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– ARTICLE –

How did a changing climate in the tropical South Pacific contribute to the eastward migration and settlement of Polynesia?

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Abstract

The migration of humans into the eastern Pacific was relatively rapid and focused around 900-1250 CE. Although the causes for this migration are varied, we put forward evidence to suggest that a change in the mean state of the tropical South Pacific from La Niña like to El Niño like conditions accompanied by an increase in climate "shocks" around the period of migration, could have created conditions to promote migration east into the Pacific. We use a range of sediment archives and hydroclimate proxies located in sites within the region of migration, to reconstruct climate conditions in the 'sending' islands, and 'receiving' archipelagos. Climate in the period immediately prior to the eastward migration was characterised by a drier southwest Pacific. During the period following settlement of the central region of eastern Polynesia, the mean climate state in receiving islands became wetter, with fewer climate "shocks". Results from socio-hydrological models highlight the sensitivity of growing populations to droughts within a drying climate. Using these lines of evidence, we suggest that as populations grew, particularly in drought-sensitive islands, people with some knowledge of eastern "Gateway islands", chose to move east, fortuitously at a time when wetter conditions supported their long-term settlement.

Keywords: Climate, Migration, Polynesia

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1. Introduction

The movement of people into the tropical South Pacific represents one of humanity's great achievements. Undertaken between c.3500 BCE and 1250 CE, people were able to traverse increasingly longer distances separating progressively smaller islands, until most small islands had been discovered and, in most cases, settled. Whilst conventional models of human movement into the South Pacific envisage a series of steps from west to east, there is increasing evidence that the timing and direction of movements were more complex, with population movements involving exchange and mixing of different groups of people over multiple time-periods (Matisoo-Smith & Gosling 2025). The accepted model until recently, envisaged peopling of the Samoa / Tonga archipelagos by the Lapita cultural complex from around 1000-800 yrs BCE with subsequent movement of people from these islands out into the eastern Pacific. Sear *et al.*, (2020), following Graves & Addison (1995), argue that this process of settlement of the eastern Pacific involved initial voyages of discovery – either intentional or accidental, including pre-settlement introduction of culturally useful commensals such as pigs and edible plants. Subsequently, larger populations moved out and were able to rapidly settle the eastern Pacific islands along with Hawaii and Aotearoa (New Zealand) over a period of < 300 years. In the last 15 years this model, which includes a Samoan/Tongan source population for the settlement of east Pacific islands (Kirch 2020), has been challenged using genetic and linguistic evidence (Matisoo-Smith & Gosling 2025; Wilson, 2021). Micronesia (Fig 1b) is an area of the Pacific colonized from west to east over the period c. 1550 – 150 BCE (Carson 2024). It is likely that these islands formed another route into Remote Oceania (Samoa/Tonga/Uvea) and east Polynesia, indeed refinements to the accepted model of eastern migration, suggest a greater role for Micronesian island population movement notably into Samoa, causing a rapid increase in population around 900-1000 CE (Harris *et al.*, 2020). Wilson (2012; 2021) has used linguistic evidence to posit that eastern Polynesia was settled by Polynesian outlier groups from the northern Solomon Islands although this evidence is contested (e.g. Carson 2024), who travelled via Micronesia eventually to Hawaii. Hudjashov *et al.*, (2018) provide genetic evidence that supports central northern Polynesian outliers in the Solomon Islands as a potential source of Polynesian peoples in the Society islands, although the authors are not conclusive. Rather, they and others highlight multiple movements of people within the Lapita cultural complex region over time, and continued contacts and movements into the period leading up to and after migrations into the eastern Pacific. Nevertheless, there is strong oral history (Kirch & Green 2001), archaeological (Kirch 2020) and genetic evidence (Gosling & Mattisoo-Smith 2025) for Samoan and Tongan population movements into eastern Polynesia, that presumably also involved influxes of people moving through Micronesia.

The timing of human migration into the eastern Pacific is converging on a *short chronology model* (e.g. Schmid *et al.*, 2018; Mulrooney *et al.*, 2011). Multiple lines of evidence confirm a later model of arrival for people into the eastern Pacific, spread over c. 350 years from the initial discovery of "gateway" Islands (*sensu* Allen & Wallace, 2007) c. 850-950 CE to the peopling of Hawaii, Aotearoa and Rapa Nui. The process of island settlement has been suggested by different signals of island discovery recorded in sediment archives including abrupt vegetation changes, (Fujiki *et al.,* 2023; fecal mammalian biomarkers, Sear *et al.*, 2020), through genetic evidence (Matisoo-Smith & Gosling 2025) and U/Th dating of archaeological material (Niespolo *et al.*, 2019). Sear *et al.*, (2020) and Fujiki *et al.,* (2023) argue for an initial early discovery c. 350-600 CE of 'gateway islands' like Atiu and Mangaia (S. Cook Islands) followed by colonisation by a small population who probably knew of the island locations c. 850-950 CE – Sear *et al.*, 2020), and then establishment on the island as the population grew or were joined by other voyagers

(c. 950-1050 CE). In the Society Island archipelago, dates for arrival are c. 997-1079 CE (Schmid *et al.*, 2018), whilst the Marquesas are dated c.1129–1212 (Allen *et al.*, 2022). Continued debate will no doubt arise as new chronological material is discovered, and dating techniques and modelling improve, but the evidence strongly suggests a period of movement into the eastern Pacific around 850-1150 CE.

1.1. Why? – drivers of voyaging and settlement

In a global synthesis of island colonisation, Leppard *et al.*, (2022) argue that the timing of colonisation is driven by multiscale socio-environmental factors affecting the sending areas; these include large scale continental processes (push factors), biogeographic factors (island isolation and area) and socio-cultural processes (notably technological developments – e.g. sail or hull design). In addition, autocatalytic processes operate over time as coastal and island societies develop enhanced methods of seaborne settlement (e.g. navigation, commensal colonization packages – taro, pigs etc.) and societal structures that promote voyaging success and select for voyaging (Cochrane 2018).

Thomas (2020) argues that in the Pacific "*Colonisation is the process by which historical relationships are established between people and landscapes, and consequently involves the interaction of ecological, demographic, social, political and cultural dynamics through time*". Accordingly, colonisation of the East Pacific can be seen as a continual process with movement phases (migrations) determined by the relationships between people and landscape (island agricultural systems), people and seascapes (e.g. marine resources and voyaging), people and environment (place and hierarchical structures related to food security), and people and people (community structures, hierarchy and the evolution of chiefdoms).

Decisions to migrate can be seen as an ecological response to either K-selected processes of resource pressure limited by carrying capacity and population density; or r-selected processes in which risk takers in a society are elevated alongside their canoes and adzes - in effect voyaging is seen as a prestigious activity, although the costs of supporting such ventures is high (Kirch 1984; Irwin 1998). Within this broader process, external factors like extreme events - eruptions, tsunami, cyclones and droughts - may be seen as additional stress either on K-selected population/resource systems, or as motivators of r-selected processes. The decision to migrate in sufficient numbers to sustain island settlement is not without considerable cost to individuals and resource expenditure (Irwin 1998; Dickson *et al.*, 2019). To form a founder settlement with sufficient genetic diversity to survive in isolation requires a minimum of c. 50-500 people (Pérez-Pereira 2022). Two ways to achieve this include the use of "fleets" of voyaging canoes as oral history describes for the settlement of Aotearoa (Irwin *et al.*, 2023), or subsequent population exchange with the original or other island(s) for which there is mounting evidence (e.g. Cochrane & Rieth, 2016; Allen, 2025). The risk or cost of voyaging east into the Pacific is the longer sailing distances involved and the technological capability of voyagers to maintain fitness and survival over the voyage (Irwin 1992). East of the Samoa/Tonga and Micronesian archipelagos, island elevations decline and island size reduces (Irwin 1992). However, groups of islands once discovered, afford relatively closely spaced voyaging, facilitating rapid movement of people within archipelagos as part of a process of advection or dispersal (Thomas 2020; Cochrane 2018).

Following the traditional model (Matisoo-Smith & Gosling 2025), a long pause of c. 1700 years is evident between the arrival of people in the Samoa/Tonga archipelagos and the later dates for human presence on islands to the east (Sear *et al.*, 2020). For Micronesia, a similar pause seems to occur between initial settlement dates of c. 2800-1800 BP (Lipson *et al.*, 2018; Posth *et al.*, 2018) and movement south and east into Samoa / Society Islands at c.1000 CE (Harris *et al.*, 2020; Wilson 2021; Sheppard 2022).

