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Holocene sea-level change and human response in Pacific Islands

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ABSTRACT: Holocene sea-level changes affected people living in the Pacific Islands and their ancestors along the western Pacific Rim. Sea-level changes, particularly those that were rapid, may have led to profound and enduring societal/lifestyle changes. Examples are given of (1) how a rapid sea-level rise (CRE-3) about 7600 BP could ultimately have led to the earliest significant cross-ocean movements of people from the western Pacific Rim into the islands; (2) how mid to late Holocene sea-level changes gradually created coastal environments on Pacific Islands that were highly attractive to human settlers; (3) a hypothesis that rapid sea-level fall during the 'AD 1300 Event' brought about widespread disruption to trajectories of cultural evolution throughout the Pacific Islands; and (4) the effects of recent and likely future sea-level rise on Pacific Island peoples.

KEY WORDS: AD 1300 Event, cultural change, postglacial sea-level rise, recent and future sea-level rise.

Most of the world's oceanic islands are found in the Pacific Ocean, and the majority of these are in the southwest quadrant where the geotectonic processes by such islands originate are most active. Oceanic islands are commonly much younger than the continents and also usually have much shorter life spans above the ocean surface. Many oceanic islands emerge above sea level and sink beneath it within a few million years. The sea-level changes of the Quaternary Period have occurred at faster rates than the long-term averages of the tectonic processes that affect island level, so over short time spans sea-level change has been responsible for the successive submergence and emergence of many islands (Nunn 1994).

This paper examines the impacts that Holocene sea-level changes may have had on the human inhabitants of the Pacific Islands. By way of introduction, the first section describes the Pacific Basin and the configuration of the islands within it, the next looks at the history of Quaternary sea-level change globally and within the Pacific region, and the next describes the history of human settlement of the Pacific Islands. The following part of the paper explains the ways in which sea-level change may have affected Pacific Islander lifestyles at four times:

- the effects of 'catastrophic sea-level rise events' on initial human dispersal during the mid Holocene into the Pacific Islands region from its western margins;
- the mid to late Holocene sea-level fall that created accessible and attractive coastal environments for human settlement in the central and eastern Pacific;
- the 'AD 1300 Event' during which sea-level fall may have contributed to a drop in food resources for people on many islands and induced profound societal changes; and finally
- future disruption to Pacific Island societies resulting from both recent and predicted sea-level rise.

The paper concludes with a discussion of the role of sea-level change as a driver of cultural change on islands.

1. The Pacific Islands region

The Pacific Ocean covers almost one third of the Earth's surface and may appear almost empty to a casual observer (Ward 1989). The indigenous people of the Pacific Islands (Oceania) view it quite differently, as a 'sea full of islands' (Hau'ofa 1993), and were probably able to cross it from New Guinea in the west to South America, possibly Panama, in the east (Fig. 1) before 26 September 1513 when the first European to see the Pacific – Vasco Nuñez de Balboa – did so (Ward & Brookfield 1992; Anderson 2003).

The southwest Pacific has most islands, including the largest and highest islands, some of which – like those in New Caledonia and New Zealand – are of continental not oceanic origin. Pacific oceanic islands – those that formed from processes operating within the ocean basins – tend to be smaller than the continental islands, often formed by or built above a single volcano. Islands in the Fiji, Samoa and Vanuatu groups of the southwest Pacific are examples of those that are exclusively oceanic in origin.

Other parts of the Pacific have fewer islands. Most in the northwest quadrant are strung out along arcs of plate convergence while those in the eastern half of the Pacific are frequently the products of hotspot volcanism and occur in lines marking the passage of the Pacific Plate across a fixed mantle hotspot (Nunn 1994, 1998).

The islands that are found in the southwest Pacific are organised into distinct archipelagos, typically with gaps of 500–1000 km between them. In general, as one moves outwards into the Pacific Ocean basin from its southwest part, islands become smaller and farther apart. Low (generally <3 m above mean sea level) atoll islands are found throughout the tropical Pacific, but are the principal types of islands in the equatorial central Pacific, where they comprise entire countries such as the Marshall Islands and Tuvalu.

