https://doi.org/10.5194/cp-2021-109
Preprint. Discussion started: 3 September 2021

Climate of the Past Discussions

Holocene climate and oceanography of the coastal Western United States and California Current System

Hannah M. Palmer[1,2], Veronica Padilla Vriesman[1], Caitlin M. Livsey[1], Carina R. Fish[1,2], Tessa M. Hill[1,2]

1. Earth and Planetary Sciences Department, University of California, Davis, Davis, California, 95616, United States of America
2. Bodega Marine Laboratory, University of California, Davis, Bodega Bay, California, 94923, United States of America

Correspondence to: Hannah M. Palmer (hmpalmer@ucdavis.edu)

Abstract

To understand and contextualize modern climate change, we must improve our understanding of climatic and oceanographic changes in the Holocene (11.75 ka-present). Climate records of the Holocene can be utilized as a "baseline" from which to compare modern climate and can also provide insights into how environments and ecosystems experience and recover from environmental change. However, individual studies on Holocene climate in the literature tend to focus on a distinct geographic location, a specific proxy record, or a certain aspect of climate (e.g., upwelling or precipitation), resulting in localized, record-specific trends rather than a comprehensive view of climate variability through the Holocene. Here we synthesize the major oceanographic and terrestrial changes that have occurred in the Western United States (bounded by 30°N to 52°N and 115°W to 130°W) through the most recent 11.75 ka and explore the impacts of these changes on marine and terrestrial ecosystems and human populations. This three-tiered systematic review combines interpretations from over 100 published studies, codes and geospatially analyzes temperature, hydroclimate, and fire history from over 50 published studies, and interprets nine representative time series through the Holocene. We find that the early Holocene is characterized by warming relative to pre-Holocene conditions, including warm sea surface conditions, a warm and dry Pacific Northwest, a warm and wet Southwest, and overall spatial and temporal stability. In the mid Holocene, these patterns reverse; this interval is characterized by cool sea surface temperatures, a cool and wet Pacific Northwest and warm and dry Southwest. The late Holocene is the most variable interval, both spatially and temporally, and a novel spatial trend appears in terrestrial climate with warmer coastal areas and cooler inland areas. Human communities interacted with the environment throughout the entire Holocene, as evidenced in archeological and paleoenvironmental records, yet the recent era of colonization (1850-present) represents an unprecedented environmental interval in many records. Overall, our analysis shows linkages between terrestrial and oceanographic conditions, distinct environmental phases through time, and emphasizes the importance of local factors in controlling climate through the dynamic Holocene.

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1 Introduction

1.1 Overview of Holocene Climate

In contrast to past intervals of glacial/interglacial variability, the Holocene has largely been regarded as a climatically stable interval. However, local and global changes in Holocene climate merit further investigation. Meta-analysis of global temperatures and patterns through the Holocene show a globally warm period from 11 to 5 ka, termed the Holocene Climatic Optimum, largely driven by a concurrent peak in solar insolation in the Northern Hemisphere (Mayewski et al., 2004; Wanner et al., 2008; Renssen et al., 2012; Marcott et al., 2013; Bader et al., 2020). Following this period of global warmth, competing lines of evidence show divergent global temperature regimes in the last 5ka (some records show global warming and others global cooling); this phenomenon is termed the Holocene Conundrum (Wanner et al., 2008; Marcott et al., 2013; Liu et al., 2014; Marsicek et al., 2018; Bader et al., 2020). Currently available global reconstructions typically under-sample records from the North Pacific and Western North America, motivating the need for further analysis of Holocene change over time in this region (Marcott et al., 2013; Kaufman et al., 2020; Praetorius et al., 2020; Walczak et al., 2020).

General trends in global temperature are interrupted by multiple shifts of rapid climate change intervals between climate modes (marked changes in aridity and temperature) (Mayewski et al., 2004; Wanner et al., 2008). Holocene climate variability on various timescales has been attributed to multiple climate forcing mechanisms, including: changes in solar insolation, volcanic activity, land-use change, variations in atmospheric greenhouse gas concentrations, and resultant ocean-climate feedbacks (Crowley, 2000; Bradley, 2003; Atwood et al., 2016). Specifically, Northern Hemisphere solar insolation peaked at 9 ka and decreased towards the present with important implications for global and regional climate (Renssen et al., 2012; Marcott et al., 2013; Marsicek et al., 2018; Bader et al., 2020). Peak summer insolation in the early Holocene contributed to a warmer Arctic and continued melting of northern hemisphere ice sheets at this time (Renssen et al., 2012; Bader et al., 2020). Globally, episodes of high fire activity were relatively common in the early Holocene with a globally observed increase in fire activity between 3-2 ka, likely due to a change in climate (Marlon et al., 2013).

In North America broadly, mean summer temperatures increased from the last glacial maximum (26-19 ka) (Clark et al., 2009; Waelbroeck et al., 2009) until between 6 and 3 ka by ~4^{O}C and subsequently decreased; variations are documented at 1100 year frequency (Viau et al., 2006). Across the continent, millennial-scale climate variability on the order of 0.2^{O}C occurs across the entire Holocene (Viau et al., 2006). In the early Holocene, solar insolation and ice-sheet dynamics are dominant drivers of North American climate; following the collapse of the Laurentide Ice Sheet, the impact of ice sheet feedbacks on climate is reduced (Viau et al., 2006). Analysis of global and continental trends show a high degree of temporal and spatial climate variability highlighting the need to assess region-specific changes through time. Understanding regional Holocene variability is particularly relevant in order to contextualize biotic and environmental responses to anthropogenic climate change.

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1.2 Modern climate and oceanography of Western North America

Western North America currently experiences impacts of drought, fire, fisheries and agricultural changes, heatwaves, and ecological shifts due to climate change (Ainsworth et al., 2011; Westerling et al., 2011; Mann and Gleick, 2015; Wise, 2016). Quantifying climatic and environmental changes over time in this region is of particular importance as it hosts a large modern human population, a multitude of natural resources, and highly biodiverse and productive ecosystems. By investigating climate and environmental change through the Holocene, we can better understand how environments and ecosystems that are climatically and tectonically similar to present experience and recover from environmental change (Finnegan et al., 2015; Barnosky et al., 2017). We consider integrated physical processes, ecological responses, and human connections in this review and outline modern climate conditions below.

We divide the region into the Pacific Northwest (abbreviated as PNW; including the US states Washington, Oregon, and northern California) and Southwest (abbreviated as SW; including the US states Nevada, Arizona and central/southern California). The interaction between the Aleutian Low-pressure system, North Pacific High-pressure system, and Continental Thermal Low-pressure system drive temperature and hydrographic gradients (Fig. 1). Modern terrestrial climate of the Western United States varies latitudinally with cooler temperatures and wintertime precipitation in the PNW and warmer temperatures, general aridity, and summer precipitation driven by the North American Monsoon (NAM) in the SW(Fig. 1) (Adams and Comrie, 1997; Barlow et al., 1998; Sheppard et al., 2002). Additionally, hydroclimate varies across topographic gradients from West to East with precipitation along the coast and increased aridity in the interior of coastal mountain ranges. Drought is a recurrent and salient feature of climate in the West, particularly in the context of anthropogenic climate change (Fig. 1) (e.g. Cook, 2004; Wise, 2016).

Wildfire is a dominant feature of the landscape of the Western United States with climate, vegetation, and human activity all contributing to fire activity (Westerling et al., 2003, 2011; Marlon et al., 2012; Higuera et al., 2021). In areas with sufficient vegetation productivity, high temperatures and drought are consistently linked with greater area burned (Westerling et al., 2003; Marlon et al., 2012; Dennison et al., 2014). In grasslands and shrublands, fire is linked to both antecedent precipitation that drives fuel development and duration of summer and fall high temperatures. As high temperatures extend into spring and fall, the fire seasons coeval lengthen (Westerling et al., 2003; Marlon et al., 2012; Dennison et al., 2014). As such, the investigation of changes in the fire regime within the paleorecord is useful in identifying the relative importance of temperature, precipitation, vegetation, and human activity on wildfire.

Marine and terrestrial climates are linked in this region; Westerly winds influenced by North Pacific ocean-atmosphere dynamics result in high correlation between North Pacific sea surface temperatures (SST) and coastal air temperatures and hydrography (LaDochy et al., 2007; Barron and Anderson, 2011). The westerly winds generated by the Aleutian Low pressure system and North Pacific High pressure system fuel the California Current System

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(CCS), which flows southward from ~50° N to ~15°N (Fig. 1) (Hickey, 1979; Checkley and Barth, 2009). The CCS is characterized by strong seasonal wind-driven upwelling that drives high surface productivity along Western North America (Hickey, 1979; Checkley and Barth, 2009; Siedlecki et al., 2015). Respiration, remineralization, and decomposition lead to high organic carbon export and oxygen-depleted (CO_2-rich) bottom waters (Chelton et al., 1982; Checkley and Barth, 2009; Siedlecki et al., 2015). The interaction of the equatorward California Current, the poleward Davidson Current, and the sub-surface, poleward California Undercurrent drive oceanographic conditions south of Point Conception (Bray et al., 1999). Seasonal, annual, and decadal events, including the Pacific Decadal Oscillation (PDO), North Pacific Gyre Oscillation, and El Niño Southern Oscillation (ENSO) play a significant role in driving Eastern North Pacific SST and productivity across multiple timescales (Lluch-Cota et al., 2001; Batchelder and Powell, 2002; Mantua et al., 2002; Chavez et al., 2003; Di Lorenzo et al., 2008). Changes to climate and oceanographic conditions have important implications for ecological systems. Changes in marine currents, upwelling regime, and temperature impact primary production, with cascading implications for the entire marine food web (Barron et al., 2003b; Yati et al., 2020). In terrestrial systems, variability in precipitation, air temperature, and fire regime exert strong control over plant and animal communities (Marlon et al., 2006; Beaty and Taylor, 2009; Clark et al., 2012; Kirby et al., 2015; Shuman et al., 2018).

Climate and environmental change through time impact human communities that have been present in Western North America throughout the Holocene. Evidence from over 40 archeological sites in North America shows humans were likely present before, during, and after the Last Glacial Maximum (26.5-19 ka) (Becerra-Valdivia and Higham, 2020). Additional evidence for human presence and societal expansion within the geographic (Washington through Baja California) and temporal (Holocene) range of this review includes archaeological evidence from shell middens as well as Indigenous oral histories (Erlandson et al., 2007, 2009; Kennett et al., 2007; Rick, 2011; Braje et al., 2012; McKechnie, 2015; Becerra-Valdivia and Higham, 2020). Previous work has investigated linkages between climate and human communities on a local scale through the Holocene (Erlandson et al., 2007; Kennett et al., 2007; Rick, 2011; Braje et al., 2012; Glassow et al., 2012; McKechnie, 2015); these relationships will be further explored in this review.

Here, we summarize and synthesize over 100 published records of both marine and terrestrial systems from the Western US and California Current System (See Appendices A-C), resulting in the most comprehensive multi-proxy Holocene climate reconstruction for this region to date. This systematic review addresses the following linked research questions: What are the major patterns and climatic phases during the Holocene for the Western United States? How do marine and terrestrial environments interact in this region during the Holocene? How do climate and oceanographic changes impact ecological and human communities in the Holocene?

