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Paleoclimates and the emergence of fortifications in the tropical Pacific islands

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A B S T R A C T

Paleoclimatic data from the tropical Pacific islands are compared to archaeological evidence for fortification construction in the Holocene. The results suggest that in some regions, people constructed more fortifications during periods that match the chronology for the Little Ice Age (AD 1450–1850) in the Northern Hemisphere. Periods of storminess and drought associated with the El Niño Southern Oscillation have less temporal correlation with the emergence of fortifications in the Pacific, but significant spatial correlation with the most severe conditions associated with this cycle. These temporal and spatial correlations require additional study to investigate possible causal relationships.

Introduction

The appearance of fortified settlements on the islands of the tropical Pacific has long been of interest to archaeologists. Often of considerable size and complexity, fortifications are widely distributed across the region from Island Southeast Asia to East Polynesia, and from Belau to New Zealand. They were constructed on both large and small islands, and span a variety of environmental contexts. The earliest known fortifications in the region date to AD 200, while the majority appear between AD 1300 and 1800. This pattern occurs on many tropical Pacific islands, regardless of the duration of human occupation in the area (initial human colonization dates range from 35 kya in Island Melanesia to 0.8 kya in New Zealand). Fortification construction increases in frequency over time, with numbers peaking in the last three centuries. Throughout the region, fortification construction behavior has typically been explained within models of cultural evolution and demographic growth. They are usually assumed to be direct physical evidence for intergroup conflict, which is thought to have emerged in the late prehistoric period when populations had grown to considerable size, and the limited resources of islands encouraged territoriality and the evolution of political hierarchies (Boone, 1992; Carneiro, 1970; Cohen, 1977; Kirch, 1984; Otterbein, 1997). However, these explanations are usually applied to individual islands or archipelagos and do not address the patterns of fortification building and use in the wider tropical Pacific region. By describing region-wide patterning in fortification building, we hope to raise questions that might produce productive explanations for fortifications at many scalar levels. For example, why do fortifications appear across the tropical Pacific when and where they do? Why are there archipelagoes in the Western Pacific (namely New Caledonia and Vanuatu) that lack fortifications? These islands are large and they also experienced cultural and ecological histories that are similar to other island groups in the Pacific. Alternately, why did smaller islands such as Rapa in the Eastern Pacific witness a vibrant period of fortification building even though they could not have fostered large population growth (Kennett et al., 2006)?

Following Allen (2006), we believe that global and hemispheric scale paleoclimate data need to be considered in explanations for the construction of fortifications in the tropical Pacific region. In particular, changes in temperature and precipitation that affected agricultural production and carrying capacity across the region (though not uniformly) need to be considered. One of the ways people could have adapted to environmental changes was by engaging in raiding and other forms of group conflict. We argue that temporal and spatial patterns of drought require special attention for the agriculturally oriented societies of the tropical Pacific islands. This paper explores the current evidence for periods of warming, cooling and drought in the Pacific, and compares these data to the chronology of initial fortification construction. These analyses indicate that over the last three millennia regions of the tropical Pacific experienced periods of warming, cooling, drought, and freshening and that the correlations between conflict and climate change is strong in some areas, and tenuous in others. Our analyses suggest that while there

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is not a simple direct correlation between drought and conflict, there are sufficient chronological and spatial correlations to suggest a causal relationship between regional fortification building and rapid change to drier conditions in some regions.

Links between climate change and conflict

Many previous studies have linked societal collapses, wars, and population decline to periods of climatic change. Much of this research has focused on the Northern Hemisphere, which contains relatively rich historic and archaeological records of societies and past climates. Warfare and societal transitions in California, the American Southwest, the Mississippi Valley, and elsewhere have all indicated a causal relationship between climate change, subsistence stress, and conflict (Benson et al., 2007; Jones et al., 1999; Kennett and Kennett, 2000; Kennett et al., 2007; Turney et al., 2006). The analyses presented by Zhang et al. (2007) provide a complete synthesis of paleoclimates from the latter part of the Holocene for the Northern Hemisphere. These analyses utilize grain prices and records of wars to conclude that conflict and famine in Europe and China were significantly correlated with the occurrence of cooling and drought during the Little Ice Age (LIA; AD 1400–1850), which followed the relatively warm Medieval Warm Period (MWP; AD 800–1300). This work is significant in that it covers an extremely large region of the Northern Hemisphere, and demonstrates a clear relationship between these two phenomena.

Zhang's work and that of other scholars indicate that conflict is a frequent outcome of rapid, climatically-induced ecological change. This potential causal relationship has been explored by both ecological and economic theory (Baker, 2003; Ember and Ember, 1992), and many anthropological cases have been documented in detail (Carneiro, 1990; Dean, 1996; Haas, 1990; Haas and Creamer, 1993; Jones et al., 1999; Kuhlken, 1999; Lambert, 1994; Lekson, 2002; Otterbein, 1985, 1997, 1999; Tainter and Tainter, 1996). The key premise at the heart of the hypothesized link between conflict and ecology is that any severe reduction in subsistence yields results in a stress on society. Conflict serves as an expedient means of resolving that stress and solving the shortfall problem: organized conflict can gain access to resources for the group, and have immediate benefits for the individual in spite of the potential costs of personal injury (Boone, 1983, 1992; Durham, 1976). The emergence of territories has often been explained as a form of competitive land tenure within evolutionary ecology models (Dyson-Hudson and Smith, 1978), suggesting that a strategy of control and defense is more profitable in some environments. Conflict and territoriality can also persist in instances of frequent or episodic ecologically driven shortfalls.

Other aspects of the archaeological record have also been linked to ecological change or climatic upheaval—such as evidence for physical trauma (Lambert, 1994), settlement pattern changes (Neff et al., 2006; Nunn et al., 2007), and cultural innovations (Grattan, 2006). In recent years, Nunn and his colleagues have suggested that changes in climate and sea-level had a pronounced impact on human societies in the tropical Pacific region, and that reactions ranged from changes in subsistence and settlement patterns to warfare, exchange, and cessation or initiation of voyaging (Nunn, 2000, 2003; Nunn and Britton, 2001a,b; Nunn et al., 2007; Nunn and Kumar, 2004). This research illuminates the potential for climate change to have far-reaching effects, but it also suggests the need to evaluate competing explanatory hypotheses. Other factors that may have also contributed to these changes such as population growth, agricultural innovation, social evolution, and the transmission of ideas need to be addressed as potential prime movers in these scenarios.