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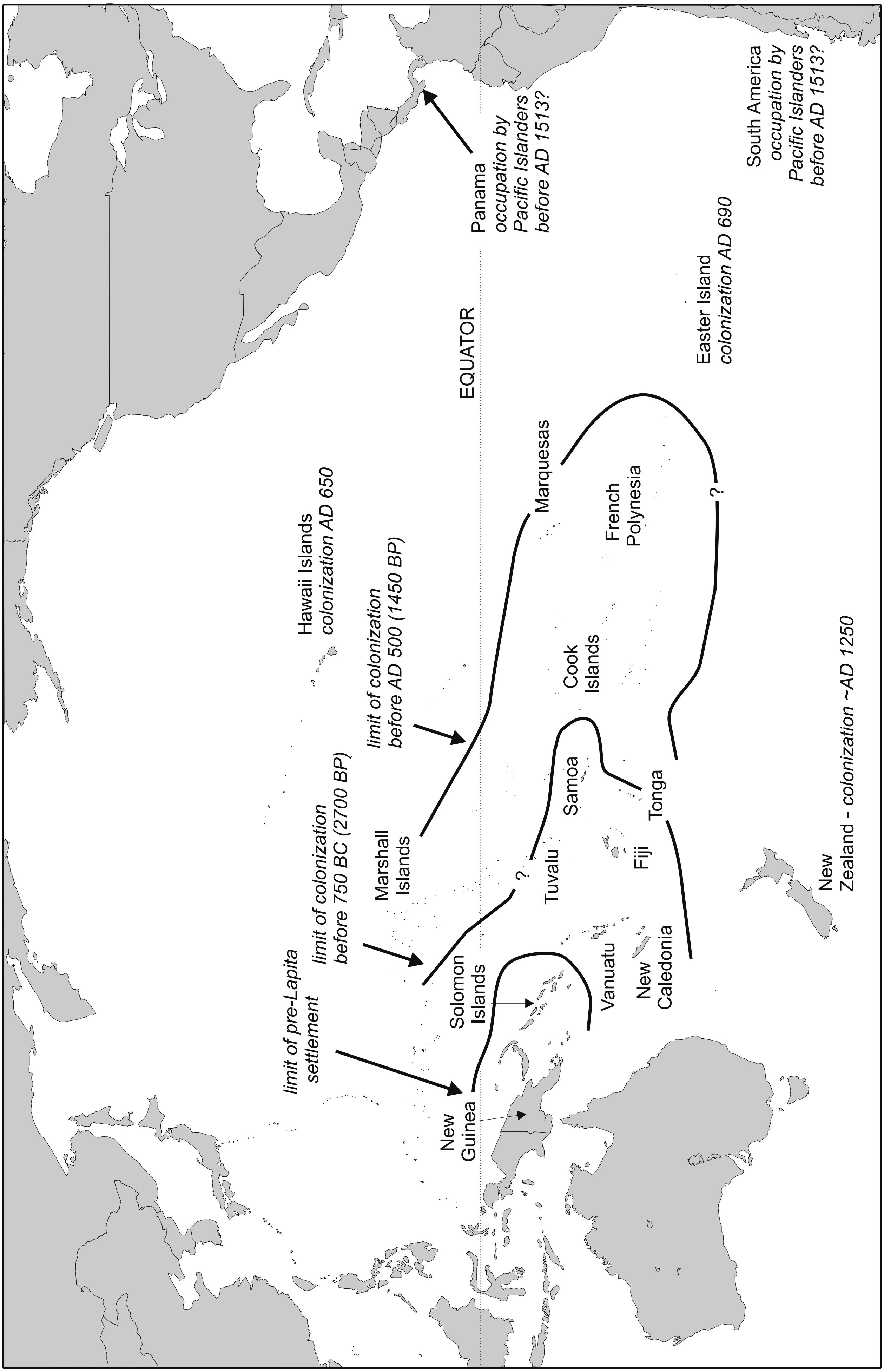

Figure 1 Map showing the progressive colonisation of the Pacific Islands (after Nunn 2004b).

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2. Quaternary sea-level changes in the Pacific

The pattern of Quaternary sea-level changes is now well known in outline although much still remains to discover about short-period changes and their role in environmental and human societal change (Lambeck *et al.* 2002; Nunn 2004a). The oscillatory pattern of sea-level changes associated with ice volume changes that reflect global temperature shifts during the past few million years, primarily as a consequence of regular changes in the Earth's orbit, has been effectively unchallenged since it was proposed (Hays *et al.* 1976). Observations from the Pacific have contributed significantly to the global synthesis (Chappell 1974; Nunn 1999; Lambeck 2002).

In the past 25 years, it has become increasingly apparent that such long-term oscillations of sea level masked smaller short-term rises or falls that could be immensely disruptive to a range of organisms including humans (Berger & Labeyrie 1987; Adams *et al.* 1999). For example, the Younger Dryas (approximately 11 200–10 200 BP) was a time of rapid cooling, in some places along the Pacific Rim marking a return to full glacial conditions, that was associated with a corresponding rapid sea-level fall (Edwards *et al.* 1993). Environmental stress on human ecology may have helped force the development of agriculture, initially as a survival mechanism, independently in various parts of the world including (along the Pacific Rim) coastal East Asia and Central America (Mannion 1999). Some disruptions to human ecology in the Pacific by rapid sea-level change may have occurred during the catastrophic sea-level rise event (CRE-3) about 7600 years BP (Blanchon & Shaw 1995).