Reasons for the “pauses” include the time taken for autocatalytic processes to result in development of the technology necessary to make longer voyages into the wind (Irwin & Flay 2023); time for the population to reach the carrying capacity of an island (Kirch 2017) or local valley (Hamilton & Khan 2007); cultural and political changes associated with evolving societies leading to social pressures around food resources (Kirch 2020) and resource pressures resulting from environmental stressors including climate – notably droughts (Sear *et al.*, 2020). As an example, oral history in the Cook Island of Atiu describes how the first people to arrive on Atiu were driven from their homeland (‘Avaiki’) due to ‘scarcity of land’, (USP, 1984).

1.2. Theoretical approaches to climate drivers of migration into the eastern Pacific

Contemporary theories for human migration are differentiated by their ability to provide empirically testable hypotheses. Examples of the former include Human behavioral ecology (HBE; e.g. Dinapoli & Morrison 2017), and Evolutionary theory (Cochrane 2018); both see climate as a proximate trigger within a broader framework of natural selection that sees human behaviour as a series of fitness-enhancing actions one of which is migration. In contrast, Ulus & Ellenblum (2021) provide a recent example of correlative evidence to argue that resource scarcity (food, water or both) is the societally relevant link between periods of climatic variability and the political, economic and social processes that lead to structural changes in societies. Formal, testable predictions based on this correlation are not possible. In contrast, HBE models can provide precise (though simplistic), testable predictions based on theoretical model representations of human behaviour under environmental constraints (Cochrane, 2018; Dinapoli & Morrison 2017); including the correlative observations of Ulus & Ellenblum (2021).

Cochrane (2018, p543) proposes that the Lapita migration through Near to Remote Oceania is best explained as a process of selection related to environmental variation and demography. Climate change and technological advances in canoe design lowered the costs of making progressively longer distance out-of-sight of land voyages. In this context, climate change was related to sailing conditions. Hipkiss *et al.*, (2025) use socio-hydrological modelling which is a specific form of HBE, that uses evolutionary principles (fitness-based selection) to explore the role of precipitation variability over time on the fitness of human populations. Such approaches can be used to frame and test possible climate scenarios that may (or may not) result in societal changes that increase fitness of individuals (expressed as change in a population). Climate in these contexts is divided into two main categories: short-term events, and gradual, long-term events. Floods, cyclones and tornadoes are examples of short-term, high impact weather events. Droughts and slow climate change (shift in mean state) are considered long term climate processes. There is a temporal component to the effectiveness of such events; with those extending over multiple years to decades resulting in long-lasting social and cultural change (e.g. Hipkiss *et al.*, 2025; Ulus & Ellenblum 2021). In evolutionary terms, the cost of staying put under short term variability is less than the cost of movement (migration). Longer and more extreme events trigger movement because the costs to individuals within a population are higher if they stay compared to those incurred by voyaging. Innovation in agriculture, canoe technology and development of territoriality are all mechanisms by which the triggering threshold of climate change can be mitigated by populations. Environmental variability (island type, geographic location of a population within a changing climate system) will produce different responses across island archipelagoes, resulting in a mixture of dispersal movements into new lands.

1.3. Evidence for Population impacts and response to drought in the Western-Eastern Pacific

The role of climate in the settlement of the Pacific has largely been explored through the lens of voyaging (Bridgeman 1983; Anderson *et al.*, 2006; Goodwin *et al.*, 2014; Dickson *et al.*, 2019). Undoubtedly, the ability to voyage safely in the direction of unknown and later known islands is dependent on sea state and wind climate and their effect on voyage length and the structural stability of seacraft (Dickson *et al.*, 2019). However, there is increasing evidence that the societal response to changing voyaging conditions can be mitigated through technological adaptation (Irwin *et al.*, 2023).

A broader role for climate has been explored theoretically (Allen 2010) and empirically through chronological association (e.g. Nunn 2000; Nunn & Brotton 2001; Allen 2006; Carson 2024). These initially drew on evidence of global climate variability in temperature or El Niño Southern Oscillation (ENSO) recorded in sites marginal to the areas of Pacific cultural development. Problems with chronology and interpretation of the paleoclimate records resulted in the allocation of 'AD 1300' as a key period between the global warmer temperatures of the Medieval Warm Period (MWP – 750-1250 CE Nunn 2000) or more accepted Medieval Climatic Anomaly (MCA 950-1250 CE Maloney *et al.*, 2022) and the cooler global temperatures of the Little Ice Age (LIA: 1450-1850 Maloney *et al.*, 2022; 1350-1850 Nunn 2000). However, there is uncertainty in the dates of these anomalies and the magnitude of the temperature anomalies across different paleoclimate records and between different regions of the Pacific (Fitzpatrick, 2010). Allen (2006) noted the problem of using global (and largely northern hemisphere) records to infer changes in the Pacific, and reviewed evidence from coral isotope records in equatorial Pacific corals (Cobb, 2013) which showed the inverse temperature and wetness response to those suggested by global (largely northern hemisphere) averages (Nunn 2000; Allen 2010). A key problem (notwithstanding uncertainty with the proxies themselves) with the equatorial and other coral reconstructions is that they do not span the ~1300 CE period neither are they located within the source areas of migration. Furthermore, SST reconstructions in atoll reefs may not reflect wider ocean thermal regimes and crucially, rainfall. Indeed, much of these earlier debates are founded on inferences drawn from relatively few empirical reconstructions and early climate model outputs that we now know do not represent Pacific climate as accurately as other areas (Brown *et al.*, 2020; Peaple *et al.*, 2025). Fitzpatrick (2010) and others critique Nunn's overly simplistic association between climate anomalies and the evidence for societal and material changes in the archaeological and ethnographic history of islands, invoking other social processes (alongside climate) and emphasising the lack of evidence for a regional signal in these records. This downplaying of a climate role in understanding the development of Pacific settlement and society has continued, exemplified by its near omission from recent syntheses of Pacific archaeology (Kirch 2020; Carson, 2024) despite ample documented evidence for its disastrous impacts on historic island populations (d'Aubert & Nunn 2012) and contemporary Pacific island nations (Iese *et al.*, 2021).

In the Pacific, Melinda Allen's contribution to the question of the role of climate has developed since her seminal paper in 2006, in which she argued that "*it was necessary to evaluate the potential influences of climate variability at a variety of scales, on Pacific peoples and the biota and landscapes with which they interact".* In 2010, Allen picked up the climate question again and turned her attention to the other side of the argument - Does climate affect behaviour and social processes? Using the Marquesas islands as a case study, she concluded that *"in localities where climate is unpredictable, perturbations common, and the risks of resource instability high, as in the Marquesas, socio-political systems that incorporate flexibility are advantageous*" (Allen 2010). Adaptations to drought involved emigration, storage practices, famine foods and rituals (Allen 2010). Allen highlights how island microclimates (something expanded on in other islands such as Hawai'i – cf Kirch's 1994 monograph "The Wet and the Dry"), and topographic complexity presents a spatial pattern within which different communities exhibit different sensitivities to rainfall variability. Direct cultural responses are found in specific names for droughts of different severity (Allen 2010). The different duration of droughts and wetter periods are considered to have similar but varied scales of impact on Marquesan culture. Longer term Interdecadal Pacific Oscillation (IPO) cycles are seen as disruptive to structures of power and authority; whilst shorter duration ENSO events may influence socio-political change through the opportunities for leadership change and land acquisition presented by drought driven famines and population decline (Allen 2010). Allen also postulates that these 3-30 year cycles of rainfall variability were imprinted over a broader climate transition from the MCA to LIA, which altered the severity and frequency of ENSO and IPO. These remained conjectural, since at the time she did not have access to proxy climate reconstructions from the locality or even within the South Pacific Convergence Zone (SPCZ).

Addison (2006) has argued that drought stress is manifested differently in Marquesan valleys driven by variable access to potable water and swamp taro production. It is posited that this variability in resource stress caused defensive responses to protecting resources (e.g. construction of houses adjacent to water sources and taro fields) and selective aggression by valleys with high sensitivity to resource pressure on those with lower resource sensitivity. Response to drought stress in Polynesian communities is still seen today in different adaptation strategies. These can take the form of preservation e.g. using traditional fermentation techniques on some islands; exchange with neighbouring islands and assistance from family/clan members elsewhere; use of different resources with more emphasis on marine resources during periods of crop stress; and migration which is a traditional adaptive response to internal and external stress (Rasmussen *et al.*, 2009).

Further evidence for possible limits to human existence on small islands, driven in part by variability in rainfall, is found in the "Mystery" or abandoned islands of east Polynesia and Micronesia (Anderson, 2001). The author notes that many of the mystery islands lie in areas of the Pacific characterised by low mean annual rainfall and high rainfall variability. The implication is that abandonment (or extirpation) was primarily a response to variability in water and / or food resources driven by climate variability.