Fortifications as analytical units for the study of human behavior

Along with skeletal trauma and trophies made from human remains, fortifications are the durable empirical remains of conflict and territoriality (Haas, 2001; LeBlanc, 1999). Fortifications are typically defined by archaeologists as settlements or refuges that incorporate some form of physical impediment that is designed to impede access (Arkush and Stanish, 2005; Arkush and Allen, 2006; Best, 1993; Field, 1998; Keeley et al., 2007). These features can utilize natural landforms, such as ridgelines or pinnacles, and thus be naturally fortified. Or, these features can be augmented with constructed features such as earth, stone, and wood walls, ditches, and gates. In recent years a number of studies have examined the diversity of fortification elements (Keeley et al., 2007), and also attempted to examine some of the intrinsic qualities of defense, including the quantification of variables that may have contributed to the defensive capacities of fortifications (Martindale and Supernant, 2009; Roscoe, 2008). These studies indicate that a number of physical features contribute to defensiveness, but they also serve as effective psychological deterrents to would-be attackers.

More importantly, fortifications have also been identified as rich sources of information for understanding human history. Recent studies have identified how conflict shapes identity, and the key role that fortifications played in sociopolitical organization and the formation of polities (Allen, 1996, 1994; Arkush and Allen, 2006; Haas, 2001; Keeley, 1996). As robust, durable features on the landscape, fortifications are perhaps the best archaeological correlate for conflict. Critically, they are the product of group investment, and indicate a groups' sense of security. The presence of a fortified habitation indicates a desire to maintain some form of land tenure and protect the groups' members and stored resources from the attacks and raids of rivals. The potential for built fortifications to record chronological information makes them especially useful for analyses. They potentially record dates of initial construction, as well as periods of abandonment and refurbishment, which ultimately can be tied to other records of cultural change, population growth or decline, environmental change, or climatic transition. In our analysis, we focus on dates of initial construction, as we believe that this time is when fortification building and by extension, human group conflict, is most straightforwardly correlated with environmental change (Bamforth, 2006; Ferguson, 2006, p. 497). After fortifications are built and social groups have re-organized around warfare, cultural factors have the potential to be more influential in driving subsequent conflict. Similarly, fortifications may accrete symbolic and physical attributes not necessarily linked to social stresses (Allen and Arkush, 2006, p. 7; Ferguson, 2006).

Fortifications in the tropical Pacific islands

For the tropical Pacific islands, fortifications offer a useful analytical unit for the study of human responses to broad climatic trends. Comprised mainly of stone and earthen construction, they were often located on steep slopes and ridgelines in order to take advantage of natural topographic defense. They vary considerably in size and function; some consist of small refuges at the tops of mountains or ridges, while others were large and elaborately constructed features that enclosed settlements (Best, 1927, 1993; Field, 1998, 2005; Green, 1967; Parry, 1977, 1981, 1987, 1997). They are ubiquitous in the tropical Pacific, spanning an area of over 60,000 km^2 and a portion of the last two thousand years of human history in the region. Fortifications have also been associated with detailed studies of subsistence and settlement, indicating the relative importance of land tenure to local patterns of habitation and gardening, and the rise of complex polities (Allen, 1994; Crosby, 1988; Field, 2003, 2005; Ladefoged, 1993). They are also well suited for the study of conflict because many have been dated using absolute methods. The incorporation of fortifications into regional chronologies is a critical part of many evolutionary sequences for Pacific societies, even though it is possible that conflict developed in earlier periods (Kirch, 1984). Oral histories and contact-era accounts describe many battles and episodes of conquest, and we can infer a long history of conflict for many Pacific island societies. However, it is only through the study of fortifications are archaeologists able to reconstruct the scale and history of conflict in the past, and in so doing evaluate its causes and consequences.

This paper explores the current evidence for prehistoric climate change in the Pacific, and compares these data to the chronology of initial fortification construction as identified by archaeologists. In the Pacific case the definition of fortification includes both natural and constructed features, but we rely on the analyses and interpretations provided by individual scholars to identify fortifications. Natural features that have not been examined for human occupation or modification, or which may have had features that failed to preserve and are undetectable archaeologically, are not included in this survey. In these cases, we expect future research will add data that meet the criteria we have established here, and will likely lead to revised conclusions about the causes of fortification building and use.

Temperature and precipitation changes in the tropical Pacific

The modern climate of the tropical Pacific is a complex system of ocean currents, wind patterns, convergence zones, and cycles of weather driven by warming at the equator and cooling at the poles (Kiladis et al., 1989; Oort, 1996; Pickard and Emery, 2002; Reverdin et al., 1994; Siedler et al., 2001). Most paleoclimatic studies in this region have focused on reconstructing sea surface temperature (SST) and sea surface salinity (SSS). These measurements can indicate climatic variations that directly impact humans, such as precipitation, air temperature, and evaporation rates. The tropical Pacific generally experiences less variation in air temperatures during periods of climate change compared with temperate regions, and these changes appear less relevant to human subsistence compared with precipitation levels and seasonality. Higher SST levels can indicate higher precipitation rates (and by extension agricultural productivity), and SST can also affect marine resource productivity. Corals serve as the main proxy record for these conditions, as they preserve a record of variations in local temperature and salinity within the calcareous skeletons of the colony. Sea-floor cores that contain strata of planktonic foraminifera are a second source, as they similarly record local conditions. These conditions are determined via the extraction of the ratio of two stable oxygen isotopes, ^{18}O and ^{16}O (expressed as δ^{18}O) (Esper et al., 2002; Schrag and Linsley, 2002). A sequence of δ^{18}O values, which are extracted from a coring of a coral head, can indicate the variations in seawater temperature and salinity at that location for several hundred years at decade-level resolution. This sequence can then be calibrated with absolute dates, and in some cases linked to tree-ring and modern instrument data. Other proxy records, such as varved lake sediments, tree-rings, speleothems, and ice-cores have been used to provide corroborative evidence for climatic transitions in the region and in areas adjacent to the tropical Pacific (Jones and Mann, 2004).

Over fifty δ^{18}O sequences derived from corals currently exist for the tropical Pacific, originating from Indonesia (Charles et al., 2003), the Great Barrier Reef of Australia (Druffel and Griffin, 1999; Hendy et al., 2002), Papua New Guinea (Tudhope et al., 2001), Belau (Morimoto et al., 2002), Nauru (Guilderson and Schrag, 1999), Guam (Asami et al., 2005), Kirimati (Evans et al., 1998), Maiana (Urban et al., 2000), Tarawa (Cole et al., 1993), Palmyra (Cobb et al., 2003), Vanuatu (Correge et al., 2004; Kilbourne et al., 2004a,b; Quinn et al., 1996), New Caledonia (Quinn et al., 1998, 2006), Fiji (Bagnato et al., 2005), Clipperton Atoll (Linsley et al., 2000a), Rarotonga (Linsley et al., 2006, 2000b), and Mo‘orea (Boiseau et al., 1998). The bulk of these records are restricted to the last four centuries or less, although a number span the earlier portions of the last millennium. These records have allowed for the determination of local conditions of warming and cooling, as well as periods of increased precipitation or drought. Concordance with cycles of climatic change, such as the El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) are also discernable within the sequences. Although several of these records extend into the early Holocene, this paper focuses on records from the last 3000 years, the period that overlaps with the main phase of expansion into the tropical Pacific (the Lapita-era colonization and subsequent colonization events in East Polynesia), and the construction of fortifications. The major trends discussed below are reproduced as a bar diagram in Fig. 2.