Sea level rose throughout the Pacific during the early Holocene, reaching its present level 7000–6000 BP in most parts, then exceeding it by 1–2 m (Grossman *et al.* 1998; Nunn & Peltier 2001). The mid to late Holocene sea-level fall, which saw the shore platforms cut at the sea-level maximum about 4200 BP gradually exposed, transformed many Pacific Island coasts from being cliffed and surrounded by deep water into places marked by fertile coastal plains fringed by shallow-water reefs and lagoons (Nunn 1994). This transformation may have assisted initial human colonisation of various parts of Remote Oceania from 3000–1000 BP (Dickinson 2003).

Sea level reached its present level about 1200 BP. Subsequent changes may be correlated with significant problems for coastal dwellers throughout the Pacific Basin (Nunn 2000a, 2007). In particular, the comparatively rapid sea-level fall marking the AD 1300 Event may coincide with widespread societal disruption in the region (Nunn 2000b). The last 100 years or so have seen Pacific sea level rise at a similar rate to other parts of the world, a change that has also led to problems ranging from shoreline erosion to groundwater salinisation for people throughout the region. Sea level is likely to rise in the foreseeable future, probably at an accelerating rate, which will increase disruption to many Pacific Island societies.

3. History of human settlement in the Pacific Islands

The earliest and most comprehensive movements of people into the vast Pacific Islands region originated along its western continental margins. Using a range of evidence, most writers cite either the south China–Taiwan area or island southeast Asia as places whence the ancestors of Pacific Island peoples came (Oppenheimer 1999; Kirch 2000). Much thought has been given as to why they moved into the island Pacific from what today appears to us as the security of the Asian continental fringe. While it is possible that the diaspora of the first Pacific Islanders had nothing to do with natural (rather than human) processes, the idea of sea-level rise flooding densely-populated lowlands of the continental margin leading to some of their inhabitants to search for new lands across the ocean is a compelling one.

Most is known about the colonisation of the tropical southwest Pacific archipelagoes (Melanesia and west Polynesia), although it seems likely that the island groups to the north (Micronesia) were colonised in separate events (Kirch 2000; Rainbird 2004). Although people had occupied the larger islands in Papua New Guinea and Solomon Islands as much as 40 000 years ago, there is no evidence that these Papuan-language speakers explored east of here. They were joined about 3500 BP (1550 BC) by groups of Austronesian-language speakers who had arrived from the northwest. Within the Bismarck Archipelago of Papua New Guinea about 3300 BP (1350 BC) some of these people developed the extraordinary Lapita culture (Kirch 1997), representatives of which, carrying their distinctively decorated and diagnostic pottery, were the first to colonise the island groups of Vanuatu, New Caledonia, Fiji, Tonga and Samoa in a series of what appear to have been intentional voyages that involved crossing open ocean distances of more than 1000 km (see Fig. 1).

With a few exceptions, the remainder of the Pacific Islands were colonised from Tonga and Samoa: this process involved open-ocean crossings of perhaps 3300 km from the Marquesas Islands of French Polynesia to the Hawaiian Islands around 1300 BP (AD 650), and around 3800 km from Easter Island to South America before AD 1513. New Zealand appears to have been the last major island group to be colonised in the Pacific, people probably reaching there around 675 BP (AD 1250–1300) by following migratory birds across an open-ocean distance from Rarotonga (a possible source in the Cook Islands) of at least some 2900 km (Hogg *et al.* 2003).

3.1. Example 1: Rapid sea-level rise as a driver of Pacific Island colonisation

One of the greatest mysteries concerning the colonisation of the Pacific Islands region is what motivated people, accustomed to much shorter ocean crossings, to venture into Remote Oceania where inter-archipelagic distances are hugely greater (Irwin 1992). One possibility is that the initial part of this colonisation process – the Lapita diaspora that led to the earliest sustained human occupation of Vanuatu, New Caledonia, Fiji, Tonga and Samoa – was not something that began in the Bismarck Archipelago, but the end of a long-term intermittent migration that began far earlier in coastal East Asia.