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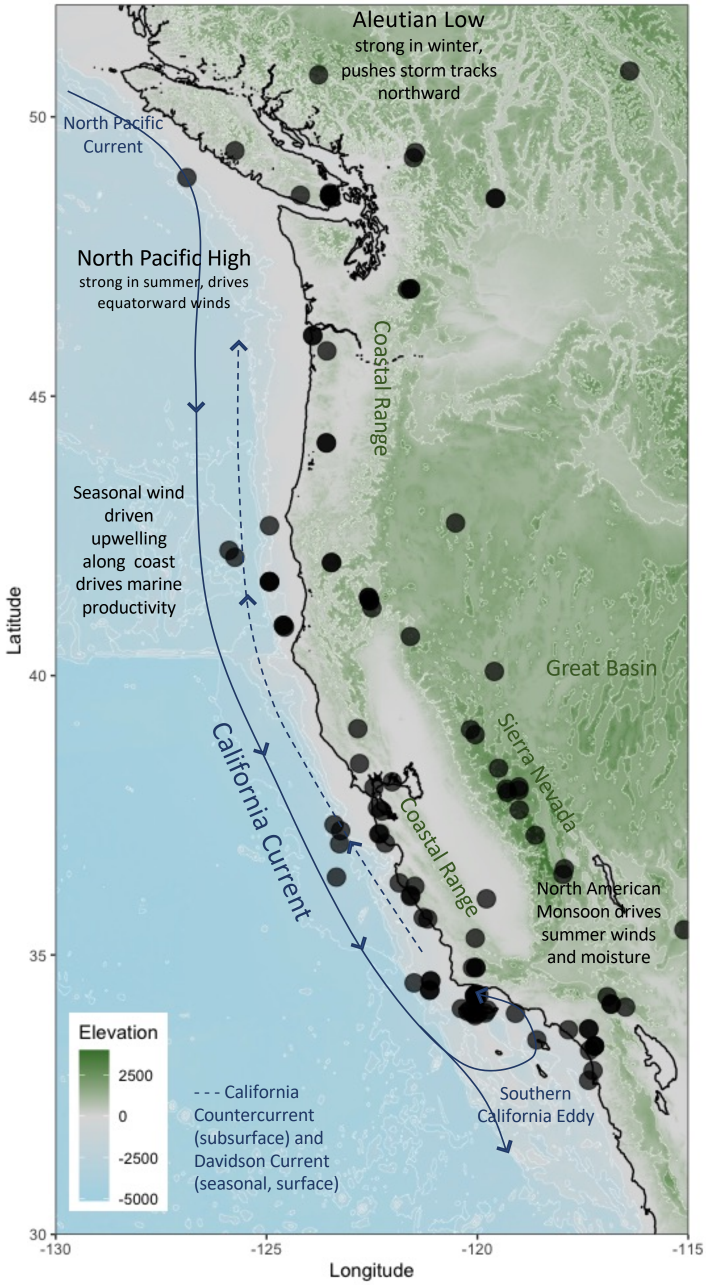

145 **Figure 1:** Map of locations of all studies reviewed in the paper with simplified schematic of modern oceanographic and hydrographic conditions.

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2 Methodology

For the purposes of this paper we follow the standard convention formally recognized by the International Commission on Stratigraphy (Walker et al., 2018); early Holocene (Greenlandian, 11.75-8.2 ka), mid Holocene (Northgrippian, 8.2-4.2 ka), and late Holocene (Meghalayan, 4.2-0 ka). We do include interpretations that span across these sub-epoch time intervals. We constrain our study to the geographic region bounded by 30°N to 52°N and 115°W to 130°W as this region has an abundance and variety of long-term records and well-documented human-environment interactions through the Holocene.

A multi-step systematic review was conducted to select previous studies for inclusion in this review. In the first step, we identified studies that met the following criteria: records from Western North America and the CCS and that represented Holocene aged reconstructions. Records were initially found using the following topics as search terms: marine temperature, ocean circulation, marine productivity, terrestrial hydroclimate, drought, floods, terrestrial temperature, fire, archaeology, marine ecology, and terrestrial ecology. Each paper was then evaluated with a second set of criteria for inclusion in the paper. Records with a published age model and scope of the study within the defined geographic region (30°N to 52°N and 115°W to 130°W) were selected for inclusion.

A total of 101 papers matched these criteria and were categorized as providing constraints on: marine temperature, circulation, and productivity; terrestrial hydroclimate; terrestrial temperature and fire; archaeology, marine ecology, and terrestrial ecology. A wide range of archive types are represented here: archaeology (8 papers), dendrochronology (2), speleothem (3), lacustrine sediments (36), marine sediments (31), and other records including geomorphology, animal midden, and lichen archives (7). This paper makes no attempt to evaluate the effectiveness of each proxy or to re-examine the primary data; rather, interpretations of data from original work are maintained. Interpretations in original papers are based on a variety of well-established proxies: alkenones (2 papers), carbon and nitrogen isotopes of bulk sediments (3), charcoal (14), diatom and silicoflagellate assemblage (7), foraminiferal assemblage (9), geomorphology (3), hydrogen isotopes from leaf wax (4), oxygen and carbon isotopes of nearshore marine organisms (7), oxygen and carbon isotopes of biogenic and non-biogenic calcite (marine and terrestrial, 10), macrofossil abundance (6), pollen assemblage (25), radiocarbon dating (as a proxy, not only for age model development 3), sedimentology, including grain size analysis, lithology, organic content, carbon content analysis (29), and tree ring/tree stump analysis (4).

In the second step of the systematic review process, we identified papers that met a second set of criteria, coded results through time, and conducted a spatial and temporal analysis of the synthesis. This criteria included all studies at least 3000 years of the Holocene, and in which the authors must have identified and described a clear climatic pattern or patterns for an entire Holocene interval. Results from each paper were binned into time intervals: early, mid, and late Holocene, and coded using the following categories: hydroclimate (wet or dry), temperature (warm or cold), and fire activity (high or low). Results were coded using keywords from the original authors' description of climate conditions at each point in time: temperature keywords: warm, cold, cool; hydroclimate keywords: wet, dry,

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moisture, arid(ity), pluvial, fluvial, precipitation; fire keywords: high, low, activity, frequency, return interval, intensity. We generated a database that contains paper (author, date), latitude, longitude (of all sites within each paper), region (PNW or SW), archive type, and coded results for each category (hydroclimate, temperature, fire activity) in each interval (early, mid, late). Primary data were not reevaluated; rather, interpretations of data from original work are maintained. For example, changes in SST may be inferred from alkenones, foraminiferal assemblages, or foraminiferal isotope records in previously published studies, but all are represented as temperature in the coded database. We utilize the term "fire activity" to be inclusive of multiple paleofire proxy types including fire return intervals, CHAR, charcoal accumulation, and others. Some papers contributed multiple data points to this step, for example, some records included interpretations of multiple processes (e.g., temperature and hydroclimate) and some include interpretations across multiple time intervals (early, mid, late). Yet, papers that only included one interpretation in one interval are also included. For the papers analyzed here, the SW (30° - 40° N, 32 papers) is more data rich than the PNW (40°- 47°N, 17 papers) and data are fairly well distributed across all three time periods (Figs.s 2,3). Results of coded analysis are plotted in space through the three time intervals (early, mid, late Holocene) (Figs. 2,3). Base maps with elevation are generated using the R package marmap (Pante and Simon-Bouhet, 2013) accessing bathymetric and elevation data from the NOAA ETOPO1 global relief model (Amante and Eakins, 2009).

Following the spatial and temporal analysis, we highlight a subset of regionally representative time series records from the PNW (Fig. 4) and SW (Fig. 5). We prioritized records with high temporal resolution, continuous records, and records that span at least two intervals of the Holocene (Kaufman et al., 2020). Further, we selected records that represent temperature, hydroclimate, and fire activity for each region (PNW and SW). For these purposes, data was accessed through original papers, supplemental information, or through the NOAA Paleoclimate Database (Appendix D).

3 Results and discussion

3.1 Early Holocene (11.75-8.2 ka)

Thirty-seven papers encompassing 60 sites fit the criteria for inclusion in the spatial analysis. Archives included lake sediments (17 papers), marine sediments (15 papers), and three others (archaeological, geomorphology, speleothem) (Appendix B, C).

3.1.1 Regional Synthesis

Spatial analysis of coded hydroclimate, temperature, and fire history indicate that the early Holocene was generally characterized by a dry and warm PNW and a wet and warm SW (Fig. 2). These trends are also observed in time series data from both regions (Figs. 4, 5). In the PNW, sea surface temperatures were warm, winters were dry, and fire activity was high (Fig. 4). In the SW, sea surface temperatures were warm, terrestrial temperatures were cold, fire activity was low, and hydroclimate was generally wet (Fig. 5).

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Generalized warming in the early Holocene relative to pre-Holocene conditions follows two abrupt Northern hemisphere climate transitions, characterized by rapid warming during the Bølling–Allerød (14.7-12.9 ka) and rapid cooling associated with the Younger Dryas (12.9-11.7 ka) (Barron et al., 2003b; McGann, 2015). Sea surface temperatures were warm across the entire coastal CCS during the early Holocene (Fig. 2), likely driven by high summer insolation (insolation maximum at 9 ka) and warming following deglaciation. Despite warm SST across the region, terrestrial hydroclimate and temperatures varied latitudinally, indicating regional differences in marine-terrestrial climate linkages and impacts of the insolation maximum (Fig. 3). In the PNW, warm SSTs co-occured with warm and dry terrestrial conditions (Heusser, 1998; Barron et al., 2003b; Steinman et al., 2016), while in the SW, wet conditions were driven by the evolution of the North American Monsoon (NAM) and the resultant increase in summertime precipitation in the early Holocene relative to pre-Holocene (Fig. 2) (Bird and Kirby, 2006; Kirby et al., 2015; Metcalfe, 2015).

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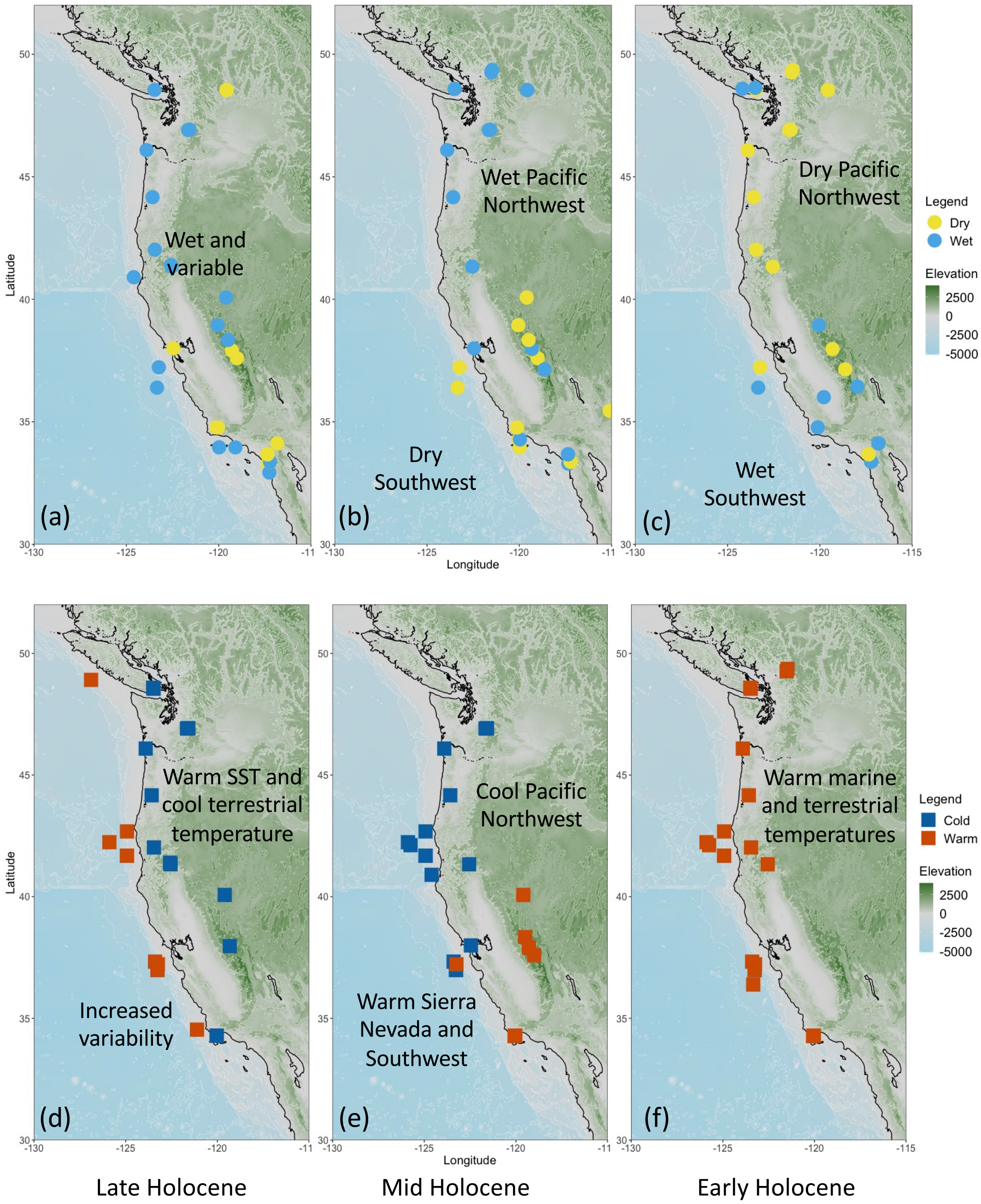

235 **Figure 2:** Top panel shows hydroclimate records in early (11.7 - 8.2 ka, (c)), mid (8.2 - 4.2 ka, (b)), and late (4.2 - 0 ka, (a)) Holocene: yellow dots represent dry and light blue represents wet. Bottom panel shows temperature records from early (f), mid (e), and late (d) Holocene: dark blue squares represent cold temperatures and orange represents warm temperatures.