The climatic regions that are routinely defined in climatic and paleoclimatic studies are used as the analytical units in this study, and fortifications will be analyzed within these boundaries (Fig. 1). These are the Indo-Pacific Warm Pool, the Southwestern Pacific, the Central Pacific, and the Eastern Pacific. The Indo-Pacific Warm Pool (IPWP) is recognized as an area of warm water east of mainland Southeast Asia that plays a critical role in atmospheric and oceanic convection. Paleoclimate reconstructions exist for a substantial portion of the Holocene from this region. Foraminiferal δ^{18}O records from Indonesia indicate that the IPWP was both warm and saline during the interval AD 1000–1400 with temperatures approximating current conditions (Newton et al., 2006), but cooled from AD 1400 onwards, and reached its lowest temperatures ca. AD 1700. This pattern closely follows the transition from the mid-Holocene warming to cooling (the MWP to the LIA) recorded for the high latitudes, especially Europe and China (Mann, 2007). Comparison of the Indonesian data with that of the tropics and subtropics, and the analysis of lake sediments from islands in the central Pacific have led Newton et al. (2006), Haug et al. (2001) and Sachs et al. (2009) to suggest that the LIA expressed itself differently in the tropical portions of the Northern and Southern Hemispheres, and this difference was due to the southward displacement of the Intertropical Convergence Zone (ITCZ) during the latter part of the last millennium. The ITCZ is region of low-pressure that encircles the earth at the equator, and its displacement is thought to have resulted in more arid conditions north of the equator and wetter conditions to the south. Like other parts of the world, the tropical Pacific experienced these periods as well.

The nearby Southwestern Pacific has a complex and varied climatic history, and research in this region suggests that conditions there were warmer, rather than cooler, during the period of the Little Ice Age. Coral sequences from the Great Barrier Reef, New Caledonia, Vanuatu, and Fiji have been used to generate a climatic sequence of over 6000 years for this region. Of these, the Great Barrier Reef record is the most developed and understood, and indicates a period of cooling stretching from AD 1565 to AD 1700 (Hendy et al., 2002). This is followed by a period of warm and saline conditions that extended from AD 1700 to the early 20th century, when cooling again recommenced. By the 1980s, the warming that is more typical of the 20th century appeared in full force. Hendy et al. propose that increased trade winds during the LIA resulted in increased evaporation and higher salinity in the Southwestern Pacific, and that the dramatic temperature differences between the higher latitudes and the equator resulted in drier conditions in the subtropics (2002, pp. 1513–1514). However, corals from

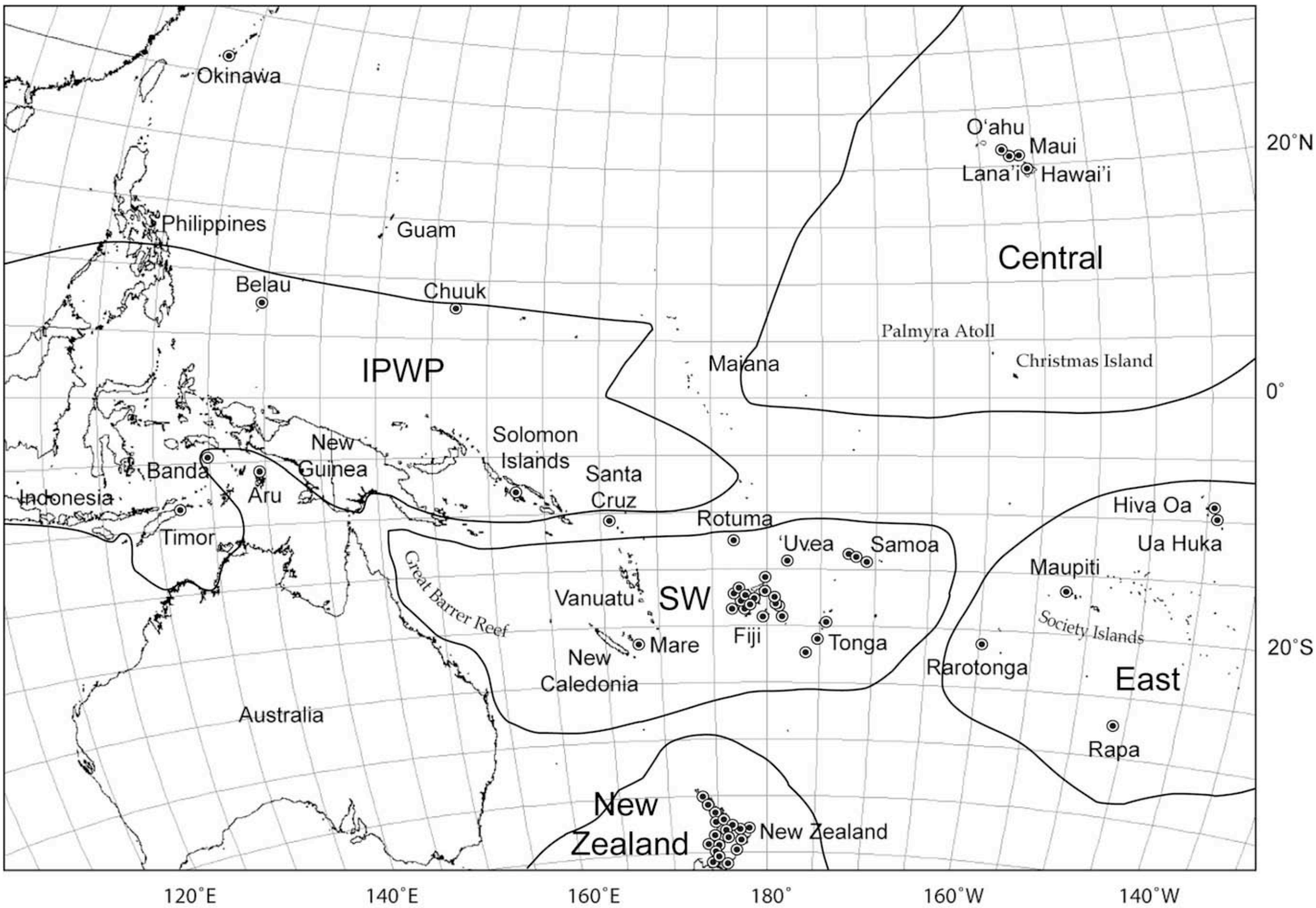

Fig. 1. The distribution of fortifications in the tropical Pacific in relation to climatic regions. The dark boundaries indicate the edges of the Indo-Pacific Warm Pool, the Southwestern Pacific, the Central Pacific, and the Eastern Pacific. Bulls-eye symbols represent the presence of fortifications on an island or in a general locale, but do not represent the total number of sites.