Agriculture based on rice and foxtail millet appeared in East Asia around 11 000 BP and spread so rapidly that city-sized communities existed as much as 7000 BP (Zhao 1998). Agriculture was most successful in the alluvium-choked valley and coastal lowlands of the largest rivers, particularly the Yangtze and Huanghe (Bellwood 2005). Even a few thousand years after the beginning of agriculture, the combined delta plain of these rivers extended hundreds of kilometres farther out to sea than it does today. This plain may have been peppered with small communities, dependent on both hunting and gathering but mostly on agriculture.

Postglacial sea-level rise caused considerable recession of this part of the East Asia shoreline leading to the displacement of the people who had settled there. Little attention has been given to where they and their descendants went, and it is argued here that a significant number went to sea and began the migration process that culminated in the South Pacific

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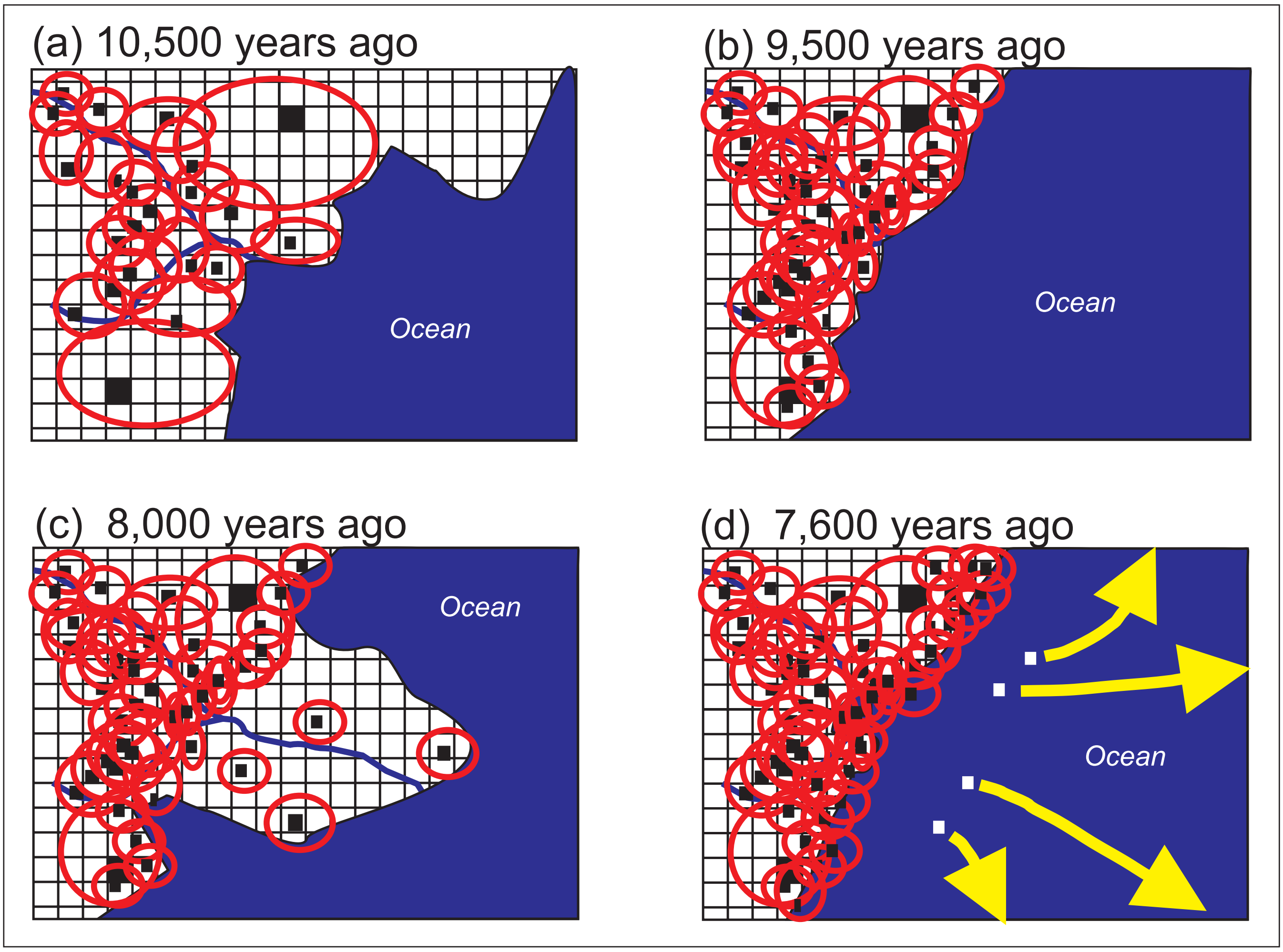