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3.1.2 Terrestrial climate

In the PNW, multiple records show warm and dry conditions in the early Holocene (Figs. 2c, 2f) (Mohr et al., 2000; Hallett et al., 2003; Briles et al., 2005; Malamud-Roam et al., 2006; Marlon et al., 2006; Gavin et al., 2007; Long et al., 2011; Steinman et al., 2019). Drier than modern conditions existed in locations dominated by winter precipitation (largely PNW) (Fig. 2c) (McGann, 2011; Hermann et al., 2018). An East-West precipitation gradient was established with warm and drier conditions in the East and wet conditions in the West (Brown and Hebda, 2002), fire activity was high at multiple locations (Hallett et al., 2003; Marlon et al., 2006; Gavin et al., 2007; Steinman et al., 2019), and the amount of biomass burning and the extent of tree cover increased during this time (Figs. 2, 3) (Marlon et al., 2006; Gavin et al., 2007). The early Holocene increase in fire activity in the PNW relative to pre-Holocene conditions may have been caused by warmer/drier conditions resulting from amplified seasonality due to increased insolation relative to pre-Holocene (Walsh et al., 2017; Steinman et al., 2019). In some locations (i.e., Scanlon and Castor Lake), fire frequency increased relative to glacial, but remained lower relative to the mid or late Holocene (Walsh et al., 2017). Few records show wet conditions in the PNW during the early Holocene (McQuoid and Hobson, 2001).

In California's Central Valley and Sierra Nevada, the early Holocene was wet with low or variable fire frequency (Figs. 2, 3) (Benson et al., 2002; Bacon et al., 2006; Negrini et al., 2006; Hallett and Anderson, 2010). Fuel abundance exerted a stronger control on fire than regional climate (Hallett and Anderson, 2010). In the Eastern Sierra Nevada (i.e., Lower Gaylor Lake and Barrett Lake near Mono Lake), low biomass (sparse pine dominated forests and chaparral shrubs) reinforced by low snowpack persistence due to the insolation maximum, led to low fire frequency (Hallett and Anderson, 2010). In the Lake Tahoe Basin, precipitation was high in the early Holocene and fire frequency was low in the very early Holocene (11-9 ka) and transitioned to higher fire frequency than modern from 9 ka through mid Holocene (Lindstrom, 1990; Benson et al., 2002; Beaty and Taylor, 2009).

In comparison to the arid PNW, early Holocene conditions in the SW were largely wetter than modern (Fig. 2). Lacustrine records from across the SW show heavy precipitation in the early Holocene (Bird and Kirby, 2006; Kirby et al., 2007, 2010, 2012, 2014, 2015; Bird et al., 2010; Du et al., 2018). Wet conditions at this time were driven by the development of the NAM (Bird and Kirby, 2006; Kirby et al., 2007; Marcott et al., 2013; Hermann et al., 2018). The enhancement of the NAM is attributed to warm SSTs in the Gulf of California and to the early Holocene winter insolation minimum and summer insolation maximum leading to an increased frequency of both winter storms and of tropical cyclones making landfall in southern California (Bird and Kirby, 2006; Kirby et al., 2007; Marcott et al., 2013; Hermann et al., 2018). A pluvial episode was synchronous across multiple sites in southern California from 9.1 to 8.25 ka and may have been driven by atmospheric river-like winter storms (Kirby et al., 2012). High moisture/precipitation is shown in both inland (desert) and coastal sites, including increased runoff into the Santa Barbara Basin from 9 to 8.5 ka (Kirby et al., 2007, 2010, 2012, 2014; Du et al., 2018). In contrast, lake sediment records from southern California that resolve summer evaporation show high evaporation and multiple intervals of

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drought in the early Holocene; high winter precipitation and high summer evaporation may explain the differences between multiple records in this region (Kirby et al., 2019).

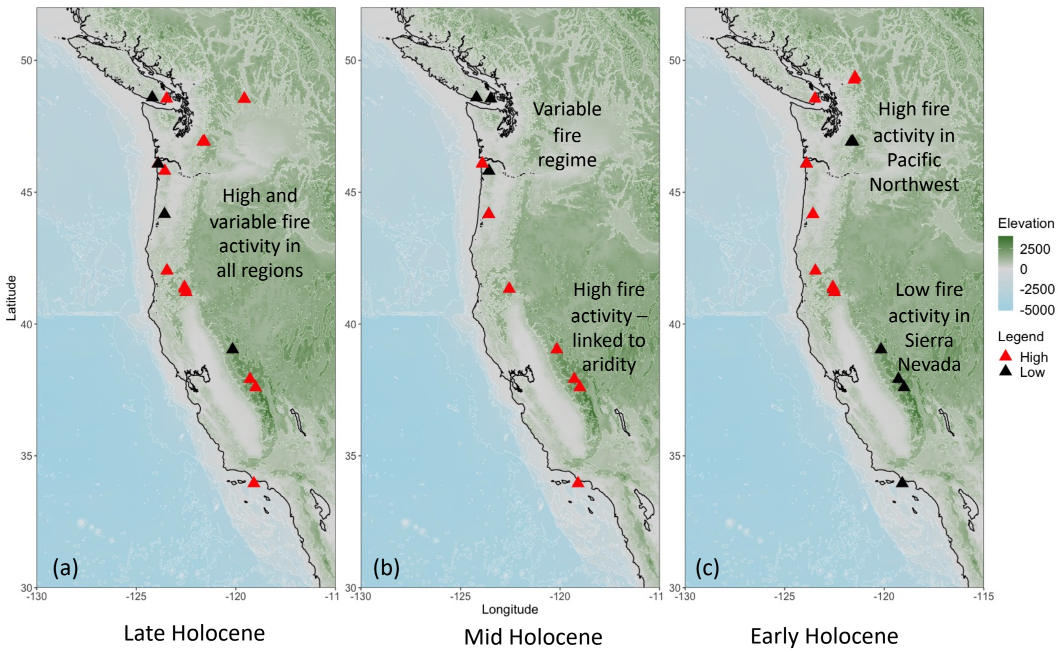

Figure 3: Fire activity as reconstructed by charcoal records through the early (11.7 - 8.2 ka, (c)), mid (8.2 - 4.2 ka, (b)), and late (4.2 - 0 ka, (a)) Holocene; red indicates high fire activity, green indicates low fire activity. Multiple metrics for fire activity are used; interpretations of original authors are preserved.

3.1.3 Marine conditions

Offshore of southern Oregon through Central California, the early Holocene was characterized by warm SSTs resulting from subtropical waters transported by currents comparable to the modern-day Davidson Current (Figs. 1, 2) (Mix et al., 1999; Barron et al., 2003b; Barron and Bukry, 2007a). In this area, the oceanographic regime was characterized by overall warm conditions, moderate to high export productivity, ventilation of deeper waters, and the development of the oxygen minimum zone (Barron et al., 2003b; McGann, 2011; Addison et al., 2017). During this time, the California Current was weaker than present allowing a strong northward Davidson-like current (Barron and Bukry, 2007a). Though upwelling was weaker than modern in the early Holocene, records from offshore Oregon show moderate marine productivity and multiple records indicate an increase in coastal upwelling beginning at 9 ka (Gardner et al., 1988; Barron et al., 2003b; Addison et al., 2017; Barron et al., 2017).

Offshore southern California (in Santa Barbara Basin), high productivity and overall warm SSTs occurred during the early Holocene (Kennett et al., 2007; Fisler and Hendy, 2008). Records extending from northern California south to the Baja California (Sur) peninsula indicate that in many locations, the onset of poorly oxygenated conditions in subsurface and intermediate waters occurred in the early Holocene, indicating changes in surface water productivity, intermediate water ventilation, or both relative to pre-Holocene conditions (Kennett and Ingram, 1995; Mix et al., 1999; Roark et al., 2003; van Geen et al., 2006; Moffitt et al., 2014). Changes in the strength or source of North Pacific Intermediate Water and the incursion of lower oxygen intermediate waters in Santa Barbara Basin (SBB) are also indicated (Roark et al., 2003; Moffitt et al., 2014).

3.1.4 8.2 ka Event

The end of the early Holocene is marked by a large-scale Northern Hemisphere cooling event initiated by an abrupt drainage of Lake Agassiz into the North Atlantic that weakened Atlantic Meridional Overturning Circulation, and is well documented in many records (Thomas et al., 2007; Matero et al., 2017; Estrella-Martínez et al., 2019; Voarintsoa et al., 2019). Although this is a globally well described event, relatively few records (fewer than 10 records reviewed in this paper) from the Northeastern Pacific and Western United States record impacts of this event. In central California (White Moon Cave), speleothem records show increased effective moisture at 8.2 ka which is attributed to intensification of the Pacific storm track that is synchronous on Eastern and Western sides of the Pacific (Oster et al., 2017). A lake record from Dry Lake in the SW (San Bernardino Mountains) shows a cooler, dryer and enhanced erosional period during the 8.2 ka event (Bird and Kirby, 2006). Marine records from off the coast of northern California (near the California-Oregon border) show a cold event at 8.2 ka, but this is not noted in other nearby marine records (Barron et al., 2003b). We hypothesize that the 8.2 ka event has a limited impact in this region, apart from the teleconnected impact of changes to the Pacific storm track impacting local hydroclimate.

3.1.5 Ecological responses to change

In the early Holocene, terrestrial plant communities generally indicate warm conditions, but show a process of succession out of glacial-associated ecosystems (Heusser, 1998). In the PNW, expansion of alder (*Alnus*) and ferns (*Pteridium*) began at the start of the Holocene, and Douglas fir (*Pseudotsuga menziessii*), western hemlock, grasses (*Poaceae*), and bracken fern (*Pteridium*) forests emerged by the end of the interval (Heusser, 1983; Pellatt et al., 2001). Southern Oregon cave records demonstrate taxonomic stability in plant communities through the early Holocene with communities dominated by pine (*Pinus*) and sagebrushes (*Amaranthaceae*, A*rtemisia*) (Beck et al., 2018). In the Klamath mountains, pine and oak (*Quercus*) dominated the pollen record during the warm dry early Holocene; similarly, pine, oak, and juniper dominated the record in the Siskiyou Mountains (Mohr et al., 2000; Briles et al., 2005). In northern California, pollen assemblages indicate warm winters, including an expansion of coastal redwoods, and declining alder (*Alnus*) forests (Barron et al., 2003b; Lyle et al., 2012). The increasing upwelling during the Holocene led to enhanced coastal fog and as a result, increasing dominance of coastal redwood (*Sequoia sempervirens*) (Gardner et al., 1988; Barron et al., 2003b; McGann, 2015; Addison et al., 2017). In Central California, increases in redwoods, oaks, *Nepenthes densiflora*, and *Asteraceae* indicate warmer and wetter conditions relative to glacial (McGann, 2015). In southern California, the early Holocene maintained a forest ecosystem distinct from the modern with more pines and conifers than in the late Holocene and modern (Heusser, 1978).