other parts of the Southwestern Pacific provide contrary evidence, and indicate that the eastern portion of the region requires additional study. The records from New Caledonia indicate a varied climate with short periods of warming and cooling beginning ca. AD 1600 (Correge et al., 2001), but also a period of cooling that commenced ca. AD 1700. After AD 1900, the New Caledonian climate transitioned to the warm, wet conditions that typify the 20th century. Vanuatu and Fiji are less studied and have much shorter records, but similarly indicate a trend of warmer and more saline conditions beginning in the 19th century (Bagnato et al., 2005; Quinn et al., 1996). Fiji and Vanuatu are in the vicinity of the South Pacific Convergence Zone (SPCZ), which is a portion of the ITCZ. Researchers from this region have also concluded that the SPCZ is highly variable, and has shifted to the east and west over the last 400 years, bringing a general condition of less saline waters, warmer temperatures, and increased precipitation (Folland et al., 2002; Linsley et al., 2006).

Far to the south, the climate of New Zealand experienced trends that are more typical of high latitude localities. Using tree-ring records that extend over the last millennium, reconstructions indicate that the South Island of New Zealand experienced a warming trend that extended from AD 1100 to AD 1300, followed by a period of cooling that spanned AD 1500–1800 (Cook et al., 2006). Speleothem data have also provided a similar chronology for late Holocene warming and cooling. Research by Williams et al. (2004) suggest that warm conditions dominated on the North Island between AD 1000 and 1300, and these ultimately gave way to minor cool event ca. AD 1675. These data indicate that the conditions of New Zealand were synchronous with the temperature changes that typified the Northern Hemisphere, although the authors do not elaborate on exactly how these conditions developed in the region. Reconstructions of climates indicate that increasing westerlies and cooler ocean temperatures were typically associated with cooling in New Zealand (McGlone et al., 1993).

The Central Pacific and Eastern Pacific are the least known of the tropical Pacific climatic regions. A lengthy record of climatic variation via a spliced coral $\delta^{18}O$ sequence has recently been generated for Palmyra Atoll (Cobb et al., 2003), and this record extends into the last millennium. This sequence indicates that the Central Pacific does not demonstrate much correspondence with periods of cooling and warming that have been recorded elsewhere. In contrast, the conditions in the Central Pacific were cool and/or dry spanning the interval AD 900–1200, a trend that is distinctly different from that of the Southwestern Pacific and the IPWP. For the remainder of the millennium, the Central Pacific remained relatively stable (Cobb et al., 2003). Other records from the islands west and north of the region such as Maiana (Urban et al., 2000) and Guam (Asami et al., 2005) indicate warming and cooling recommenced between the 18th and 20th centuries. The Eastern Pacific records are short, extending only into the 1970s for Rarotonga (Linsley et al., 2006), and to the mid 19th century for Mo'orea (Boiseau et al., 1998). These records provide support for warmer climates and wetter conditions during the late 20th century, and the westward shifting of the SPCZ during this period.

The climatic reconstructions summarized above indicate that trends of precipitation and temperature that typify the higher

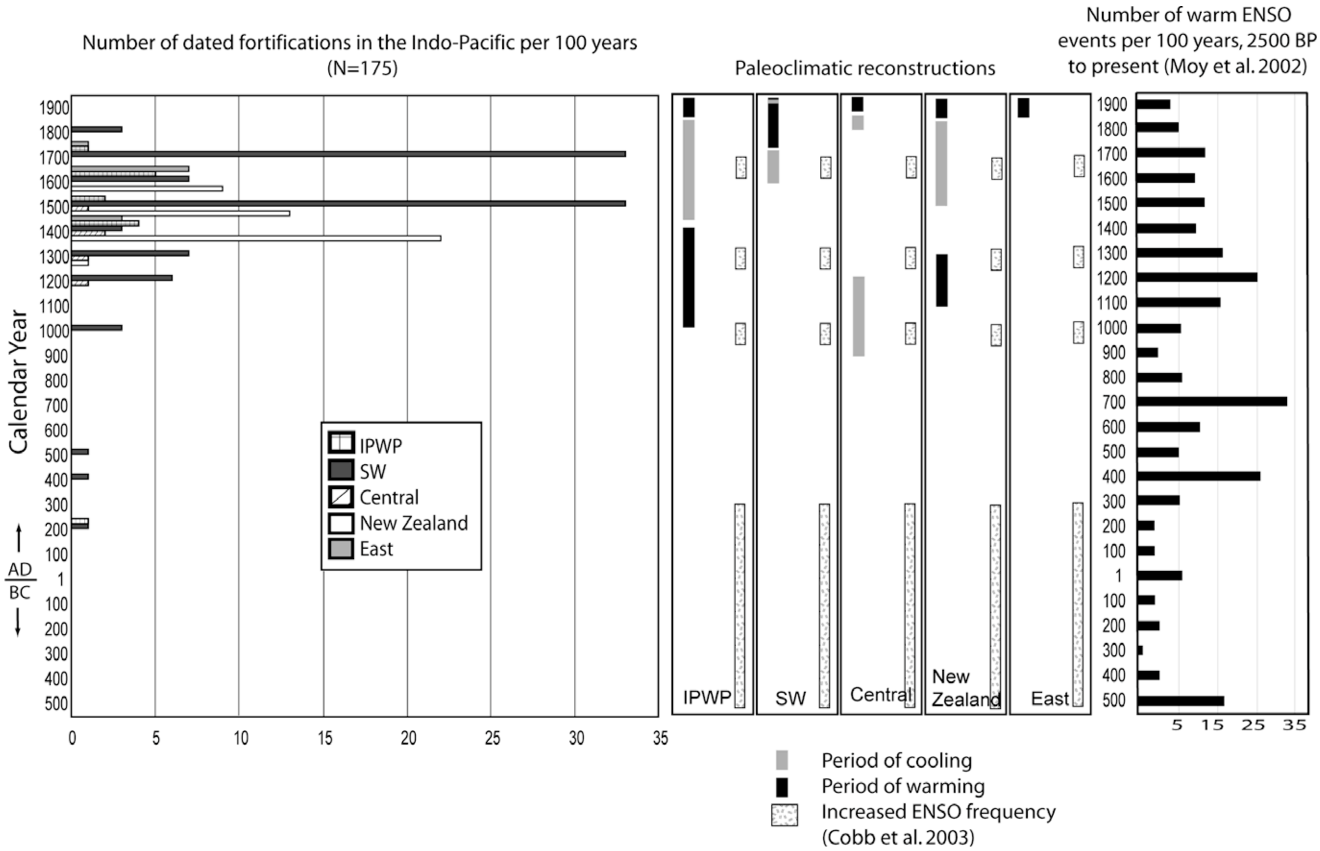

Fig. 2. Comparison of the frequency of dated fortifications per 100 years for the tropical Pacific compared with paleoclimatic reconstructions mentioned in the text. Fortification numbers are subdivided by region and indicated by century along the *Y*-axis. Paleoclimatic reconstructions mentioned in the text are summarized as periods of warming/cooling and ENSO frequency (Cobb et al., 2003), and are also subdivided by region. To the far right of the diagram are the frequencies of ENSO events per 100 years in the Ecuadorean Andes (Moy et al., 2002).

latitudes during the Holocene (especially the Northern Hemisphere) were not similarly expressed in the records of the tropical Pacific. Although there are several instances of congruence, as a whole the responses of this region were varied, and reflect the importance of regional trends in oceanic and atmospheric circulation.

