.

Ulm, S. 2011. Coastal foragers on southern shores: marine resource use in northeast Australia since the late Pleistocene. In Bicho, N.F., Haws, J.A., and Davis, L.G. (eds.), *Trekking the Shore: Changing Coastlines and the Antiquity of Coastal Settlement*. Springer New York, New York, NY, pp. 441–461.

van Zeist, W. 1935. De Mesolitische Boot van Pesse. *Nieuwe Drentse Volksalmanak* 75, 4–11.

Veth, P., Ward, I., and Manne, T. 2017a. Coastal feasts: a Pleistocene antiquity for resource abundance in the maritime deserts of north west Australia? *The Journal of Island and Coastal Archaeology* 12, 8-23.

Veth, P., Ward, I., Manne, T., Ulm, S., Ditchfield, K., Dortch, J., Hook, F., Petchey, F., Hogg, A., Questiaux, D., Demuro, M., Arnold, L., Spooner, N., and Demuro, M. 2017b. Early human occupation of a maritime desert, Barrow Island, north-west Australia. *Quaternary Science Reviews* 168, 19–29.

Walter, R.C., Buffler, R.T., Bruggemann, J.H., Guillaume, M.M.M., Berhe, S.M., Negassi, B., Libsekal, Y., Cheng, H., Edwards, R.L., von Cosel, R., Néraudeau, D., and Gagnon, M. 2000. Early human occupation of the Red Sea coast of Eritrea during the last interglacial. *Nature* 405, 65–69.

Ward, I., Larcombe, P., and Veth, P. 2015. A new model for coastal resource productivity and sea-level change: the role of physical sedimentary processes in assessing the archaeological potential of submerged landscapes from the northwest Australian continental shelf. *Geoarchaeology* 30, 19–31.

Ward, I., Ward, I., Larcombe, P., Mulvaney, K., and Fandry, C. 2013. The potential for discovery of new submerged archaeological sites near the Dampier Archipelago, Western Australia. *Quaternary International* 308–309, 216–229.

Weatherall, P., Marks, K.M., Jakobsson, M., Schmitt, T., Tani, S., Arndt, J.E., Rovere, M., Chayes, D., Ferrini, V., and Wigley, R. 2015. A new digital bathymetric modelof the world's oceans. *Earth and Space Science* 2, 331–345.

Webster, M.A. and Petkovic, P. 2005. Australian bathymetry and topography grid, June 2005. *Geoscience Australia Record* 2005/12, http://www.marine.csiro.au/marq/edd_search.browse_citation?txtSession=8820 (last accessed 09/06/2021).

Williams, A.N. 2013. A new population curve for prehistoric Australia. *Proceedings of the Royal Society B: Biological Sciences* 280, 20130486.

Wilmes, S.-B. and Green, J.A.M. 2014. The evolution of tides and tidal dissipation over the past 21,000 years. *Journal of Geophysical Research: Oceans* 119, 4083–4100.