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In marine systems off the coast of northern California (Farallon Escarpment and offshore of the Russian River) transitions in planktic and benthic fauna occurred during the early Holocene as environmental conditions transition out of the glacial (Gardner et al., 1988; McGann, 2011). From 11.75 to 10 ka marine sediment records show low abundance of the upwelling-associated diatoms *Thalassionema nitzschioides* and *Thalassionema longissimi,* and the dominance of a cool, subpolar foraminiferal assemblage (Gardner et al., 1988). By 10.5-9 ka, carbonate productivity and total carbon peaked and warm water morphotypes of foraminifera were dominant across two northern California marine sediment records during this spike in productivity (Gardner et al., 1988; McGann, 2011). In coastal systems, kelp forests were present along the entire coastline from the SW to the PNW and increased in both size and range during the early Holocene (Erlandson et al., 2007; Graham et al., 2010). In deeper waters, the gradual development of the oxygen minimum zone in the early Holocene led to a transformation of seafloor ecosystems to a low oxygen-adapted assemblage (Cannariato and Kennett, 1999; Moffitt et al., 2014). Off the coast of Point Conception, seafloor fauna (e.g., benthic foraminifera) were variable in the early Holocene, with the establishment of the modern fauna by 9ka (McGann, 2015). In Northern (Farallon Escarpment) and southern California (SBB), low oxygen conditions developed during the early Holocene and caused a shift in benthic fauna during this interval (Cannariato and Kennett, 1999; McGann, 2015).

3.1.6 Human-environment interactions

Evidence for human presence and settlement along the North American Pacific coast throughout the Holocene is well documented in Indigenous ethno-history and archaeological records, yet these records are geographically disparate (Erlandson et al., 2007; McKechnie, 2015; Edinborough et al., 2017). In the PNW, archeological evidence for human presence is documented prior to the start of the Holocene (Kaufman et al., 2016; Beck et al., 2018; Becerra-Valdivia and Higham, 2020). One hypothesis for human migration across this region suggests that the southward migration of people just prior to the Holocene was correlated with the availability of marine resources, specifically the expansion of kelp forests may have been linked to the expansion of available coastal resources and thus human migration (Erlandson et al., 2007). Abundant early Holocene archaeological records from the Channel Islands show evidence of a diversified maritime economy, consumption of shellfish, marine mammals, and fin fish, yet a relatively small population size relative to later in the Holocene (Erlandson et al., 2007, 2009; Braje et al., 2012). Additional localized studies of human responses to environmental and ecological variability on the Channel Islands capture snapshots of human-environment interaction in the early Holocene, but do not capture the full time interval and thus are not included here.

https://doi.org/10.5194/cp-2021-109
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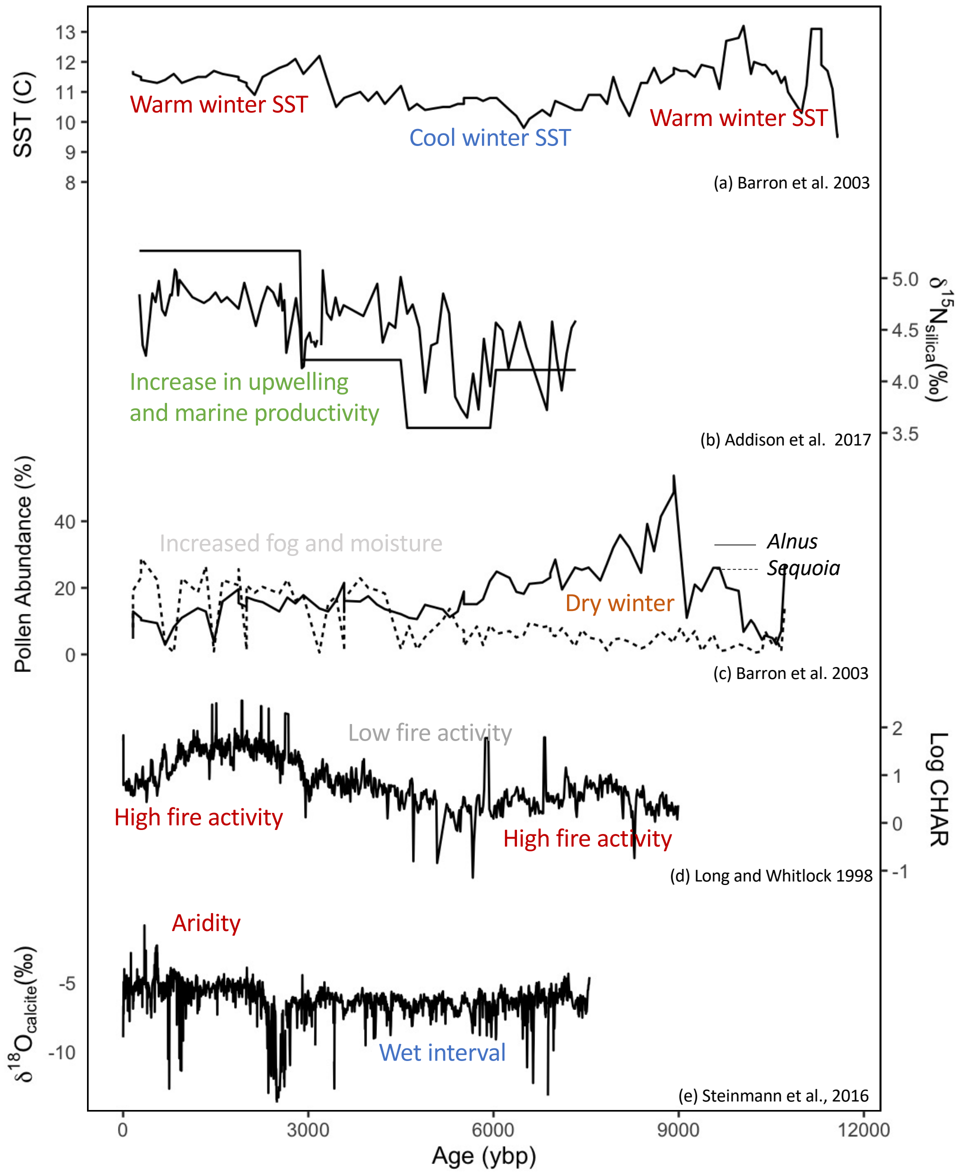

365 **Figure 4:** Representative datasets from the Pacific Northwest. Panels from top to bottom Alkenone sea surface temperature from core ODP1019 ((a), Barron et al. 2003). Bulk sediment δ15N and opal regime index from core TN062-O550 ((b), Addison et al. 2017). Relative abundance of pollen: solid line is *Alnus* (alder) and dashed line is *Sequoia* (coastal redwood) from core ODP1019 ((c), Barron et al 2003). Log charcoal accumulation rate at Little Lake ((d), Long and Whitlock 1998). Lake sediment bulk calcite δ18O from Cleland Lake, Washington ((e), Steinman et al. 2016).

https://doi.org/10.5194/cp-2021-109
Preprint. Discussion started: 3 September 2021

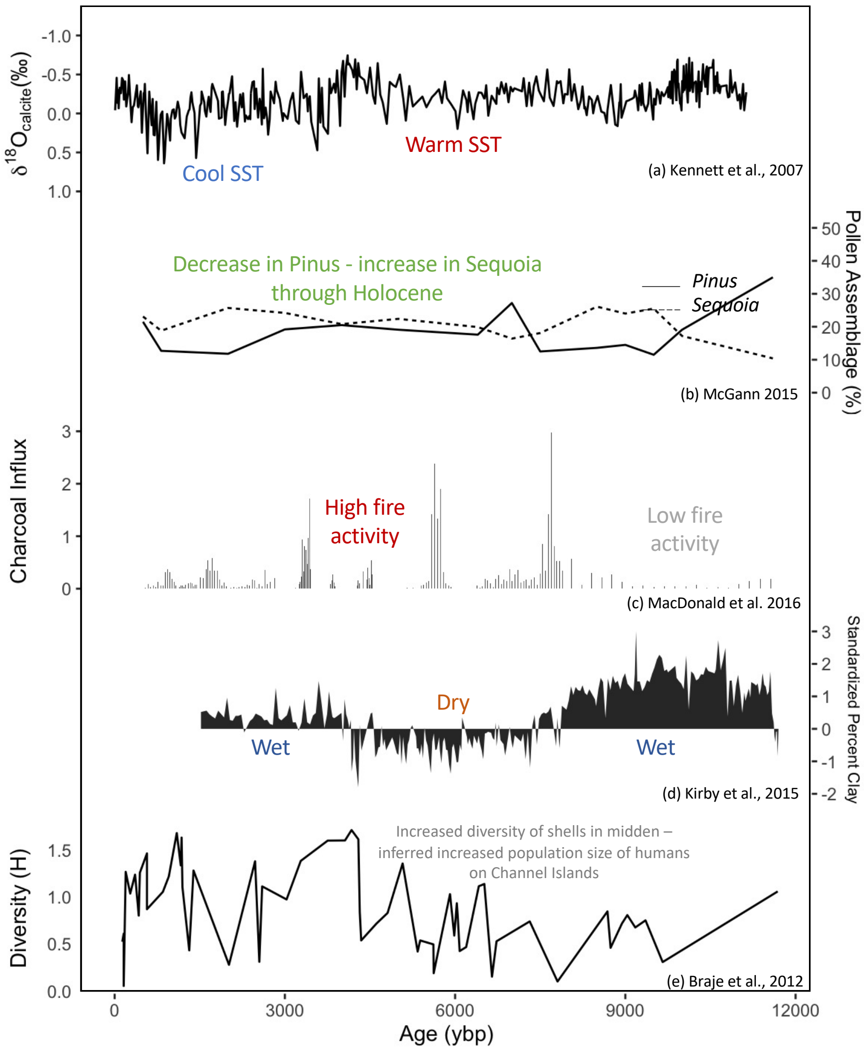

Figure 5: Representative datasets from the Southwest. Oxygen isotope record from planktonic foraminifera G.
375 bulloides from Santa Barbara Basin core ODP 893 ((a), Kennett et al. 2007). Pollen assemblage (%) of Pinus and Sequoia from Central California marine sediment core ((b), McGann 2015). Charcoal influx to Kirman Lake in the Sierra Nevada mountains ((c), Macdonald et al., 2016). Standardized percent clay as a proxy for relative lake status for Silver Lake ((d), Kirby et al., 2015). Diversity of shells from shell midden sites on Channel Islands, grey lines are average 6-12 ka (0.69) and 0-6 ka (0.98) ((e), Braje et al. 2012).

3.2 Mid-Holocene (8.2-4.2 ka)

Thirty-five papers encompassing 60 sites met the criteria for spatial analysis and were coded and plotted in Figs. 2 and 3. Archives included lake sediments (n=19), marine sediments (n=14), and two others (terrestrial midden, tree stump) (Appendix B, C).

3.2.1 Regional Synthesis

Spatial analysis of coded hydroclimate, temperature, and fire history indicates that the mid Holocene was characterized by a wet and cool PNW and a dry and warm SW relative to modern conditions (Fig. 2). Fire activity was high in the Sierra Nevada mountains and variable and transitional in the PNW (Fig. 3). Time series analyses supports these findings: offshore of the PNW, sea surface temperatures were cool, upwelling activity was moderate and terrestrial PNW winters were wet, fire activity was low and variable, and the overall hydroclimate was wet relative to the early Holocene (Fig. 4). In the SW, sea surface temperatures were warm, fire activity was high, hydroclimate was generally dry, and human-environment interactions increased as populations in this region increased relative to the early Holocene (Fig. 5).