1.4. The Drought Hypothesis

From the evidence available it is possible to develop a set of conditions under which droughts may have sufficiently severe impacts to have triggered emigration. These can be summarised as:

1. A change in island habitability (*sensu* Duvat *et al.*, 2021) over a period greater than the ability of a population to adapt. Or in evolutionary theory – where the cost of movement is lower than the cost of staying- Cochrane (2018). For example, a reduction in food yield and productivity, and an increase in population towards but not necessarily at carrying capacity.
2. Adequate rainfall in the receiving islands to support the longer-term water, nutritional and calorific requirements of the growing population following discovery.
3. Amenable sailing conditions to make the journeys necessary to deposit and maintain a genetically viable population, which might typically involve multiple canoe "fleets" and / or continuous voyages of contact with surrounding or original island populations.

For such conditions to be met would require a change to the mean state of the tropical Pacific from La Niña (negative IPO) like to El Niño (positive IPO) like SST patterns, with concomitant reductions in precipitation in the SW/Central SPCZ region of sufficient magnitude to alter people's attitudes voyaging risk, triggering emigration eastwards into the Pacific from Samoa/ Tonga/Uvea and north westwards to other known areas of remote and Near Oceania (Cochrane 2018). It is not the purpose of this paper to theorize on the expression of such droughts on the cultural or archaeological record, but others have made theoretical (Cochrane 2018; Allen 2010); modelled (Dinapoli and Morrison 2017) and directly observed estimations of the possible human responses to variable climate that may leave detectable (and testable) records in the physical archaeology.

1.5. Climate of the Pacific – the template of the drought hypothesis

The climate of the tropical South Pacific (TSP) is a coupled ocean-atmosphere system, in which water of different temperature and salinity is distributed in predictable pathways or currents. The temperature patterns of the ocean are influenced by solar radiation inputs which vary seasonally with latitude and with long term ocean circulation that transfer energy around the globe. The atmosphere above the ocean is perturbed by the patterns of sea surface temperatures (SST) and associated large scale temperature gradients (ΔSST) set up by orbital and latitudinal distributions of solar energy and modified by atmospheric and ocean circulations. The resulting coupled system generates a series of mean ocean SST patterns and atmospheric fluxes which provide both structure to hydroclimate in the TSP and create a set of temporal variations in the strength and location of these climate features (Figure 1a). Key to the regions of interest in Polynesia are those which drive precipitation in the region, and those which influence wind strength and direction. It is important to recognise that direct measurements of the variability and detailed spatial patterns of what are large climate systems are short (<100 years) and do not reliably extend back into the last millennium period of interest to archaeology.

Most of the rainfall in the Tropical South Pacific (TSP) is associated with the major convection areas: the Intertropical Convergence Zone (ITCZ); and the South Pacific Convergence Zone (SPCZ) (Figure 1a). Precipitation trends on islands that lie within the SPCZ and ITCZ are dependent on the intensity, spatial extent and position of convection within these major climate features (Figure 1a). The intensity of rainfall within the SPCZ is tied to the ocean state via absolute sea surface temperature, and dynamically via zonal (E-W) and meridional (N-S) SST gradients (Brown *et al.*,2020). Spatially, the eastern margin of the SPCZ is controlled by easterly trade wind moisture content and orographically forced subsidence resulting from the mountain areas in South America (van der Wiel *et al.*, 2016). The alignment of the SPCZ is determined by the E-W temperature gradients across the Pacific which vary seasonally (Matthews *et al.*, 1996) and interannually via the El Niño-Southern Oscillation (ENSO). During regular El Niño events, changes in SST and ΔSST can cause the eastern SPCZ to move northeastwards, resulting in drier conditions in the SW SPCZ region (Samoa, Tonga, Vanuatu, Fiji) and wetter conditions in the NE SPCZ (Marquesas, Society Islands, Micronesia). In extreme 'cold tongue' El Nino events, there can be a complete collapse or merging of the SPCZ into the ITCZ. ENSO-driven droughts can last for several years and are those reported in historical accounts of Pacific islands (e.g. d'Aubert & Nunn, 2012).

On decadal time scales, the extent and location of the SPCZ varies with the state of the Interdecadal Pacific Oscillation (IPO); a large scale, repeating pattern of TSP anomalous sea surface temperatures with a 10-30 year cycle (Fig 1c Power *et al.*, 1999). During negative IPO, conditions are more La Niña-like with cooler central and NE Pacific SST and a resulting stronger SST gradient across the Pacific. During negative IPO, the islands in the SW SPCZ are wetter. Conversely, during positive IPO and El Niño, the central and NE Pacific SST are warmer, and SST gradients are weaker. Precipitation decreases in western and southern margins of the SPCZ. In essence, the IPO acts as a "background state" that influences where the SPCZ's rain-bearing convection is most likely to occur over periods of a decade or more, leading to persistent wet or dry regimes in affected areas.

While longer reconstructions of ENSO have been estimated (e.g. Jiang *et al.*, 2023), equivalent reconstructions of the IPO are relatively few and fall shorter than the period of migration into the Eastern Pacific (Hernandez *et al.*,2020). IPO and ENSO reconstructions provide information on the very large-scale gradients of SST and precipitation across the whole Pacific basin, but they do not actually provide direct information on the precipitation within the SPCZ region, although data model intercomparison approaches purport to provide some spatial hydroclimate evidence (Steiger *et al.*, 2018). However, there are inherent challenges in methods that rely on Global Climate Models (GCMs), such as palaeodata assimilation because GCMs have well documented cold biases in the equatorial eastern Pacific that results in a poor simulation of the SPCZ and ITCZ rainfall bands (Brown *et al.*, 2020). A recent compilation of proxy records of precipitation in the SPCZ together with atmosphere only GCM modelling, shows a mean state change from La Niña like (negative IPO) condition prior to human migrations into Eastern Polynesia, followed by a persistent El Niño like mean state in the SPCZ around and following the migrations (Peaple *et al.*, 2025). This paper focusses on a compilation of recent paleoclimate reconstructions from within the SPCZ region in order to evidence the possibility for the first two conditions in the drought hypothesis and potentially the third.