Figure 2 Maps showing the suggested coastline changes and human response associated with postglacial sea-level rise 10 500 to 7600 years ago along a hypothetical part of the East Asia coast. The earliest map shows the spheres of influence of human communities overlapping for the first time, particularly along valley floors, meaning that a hunting and gathering lifestyle alone could no longer feed those communities. This time saw the plant domestication as a direct response to sea-level rise and associated shorelines recession. The second map shows the effects of continuing postglacial sea-level rise which, combined with population increase, led to increasing dependence of these communities on agriculture and on littoral hunting and gathering. The third map illustrates how the rate of sea-level rise at this time was insufficient to drown the most rapidly prograding coasts, particularly around the mouths of large rivers, and how newly-formed deltas would have been occupied by agriculturalists. The final map shows the effects of CRE-3 (6·5 m in <140 years) and how some of the displaced agriculturalists and coastal dwellers would have migrated across the ocean.

3000–4000 years later with the terminal Lapita settlement of Tonga and Samoa.

Figure 2 shows plausible changes along a hypothetical part of the East Asia shoreline during the latest Quaternary. Communities are represented by filled squares and the surrounding circles represent the 'spheres of influence' within which the community hunted and gathered wild foods in order to survive. The overlap between circles represents the need to plant crops and domesticate animals in order to survive. Figure 2a and 2b represent times when postglacial sea-level rise was slow, and communities were able to adapt to its effects. In Figure 2c, sediment deposition at the mouth of a large river is sufficient to cause shoreline progradation even though sea level continues to rise. Yet in Figure 2d, the effects of a catastrophic sea-level rise event causes the shoreline to recede rapidly. The resulting overcrowding prevented all the area's inhabitants from long-term *in-situ* adaptation, forcing some to migrate across the sea. The basic sea-level rise data are from Blanchon & Shaw (1995); various compatible scenarios of East Asia delta evolution are in Hori *et al.* (2002) and Saito *et al.* (2000). While this scenario is largely speculative, it is plausible although other factors may also have helped force over-ocean migration.

There are innumerable pathways that migrants could have followed from the East Asia coast about 7600 BP before reaching Tonga about 3000 BP. Most involve extended periods of settlement in parts of island southeast Asia and western Melanesia before some migrants evidently continued the eastward push (Bellwood 1978; Kirch 2000). It is possible that some of these migrants became sea nomads, as described by Chen (2002), finally settling Pacific Islands only after the attractiveness of their coasts increased sharply with the fall of sea level during the late Holocene.

3.2. Example 2: Late Holocene sea-level fall and human occupation of Remote Oceania

Following its mid-Holocene maximum of 1–2 m above present, sea level fell to its present level between approximately 4000–1200 BP. To understand the effects of this sea-level fall it is necessary to understand what happened along Pacific Island coasts in earlier times.

Around 9000 BP the waters in the tropical (non-equatorial) Pacific became warm enough once again to allow the widespread recolonisation of submerged shallow-water flats by corals and associated organisms which began the process of coral-reef growth. As sea level continued to rise, so these nascent coral reefs attempted to build themselves upwards at the same rate as sea level was rising (Neumann & MacIntyre 1985). Some – the so-called 'keep-up reefs' – succeeded. Others – so-called 'give-up reefs' – failed and drowned. A number of others, perhaps the commonest type in the tropical Pacific (Nunn 1994), are known as 'catch-up reefs' because they caught up with sea level later, possibly only when sea level fell during the late Holocene.

When sea level reached its mid-Holocene maximum (perhaps 5000–4000 BP) it was stable for the first time in around 14 000 years. Until that time many Pacific Island coasts had been cliffed – the common form of a coast around which sea level has been rising for a long time – and there would have been little coastal lowland. Most coral reefs would not have been at the ocean surface; only a few coasts in the warmest parts of the Pacific (for example, in western Kiribati – Marshall & Jacobson 1985) or along unobstructed windward coasts (in Fiji, for example: Nunn 2005) may have had ocean-surface reefs at this time. So wave erosion dominated along Pacific Island coasts at this time.

Stabilisation of sea level in the mid Holocene induced profound geomorphological changes along most Pacific coasts. Particularly around the mouths of large rivers along the Pacific Rim, estuaries expanded and wetlands and enclosed bays developed. Keep-up reefs reached the ocean surface in some places. Along many island coasts, broad shore platforms were cut at low-tide level.