El Niño Southern Oscillation

The El Niño Southern Oscillation (ENSO) is a global phenomenon that has wide-ranging impacts on atmospheric and oceanic processes. Related to changes in water temperature and convection cycles in the equatorial Pacific, ENSO episodes vary in duration and intensity, and produce a range of anomalous weather conditions (Gergis et al., 2006). During an El Niño event, the Walker circulation diminishes and allows the warm waters of the Western Pacific to flow eastwards along the equator, bringing warm, wet and stormy conditions to the Central and Eastern Pacific and cool/dry conditions to much of the Western Pacific (Salinger et al., 1995). A La Niña event, which is also part of the ENSO cycle, brings easterly winds, storminess, increased precipitation and cool sea conditions to the Western Pacific. Differences in the manifestation and timing of ENSO events are not well understood, and appear to be due to a number of factors. However, recent research indicates that small changes in the tropical SST gradients and convergence zones can modify the impact of El Niño events throughout the tropical Pacific (Folland et al., 2002; Juillet-Leclerc et al., 2006), and that in previous millennia these processes served to suppress El Niño events throughout the region (Clement et al., 2000).

Contemporary observations in Island Southeast Asia and much of Western Oceania demonstrate that modern El Niño events are generally associated with drought conditions, decreased monsoon strength, and changes in marine productivity. For example, the strong El Niño of 1997–1998 caused major droughts throughout Island Southeast Asia and Western Oceania with resultant widespread forest burning, crop failure and food shortages (Kaloumaira, 2000; Terry et al., 2001). In Island Southeast Asia, years immediately following El Niño events have recently been associated with heavier than normal rainfall and associated environmental damage including erosion, mud slides, and increases in mosquito-borne illness. In congruence with these data, the tracking of storm paths and severity over the past twenty years has identified regions that are more prone to storms and cyclones during ENSO periods. The most active region for cyclonic activity in Oceania occurs in the vicinity of New Caledonia, Vanuatu, and Fiji (Renwick, 2000). These archipelagoes average between 2.4 and 4 cyclones per year, and experience an increase in storm frequency of approximately 40% during ENSO events. In contrast, cyclones are relatively rare in Island Southeast Asia except for the Northern Philippines, where their frequency does not appear to be directly related to ENSO.

Precipitation anomalies derived from historic rain-gauge records (1900–1998) and satellite estimates show a more detailed view of ENSO patterns in the Pacific region (Dai and Wigley, 2000, p. 1284). On average, the most extreme deficits in rainfall during ENSO events of the last century occurred in the regions of Samoa, Tonga, Fiji, New Caledonia, Vanuatu, Indonesia, and the Southern Philippines (Fig. 3). The Central Pacific Islands that hug

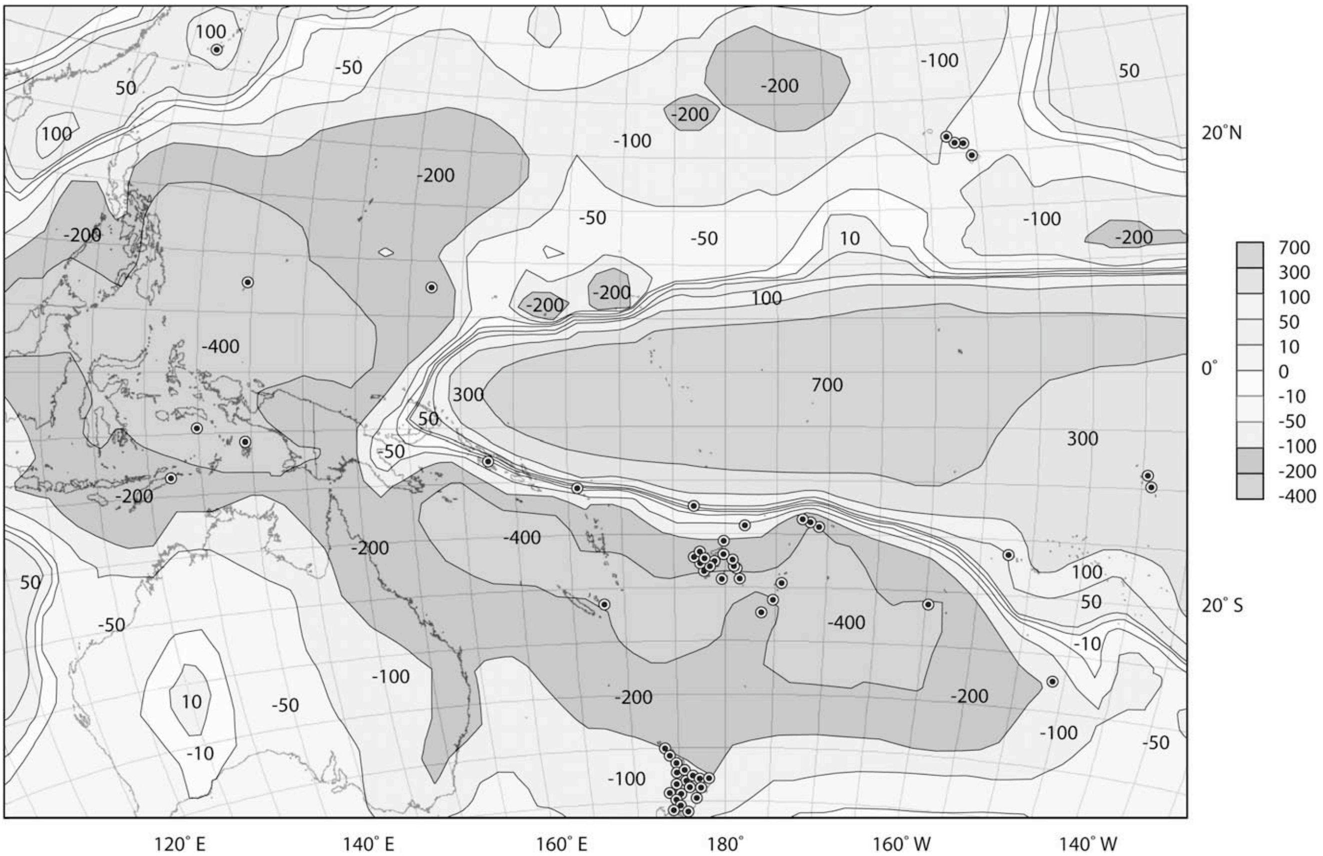

Fig. 3. Average annual precipitation anomalies (mm) associated with El Niño events derived from historic rain-gauge records (1900–1998) and satellite estimates of precipitation (1979–1998) (Dai and Wigley, 2000). Positive and negative anomalies indicated by shading and text. Location of fortifications indicated by bull's-eye symbols.

the equator generally experienced moderate precipitation increase. However, a narrow band that includes the Solomon Islands and part of Samoa showed almost no variation in relation to ENSO, although comparison of 1982–1983 ENSO data indicate that these areas can swing between positive and negative anomalies (Dai and Wigley, 2000, p. 1285).