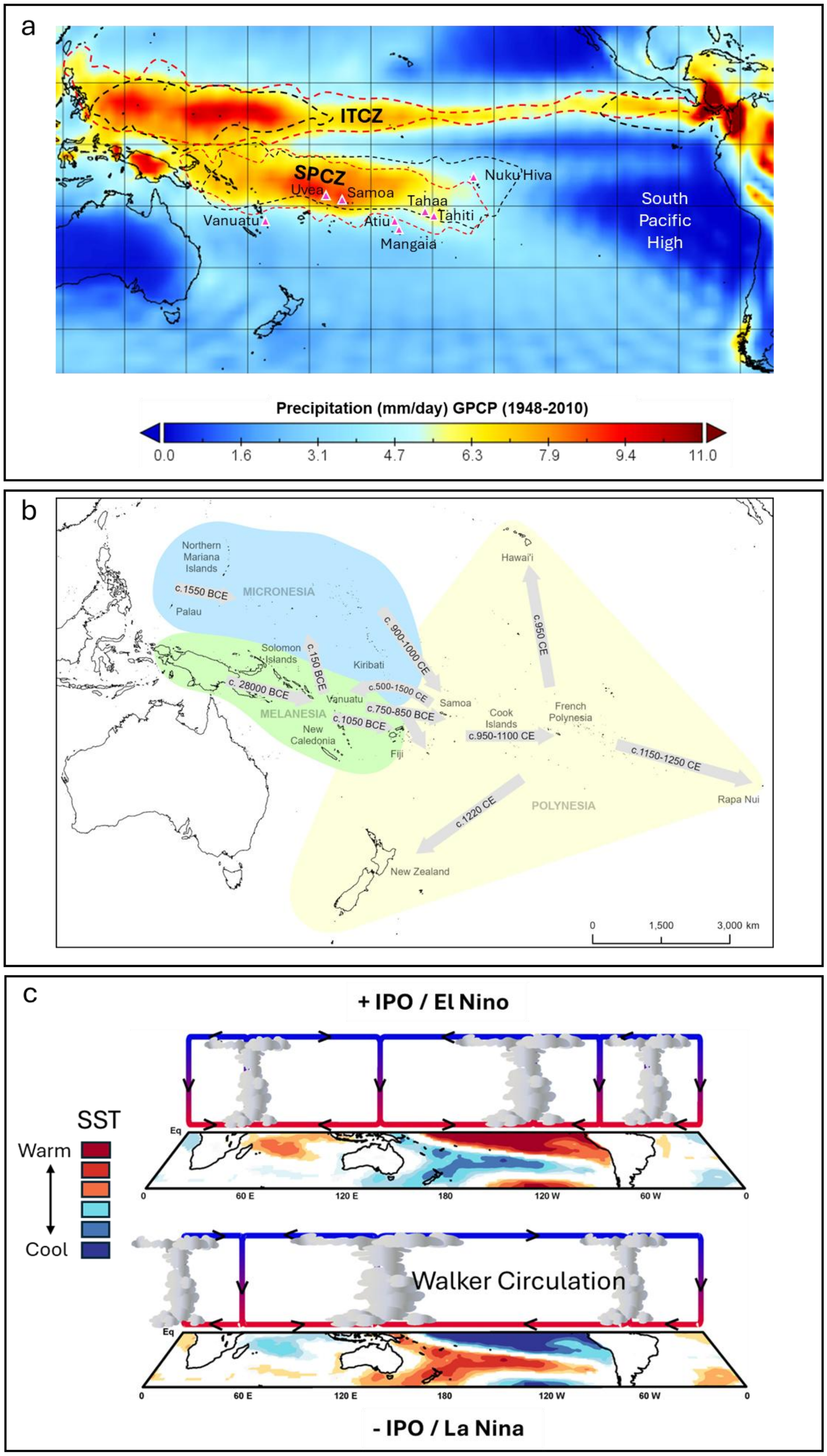

Figure 1: Climate of the Tropical South Pacific. a) Distribution of precipitation and main climate features in the TSP including locations of proxy climate records and indication of changes in the area and location of SPCZ and ITCZ rainfall bands during El Niño like (dashed red lines) and La Niña like (dashed black lines) state. b) Generalised map of the Pacific islands showing

approximate dates of migrations. c) Change in sea surface temperature patterns, main areas of convection and strength and direction of Pacific Walker Circulation which influences trade winds. Map in b) was made with Natural Earth. https://www.naturalearthdata.com/downloads/10m-physical-vectors/10m-land/

2. Materials and methods

Approaches to the reconstruction of past climates draw on a range of proxies that represent the target variable e.g. precipitation or SST. For links to human social and cultural changes, quantitative estimates are preferred since these can be directly related to relevant measures such as water and food security, thus enabling estimation of likely impact on a population. In many cases it is more likely the measures will be qualitative, and it is trends and estimates of amplitude that are of interest. Resolution and accuracy of the chronology of proxy reconstructions is a further constraint on the ability to link human responses to a given change in climatic variability and represents one of the most important elements in understanding Pacific archaeology and paleoclimate reconstruction. Statistical models that can account for the uncertainties in both proxy reconstruction and age models enable a better representation of the uncertainties in proxy data and highlight the importance of reducing or representing uncertainty in datasets generated across the Pacific (Peaple *et al.*, 2025). Here we draw on these developments to provide new proxy records of hydroclimate across the SPCZ region (Fig 1a), and synthesize them within a statistically robust framework.

2.1. Proxy Reconstructions

We developed proxy reconstructions from lake and swamp sediment archives located within the SPCZ region of the TSP. Lake and swamp sediment archives offer longer continuous archives than coral or speleothems and multiple indicators of environmental and climate change (plant community and species change, soil erosion, records of burning etc.). Where laminated, they can also provide higher temporal resolution archives (seasonal-decadal), but such records are rare. We utilise two main sources of proxy climate both based on the fractionation of hydrogen isotopes that occurs from the evaporation of source (oceanic) water to the production of precipitation, and the subsequent fractionations along biological pathways (Sachse *et al.*, 2012; Maloney *et al.*, 2019).

In tropical regions, the isotopic composition of rainfall is largely governed by the amount effect, whereby greater precipitation leads to the progressive depletion of heavy hydrogen isotopes in atmospheric water. Once deposited, this primary signal can be modified by post-precipitation processes, particularly evaporation from soils and surface waters. Organisms record this environmental signal through two main pathways: algae incorporate hydrogen directly from lake or swamp water, whereas terrestrial plants take up hydrogen via soil water. Subsequent biochemical synthesis imposes additional fractionation, creating an offset between the isotopic characteristics of each organism's lipids (e.g. leaf waxes) and the water they draw from. When these offsets are accounted for, the isotopic composition of precipitation can be reconstructed.

For leaf waxes, the proxy is often qualitative because the original signal is overprinted by variable soil evaporation, leaf-level processes such as transpiration and varying biosynthetic fractionations among different plant groups (Sachse *et al.,* 2012). Nevertheless, if the amount effect is assumed to dominate, leaf wax hydrogen isotopes can still be interpreted in terms of relative changes in precipitation (Ladd *et al.*, 2021). In contrast, algal lipids from lakes or swamps follow a more direct hydrological pathway and integrate the catchment-wide precipitation isotopic signal. As a result, they often allow for robust, quantitative estimates of mean annual precipitation, based on regional core top calibrations (Maloney *et al.*, 2019).

For lake sediments, carbonate analysis focuses on oxygen isotopes ($\delta^{18}O$). Unlike lipid biomarkers, the isotopic signature of carbonates is complicated by two primary uncertainties. First, the fractionation of oxygen during carbonate formation is temperature-dependent (Romanek *et al.*, 1992); thus, the resulting $\delta^{18}O$ signal reflects both the temperature of the lake water and the isotopic composition of the water itself (Hostetler and Benson, 1994). However, in the tropics this effect is less important than precipitation amount due to more stable temperature regimes. Second, carbonates act as an 'open system' post-deposition: they are susceptible to diagenesis, where recrystallization or exchange with pore waters can chemically alter the original isotopic signal (Swart 2005). Given these confounding factors – disentangling temperature from hydrology and accounting for potential preservation bias – this proxy is typically used for qualitative reconstructions of relative 'wet' or 'dry' phases rather than quantitative precipitation estimates (e.g., Menking *et al*., 1997; McGee *et al.*, 2012).

2.2. *Probabilistic Hydroclimate Reconstruction*

To reconstruct hydroclimate variability across the study region (0–2000 CE), we employed a Monte Carlo ensemble approach that accounts for both chronological uncertainty and analytical measurement error. The analysis distinguishes between two distinct modes of climate variability: (1) Climate States, defined as significant deviations from the long-term hydroclimate mean (i.e., sustained wet or dry phases), and (2) Climate Shocks, defined as statistically extreme transitions between values (i.e., rapid abrupt shifts), regardless of the absolute state.

2.3. *Data Standardization and Uncertainty Modelling*

All proxy records were standardized to allow for inter-record comparison. For each proxy series x we calculated the median (μ) and standard deviation (σ) of the raw values. To incorporate analytical uncertainty, we generated n=1,000 realizations for each proxy. In each realisation i, the proxy value x_t at depth t was perturbed by drawing from a normal distribution:

$$\mathcal{N}(x_t, \epsilon_t)$$

where ϵ_t represents the analytical error of the specific measurement.

Chronological uncertainty was modelled by sampling from 1,000 distinct age-depth ensemble members, that link depth *z* to time *t*, generated via the Bacon age modelling package (Blaauw and Christen 2011). Thus, the resulting data are sampled from a population defined by both analytical and age model uncertainty based on the resolution of the actual data.

2.4. *Definition of Climate States (Mean State Excursions)*

We defined "Climate States" to identify periods where hydroclimate conditions significantly exceeded the background variability of the record. For each realization, the standardised Z-score $Z_{state}$was calculated as:

$$Z_{state} = \frac{x_{sim} - \mu}{\sigma} \times d$$

where d represents the directionality of the proxy (-1 or 1), ensuring that positive Z values consistently represent "Wet" conditions and negative values represent "Dry" conditions.

A Wet State was defined as any interval where $Z_{state} > 1\sigma$. Conversely, a Dry State was defined as any interval where $Z_{state} < -1\sigma$. These thresholds identify robust departures from the mean conditions, filtering out minor background noise.

2.5. *Definition of Climate Shocks (Abrupt Transitions)*

While "States" measure the magnitude of wetness or dryness, "Shocks" measure the rapidity and magnitude of change. We calculated shocks by analysing the first difference (rate of change) between consecutive chronological data points in the Monte Carlo simulations.

For each realisation, the first difference series D was calculated as $D_t = x_{t+1} - x_t$

This difference series was then standardised relative to itself to produce a Shock Z-score Z_{shock}:

$$Z_{shock} = \frac{D_t - \mu_D}{\sigma_D}$$

where $\mu_D$and σ_D are the mean and standard deviation of the inter-sample differences for that specific record.

A Climate Shock was identified when the rate of change over 20 years, exceeded a stricter threshold of 2σ (i.e., $|Z_{shock}| > 2.0$). This threshold isolates only the most extreme rapid reorganisations of the hydroclimate system. A positive shock >2σ indicates a rapid shift toward wetting, while a negative shock <-2σ indicates a rapid shift toward drying. The timing of the shock was assigned to the temporal midpoint between the two data points involved in the transition.