As sea level fell during the late Holocene, so these shore platforms gradually emerged and became covered with sediments of colluvial–alluvial–marine origin to form the 'coastal plains' that are found on many Pacific Islands today. Many 'catch-up' coral reefs succeeded in re-establishing themselves at sea level at the same time because it fell 1–2 m. So within perhaps as little as 2000 years, the majority of tropical Pacific Island coasts were transformed from being cliffed with only deep water offshore to being fringed with fertile well-watered coastal plains and newly-established coral reefs. The attractiveness of these environments for potential human settlers increased considerably after 4000 BP as a result and may thus have supported the colonisation of Pacific Islands (Nunn 1988). There is clear evidence for regular return voyaging from outpost to homeland within the Lapita world (see Fig. 1), a process that would have spread favourable reports of island coasts to the east among potential colonists and would have probably then encouraged further deliberate voyages of colonisation (Kirch 1997).

It is evident from the records of Holocene sea-level change from various parts of the Pacific Islands region that late Holocene sea-level fall took neither the same course nor fell at the same rate(s) in different parts of the region (Dickinson 2001). A critical factor in human settlement, especially but not exclusively for the low atoll islands of the region, would have been the date at which the fringing shore platforms (or reef flats in the case of 'keep-up reefs') emerged permanently above sea level thereby becoming available for human occupation. This 'crossover date' was calculated for most tropical Pacific Island groups by Dickinson (2003), who found that it matched extremely well their earliest-known dates for human settlement. Dickinson therefore concluded that the emergence of flats suitable for coastal dwelling was a critical factor in the colonisation of many Pacific Islands.

3.3. Example 3: Effects of sea-level fall during the 'AD 1300 Event'

Recent work building on the compilation of Nunn (2000a) suggests that sea level fell a total of 50–80 cm at a rate of 10 mm a^{-1} around AD 1350 throughout the Pacific Basin (Nunn 2000a, forthcoming). Part of the 'AD 1300 Event', this sea-level fall appears to have been driven by temperature fall. The magnitude of this was about 1·4°C in New Zealand (Grant 1994) and as much as 3·2°C in China and the tropical Andes (Ge *et al.* 2003; Polissar *et al.* 2006).

Sea-level fall during the AD 1300 Event potentially caused problems for human occupants of the Pacific Islands in many ways. Prior to the AD 1300 Event, during the Little Climatic Optimum, humans along many Pacific island coasts had become dependent on foods growing in coastal plains (particularly coconuts and root crops such as taro and yams), and found offshore, particularly within nearshore lagoons or on offshore coral reefs.

Sea-level fall could potentially lead to a fall in the water tables of coastal lowlands that could conceivably have affected crop productivity at this time. Offshore, sea-level fall may have led to increased turbidity in lagoons, reducing their biological productivity, and to the exposure of the surface of offshore coral reefs killing their most productive parts. The overall effect may have been to reduce food availability on some islands coasts by as much as 80% within perhaps 100 years.

The effects on human society varied considerably across this vast region, but sea-level fall may coincide with a region-wide increase in conflict (where hardly any existed before). Possible examples range from the toppling of the statues on Easter Island and the associated mining of the island's obsidian to manufacture spearheads (Bahn & Flenley 1992), to the abandonment of open coastal settlements in favour of hilltop inland or offshore settlements surrounded by defensive walls and fences in Fiji and Palau (Kumar *et al.* 2006; Masse *et al.* 2006).

Another Pacific-wide phenomenon that occurred soon after the AD 1300 Event was the end of long-distance and sub-regional interaction (Fig. 3). The coincidence of the sea-level fall and profound change in many Pacific societies may plausibly include:

- the breaking up of large communities into smaller groups that could not so readily organise a long-distance or even inter-island voyage;
- the initiation of inter-tribal conflict at a level where trade and other 'friendly' contacts were not desired; and
- the creation, through the emergence of numerous reefs and associated changes to lagoonal circulation, of impediments to successful routine inter-island sailing.

In all, the AD 1300 Event is a possible case of how small magnitude sea-level changes and probably associated climate shifts may have affected human societies. Other factors besides sea-level changes may have contributed to societal disruption around this time, including population-linked stress and internal societal changes, although it could be argued that these were manifestations of climate-driven changes.