Hydroclimate and temperature trends functionally reversed in the mid Holocene relative to the early Holocene, and the mid Holocene was a time of transition and variability in many records (Figs. 4, 5). In the PNW, SST transitions from warm to cool temperatures coeval with a shift from warm and dry to cool and wet terrestrial conditions. These coincident transitions suggest that the mechanisms for marine-terrestrial climate linkages persisted through the early and mid Holocene, namely a negative correlation between marine temperatures and terrestrial moisture/precipitation (Fig. 2). Yet nuanced changes occurring on shorter timescales may play an important role in determining hydroclimate of the region. A previously published review of hydroclimate records in Western North America (PNW, northern Rockies and most of California) at 6 ka shows aridity in areas that are dominated by winter precipitation, including multi-decadal to centuries-long 'mega droughts' due to reduced winter water vapor transport (Hermann et al., 2018). However, our findings reveal that when evaluated at a broader timescale (8.2-4.2 ka), the mid Holocene PNW is cool and wet (Fig. 2). We posit two hypotheses to reconcile these differences. First, we propose that the coastal PNW was wet and cool whereas interior areas may have been dry (Hermann et al., 2018). Alternatively, in the PNW, this time period may have been characterized by seasonal hydroclimate extremes, multiple records identify high winter precipitation and warm summers with high evaporation (Marlon et al., 2006; Whitlock et al., 2008; Steinman et al., 2016), thus exhibiting both wet and dry phases on short timescales. As such, seasonally resolved proxies are particularly advantageous to fully capture climate in the past.

The shift in SW terrestrial hydroclimate from wet in the early Holocene to dry in the mid Holocene (Fig. 2) may be due to several processes. A southward shift in NAM occurred between 9 and 6 ka, resulting in Mexico, rather than California, receiving a higher amount of precipitation (Metcalfe, 2015). Further, pluvial episodes driven by atmospheric river-type storms are rare in the mid Holocene, with the exception of one pluvial episode from 7.0-6.4

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ka that is synchronous across several southern California records (Kirby et al., 2012). Both phenomena (atmospheric rivers and NAM) are linked to changes in eastern tropical Pacific SSTs, rather than adjacent marine conditions in the California Current System (Fisler and Hendy, 2008; Kirby et al., 2012; Metcalfe, 2015). Thus, the lack of precipitation, driven by a local reduction in the NAM, a southward shift in the NAM, or absence of atmospheric river-like storms or the combination of all three led to overall aridity in the Southwest in the mid Holocene, and may not have been driven by local changes in SST of adjacent marine systems (Fig. 2).

3.2.2 Terrestrial climate

Between 8.2 to 4.2 ka, terrestrial conditions were generally cool and wet in the PNW and warm and dry in the SW, while marine systems were generally cool (Fig. 2), yet the mid Holocene was a time of transition and variability in terrestrial climate. A transition to cooler, wetter conditions during the mid Holocene occurred across several sites in the PNW (Nederbragt and Thurow, 2001; Marlon et al., 2006; Long et al., 2011; Walsh et al., 2017). For example, lake sediment records from north-central Washington (Scanlon and Castor Lake) demonstrate the variability in mid Holocene hydroclimate including low lake stand at 7 ka and high lake stand at 5 ka (Steinman et al., 2019).

Fire records from the PNW indicate a transition in hydroclimate and vegetation (Fig. 3). Fire activity increased on Vancouver Island, in the Oregon coast range, and in the Klamath and Siskiyou mountains through this interval (Brown and Hebda, 2002; Briles et al., 2005; Whitlock et al., 2008; Long et al., 2011). In Oregon and the northern Rocky Mountains, the combination of cooler, wetter conditions increased fuels and hot, dry summers led to more severe and larger fires relative to the early Holocene (Marlon et al., 2006; Whitlock et al., 2008). In coastal areas, increases in fire activity were linked to increased summer drought over time (Briles et al., 2005; Whitlock et al., 2008). Yet, in other nearby regions, fire activity was variable: on Mount Rainier, fire activity increased from 8 to 6.6 ka and decreased from 6.6 to 4 ka (Walsh et al., 2017), in northern Washington, fire frequency decreased at the start of the mid Holocene with the development of cooler, wetter summers, yet increased again at 4.5 ka (Gavin et al., 2007).

In the mid Holocene, the Sierra Nevada was dry relative to the early and late Holocene (Lindstrom, 1990; Benson et al., 2002; Hallett and Anderson, 2010; MacDonald et al., 2016). A northerly shift in the Intertropical Convergence Zone (ITCZ) in the mid Holocene led to reduced winter precipitation (including snowpack), which led to drier summers and increased fire frequency relative to early Holocene (Hallett and Anderson, 2010). Previous work investigating paired marine-terrestrial records from the Sierra Nevada (Kirman Lake) and eastern tropical Pacific highlight the connection between SST cooling (in the eastern tropical Pacific) and increased aridity (MacDonald et al., 2016). The marine-terrestrial link driving precipitation patterns was strongest throughout the mid Holocene, particularly from ~ 8 to 3 ka (MacDonald et al., 2016). The combination of aridity and increased biomass, led to control of fire by climate in the Sierra Nevada Mountains (Fig. 3) (Hallett and Anderson, 2010). Increased fire activity was synchronous with warming in the Eastern Sierra beginning at 5 ka (Hallett and Anderson, 2010). Additionally, high fire frequency in Lake Tahoe Basin in the mid Holocene (peak at 6.5 ka) was synchronous with high fire frequency in N. California and Oregon and is attributed to warm dry climate in the Lake Tahoe Basin at this time (Beaty and Taylor, 2009).

In the SW, the mid Holocene is characterized by generalized arid conditions. Lake records from the Mojave Desert (Silver Lake, California) indicate a distinct dry period from ~4.2-7.8ka (Kirby et al., 2015). Vegetation traces (macrofossils and pollen) from packrat middens in the Mojave Desert indicate increased aridity compared to modern with a particularly arid period from 6.8 to 5.0 ka (Spaulding, 1991). Pollen records from marine sediments offshore Central California identify a "mid Holocene dry period" from 8-6.4 ka (McGann, 2015). On the Channel Islands, hydroclimate conditions shifted from dry to wet at ~6.9 ka, coincident with an increase in fire activity (Anderson et al., 2010). Despite aridity in the desert SW, marine sediment records from SBB show extreme precipitation events with increased flooding occurring between 7.3-6.6 ka and 5.5-3.0 ka (Du et al., 2018). Finally, lake sediment records from Lake Elsinore show multiple pluvial episodes and lower relative evaporation in the mid Holocene (Kirby et al., 2019).

3.2.3 Marine conditions

In the mid Holocene, records indicate that off the coast of Oregon and California, sea surface temperatures were cool, while the Santa Barbara Basin was warm (Fig. 2) (Mix et al., 1999; Fisler and Hendy, 2008; Barron and Anderson, 2011; Barron et al., 2019). Generally, the North Pacific was experiencing negative PDO or La Niña-like conditions, with a weak/west-shifted winter Aleutian Low and strong/northward summer North Pacific High (Barron and Anderson, 2011). A dominant feature of mid Holocene Eastern North Pacific oceanography was an increase in coastal upwelling. Marine sediment records from offshore of northern California (40.9°N, 124.6°W) suggests a two-fold increase in upwelling and coastal fog beginning at 5.4 ka and a decrease in SST at 5 ka (Barron et al., 2003b; Addison et al., 2017). Coastal upwelling off California was enhanced during the summer and fall but suppressed during the spring as a result of a strong North Pacific High driven by orbital forcing (Diffenbaugh et al., 2003; Diffenbaugh and Ashfaq, 2007; Barron and Anderson, 2011). The increase in upwelling is due to a strengthening of the California Current and is documented as far south as Point Conception but is not documented in Santa Barbara Basin (Barron and Bukry, 2007a). Despite a cooling trend seen in multiple records from off the coast of Oregon and northern California, records from offshore Central California (Farallon Escarpment) show a slight warming trend through time, but at a decreased rate relative to the early Holocene, a decrease in carbonate productivity and total carbon export, relative to the early Holocene and continued low oxygen at depth (McGann, 2011). Warming conditions through the mid Holocene observed offshore Central California conflict with studies from further north showing a cooling trend, but compare favorably with records of warming from farther south (McGann, 2011).

Sea surface temperatures during the mid Holocene were generally warm in SBB and periodically punctuated by short cool periods at 8.2, 7.6, 5, 4.2 ka (Fisler and Hendy, 2008) and an interval of cold, high productivity from 5.8-6.3 ka (Kennett et al., 2007). Additional evidence from SBB shows that the mid Holocene was warmer and more variable than the early Holocene which may have been due to increased decadal scale variability (Friddell et al., 2003; Fisler and Hendy, 2008). SSTs in SBB initially rose by 3-4^{O}C followed by an abrupt increase of > 2^{O}C in less than 40 years at 7.5 ka (Friddell et al., 2003). Nearshore conditions on the Channel Islands were variable with an interval of cooler than modern SST during 6.3-5.3 ka preceded and followed by intervals of warmer than modern SSTs (Glassow et al., 2012). Circulation and ventilation of relatively young North Pacific Intermediate Water into SBB was stable through the mid Holocene (Roark et al., 2003). When compared to global records, SST trends from the North Pacific (generalized warming in the North Pacific from 7 ka to present) are inversely correlated with the SST in the North Atlantic (Kim et al., 2004).

3.2.4 Ecological responses to climate change

In the PNW, ecosystems responded to increases in moisture in the mid Holocene. The establishment of rainforest taxa in northern Cascades forest occurred during wet conditions and a variable fire regime in the mid Holocene (Hallett et al., 2003). Lake sediment records from near Mount Rainier show a shift to cooler, wetter conditions and a transition to mesic forests, indicating an increase in effective moisture (Walsh et al., 2017). In British Columbia, mild winters led to an increase in oaks, hemlock, and grasses during this interval (Pellatt et al., 2001). In northern Washington, lodgepole pine-dominated forest transitioned to a forest with abundant western white pines and Douglas-fir trees (Gavin et al., 2003, 2007). Near the end of the mid Holocene (~4.5 ka), fire frequency once again increased, despite the development of the modern western hemlock and redcedar forest that typically indicate cooler, wetter climate and mild summers (Gavin et al., 2003, 2007). In contrast, one record from the Saanich Inlet (British Columbia) shows that oak and Douglas fir increased during this time (Heusser, 1983, p.19). In northern California, terrestrial systems shifted from dominance by pine to an increased presence of *Sequoia* coastal redwoods, indicating an increase in fog (Barron et al., 2017)

Farther south, pollen records from Santa Barbara Basin show numerous changes in terrestrial ecosystems during this interval, including a decrease in *Pinus* and conifers; a general decrease in all trees leads to a temporary peak in herbaceous plants (*Asteraceae*) (at 5 ka) followed by a transition to a chaparral, coastal sage scrub dominated ecosystem and an increase in oaks (Heusser, 1978, 1998). A brief period of dry conditions from 8-6.4 ka led to an increase in herbs (*Asteraceae*) and pines with a coincident decrease in oaks and tanoak (*N. densiflora*) in Central California (McGann, 2015). In southern California, salt marsh fauna peaks at 6 ka and riparian community plants generally decrease through the Holocene; changes that are linked to drying trends in the SW in the mid Holocene (Heusser, 1978).

In marine systems offshore northern California, the increase in upwelling through the mid Holocene impacted both planktic and benthic ecosystems. For example, *T. nitzschioides* dominate the diatom/silicoflagellate assemblage, which indicates a shallow thermocline, high productivity within the California Current, and increased upwelling (Gardner et al., 1988; Barron et al., 2017). In SBB, an increase in warm water planktics and a *Neogloboquadrina incompta* dominated assemblage indicates a stable, warm, and stratified water column (Fisler and Hendy, 2008). The establishment of the modern low oxygen zone continues in this interval, with important implications for seafloor

https://doi.org/10.5194/cp-2021-109
Preprint. Discussion started: 3 September 2021

ecosystems including the development of a novel community between 7-5 ka, associated with sulfide-rich, anoxic chemosynthetic seafloor ecosystems in SBB (Moffitt et al., 2015).