2.6. *Composite Construction*

The resulting State and Shock occurrences were aggregated into 20-year bins spanning 0–2000 CE. For every bin, we summed the number of realisations that triggered the state or shock thresholds and normalised by the total number of Monte Carlo repetitions. The resulting histograms represent the probability density of a climate event occurring within a given 20-year window, robust to chronological and analytical uncertainties. Finally, the composite records were normalised to a 0–1 scale relative to the maximum probability density observed in the record.

Three key areas for proxy climate reconstruction are the sending islands of Tonga/Samoa (traditional model) and Micronesia (e.g Addison & Matisoo-Smith 2010; Wilson 2021 and others) and the Eastern Pacific receiving area. Unfortunately, Proxy records of hydroclimate from Micronesia are fragmentary and do not extend back into the period of human arrival or possible migration into eastern Polynesia. It is however worth noting the evidence for a westward migration back into the Polynesian outliers by Polynesian migrants which some posit as evidence that the emigration around 1000 CE was not simply unidirectional – east (Sheppard 2022). However, there is uncertainty around the dates and scale of this migration, with evidence of earlier (pre 1000 CE) and much later (post 1000 CE) migrations of Polynesian type artefacts, linguistics and culture (see Carson 2024 and Sheppard 2022 for reviews). The north-central outlier islands of the western pacific region would represent a relatively low-cost option in terms of voyaging due to the westerly wind direction, existing canoe technology tested in earlier west-east voyaging and likely prior knowledge of their existence. However, westward voyaging into already inhabited islands (Sheppard 2022), may also have incurred a higher cost in terms of potential conflict, drier hydroclimate at the time, and relative sensitivity to drought given their Atoll or Makatea hydrogeology (Bayliss-Smith 1974). Thus, migration west around c.1000 CE can be explained by a comparatively low-cost response to a triggering process in Remote Oceania. We therefore focus on the migration east into the Pacific from the Samoa-Tonga archipelagos as per the traditional model (e.g. Kirch 2017)

3. Results

Proxy hydroclimate evidence shows strong variability between and within sites across the SPCZ region (Figure 2). These reflect the strong precipitation gradients within the SPCZ that are themselves a function of natural variability in SSTs and moisture fluxes within the atmosphere over multiple timescales (seasonal, interannual: ENSO, interdecadal: IPO) which drive convection, condensation and ultimately precipitation. For example, islands located centrally within the SPCZ core tend to show less variability or trends over the last 1500 years compared to more marginal locations, as is shown in reconstructed precipitation averaged over the past 1000 years (Figure 2). Given the low resolution of these records, we cannot comment on these modes of variability specifically, but there are clear periods when all records show wetter or drier phases, and multi-centennial trends that describe mean state changes in background Pacific hydroclimate (Peaple *et al.*, 2025).

Focusing on the timing of human migration into Eastern Pacific and constrained by evidence to the traditional model of Samoa/Tonga as a source for these settlers, Figure 2 shows a period of drier conditions across all the sites in the centuries before and during that time. Sear *et al.* (2020), Maloney *et al.* (2022) and Peaple *et al.*, (2025) have identified this drier phase, but here we can observe it across the SPCZ. In eastern islands (S. Cook Islands, Society and Marquesas), there is a drier period prior to the earliest dates of arrival. We therefore conclude that at the time of initial exploration (*sensu* Sear *et al.*, 2020), migration and arrival, the Pacific SPCZ hydroclimate was generally drier.

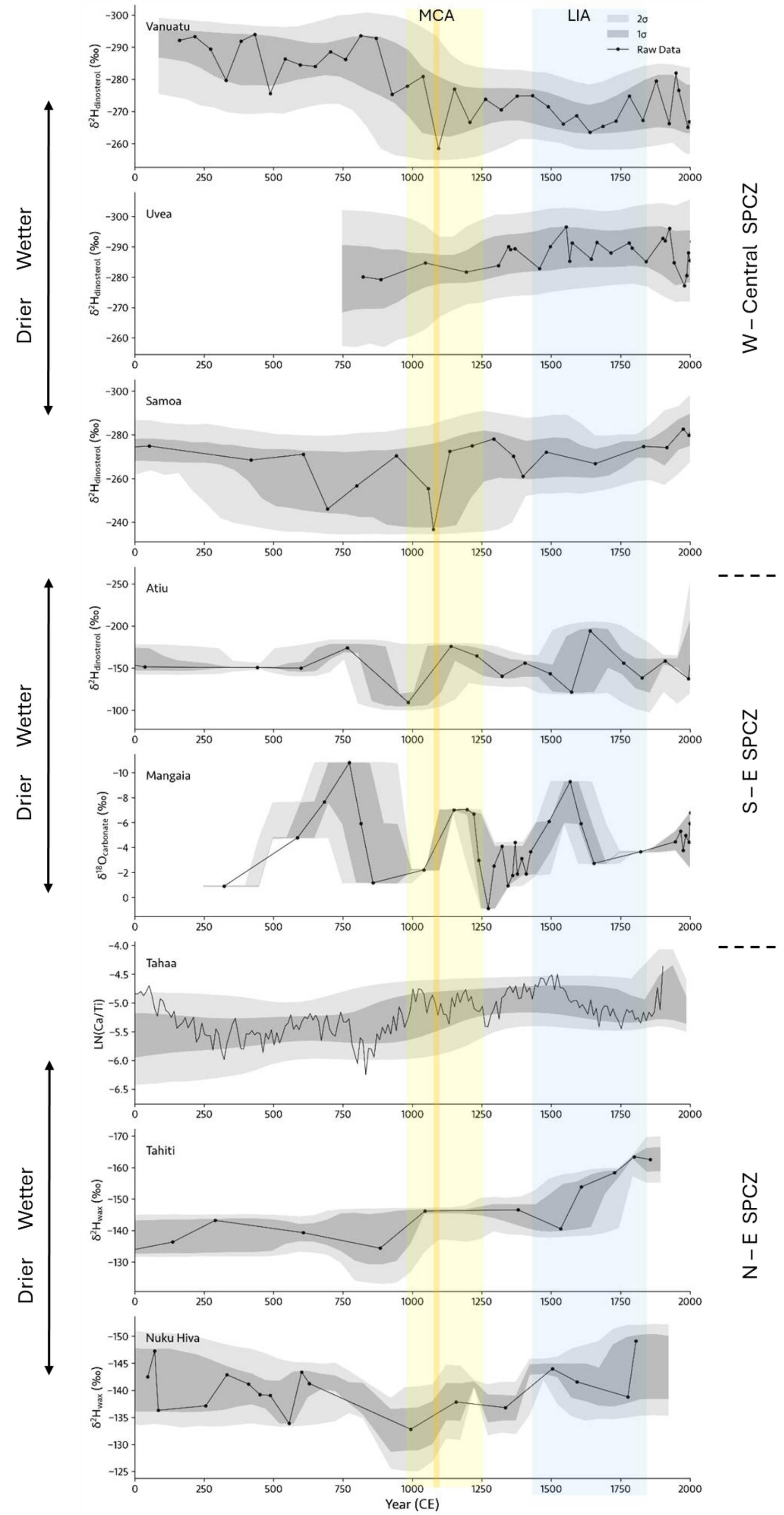

Figure 2. Compilation of high-resolution hydroclimate proxy records for the Central Pacific over the Common Era (0–2000 CE). From top to bottom, the panels display: (A-D) $\delta^2H_{dinosterol}$ records; (E) $\delta^{18}O_{carbonate}$; (F) LN(Ca/Ti); and (G–H) $\delta^2H_{leaf\ wax}$ records. Black lines and markers represent the

primary raw data series (interpolated to a decadal resolution for the Tahaa record). The shaded envelopes depict probabilistic uncertainty bounds generated via 10,000 Monte Carlo simulations, which account for both chronological (age model) and analytical proxy errors. Darker and lighter shading correspond to 1 sigma and 2 sigma confidence intervals, respectively. Note that the y-axes for all isotope records are inverted to align hydroclimate phasing with the Tahaa runoff proxy (where higher values indicate increased precipitation/runoff). Orange bars give the range for the probabilistic distribution of human arrival in the Eastern SPCZ region and darker orange shows the median arrival year 1074 CE. Yellow area shows the MCA and blue the LIA. Despite age model uncertainty and low proxy resolution, there is evidence that an SPCZ-wide reduction in precipitation occurred around the timing of the early migration into eastern Polynesia.