Like the trends of warming and cooling reconstructed for the Pacific, paleoclimatic data can also indicate the occurrence of El Niño and La Niña events. These reconstructions rely on $\delta^{18}O$ records from around the region, and calibrations with tree-rings from the historic period that are known to identify an ENSO-related growth pattern (D'Arrigo et al., 2005; McGregor and Gagan, 2004; Stott et al., 2002; Woodroffe et al., 2003). The Laguna Pallcacocha sediment sequence from Ecuador spans over 12,000 years and indicates the frequency of El Niño events within 100 year intervals (Moy et al., 2002). Analysis of this sequence indicates that ENSO events were infrequent and weak prior to 7000 years ago. After this date, ENSO events increased in number and magnitude and peaked ca. 4800 years ago, and then decreased again. The next period of increase spanned the years between 3200 and 2400 years ago, followed by a series of pulses at AD 400 and AD 700, and a sustained increase between AD 1100 and AD 1900 with a peak between AD 1100 and AD 1400 (Fig. 2). A more recent synthesis of tree-ring, coral, and ice-core data from global sources also identifies the late Holocene as the peak period of ENSO activity (Gergis and Fowler, 2006). These reconstructions identify the years AD 1650, 1718, 1723, and 1737 as extreme El Niño events, while 1528, 1533, 1572, 1632, 1645, 1742, 1879, and 1894, were extreme La Niña events.

The Pallcacocha reconstruction mirrors ENSO chronologies that have been generated from within the tropical Pacific and beyond. Corals from New Guinea and Kirimati have indicated that ENSO events increased in frequency and amplitude between 2500 and 1700 years ago (Gagan et al., 2004; McGregor and Gagan, 2004; Tudhope et al., 2001; Woodroffe et al., 2003), and records from Palmyra Atoll have indicated peaks in late Holocene ENSO frequency ca. AD 300, 1100, 1300, and 1650 (Cobb et al., 2003). The comparison of 400 years of reconstructed SST data indicates that the Palymyra record shows good agreement with other ENSO chronologies (D'Arrigo et al., 2005). However, as demonstrated by Dai and Wigley's (2000) analysis of rainfall anomalies, the tropical Pacific region would not have suffered equally during centuries that experienced multiple severe ENSO events. Principle component analyses of temperature and precipitation data collected between the years 1951 and 1980 has defined regions that behave consistently with respect to the interaction of convergence zones and the cyclical anomalies of ENSO (Salinger et al., 1995). The Central Pacific, which includes the atoll nations of the Gilberts, Phoenix, and Line Islands, would have been less affected, but experienced increased rainfall and warmer sea temperatures. The most extreme deficits in rainfall would have occurred in the regions of Tonga, Fiji, New Caledonia, and Vanuatu, and these regions would have also experienced an increase in cyclone activity. A narrow band that includes the Solomon Islands, Samoa, the Southern Cooks and Austral Islands would have remained relatively stable, with few detectable anomalies in temperature or precipitation.

Chronology and distribution of fortifications in the tropical Pacific

To generate a picture of the chronology and spatial distribution of fortifications in the tropical Pacific, we reviewed the published archaeological literature and identified features that have been classified as fortifications, and which also have been securely dated (Table 1). Fig. 1 shows the spatial distribution of identified fortifications, and Fig. 2 indicates the frequency of fortifications over time in each climatic region. We used the oldest secure date obtained from fortification habitation as a proxy for the date of the initial construction of the fortification. There is some evidence that initial fortification construction is most strongly sensitive to environmental variability, and that later uses of fortified structures have a wider variety of social and environmental factors involved (Lape, 2006; Lape and Chao, 2008). In general, fortifications were rare in the tropical Pacific prior to AD 900. After this date construction increased gradually until AD 1400, when the number of fortifications multiplied dramatically. By AD 1500 the first peak of growth had been reached, and during this century over 80 new fortifications were established. A similarly high number were constructed from AD 1600 to AD 1750. However, these peaks in construction did not occur equally across all regions. For example, fortifications were built early on in Belau, but they do not increase in number until AD 1400, and then only in low numbers (Masse et al., 2006). Similarly, the Eastern Pacific and the Central Pacific has no fortifications at all until AD 1200, and they remain few in number throughout the sequence. In the Eastern Pacific, the number of fortifications reaches a peak of less than 10 by the year 1750.

Fortifications in the Southwestern Pacific and New Zealand have been subject to the most scrutiny and survey (and therefore they may be overrepresented in our total sample). In the Southwestern Pacific, fortifications emerge in small numbers in Fiji between AD 200 and 500, and then appear more frequently after AD 1000. Between AD 1400 and AD 1700 the number of new fortifications per century peaks at over 60, and are distributed throughout Samoa, Tonga, and Fiji. Similarly, the New Zealand sample shows a small number of new fortifications prior to AD 1400, and then a dramatic increase in number between AD 1400 and AD 1800.

Spatial and temporal correlation between fortification building and climate change

In order to assess the potential for a causal relationship between climate and fortification construction, we analyzed temporal and spatial correlation between the date of initial fortification construction and known episodes of warming and cooling. In general, the frequency of fortification constructions per century shows some correlation with various reconstructed paleoclimatic anomalies (Table 2). These correlation coefficient values resulted from the statistical analysis of the number of fortifications per century and the designation of each century as either cooler or warmer than average. If we look at relationships in the different subregions of the Pacific, there is some variation in the strength of the correlation. In the IPWP, the peak building period for fortifications in the region demonstrates a significant correlation with the occurrence of cooling/drying. Similarly, fortification construction in the Southwestern Pacific shows a moderately significant positive correlation with periods of cooling/drying, and a positive correlation with a short period of warming in the late Holocene. New Zealand shows moderate positive correlation in the cool periods, as many of the dated fortifications were constructed just prior to the peak of the LIA. Fortifications in the East and Central portions of the Pacific show no significant correlation with warming and cooling trends, although the limited paleoclimate data from this region severely limits even this simple analysis.