3.2.5 Human-environment interactions

Similar to the early Holocene, much of the evidence of human activity and interaction with the environment during the mid Holocene is centered at the Channel Islands due to exceptional preservation of shell middens. In the mid Holocene, human population on the Channel Islands increased resulting in enhanced marine harvesting pressure after 6 ka, as indicated by an increase in shell midden diversity (Fig. 5) (Braje et al., 2012). Increased reliance on marine resources for food may have also been due to severe arid conditions (6.3 – 5.0 ka) that reduced terrestrial resources and availability of drinking water. This environmental shift facilitated an increase in fisheries as well as coastal shellfish harvesting (Kennett and Kennett, 2000; Kennett et al., 2007). Further, evidence of exchange between people on the Channel Islands with people in the Great Basin increased during this time and by the mid Holocene, semi-permanent villages were established on the Channel Islands (Kennett and Kennett, 2000; Kennett et al., 2007). As in the early Holocene, records of human community occupation and interactions with the environment are widespread in the mid Holocene, yet most represent snapshots in time and thus, are not included in the review.

3.3 Late Holocene (4.2 ka-present)

Twenty-eight papers encompassing 66 sites met the criteria for spatial analysis and were coded and plotted in Figs. 2 and 3. Archives included lake sediments (n=16) and marine sediments (n=12) (Appendix B, C).

3.3.1 Regional Synthesis

Analysis of coded hydroclimate, temperature, and fire history shows that the late Holocene was characterized by a wet PNW and wet and variable SW relative to the early and mid Holocene (Fig. 2). Marine temperatures were warm while terrestrial temperatures were cool and variable across both regions (Fig. 2). Fire activity was high and varied across both regions (Fig. 3). In the PNW, SSTs were warm, upwelling activity was high, coastal fog and moisture increased, fire activity was high, and the overall hydroclimate was variable (Fig. 4). In the SW, SSTs were variable, fire activity was high and variable, hydroclimate was generally wet, and human-environment interactions increased as populations in this region grew (Fig. 5). Due to the accessibility of more recent records, late Holocene records are abundant, yet despite this, fewer late Holocene studies were included in the coded spatial analysis relative to the mid or early Holocene as relatively few presented a coherent finding for the entire interval and intra-record variability was high in the late Holocene. Although for some records, temporal resolution increases towards the present, increased variability relative to the early and mid Holocene is persistent across multiple proxy types and temporal scale of record.

In comparison to the early and mid Holocene, the late Holocene shows greater variability in hydroclimate, temperature, and fire history both within and among records. Marine-terrestrial linkages in the late Holocene also show high variability and an increase in dominance of decadal to annual phenomena (Fig. 2). Coastal upwelling and precipitation are linked; intervals of stronger upwelling are linked to wetter conditions, and reduced upwelling is tied to aridity. In the late Holocene, upwelling and precipitation increased in magnitude and variability through this interval (Ingram, 1998; Addison et al., 2017). Changes in PDO exerted control on terrestrial hydroclimate. A period of negative PDO at 1.1-0.7 ka, with cooler North Pacific SST and higher upwelling, is coeval with prolonged drought in western North America (MacDonald and Case, 2005). Southwestern droughts in late Holocene co-occur with cooler than average SST in SBB. Similarly, nearshore records from Central California show high SST variability coincided with drought during the interval from 0.7-0.5 ka (Fig. 2) (Jones and Kennett, 1999; Barron et al., 2010). Late Holocene changes to PDO and ENSO progressed northward, with enhanced ENSO/PDO effects beginning at 4 ka in southern California and 3.4 ka in northern California (Barron and Anderson, 2011). Further, the late Holocene exhibited alternating wet and dry cycles that may be linked oscillation of precipitation sources between tropical and North Pacific-sourced water (Feakins et al., 2014; Kirby et al., 2014). High variability within and between records (Figs. 2, 3) is a dominant trend across both the PNW and SW in the late Holocene.

3.3.2 Terrestrial climate

Hydroclimate varies spatially and temporally through the late Holocene with the highest and most variable fire activity relative to the early or mid Holocene (Figs. 2, 3). In the PNW, multiple records show a cool and wet climate, with pronounced wet periods (Mohr et al., 2000; Nederbragt and Thurow, 2001; Reyes and Clague, 2004; Briles et al., 2005; Malamud-Roam et al., 2006). However, trends of increasing aridity towards the present and intervals of drought are also documented (Steinman et al., 2016, 2019; Walsh et al., 2017; Shuman et al., 2018). In the San Francisco Bay region, hydroclimate was also variable, with intervals of aridity documented at 3.0-2.5 ka and 1.7-0.73 ka (Byrne et al., 2001; McGann, 2008).

In the PNW, fire activity was high and variable in the late Holocene, despite intra-regional differences in hydroclimate and vegetation. Fire activity on Mount Rainier was highest in the past 4 ka relative to the rest of the Holocene, and conditions became increasingly dry throughout the late Holocene (Steinman et al., 2016, 2019; Walsh et al., 2017). Vegetation records show a surprising dominance of flora associated with cooler, wetter conditions despite the highest number of fire episodes and shortest fire return intervals during this period (Walsh et al., 2017). In North Cascades National Park in northern Washington, high variability in fire frequency and lower synchrony among forest fire events occurred even within the same forest. A decrease in fire frequency from 3.5-2.4 ka corresponded with a cool, humid climate, while high fire frequency from 2.4-1.3 ka suggests more frequent prolonged summer drought (Hallett et al., 2003; Gavin et al., 2007). In this region, the present-day fire regime was established by 1.3 ka (Hallett et al., 2003; Gavin et al., 2007). In the Oregon coast range, changes in vegetation led to a decrease in fire activity beginning at 2.75 ka. The increase in fire frequency and variability in the PNW may have been due to changes in forest composition, changes in temperature and precipitation, increased ENSO frequency leading to increased summer drought, or due to increases in human population and thus, human-induced fire (Walsh et al., 2017). Despite an increase in precipitation and a decrease in temperature, charcoal accumulation rates from the Oregon Coast Range and northern California (Klamath-Siskiyou Mountains) suggest that fires became larger and more severe in this region, with high variability during the latter part of the Holocene, likely due to increases in woody vegetation to fuel forest fires (Marlon et al., 2006, 2013; Whitlock et al., 2008).

Spatial and temporal variability in climate and fire history occurred across the Sierra Nevada mountains (Figs. 2, 3). In the eastern Sierras, hydroclimate varied throughout the late Holocene; Mono Lake water level fluctuated through this time (3.77 ka- highest in last 7 ka, 1.8 ka low stand, multiple rapid fluctuations in last 1.2 ka), Owens Lake exhibited three intervals of wetter and cooler climate at 3.6 ka, 0.8 ka, and 0.35 ka (Bacon et al., 2018), and increased precipitation through the late Holocene at Pyramid Lake led to rising lake levels (Benson et al., 2002). Strong fire synchrony occurred in the Sierra Nevada since 2.5 ka which is linked to periods of drought (Hallett and Anderson, 2010). In the Lake Tahoe Basin, changes in vegetation from open forest to mesic forest drive a decline in fire frequency from the Mid-Holocene to modern, with a particularly low fire interval from 4.0 to 3.5 ka (Beaty and Taylor, 2009). Records from the Sierra Nevada show glacial advancement linked to cooling beginning 3.9 ka (Konrad and Clark, 1998)

In Central and southern California, multiple wet and dry phases occurred through the late Holocene (Fig. 2) (Feakins et al., 2014; Kirby et al., 2014). In coastal Central California, marine records show that winter precipitation increased in the late Holocene (McGann, 2011). Several lake records from southern California (Lower Bear Lake, Lake Elsinore, Tulare Lake, and Owens Lake) all indicate a return to wetter conditions beginning between 4.0-3.35 ka (Kirby et al., 2010, 2014). Records from coastal lagoons on Santa Rosa Island and in southern California show multi-centennial fluctuations between wet and dry conditions (Davis, 1992; Anderson and Byrd, 1998; Cole and Wahl, 2000; Anderson et al., 2010). Similarly, records from Zaca Lake and Lake Elsinore indicate multiple wet and dry intervals, including multi-centennial drought from 2.0-2.7 ka (Dingemans et al., 2014; Kirby et al., 2014, 2019). This alternation of wet and dry cycles may be linked to alternation of precipitation source water between more tropical and more North Pacific source water (Feakins et al., 2014; Kirby et al., 2014). In some records, a late Holocene Dry Period (1 – 0.2 ka) is identified (Platzman and Lund, 2019), and persistent droughts and elevated aridity are dominant across the Western US from 1.1 to 0.7 ka (Cook, 2004). In the Mojave Desert (Silver Lake, California) conditions returned to ephemeral, wet lake conditions beginning at 3.8 ka after a mid Holocene period of aridity (Fig. 5) (Kirby et al., 2015). Yet other records show increased aridity in the Mojave Desert compared to the mid Holocene (Spaulding, 1991).

Across the study region, extreme events (rainfall, drought, flooding) become a dominant feature across multiple records over the past 2 ka (Cook, 2004; Malamud-Roam et al., 2006; Rasmussen et al., 2006; Kirby et al., 2015). A pronounced megadrought occurred in Western North America from 1.1 - 0.7 ka, that was previously linked to cool SST over the Eastern Tropical North Pacific (Cook, 2004). More variable conditions have been attributed to changes in insolation as well as shorter term processes including ENSO and PDO (Cook, 2004; Kirby et al., 2007, 2010; Barron and Anderson, 2011). Gradual decreases in summer insolation and increases in winter insolation contribute to maximum drying in the late Holocene relative to the early Holocene (Kirby et al., 2007). Enhanced PDO and

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ENSO variability in the last 4 ka contribute to increased terrestrial hydroclimate and temperature variability (Kirby et al., 2010; Barron and Anderson, 2011).

3.3.3 Marine Conditions

In the late Holocene, SST increased and spring upwelling increased off the coast of Oregon and California and SST decreased in the Santa Barbara Basin relative to the mid Holocene (Figs. 2, 4, 5) (Barron et al., 2003a; Kennett et al., 2007; Barron and Anderson, 2011). Late Holocene marine conditions show increased variability in SST, intensification of the California Current, and increased upwelling relative to the mid Holocene (Fig. 3) (Barron and Bukry, 2007a; Barron and Anderson, 2011). While global records suggest a shift in climate characteristics at 4.2 ka, several California and Oregon records experience a delayed mid to late Holocene shift (Barron and Bukry, 2007a; Addison et al., 2017; Barron et al., 2017). Modern seasonality within the California Current (strong spring-summer upwelling with cool SSTs, and relaxation with warmer SSTs during fall) was established between 3.5 and 3.2 ka (Barron and Bukry, 2007a). Diatom-based productivity increased at 2.9 ka offshore of northern California and changes in relative abundance of diatom and pollen species suggest significantly increased upwelling and productivity at this time (Addison et al., 2017). Additional evidence from offshore of northern California shows cooler SSTs occurred from ~3.6 and 2.8 ka, accompanied by increased precipitation, an abrupt warming of winter SSTs at 2.8ka, and an intensification of spring upwelling beginning 2.6 ka (Barron et al., 2017). Since 2.6 ka, PDO-like warm-cool oscillations have dominated the SST regime (Barron et al., 2017).

Further south, off the coast of Santa Cruz, California, upwelling and productivity increased steadily through the late Holocene (Barron et al., 2019). Additional records from offshore Central California indicate the late Holocene marked the onset of warm modern offshore conditions with high productivity (total and organic carbon export) relative to the mid and early Holocene (McGann, 2011; Barron et al., 2019). Marine oxygenation off the coast of Central California declined through the late Holocene (McGann, 2011). Nearshore records from Central California show that SST was 1^{O}C cooler than modern from 2-0.7 ka (Jones and Kennett, 1999).