The mean state of the hydroclimate in the SW and Central SPCZ changes from a wetter (La Niña like state) to drier more El Niño like state (Peaple *et al.*, 2025 and Figure 3a) in the period prior to and during initial expansion into eastern Polynesia in the SW -Central SPCZ . Variability and the amplitude of climate shocks are high in the period preceding and running through the migration period (Figure 3b). Earliest reliable calibrated radiocarbon dates based on short lived materials recorded for the gateway archipelagos of the Cook and Society Islands confirm a median date of c. 1074 CE, with earlier arrivals ranging from c.950 – 1074CE. The period of dry mean climate state and high amplitude of climate shocks occur between c. 800-1050 CE, overlapping with these earliest arrival dates.

A key link between the archaeological, anthropological and climate sciences is determining what is meant by “drier” or “wetter”. Ideally, quantitative estimates of surface water balance (P-E)-R (where P is rainfall, E is evaporation and R is runoff) should be estimated with which to determine impacts on agricultural productivity and water resources. Here we attempt to put estimates on the magnitude of changes in mean annual rainfall using direct rainfall reconstructions, and statistical estimations of the scale of changes in mean annual rainfall derived using proxy reconstructions. The resolution and methodological approach necessarily limit these to mean annual estimates, but as Hipkiss *et al.*, (2025) and others have reasoned, it is also duration of dry periods that can trigger societal adaptations.

The magnitude of dry shocks in Figure 3b (S-Central SPCZ) shows large magnitude shifts to drier climates around c. 900 CE. These shocks were the largest drying shocks in these records over the past 1500 years. There is a spatial difference in the magnitude of shocks according to the location of the islands within the SPCZ. For example, in Uvea the ‘shock’ threshold is 329 mm / yr, Samoa 595 mm / yr and Vanuatu 580 mm/yr. In percentage terms, these amount to a 15% decrease in mean annual rainfall in Uvea, 28% in Samoa and a 33% decrease in Vanuatu. These shocks are mean states, and do not consider higher resolution variability due to IPO or ENSO states. It is therefore possible that depending on the state of these modes of variability, the shocks could have been larger or smaller. Maximum reconstructed proxy rainfall shocks relative to the pre-industrial (1850) mean of the records, show –30% (Vanuatu), -2% (Uvea) and -53% (Samoa) in mean annual rainfall. These reductions are larger than any in the past 1500 years and are far larger than any recorded ENSO or IPO related reductions (Sear *et al.*, 2020).

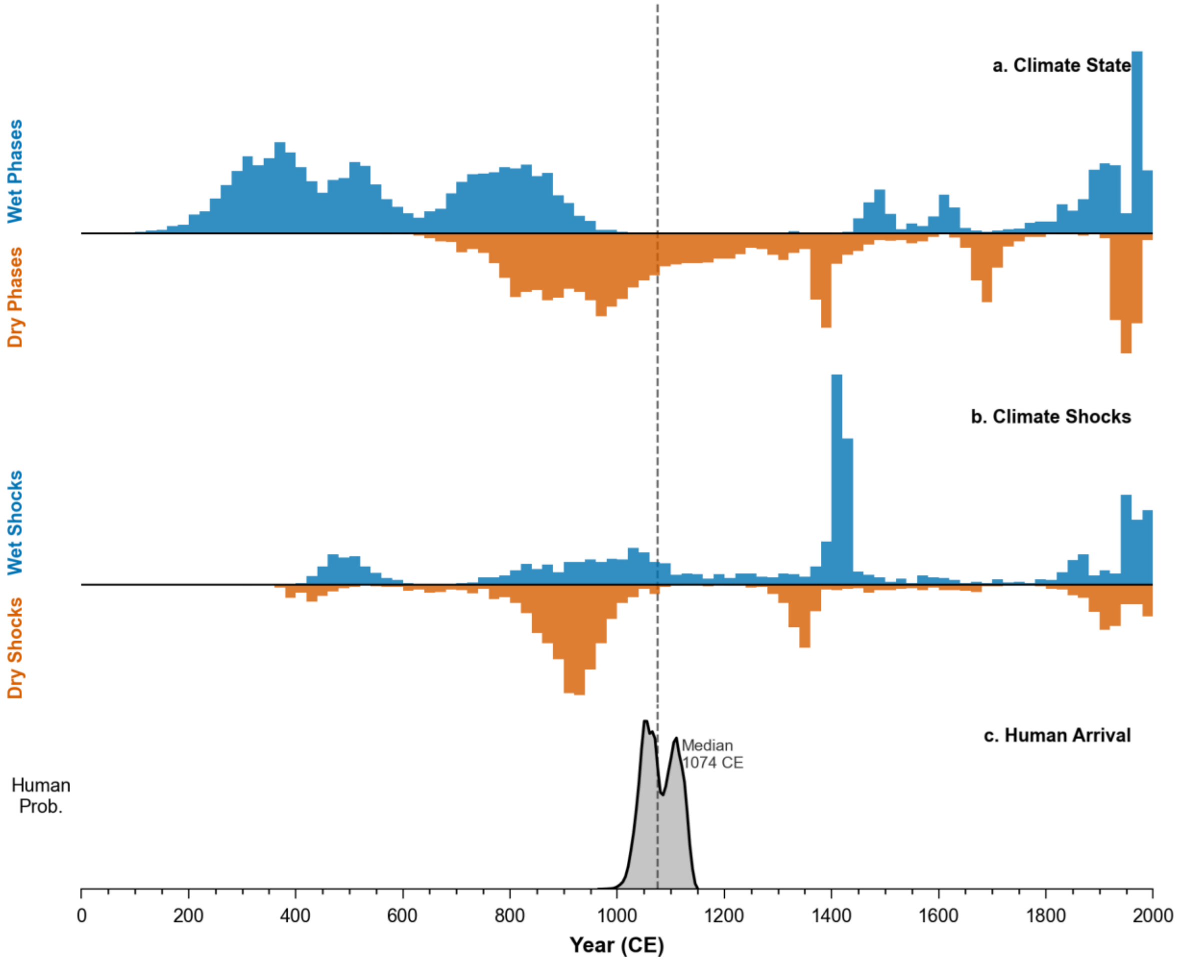

Figure 3. Hydroclimate instability and the timing of human settlement in the Southwestern-Central SPCZ. a, Composite hydroclimate state reconstruction derived from three proxy records in SW-Central SPCZ (Samoa, Vanuatu, Uvea). Blue and orange bars indicate significant wet and dry phases, respectively (deviations > 1σ). b, Analysis of rapid hydroclimate "shocks" (rates of change). Bars represent periods of abrupt transitions exceeding a 2σ threshold in the proxy ensemble derivatives. c, Probabilistic distribution of human arrival in the Eastern SPCZ. The distribution is derived from short-lived calibrated radiocarbon dates only (*n* = 64) to ensure chronological precision, independent of "old wood" effects. The vertical dashed line indicates the median estimate of the colonization pulse (c.1074 CE).

Sear *et al.*, (2020) and latterly Peaple *et al.*, (2025) have posited that for the Eastern Pacific migration and settlement to have proceeded, the hydroclimate must have been amenable to the settlers. Whilst the smaller initial populations relative to carrying capacity would have made survival more sustainable with smaller initial populations (Hipkiss *et al.*, 2025), a drier mean state with dry shocks would have remained a challenge as recorded for smaller post-European impacted populations in the 19th century and contemporary droughts (d'Aubert & Nunn 2012). Figure 4 uses proxy hydroclimate records from within the Eastern SPCZ region from the Cook Islands to the Marquesas to reconstruct the mean climate state through the arrival and settlement period. Dating of human occupancy continues through the period confirming continuous presence of people on most islands throughout the period c. 800-1570 CE before European contacts begin. During this time, the mean climate state was wetter (suggesting El Niño like) relative to the period prior to the initial arrival phase and was likely supportive of the early communities on these islands. Although abandoned "Mystery" islands (*sensu* Bellwood 1978) occurred during this period, dates for their abandonment are rare and generally later in the LIA (c. 1600-1650 CE - Henderson-Pitcairn, Wiesler 1996), moreover abandoned islands tend to be resource limited, isolated, small and located in regions of the SPCZ subject to strong climate shocks (Weisler 1996; Anderson 2001).