3.4. Example 4: Effects of recent and future sea-level rise on Pacific Islands

If no humans lived on the Pacific Islands or depended on them for any valuable commodity, then probably there would have been a lot less discussion of their singular vulnerability to recent and future sea-level rise. Yet this discussion has been so intense, particularly in international fora mandated to find global solutions to the challenges of contemporary climate change (see for example, Leatherman & Beller-Simms 1997;

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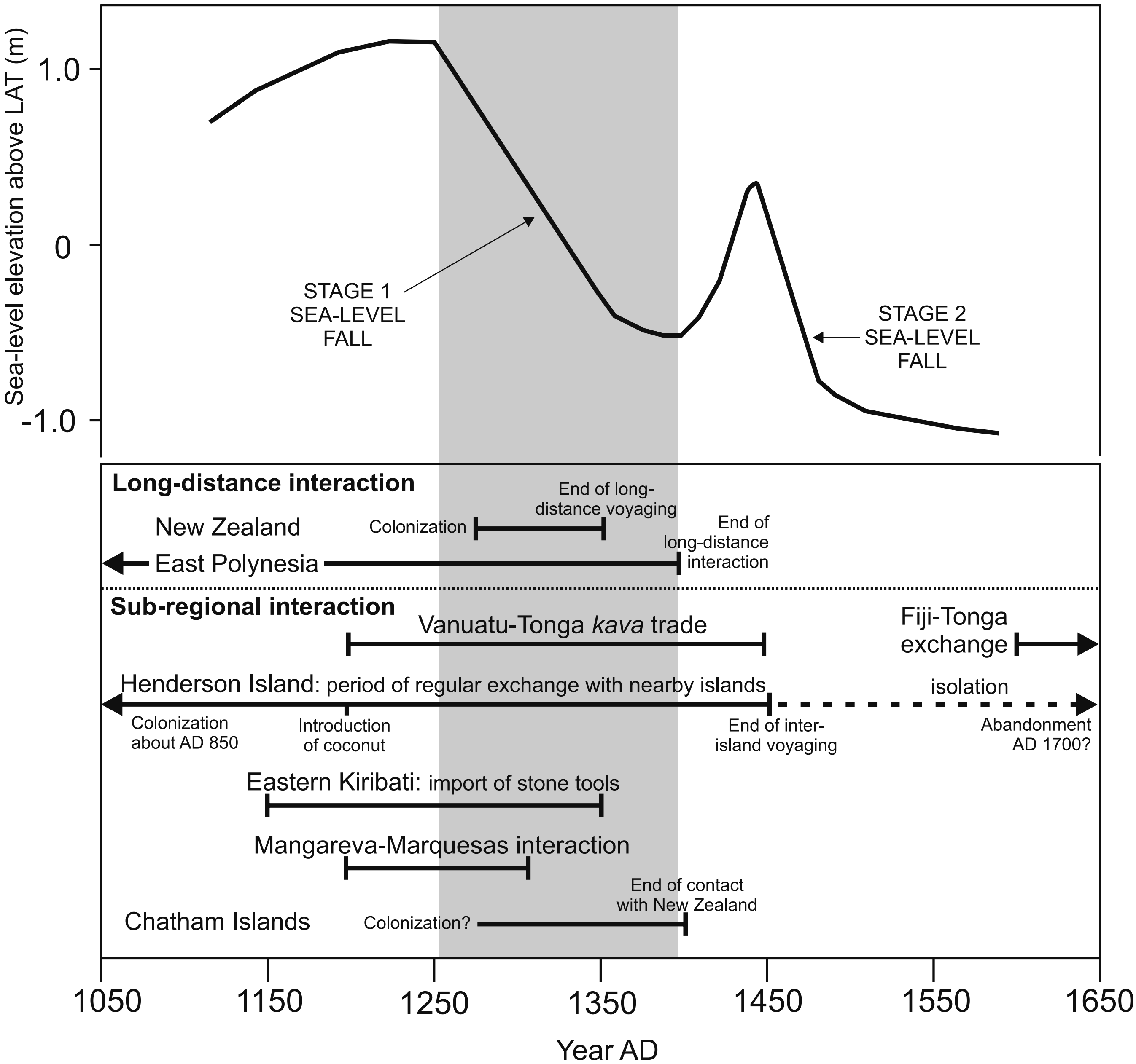

Figure 3 Links between well-dated chronologies of culture change in the Pacific Basin and the sea-level changes of the AD 1300 Event. The shaded bar represents the main period of sea-level fall during the AD 1300 Event in the tropical Pacific, dated by graphical fit to AD 1255–1398 (after Nunn 2007). Chronologies of Pacific Island ocean interaction from New Zealand (Anderson 1991; Buck 1949), East Polynesia (Fornander 1969), Vanuatu-Tonga (Luders 1996), Fiji-Tonga (Reid 1977), Henderson Island (Weisler 1995, 1996), eastern Kiribati (Kiritimati, Manra and Tabuaeran islands – Di Piazza & Pearthree 2001), Mangareva-Marquesas (Weisler & Green 2001), and Chatham Islands (interaction with New Zealand; Sutton 1980).

Kaluwin 2001), that sea-level rise is widely yet misleadingly perceived as 'the' problem confronting Pacific Islands in the 21st-century (Nunn 2004a, b).