In southern California, late Holocene SST cooling with high SST variability (in Santa Barbara Basin) began at ~4 ka (Fig. 5) (Kennett et al., 2007; Fisler and Hendy, 2008). High amplitude changes in salinity due to variability of input of freshwater into the basin are documented within SBB (Kennett et al., 2007). Brief cold events occurred in SBB at ~4.2-3.8, 1.5-1.2, and 0.8-0.3 ka and correspond to glacial advances in the Sierras (Fisler and Hendy, 2008). Variable oceanographic conditions in the late Holocene may be due to increasing ENSO variability in the tropical Pacific (Barron and Bukry, 2007b). Intensification of the California Current and increased East-West seasonal gradients (driving increased winds that enhance upwelling) are documented offshore northern California (Barron et al., 2003b; Barron and Bukry, 2007b, b) and across the southern California Borderlands. Nearshore records from Santa Cruz Island show persistently cold SSTs and persistent upwelling on the west coast of Santa Cruz Island in late Holocene compared to a wider range of nearshore conditions on the south side of the island (Flores, 2017). In deeper waters, a drastic change in the age of North Pacific Intermediate Water in SBB (shift to older water and lower bioturbation) at 2 ka with a subsequent stable age of water entering from 2 ka to present suggests changes in the North Pacific Intermediate Water circulation pattern (Roark et al., 2003). This shift is concurrent with a decrease in Greenland temperature and increase in ice accumulation rate suggesting trends in SBB relate to larger atmospheric circulation patterns (Roark et al., 2003). Further, the oxygen minimum zone persists in intermediate waters off the coast of southern California, but is reduced in intensity relative to the mid Holocene (Balestra et al., 2018; Wang et al., 2020).

3.3.4 Ecological responses to change

Forested ecosystems in the PNW and northern California transitioned to modern temperate, cool, wet, highly fire-adapted systems with increased fir and pine (Heusser, 1983; Mohr et al., 2000; Pellatt et al., 2001; Barron et al., 2003b, 2019; Briles et al., 2005; Anderson et al., 2013) while SW systems became increasingly dominated by chaparral and sage scrub ecosystems (particularly since ~2.5 ka) (Heusser, 1978; Anderson and Byrd, 1998; Cole and Wahl, 2000; Anderson et al., 2010; Dingemans et al., 2014). In the Siskiyou mountains, a shift in hydroclimate to wet, cool conditions at 2.1 ka led to the development of the modern forest dominated by firs (*Abies*) and cypress (*Pseudotsuga*) and moderated by a modern fire regime (Briles et al., 2005). In parallel with increases in hydroclimate and temperature variability, in northern California the amplitude and frequency of changes between pine and alder intensified in the late Holocene and coastal scrub expanded (Fig. 4) (Barron et al., 2003b; Anderson et al., 2013). In Central California, changes to forest assemblages occurred gradually through time, trending towards decreased dominance of pine in the modern (Fig. 5) (McGann, 2015; Barron et al., 2019). Finally, in southern California, ecological change varied locally, with transitions in pollen regimes indicating increased moisture occurring around 2 ka in multiple records (Anderson and Byrd, 1998; Cole and Wahl, 2000; Dingemans et al., 2014).

Marine ecosystems reflect the establishment of modern levels of coastal upwelling and productivity in the late Holocene (Addison et al., 2017; Barron et al., 2017). Offshore northern California, the gyre-associated diatom species *Pseudoeunntia doliolus* increased threefold indicating the onset of modern oceanographic conditions in this region (Barron et al., 2003b). Offshore Central California, upwelling evolved gradually over time and the upwelling-indicator diatom species *T. nitzschioides* gradually increased through this interval (Barron et al., 2019). In SBB, late Holocene cooling led to an increase in the abundance of cold-associated (*N. pachyderma*) and upwelling-associated (*Globigerina quinqueloba)* planktic foraminifera (Fisler and Hendy, 2008). Oxygen deficient zones were well established by the late Holocene and persisted throughout the interval, structuring seafloor and pelagic ecosystems (Ohkushi et al., 2013; Moffitt et al., 2014, 2015).

3.3.5 Human-environment interactions

Human-environment interactions are well documented in the late Holocene relative to previous time intervals both due to the increase in human population and the preservation bias in archaeological records and recency bias in oral histories. In multiple locations, a late Holocene drought was a destabilizing factor for societies. In the SW, a 26-

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year-long drought that occurred 0.8 ka is linked to social destabilization and abandonment of well-established Ancestral Puebloan villages (deMenocal, 2001). In northern California, the abandonment of shell mounds following four millennia of occupation (5 to ~1.2 ka) co-occurs with drought in this region revealing potential societal impacts of drought (Ingram, 1998). Human control of the fire regime led to land use and ecosystem changes across the Western US during this interval. In Washington, an increase in human artifacts in the subalpine zone beginning at 3.6 ka, combined with a change in climate and thus ranges of game species, provide some evidence for increased presence of people in subalpine terrain and potentially an increase in human-caused fire (Walsh et al., 2017). Across California, late Holocene increases in chaparral, grassland, and sage scrub ecosystems were reinforced by intentional burning and prescribed burning played an important role in structuring ecosystems (Heusser, 1978; Anderson et al., 2010, 2013; Cowart and Byrne, 2013; Lightfoot and Cuthrell, 2015; Klimaszewski-Patterson et al., 2021).

Human interactions with the marine environment were critical factors in structuring societies, and conversely, changes in ocean conditions impacted users of coastal resources. In Central California, marine resources including shellfish and fish, were harvested throughout the late Holocene (Jones and Kennett, 1999). Occurrence of drought from 0.5-0.3 ka led to an increase in fish bone presence in middens, indicating enhanced use of fisheries as a resource during a time of drought, despite a documented decrease in marine productivity and high-amplitude marine seasonality coeval with the interval of drought (Jones and Kennett, 1999). Indigenous coastal populations were highly reliant on marine resources (largely *Mytilus californianus*) and even inland occupants of Central California traveled to the coast seasonally to harvest mussels (Jones et al., 2008). On the Channel Islands, human population and sociopolitical complexity increased in the late Holocene (Rick, 2011; Braje et al., 2012). As populations increased, diet breadth expanded and human harvesting pressure on marine ecosystems increased, including an expansion of consumption of finfish and pinnipeds and a diversification of taxa in middens (Erlandson et al., 2009; Rick, 2011; Braje et al., 2012). Expansion of sociological complexity, and competitive (including violent conflict) and cooperative strategies on the northern Channel Islands from 1.3-0.7 ka is attributed to of high climatic instability, cool marine conditions with relatively high productivity, low terrestrial productivity, and aridity (Kennett and Kennett, 2000). This climate instability led to conflicts over resources, but eventually resulted in more complex sociopolitical societies due to the need to cooperate, regulate, and manage resources (Kennett and Kennett, 2000). Human-environment interactions and Indigenous land stewardship were important environmental and ecological drivers throughout the late Holocene. The onset of colonization, genocide of Indigenous people, land-use change, urbanization, industrialization, and anthropogenic climate change in the last few hundred years dramatically impacted climate, ecosystems, and records used to interpret past change (see Sect. 3.5 on Era of Colonization below).

3.4 Medieval Climate Anomaly and Little Ice Age

Specific investigation of the Medieval Climate Anomaly (MCA) and the Little Ice Age (LIA) are included in some of the papers reviewed here. Generally, the MCA was an anomalously warm event that is linked to pronounced drought conditions throughout the Western United States. Alternatively, the LIA was a brief period of cooling

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predominantly identified in Northern Hemisphere records (Cook, 2004). Evidence of dry conditions during the MCA is indicated in a breadth of records: from Mono Lake and Owens Lake in the Eastern Sierra Nevada (Stine, 1990; Bacon et al., 2018), freshwater input into San Francisco Bay, Abbot Lake and Zaca Lake in coastal Central California (Dingemans et al., 2014; Hiner et al., 2016; Platzman and Lund, 2019), Central California pollen history (McGann, 2015), flood events in SBB (Schimmelmann et al., 2013; Du et al., 2018), tree stump dating in the Sierra Nevada (Stine, 1994), and a synthesis of tree-ring records (Cook, 2004). Dry conditions were likely caused by anomalously warm terrestrial temperatures and are linked to cool SSTs over the Eastern Tropical Pacific (Cook, 2004) and in the adjacent Santa Barbara Basin (Kennett and Kennett, 2000; Fisler and Hendy, 2008; Barron et al., 2010; Asmerom et al., 2013). Fire activity increased in the MCA in the Eastern Sierra and Lake Tahoe Basin, which may be due to warm summer enhanced growth and decreased snowpack, but in Western North America more broadly, fire activity was reduced during the MCA and LIA relative to the past 3 ka (Beaty and Taylor, 2009; Hallett and Anderson, 2010). The LIA was characterized by warm SSTs in southern California, wetter conditions in the Sierra Nevada and southern California, and minimum fire frequency in Western North America (Reyes and Clague, 2004; Whitlock et al., 2008; Barron et al., 2010; Feakins et al., 2014; Kirby et al., 2019). Further investigation of the MCA and LIA are merited but are not within the scope of this paper.

3.5 Era of Colonization

Humans have been interacting with the environment in Western North America throughout the entirety of the Holocene. As described above, Indigenous peoples exerted control of fire and interacted with, managed, and cultivated marine and terrestrial plants and animals throughout the Holocene (Braje et al., 2012; Taylor et al., 2016; Platzman and Lund, 2019; Ellis et al., 2021; Klimaszewski-Patterson et al., 2021; Minnis, n.d.). Yet, the impacts of settler colonization, genocide of indigenous people, and conversion to Western, Euro-centric land and marine management practices are evident in many records examined here and represent an unprecedented environmental regime in multiple records (Ellis et al., 2021).

Impacts of land-use change and human control of fire at the time of colonization precede changes due to urbanization and anthropogenic climate change (Waters et al., 2016). Changes in the view and management of fire shaped the landscape and climate in the last several hundred years, beginning with a measurable increase in fire (relative to Indigenous prescribed burning) following settler colonization and a subsequent measurable decrease in fire in the last 100 years due to fire suppression (Gavin et al., 2007; Anderson et al., 2010, 2013; Dingemans et al., 2014; Taylor et al., 2016; Walsh et al., 2017; Platzman and Lund, 2019). Prior to 1860, fire activity in the Sierra Nevada was positively correlated with temperature, but in the last 150 years (after 1860 CE) fires are linked to human activity and socio-ecological change, rather than temperature or moisture (Anderson et al., 2013; Taylor et al., 2016). In the Sierra Nevada the highest fire activity in the last 400 years occurred following Spanish colonialism and the lowest fire activity occurred with the onset of fire suppression beginning in 1904 CE (Taylor et al., 2016). In coastal Central California recent increases in fire beginning in the mid nineteenth century are attributed to burning of logging slash (Cowart and Byrne, 2013).

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Increases in extractive processes and land-use conversions for ranching and agriculture have also contributed to changing fire regimes over the last several hundred years and led to changes in hydrology and landscape geomorphology (Heusser, 1983; Byrne et al., 2001; Cowart and Byrne, 2013; Platzman and Lund, 2019). Pollen records in British Columbia show the impacts of colonization, logging, farming, and urbanization on local terrestrial ecosystems (Heusser, 1983). Influx of freshwater to the San Francisco Bay decreased dramatically relative to the late Holocene at 1930 CE due to diversion of upstream water flow (Byrne et al., 2001). The extractive processes of the Gold Rush Era (beginning at 1850) in northern California led to increased sedimentation and heavy metal pollution in the San Francisco Bay Delta; post-colonization lead (Pb) levels are unprecedented throughout the rest of the Holocene and concentrations of Sr, Ti, Cu, Ni, and Zn also increased following colonization (Fard et al., 2021). The onset of logging and ranching caused land use change including transition of redwood forest to grasses and oak landscapes in coastal Central California (Cowart and Byrne, 2013). Further, the introduction of non-native species is well documented across the region (Anderson and Byrd, 1998; Cole and Wahl, 2000; Anderson et al., 2010, 2013; Dingemans et al., 2014). The impact of both a changing fire regime and land use change resulted in shifts in terrestrial ecosystems (Cowart and Byrne, 2013; Dingemans et al., 2014; Platzman and Lund, 2019).