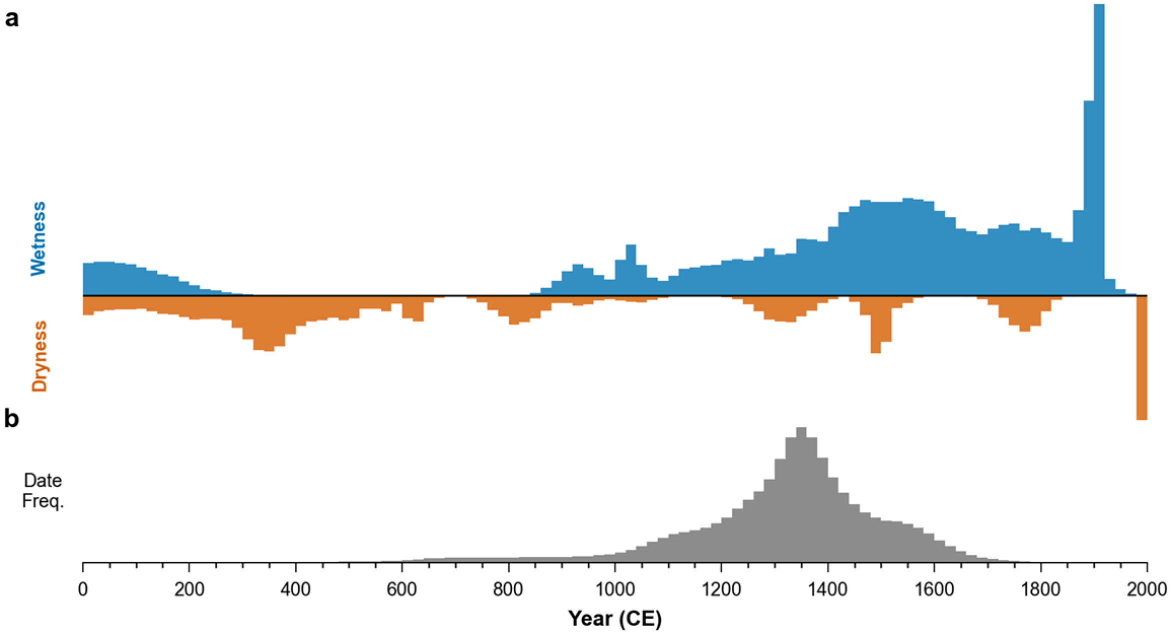

Figure 4. Hydroclimate variability and human activity in the Eastern South Pacific Convergence Zone (SPCZ) a. Composite hydroclimate reconstruction derived from four proxy records (Atiu, Tahiti, Nuka Hiva, Tahaa). Blue bars indicate wet phases and orange bars indicate dry phases (deviations > 1σ), normalized by the maximum variability. b, Probabilistic distribution of archaeological radiocarbon dates (*n* = 340) from the Eastern SPCZ, using short-lived samples. The histogram represents the temporal density of dated events, generated via 10,000 Monte Carlo realizations per date to account for measurement uncertainty and calibration error, binned at 20-year intervals.

4. Discussion

The results presented herein demonstrate from the SPCZ region that changes in both the mean state of the tropical Pacific and the amplitude of hydroclimate variability were coincident or immediately prior to the timing of eastern migration into Polynesia. Moreover, the timing of the SPCZ dry phase is coincident (+/- age uncertainty) with other dry periods including megadroughts in areas teleconnected or statistically linked to variability in the equatorial Pacific (Cook *et al.*, 2022). Recent proxy reconstructions of ENSO mean state and variability for the equatorial Pacific show a perturbation around the same time (Jiang *et al.*, 2023; Peaple *et al.*, 2025). Atwood *et al.*, (2021) drawing on a smaller range of proxy data from the SPCZ, also identify a coherent dry period in the eastern equatorial Pacific cold tongue region between c.800-1000 CE which is characterised by strong El Niño, drier conditions in the S-W SPCZ (Samoa/Tonga and Vanuatu and Mesoamerica), and wetter conditions in eastern Polynesia. Evidence from proxy precipitation records in Mesoamerica suggests phases of drier climate punctuated by wetter periods over the period c.800-1000 CE with reductions in mean annual precipitation deficit estimated to of the order of c. 25-70%, though most report c.40-60% (Cook *et al.*, 2022 and refs therein). The proximate cause of SST variability is uncertain but could be a feature of complex interactions between the ocean and atmosphere. Precipitation locally is conditioned by variations in moisture flux and land-use feedback (e.g. Cook *et al.*, 2022). The latter may be important in changing the balance between precipitation and evaporative processes altered by the transformation of plant communities which has been shown to be rapid and locally extensive on small islands (Nogue *et al.*, 2021; Stranberg *et al.*, 2024).

During +IPO / El Niño like conditions in the TSP, trade wind strength decreases with a reduction in the strength of the Pacific Walker circulation (Brown *et al.*, 2020). Modelling studies have demonstrated that under these conditions, the risk of sailing east from Samoa and Tonga area reduces as periods of easterly and weaker E-W winds permit voyaging (Anderson *et al.*, 2006). Recent modelling studies using different canoe technology indicate that these climate conditions may have been unnecessary (Irwin *et al.*, 2024). Until voyaging canoes from this period are found, the technology vs. sailing conditions debate remains unresolved, but regardless, it would likely have been less risky to undertake voyages east and northeast from Samoa/Tonga during this period.

The conditions required to trigger adaptive responses on islands are not simply down to hydroclimate. Ultimately, human - climate interactions in the Pacific must account for a range of factors and lines of evidence. Approaches to integrating these vary (see HBE, and Evolutionary Ecology theory discussed above, Dinapoli & Morrison 2017; Cochrane 2018), but a promising approach lies in the field of socio-hydrological modelling (Hipkiss *et al.*, 2025; Kuil *et al.*, 2019). While it should be stressed that these models are simplified constructs of complex systems, they provide opportunities to develop and test hypotheses and determine scenarios under which human responses may have been sufficiently impacted to trigger adaptations. As paleoclimate reconstructions improve, and model downscaling begins to represent the spatial expression of hydroclimate within small islands, it becomes possible to test outputs against the archaeological and ethnographic evidence (Rull *et al.*, 2022; Puleston *et al.*, 2024).

A key variable identified in such models is the rate of increase in population, a measure of the total calorific requirements to be met by agricultural and marine resources. Hipkiss *et al.*, (2025) use a socio-hydrological model to explore the effect of drought severity under different population scenarios for a makatea island (Mangaia, S Cook Is.). Their results reveal different thresholds of population density under which droughts of differing severity (defined by duration and intensity) result in population declines as the island resources fail to meet the calorific requirements of the population. Droughts of longer duration, intensity and frequency have the highest impact on population numbers. Intense, long duration droughts have lower population thresholds before major impacts are felt on population numbers. Less intense, shorter duration droughts are survivable by island populations and represent the ENSO / IPO neutral conditions experienced by islands. Population densities larger than 100 people/km^2 are sensitive to more severe droughts in the island scenario used in the model. Reconstructed pre-European contact population densities across different islands and modelled using different approaches, exceed these threshold values (Table A1 Appendix A). Tongatapu, a makatea island, has a reconstructed peak population density of c. 214 people/km^2 (Parton & Clark 2022). However, Samoa as an archipelago, has a reconstructed population based on genetic evidence of c.109,000 (Harris *et al.*, 2020), with the main island of Upolu resulting in a lower population density (85/km^2) (Table A1, Appendix A1).

Evidence for lower initial population density in Samoa and for other island populations at the time of initial settlement, it is necessary to explain the potential impact of climatic variability in island populations associated with eastern migration. One possibility is that measures of population density and agricultural carrying capacity are influenced by the topography and geology of islands. Strong precipitation gradients exist on many higher islands because of leeward-windward gradients in precipitation, or altitudinal gradients created because of enhanced rainfall over orography. These result in different forms of agricultural technology, and initially until dryland agriculture developed, were marginal, unproductive land (Kirch 2017). Pacific islands have been classified into distinct types (Nunn *et al.*, 2016). The differences in type reflect geological and topographical distinctions that were exploited by Polynesian voyagers. In turn, the communities of humans present on each island were focused by geology, hydrology and topography into locally high concentrations. For example, in the Marquesas, narrow deep valleys with specific water sources, focused communities into smaller areas, resulting in concentrations of people with different sensitivity to climatic variability (Allen 2010) which triggered cultural responses in the form of protection of taro swamps (Addison 2006). Similarly, makatea islands focus human settlements around the productive ‘puna lands’ where lake and swamps provide for production of taro and associated crops (Kirch 2017). Atoll islands have limited agricultural carrying capacity and water resources – populations tend to be focused on lagoon coasts and adjacent to water supplies. Similarly, on Rapa Nui, a low volcanic island, there is evidence for the association of religious structures and settlements with the emergence of groundwater at coastal margins. This groundwater was more reliable than inland lakes that show evidence for drying up in periods of prolonged precipitation deficit (Rull *et al.*, 2022).