If we look at correlations between fortification building and warming/cooling trends in different time periods, the strongest correlation is for the second millennium AD, when intense fortification construction occurred at the same time that cool/dry conditions occurred in parts of the tropical Pacific. The abundance of fortifications constructed during the 14th and 17th centuries in the IPWP and the Southwestern portion of the Pacific is the most noteworthy. The relatively small number of dated fortifications built before this time may mask correlations at earlier time periods.

There appears to be less temporal linkage between changes in frequency of ENSO events and fortification construction. This correlation is weak when compared with either the century-scale ENSO reconstructions from South America or the coral-generated sequences from the Central Pacific (Table 3). However, the spatial correlation between areas that experience drought during El Niño and fortification location is quite strong with 99% of the fortifications in the study sample built on islands that experience moderate to severe drought during ENSO events (Fig. 3).

Discussion

There are two major factors that limit the conclusions that can be drawn from the data presented here. These serve to highlight areas of potential future research. One is the relative lack of securely dated fortifications. As is indicated by Table 1, several thousand fortifications are known from the tropical Pacific, but only 184 have been securely dated. This small percentage biases our analyses by overemphasizing the large number of dated sites from New Zealand and Fiji. New Zealand's position in its own unique climate zone means that climate/conflict relationships may be best investigated independently of those in other areas of the Pacific. The lack of dates may also be hiding a clearer correlation (positive or negative) between the occurrence of ENSO events and fortification building in each subregion. Additional research that provides dates for fortifications that are known to exist in Island Southeast Asia, Samoa, Tonga, and East Polynesia would serve to fill the information gap, and may significantly change the chronology of fortifications in the tropical Pacific as it is currently known. In addition, the inclusion of re-establishment dates may provide a more precise picture of when fortifications were re-furbished and expanded. These data were excluded from this study, as re-occupation is not uniformly recorded in archaeological literature. This information could also be crucial to linking the use and re-use of fortifications to changes in climate, as populations may have opted to increase the size of sites over time, rather than construct new outposts.

A second limiting factor is the lack of regionally specific paleoclimate records for many areas of the tropical Pacific at scale and resolution appropriate for the human occupation of those regions. Coral records are the most abundant but their usefulness is limited by the way $\delta^{18}O$ values can conflate SST and salinity values. We hope that alternate proxy records can fill in some gaps here (e.g., Sachs et al., 2009), particularly those most directly related to factors that affect human subsistence such as precipitation. The Central and Eastern tropical Pacific would benefit greatly from increased study.

The issue of population growth, decline, and status-rivalry among elites also remains a critical issue for the study of the effects of climate change in the tropical Pacific. As has been argued elsewhere, the frequency of fortification construction over time could also be explained as a product of population growth and evolving cultural complexity (Earle, 1991; Johnson and Earle, 1987; Kirch, 1984). Hawai'i has often been used as a model for this mode of development, as it is thought to have generated a dense population near the end of the prehistoric period, which also appears to be the time that fortifications and fortified caves were developed (Hommon, 1986; Kolb and Dixon, 2002). However, equally large and diverse archipelagoes such as New Caledonia and Vanuatu lack fortifications, despite their long histories of colonization and potentially high population levels. Research in Fiji that compares the chronology of fortifications with modeled agricultural outputs suggests that the earliest fortifications were not related to popula-

Table 1
General data on fortifications in the tropical Pacific.

Location	Number of Fortifications	Number of Dated Fortifications[a]	Range of Calibrated Ages[b]	Earliest Calibrated Age	References
Okinawa Island	192	4+	1(1200) 1(1300) 1(1400) 1(1500)	1200	Ladefoged and Pearson (2000) and Takamiya (2001)
Banda Island (Indonesia)	2	2	2(1450)	1450	Lape (2000)
Aru Island (Indonesia)	1	0	–	–	O'Connor et al. (2005)
Timor Island (Timor)	25	9	2(1400) 2(1500) 3(1600) 1(1700)	1400	Lape (2006) and Lape and Chao (2008)
Babeldaob Island (Belau)	235	17	1(200)	200	Liston and Tuggle (2006), Masse et al. (2006), Wickler (2002) and Clark (2005)
New Georgia Island (Solomon Islands)	1	1	1(1600)	1600	Thomas et al. (2001)
Chuuk Island (Fed. State Micro.)	26	1+	1(1600)	1600	Rainbird (1996)
Nendo Island (Santa Cruz Islands)	1	1	1(1500)	1500	McCoy and Cleghorn (1988)
Mare Island (New Caledonia)	1	1	1(200)	200	Sand (1996)
Rotuma Island (Fiji)	14	10	10(1700)	1700	Ladefoged (1993)
Waya Island (Fiji)	10	4	1(1350) 1(1400) 1(1450) 1(1660)	1350	Cochrane (2004)
Nacula Island (Fiji	7	1	1(1650)	1350	Cochrane (2004)
Naviti Island (Fiji)	17	1	1(1650)	1650	Cochrane (2004)
Matacawa Island (Fiji)	4	1	1(1500)	1500	Cochrane (2004)
Yasawa Island (Fiji)	2	0	–	–	Cochrane (2004)
Rewa Delta (Fiji)	605	0	–	–	Rosenthal. (1991)
Navua Delta (Fiji)	96	0	–	–	Parry (1981)
Northern Viti Levu (Fiji)	285	0	–	–	Parry (1997)
Beqa Island (Fiji)	40	2+	2(1500) 2(1600)	1500	Crosby (1988)
Central/Southern Lau Group (Fiji)	47	0	–	–	Best (1984, 1993)
Northern Lau Group (Fiji)	19	0	–	–	Best (1984, 1993)
Wakaya Island (Fiji)	8	2	1(1200) 1(1300)	1200	Rechtman (1992)
Sigatoka Valley (Fiji)	298	10	1(500) 1(1000) 1(1300) 2(1400) 2(1500) 3(1750)	500	Field (2003, 2004)
Nadrau Plateau (Fiji)	2	2	2(1750)	1750	Vickers and Eyman (1980)
Cikobia Island (Fiji)	8	3	1(1000) 2(1500)	1750	Sand et al. (2002)
Taveuni Island (Fiji)	31	7	3(1200) 1(1300) 2(1600) 3(1850)	1850	Frost (1974)
Lakeba Island (Fiji)	24	4	1(1000) 1(1250) 10(1500) 18(1750)	1000	Best (1984)
Matuku Island(Fiji)	14	14	14(1500)	1500	Kirkendall (1998)
Nayau Island (Fiji)	6	1	1(1300)	1300	O'Day et al. (2004)
Uvea Island (Wallis and Futuna)	22	1	1(1500)	1500	Sand (1998) and Pollock (1996)
Savai'I Island (Samoa)	3	0	–	–	Green (2002)
Upolu Island (Samoa)	28	2	1(450)	450	Green and Davidson (1969, 1974)
Tutuila Island (Samoa)	15	3	1(1250) 2(1300)	1250	Best et al. (1989), Green (2002) and Pearl (2004)
Tongatapu Island (Tonga)	34	1	1(1500)	1500	Burley (1998)
Ha'apai Island (Tonga)	4	1	1(1600)	1600	Marais (1995)
Ata (Tonga)	1	0	–	–	Anderson (1978)
Hiva Oa Island	3	1	1(1500)	1500	Suggs (1961)
Ua Huka Island	1	0	–	–	Suggs (1961)
Rapa Island (Austral Islands)	35	5	2(1500) 7(1700) 1(1800)	1500	Kennett et al. (2006)
New Zealand (North and South Islands)	6796	130	2(1300–1500) 28(1400–1600) 13(1500–1700) 12(1600–1800)	1300	Allen (1994), Davidson (1987), Sutton et al. (2003) and Schmidt (1998)
Rarotonga (Cook Islands)	1	0	–	–	Best (1993)
Maupiti (Society Islands)	1	0	–	–	Blond et al. (2006)
O'ahu (Hawaiian Islands)	1	0	–	–	Kirch (1985), Kolb and Dixon (2002)
Maui (Hawaiian Islands)	4	0	–	–	Kolb and Dixon (2002)
Lana'i (Hawaiian Islands)	1	0	–	–	Kolb and Dixon (2002) and Emory (1924)
Hawai'i (Hawaiian Islands)	10	1	1(1400)	1400	Kolb and Dixon (2002) and Kennedy and Brady (1997)