Sea level has been rising at an average rate of about 1·0–1·5 mm a^{-1} for the past 100–200 years in the Pacific (Wyrtki 1990; Nunn 2004a) but the precise rate matters less, as for the future, than the environmental and other effects of sea-level rise. Most Pacific Island coasts, except for those that are rising tectonically, have experienced inundation and erosion over the past hundred years or so that is attributable directly to sea-level rise. Associated mobilisation of sand in nearshore areas has changed lagoonal dynamics, as have a range of human impacts. Sea-level rise has also been associated with the inland extension of saltwater wedges into low-lying coastal plains increasing groundwater salinisation and forcing agricultural changes, although the latter have often exacerbated the situation.

Twentieth-century sea-level rise in particular was accompanied on most Pacific Islands by changing and generally increased human demands of the environment, both terrestrial and marine. Many of the associated effects, particularly of logging, cash cropping, coastal infrastructural growth, and increased coral-reef exploitation, have exacerbated the effects of sea-level rise creating communities that are experiencing unprecedented crises of subsistence and land loss (Fig. 4).

The rate of sea-level rise experienced over the past hundred years or so is likely to accelerate within the next hundred years (IPCC WGI 2001). If this happens then the effects of recent sea-level rise are likely to be amplified, although parts of many coastal plains are higher than sea level is predicted to rise. It

Figure 4 (Upper photo) shows the coast at Uluibau Village, Moturiki Island, central Fiji, typical in many ways of settlements of largely subsistence dwellers along Pacific Island coasts. The settlement is located on a coastal flat that rises less than 1 m above mean high-tide level and is often flooded. Community responses to this problem have involved placing cut trees along the back of the beach and piling rubbish up behind them. A partly-complete seawall is also visible. The reef flat immediately offshore the village is largely barren of marine foods because of pollution associated with village activities and because of long-distance sediment transport from nearby larger islands [photo: P. Nunn]. (Lower photo) shows the seawall and associated structures built along the front of the port area of Avarua, Rarotonga Island, Cook Islands. The port is the conduit for most imported goods to the Cook Islands, and its sustainability has been a priority for the government. Before the seawall, the coastal plain on which Avarua is built, 1–3 m above mean high-tide level, was being eroded [photo: P. Nunn].

has been suggested that potentially catastrophic sea-level rise may also occur this century (Rignot & Kanagaratnam 2006).

Coastal inundation and erosion are likely to render parts of many modern coastal plains uninhabitable, forcing their occupants (and their means of livelihood) elsewhere. Increased nearshore sediment mobilisation, combined with increased ocean-surface temperatures, may mean that bleaching of coral reefs – a response to unacceptably high stress – will continue and become more frequent and widespread, perhaps leading to massive losses of coral reef ecosystems (Hoegh-Guldberg 1999). This will have huge consequences for subsistence dwellers in the Pacific Islands but also for the dynamics of physical ocean-coast interactions. Some low-lying islands may become uninhabitable, both because of inundation and because of increased groundwater salinisation.

In summary, future sea-level rise is likely to fundamentally change the geography of the Pacific Islands, force migration, and lead to profound changes in both individual livelihoods and national productivity. Pacific Island governments and communities face huge challenges yet appear to presently lack both sufficient understanding of these and the will to confront them (Barnett 2001).

4. Conclusions: the vulnerability of island societies to sea-level change

Through a series of examples from Pacific Islands, it has been shown that both sea-level rise and sea-level fall may have the potential to disrupt, often quite profoundly, the nature of island societies. This is not a widespread view and this paper represents one of the first syntheses to review the role of sea-level change in cultural change on islands. Several themes appear common to the examples given and worthy of further research.

The first is the response of vulnerable (island) societies to sea-level changes of varying rapidity. In general, island communities are better able to adapt to slow rather than rapid sea-level change. Yet slow change may well involve environmental thresholds that may trigger similar abrupt responses, particularly when they involve primary food resources. The study of change-response patterns in the past may improve understanding of how best to confront future sea-level changes.

The second is the effects of sea-level change on the diversity and amount of food resources available to subsistence dwellers. Pacific Island people who depend, as most do today, on lowland-nearshore foods may be vulnerable in the future to changes in their diversity and amount arising from accelerated sea-level rise.

Finally is the heightened vulnerability of sedentary communities (like those of recent centuries) over those able to adapt to undesirable environmental change, including that associated with sea-level change, by shifting elsewhere (as in the distant past). Studies of community mobility in response to past sea-level changes could inform studies of likely future relocation of communities in response to accelerated 21st-century sea-level rise.

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