Whilst climate was drier and more variable around the time of the migrations into the eastern Pacific, other island level factors undoubtedly conditioned community responses, some of which might have included emigration. Coincidence in time is not causality, but simple HBE type models provide evidence for potential societal pressure resulting from longer severe dry periods such as evidenced in this paper (Tomlinson *et al.*, 2024; Hipkiss *et al.*, 2025; Kuil *et al.*, 2019). Such integrative frameworks as part of the wider evolutionary ecological theories being applied to the Pacific islands (Cochrane 2018), provide opportunities for exploring the relative sensitivity of different island types to a range of climatic and socio-ecological scenarios, ultimately identifying conditions under which populations might take decisions to migrate. Such scenarios can contribute to hypothesis testing as part of wider HBE and general evolutionary-ecological frameworks using physical archaeological and genetic evidence.

5. Conclusion

We posit that the migration of humans into eastern Polynesia represents a coincidence of three key factors that enabled the eastward migration into the Pacific; 1) an extended period of dry climate including severe droughts of long duration; 2) increased population pressure from migrations alongside population growth to higher densities that produced greater sensitivity to drought, and 3) possible technology transfer or innovation over time that facilitated a change in voyaging canoe sailing capability. A fourth ‘pull factor’ is increased rainfall across the eastern TSP at the time of migration which supported the initial settlement of gateway islands and subsequently the rest of the Polynesian triangle.

Evidence for drier conditions around the time of the migration east into the Pacific from different source areas is compatible with multiple global records and is evident in local proxy records within the SPCZ. We can determine with some certainty, using proxy climate reconstructions from within the SPCZ region, that the period of drier hydroclimate comes before the "AD 1300 event" of Nunn (2007) but does correspond with the AD 1000 event presented by Carson (2024). However, the precise expression of these regional phenomena is determined locally by the location of the island within the SPCZ, the position of the community within the topography of an island (leeward/windward) and the hydrological resources of the island. A similar spatial filter influences the societal response to a dry period and associated drought conditions; local resource availability varies between island types and within islands, determined by the presence of soil types, marine resources (reef vs pelagic), altitudinal gradients in rainfall, and nutrient status of the soils. Cultural (and genetic) variability evolves from a starting group of settlers who over time diverge from initial experience as they adapt to the ecological resources, local climate and topographic 'islandscape'. Emerging cultural distinction therefore includes adaptive strategies. A part of the complexity of how Pacific communities respond to climate variability is determined by the ebb and flow of populations caused by waves of migration, disease and famine since they alter the resource pressure, which modelling and ethnographic records show to be an important control on population response to drought. Thus, the emerging genetic history in the Pacific peoples becomes a vital part of understanding human - climate interactions.

We end with a call for improved resolution and chronology of proxy and archaeological records, an improved representation of the uncertainty in these, and the analytical and structural assumptions in proxies themselves. Allied to these, there is a need for improved estimates of island populations and the extent to which these were focused into areas of higher population density around the time of the migration into the eastern Pacific. The time of general causation in human-climate scholarship in the Pacific is drawing to a close, the step of detailed (yet distributed) studies of specific islands should be part of the next phase of understanding. Carefully constructed hypotheses involving paleoclimate, archaeological and Pacific Island cultural communities could, through modelling frameworks such as HBE and socio-hydrological models, informed by local evidence can start to test some of the existing insightful conjectures developed by Melinda Allen and others on the role that climate variability had on prehistoric Polynesians.

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Data Availability Statement.

Proxy data generated as part of this study are available via the Open Science Framework https://doi.org/10.17605/OSF.IO/VMK7X (2025), and via Maloney et al., (2019) https://doi.org/10.1016/j.gca.2018.10.028 and Maloney et al., (2022) https://doi.org/10.1016/j.quascirev.2022.107421

Partnerships

This research did not use any primary data from Indigenous contexts.

Conflicts of Interest

The authors declare no conflicts of interest.

Author Contributions

Conceptualisation DAS, MP, PGL, CH, MJ, AM, DS. Methodology DAS, MP, GI, CH, JS, MJ, AM, DS. Draft preparation ALL; writing review and editing ALL, project administration DAS, MJ. Funding acquisition DAS, MJ, PGL. All authors have read and agreed to the published version of the manuscript.

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Appendix A

The appendix is an optional section that can contain details and data supplemental to the main text—for example, explanations of experimental details that would disrupt the flow of the main text but nonetheless remain crucial to understanding and reproducing the research shown; figures of replicates for experiments of which representative data is shown in the main text can be added here if brief, or as Supplementary data.

Table A1: Supplementary Data. Estimated island populations and resulting population density illustrate the ranges derived from different methods of estimation. Bold are values of Population density that are in the range estimated by Hipkiss *et al.*, (2025) as showing population density values more sensitive to severe droughts. Population densities below this threshold are still sensitive to droughts but can mitigate impacts through agricultural change.

Site	Archipelago	Island Type*	Potential peak population estimates	Island Area (km^2)	Population Density (No./km^2)	Method	Source
Tongatapu	Tonga	Makatea	50,000 – 60,000	257	**214**	LiDAR	Parton & Clark (2022)
Tonga Archipelago	Tonga	Mixed	110,000	748	147	LiDAR	Parton & Clark (2022)
Samoa	Samoa	Volcanic High	109,000 (75,400 Upolu)	3041 (1125 Upolu)	36 85	Genetics	Harris *et al.*, (2020)
Samoa	Samoa	Volcanic High	70,000	3041	23	Demography	Green (2002)
Tahiti	Society Is.	Volcanic High	198,550	1045	**190**	Demography	Rallu (2024)
Mo'orea	Society Is.	Volcanic High	22,906	134	**171**	Archaeological	Hamilton & Khan (2007)
Maupiti	Society Is.	Volcanic High	1,682	4.1	**410**	Modelling	Puleston *et al.*, (2024)
Mangareva	Gambier Is.	Volcanic High	3,537	16.58	**213**	Modelling	Puleston *et al.*, (2024)
Taravai	Gambier Is.	Volcanic High	878	5.03	**175**	Modelling	Puleston *et al.*, (2024)
Cook Islands	Cook Is.	Mixed	34,000	237	144	Estimate	Davis (1947)^
Rarotonga (Cook Is.)	Cook Is.	Volcanic High	12,998	67	**194**	Demography	Rallu (2023)
N. Cook Is.	Cook Is.	Atoll	2,290	21.8	105	Demography	Bayliss-Smith (1974)
Mangaia	Cook Is.	Makatea	19,548	52	**377**	Carrying Capacity	Hipkiss *et al.*, (2025)
Atiu	Cook Is.	Makatea	1,998	27	74	Estimate	Cook (1797)^
Aitutaki	Cook Is.	Atoll	1,998	18	111	Demography	Royal (1839)^
Marquesas	Marquesas	Volcanic High	55,000	1048	52	Demography	Kirch (1984); Rallu (2022)
Ua Uka	Marquesas	Volcanic High	2,100	25	76	Archaeological	Molle & Conte (2015)
Rapa Nui	Rapa Nui	Volcanic Low	17,548	164	107	Archaeo-Demography	Lima *et al.*, (2020)
Ontong-Java	N. Solomon Is.	Atoll	2,018	7.76	**260**	Carrying Capacity	Bayliss-Smith (1974)
Luangiua	N. Solomon Is.	Atoll	1,706	6.32	**270**	Carrying Capacity	Bayliss-Smith (1974)
Pelau	N. Solomon Is.	Atoll	331	1.44	**230**	Carrying Capacity	Bayliss-Smith (1974)
Sikaiana	N. Solomon Is.	Atoll	434	1.81	**240**	Carrying Capacity	Bayliss-Smith (1974)
Takuu	N. Solomon Is.	Atoll	612	0.9	**680**	Carrying Capacity	Bayliss-Smith (1974)
Tokelau	Tokelau	Atoll	1,640	10.1	**162**	Demography	Bayliss-Smith (1974)
Ellice Is.	Tuvalu (Micronesia)	Atoll	5,782	25.6	**226**	Demography	Bayliss-Smith (1974)
Gilbert Is.	Kiribati (Micronesia)	Atoll	35,522	248.6	143	Demography	Bayliss-Smith (1974)
Marshall Is.	Marshall Is. (Micronesia)	Atoll	9,561	133	72	Demography	Bayliss-Smith (1974)
Ponape	Micronesia	Atoll	2,370	7.4	**320**	Demography	Bayliss-Smith (1974)
Truk	Micronesia	Atoll	9,314	26.7	**349**	Demography	Bayliss-Smith (1974)
Yap	Micronesia	Atoll	2,692	16.7	**161**	Demography	Bayliss-Smith (1974)

*Island Type after Nunn *et al.*, (2016). Critical threshold for drought sensitivity on Makatea islands is 165-230 people km^2 although this threshold can be lower for more severe droughts (Hipkiss *et al.*, 2025).

^ Rallu J-L (2023a) Rarotonga Population from contact to the 1880s. URL: https://hal.science/hal04354860

**Area of agricultural land (Molle & Conte, 2015)