[a] Presence of the + symbol indicates that the precise number of dated sites is likely to be larger, but the number was not explicitly stated in the literature.
[b] Text indicates the number of dated sites, followed by the calibrated age in parentheses.

Table 2
Correlation coefficients between the number of fortifications per century and the occurrence of warm and cool centuries.

Region	Correlation coefficient (*r*)
Number of fortifications per century compared with cool periods	
IPWP	0.75*
SW	0.452**
East	No data for cooling
Central	0.076
New Zealand	0.303
Number of fortifications per century compared with warm periods	
IPWP	0.071
SW	0.357**
East	0.07
Central	0.095
New Zealand	0.106

* Correlation is significant at the .01 level.
** Correlation is significant at the .05 level.

tion pressure on resources (Field, 2004). Until more studies are conducted that model demography and productivity (Ladefoged et al., 2008), it will be difficult to exclude population pressure as an explanation for conflict, territoriality, and fortification construction.

In the case of ENSO in the tropical Pacific, a tighter correlation between drought and conflict appears to be plausible, especially for the period AD 1100–1900. The overlay of the geographical location of fortifications indicates that the occurrence of negative rainfall anomalies also coincides with 99% of the fortifications (8745 out of 8765) in the study sample. This strongly suggests that fortification construction is linked to drought, or more specifically, to subsistence systems that are significantly impacted by drought. Tests of ENSO drought relationships to fortification building have shown a probable direct causal relationship in East Timor (Lape and Chao, 2008).

When compared as a group to the Pallcacocha chronology for ENSO events, the fortifications of the tropical Pacific demonstrate no significant positive correlation ($r = .190$) with higher frequencies of El Niño events in the mid and late Holocene (Table 3). When subdivided into the climatic response regions, slightly more significant positive correlations can be determined between ENSO frequency and the construction of fortifications in the Central Pacific ($r = .323$) and the Southwestern Pacific ($r = .196$), but these also would not be considered to be strongly correlated. Similarly, when compared with the Palmyra Atoll data significant correlation with fortification building is also not apparent ($r = .144$), and correlations within particular regions is even weaker. What these analyses suggest is that although significant ENSO events undoubtedly occurred in the regions in which fortifications were built, the peak periods of both phenomena do not exhibit any temporal correlation. As a group, fortifications in the tropical Pacific lag behind the periods in which ENSO was the most intense and active.

Table 3
Correlation coefficients between the number of fortifications per century and the number of ENSO events. Data from Moy et al. (2002) is listed in the upper portion of the table, data from Cobb et al. (2003) in the lower portion of the table.

Region	Correlation coefficient (*r*)
Number of fortifications per century compared with number of warm ENSO events (Moy et al., 2002)	
IPWP	0.045
SW	0.196
East	0.095
Central	0.323
New Zealand	0.106
Entire Sample	0.190
Number of fortifications per century compared with number of warm ENSO events Cobb et al. (2003)	
IPWP	0.169
SW	0.111
East	0.093
Central	0.127
New Zealand	0.110
Entire Sample	0.144

For both ENSO and other cycles of wet/dry climate, the potential causal factors behind possible chronological correlations require additional investigation. Many agricultural societies adapt to a certain level of buffering against uncertainty regarding precipitation levels and seasonal scheduling. In other cases, remembered climate may cause societies to engage in more risky agricultural practices (e.g. less storage, farming of marginal lands) which prove disastrous when climate changes even a relatively small amount. We need more studies of how people choose to invest in risk buffering strategies in different climate patterns. If the timing of the ENSO events is not directly linked to periods during which fortifications were constructed, then perhaps there was lag period following these centuries in which populations attempted claim new territories, or perhaps buffer against the threat of future droughts by maintaining fortifications or core territories. The inclusion of other data sources, in particular demographic and subsistence data, would allow this and other hypotheses to be discussed further.

Conclusion

This research compares the chronology of fortifications in the tropical Pacific with paleoclimate reconstructions. It has been suggested in many parts of the world that climatic change encouraged conflict and territorialism, as this response serves as an immediate means of gaining resources and alleviating shortfalls. Recent studies of population size, war, and subsistence in China and Europe have indicated a significant correlation between climatic cooling and conflict, lending support to this proposition. Periods of cooling and warming related to hemispheric-level transitions (namely the MWP and the LIA) were identified in subregions of the Pacific and compared with the occurrence of fortifications at the century-level. The comparison of fortification chronologies with paleoclimatic data indicate that fortification construction was significantly correlated with periods of cooling, which in the tropical Pacific is also associated with drying. The correlation was most significant in the IPWP, the Southwestern Pacific and New Zealand. However, data pertaining to the frequency of ENSO events did not show a significant chronological correlation with the occurrence of fortifications in all subregions. Although the chronology varied between regions, fortifications did not appear in large numbers until the period immediately after the peak in ENSO frequency. There was, however, a significant spatial correspondence between fortification locations and areas that suffer drought during El Niño events.

This study suggests that the relationship between conflict and climate in the tropical Pacific should be investigated in the future. Additional data pertaining to fortification chronology, population growth, and subsistence would provide critical information for determining how populations were impacted by climate change, and how these responses varied between regions.

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