Human impacts on nearshore marine ecosystems are documented throughout the Holocene (as discussed above). Yet widespread and detectable impacts of land use change and anthropogenic climate change on marine systems do not appear until the last several hundred years, following colonization and the Industrial Revolution, respectively. Land use change and the conversion of land to rangeland and cultivated agricultural land beginning around 1800 CE led to the collapse of benthic marine ecosystems and may have contributed to a decrease in oxygenation across the southern California Bight (Christensen et al., 1994; Tomasovych and Kidwell, 2017; Wang et al., 2017; Palmer et al., 2020). Impacts of anthropogenic climate change on marine systems in this region include species range shifts caused by rising SSTs and geochemical and structural changes to organisms due to ocean acidification; these changes represent a divergence from scales of past variability (Field et al., 2006; Pak et al., 2016; Osborne et al., 2020). Human activity, including intentional use and alteration of marine and terrestrial systems, has been a feature of Western North America throughout the Holocene that is detectable in multiple archives (lake sediments, marine sediments, archaeological records), yet colonization, urbanization, and industrialization led to a novel environmental interval.

4 Conclusions

Understanding Holocene climate and oceanographic patterns in the Western United States and California Current System is critical for contextualizing and predicting modern changes. Relative to pre-Holocene conditions, the early Holocene was dry and warm in the PNW and wet and warm in the SW; sea surface temperature was warm along the coast (Fig. 2). The mid Holocene was characterized by a wet, cool PNW and dry, warm SW with generalized cool SST, except for Santa Barbara Basin (Fig. 2). The late Holocene is the most variable interval with a general pattern

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of warm marine conditions and cool terrestrial conditions (Fig. 2). Control of fire regime shifts throughout the Holocene; in the early Holocene, fire activity is linked to changes in vegetation following the deglacial, but in multiple locations shifts to control by climate in the mid Holocene and in most records is highest and most variable in the late Holocene (Fig. 3). Human-environment interactions persist throughout the Holocene and impact the climate, landscape, and ecosystems of Western North America. Prior to settler colonization, marine harvesting and prescribed burning shaped past ecosystems and landscapes, while intervals of drought and variability in marine productivity impacted sociological complexity and migration of Indigenous people. Impacts of settler colonization, urbanization, and industrialization in recent centuries are documented broadly and, in some cases, represent divergences from scales of expected variability as recorded throughout the rest of the Holocene.

Multiple factors combine and interact to drive climate changes through the Holocene across timescales including orbital forcing, ice sheet dynamics, solar forcing, annual to decadal phenomena, and marine-terrestrial interactions. Orbital forcing, including the northern hemisphere solar insolation peak in the early Holocene, drives climate change on millennial timescales. Annual to decadal phenomena such as ENSO and PDO become dominant drivers of climate in the late Holocene and lead to increased temporal variability. The relationship between marine and terrestrial systems evolves through time; notably, continental conditions in the Pacific Northwest and Southwest respond differently to changes in marine conditions. In the PNW broadly, marine temperatures are inversely correlated with precipitation. In the early Holocene, warm SSTs coeval with warm, dry inland conditions, in the mid Holocene, the trend reverses. Yet, the increase in upwelling as a dominant oceanographic feature throughout the Holocene complicates this relationship, as upwelling in the PNW is positively correlated with precipitation yet characterized by cool SSTs. Thus, in the late Holocene, the interaction between an enhanced upwelling regime yet generalized warm SST patterns may both play a role in influencing terrestrial hydroclimate. In contrast, in the SW, marine temperatures are generally positively correlated with precipitation; warm intervals (such as the early Holocene) coeval with wet intervals and periods of drought coeval with cool SSTs offshore southern California. In addition to marine-terrestrial interactions on regional scales, changes in source and strength of precipitation sources impact hydroclimate of the region; for example, changes in the intensity or geographic extent of the North American Monsoon and occurrence of atmospheric-river storms are both linked to processes in the Eastern Tropical North Pacific and have implications for hydroclimate across the region studied here.

Although general trends can be identified across broad regions (PNW and SW), local factors play a key role in determining the exact conditions for a particular location. Complete synchrony between records across a full time period for marine conditions, for terrestrial climate, or for fire activity is functionally absent; multiple anomalous or contradictory records exist (Figs. 2, 3). For example, fire activity in adjacent lake basins show different trends and nearshore vs. offshore records of marine conditions present apparently competing evidence (Fig. 3). Marine sediment records from Santa Barbara Basin are often utilized as records of the entire North Pacific, but here we find that trends in Santa Barbara Basin are not always synchronous with other records in this region (Fig. 2). We posit that these instances do not present competing evidence, but rather that local factors are critical in determining local

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climate. This is of critical importance for interpreting present and future climate change. This synthesis of climate and oceanographic processes and resultant impacts on ecosystems and human communities provides a window into understanding modern patterns of climate and climate change in the Western United States and Northeast Pacific and amplifies the need for future research investigating marine-terrestrial interactions, local and regional scale processes, and integrated physical-ecological-human systems.

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Appendices

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Appendix A contains a list of papers used in the literature review (step 1 of systematic review). Abbreviations are as follows: Southwest – SW, Pacific Northwest – PNW.

Paper	Paper	Latitude	Longitude	Region	Archive
Addison et al., 2017	Addison et al 2017	40.8656	-124.573	PNW	Marine sediment
Anderson and Byrd 1998	Anderson and Byrd 1998	33.291667	-117.341667	SW	Lake sediment
Anderson et al., 2010	Anderson et al., 2010	33.965278	-120.097222	SW	Lake sediment
	Anderson et al., 2010	33.955556	-119.095833	SW	Marine sediment
Asmerom et al., 2013	Asmerom et al 2013	32.163745	-104.517682	SW	Speleothem
Bacon et al 2018	Bacon et al 2018	36.542	-117.938	SW	Geomorphology
Bacon et al., 2006	Bacon et al., 2006	36.441174	-117.970433	SW	Lake sediment
Barron and Anderson 2011	Barron and Anderson 2011	review paper			
Barron and Burky 2007	Barron and Bukry, 2007	42.24	-125.89	PNW	Marine sediment
	Barron and Bukry, 2007	36.99	-123.268	SW	Marine sediment
	Barron and Bukry, 2007	41.68	-124.93	PNW	Marine sediment
Barron et al., 2003	Barron et al 2003	42.682	-124.93	PNW	Marine sediment
Barron et al., 2010	Barron et al., 2010	34.2875	-120.036667	SW	Marine sediment
	Barron et al., 2010	34.221667	-120.028333	SW	Marine sediment
Barron et al 2017	Barron et al., 2017	40.9	-124.6	PNW	Marine sediment
	Barron et al., 2017	40.9	-124.6	PNW	Marine sediment
Barron et al., 2019	Barron et al., 2019	37.3317	-123.3992	SW	Marine sediment
Beatty and Taylor 2009	Beatty and Taylor 2009	39.034637	-120.1624	SW	Lake sediment
Beck et al 2018	Beck et al 2018	42.730113	-120.517458	PNW	Lake sediment
Benson et al., 2002	Benson et al 2002	40.073646	-119.5969	PNW	Lake sediment
Bird and Kirby 2006	Bird & Kirby 2006	34.120426	-116.82766	SW	Lake sediment
Bird et al., 2010	Bird et al., 2010	34.121045	-116.828569	SW	Lake sediment
Braje et al., 2012	Braje et al 2012	34.038578	-120.37907	SW	Archeological record
	Braje et al 2012	34.016987	-119.765051	SW	Archeological record
	Braje et al 2012	33.955317	-120.1062	SW	Archeological record
Briles et al., 2005	Briles et al., 2005	42.025	-123.458333	PNW	Lake sediment
Brown and Hebda 2002	Brown and Hebda 2002	48.595278	-124.197325	PNW	Lake sediment

	Brown and Hebda 2002	48.547796	-123.475786	PNW	Lake sediment
Byrne et al., 2001	Byrne et al., 2001	38.098287	-122.02125	SW	Marine sediment
Cannariato and Kennett 1999	Cannariato and Kennett 1999	34.535	-121.107167	SW	Marine sediment
	Cannariato and Kennett 1999	34.5	-121.5	SW	Marine sediment
Cole and Liu 1994	Cole and Liu 1994	33.956389	-119.976667	SW	Lake sediment
Cole and Wahl 2000	Cole and Wahl 2000	32.929595	-117.256734	SW	Lake sediment
Cook et al., 2000	Cook et al., 2000	review/modeling paper			
Cowart and Byrne 2013	Cowart and Byrne 2013	37.173889	-122.314444	SW	Lake sediment
Davis 1992	Davis 1992	33.660482	-117.840775	SW	Marine sediment
Dingemans et al 2014	Dingemans et al 2014	34.76666667	-120.0333333	SW	Lake sediment
Du et al 2018	Du et al., 2018	34.281767	-119.963967	SW	Marine sediment
Erlandson et al., 2007	Erlandson et al., 2007				
Erlandson et al., 2009	Erlandson et al., 2009				
Feakins et al 2014	Feakins et al 2014	34.777634	-120.039859	SW	Lake sediment
Field et al 2006	Field et al., 2006	34.287133	-120.035583	SW	Marine sediment
Fisler and Hendy 2008	Fisler and Hendy 2008	34.2875	-120.036667	SW	Marine sediment
Flores et al., 2017	Flores et al., 2017	33.987079	-120.222156	SW	Archeological record
	Flores et al., 2017	33.914652	-120.053465	SW	Archeological record
Friddell et al 2003	Friddell et al 2003	34.271167	-120.072667	SW	Marine sediment
Gardener et al., 1988	Gardner et al., 1988	39.05	-122.835583	SW	Lake sediment
	Gardner et al., 1988	38.425167	-122.796167	SW	Marine sediment
Gavin et al. 2007	Gavin et al. 2007	review paper			
Gavin et al., 2003	Gavin et al., 2003	49.3911	-125.748781	PNW	Tree stump
Glassow et al., 2012	Glassow et al., 2012	33.960648	-119.817915	SW	Archeological record
Hallett and Anderson 2010	Hallett and Anderson 2010	37.90857222	-119.2864	SW	Lake sediment
	Hallett and Anderson 2010	37.59570278	-119.0067	SW	Lake sediment
Hallett et al., 2003	Hallett et al., 2003	49.36	-121.4666667	PNW	Lake sediment
	Hallett et al., 2003	49.266667	-121.516667	PNW	Lake sediment
Hermann et al 2018	Hermann et al 2018	review paper			
Heusser 1978	Heusser 1978	34.266667	-120.066667	SW	Marine sediment

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Heusser 1983	Heusser 1983	48.59065	-123.503333	PNW	Marine sediment
Heusser 1998	Heusser 1998	review paper			Marine sediment
Hiner et al 2016	Hiner et al 2016	36.231354	-121.482348	SW	Lake sediment
Ingram 1998	Ingram 1998	37.576171	-122.261235	SW	archeological
Jones and Kennett 1999	Jones and Kennett 1999	36.288439	-121.853672	SW	archeological
	Jones and Kennett 1999	35.642784	-121.177744	SW	archeological
	Jones and Kennett 1999	36.045231	-121.584481	SW	archeological
	Jones et al., 2008	35.668278	-121.284271	SW	archeological
	Jones et al., 2008	36.070611	-121.582634	SW	archeological
Kaufman et al., 2020	Kaufman et al., 2020	global synthesis			
	Kennett and Ingram 1995	34.2875	-120.036667	SW	Marine sediment
Kennett and Kennett 2000	Kennett and Kennett 2000	34.2875	-120.036667	SW	Marine sediment
Kennett et al., 2007	Kennett et al., 2007	34.2875	-120.036667	SW	Marine sediment
Kim et al 2004	Kim et al., 2004	48.912	-126.89	PNW	Marine sediment
	Kim et al., 2004	22.99	-109.47	SW	Marine sediment
	Kim et al., 2004	34.535	-121.107	SW	Marine sediment
	Kim et al., 2004	41.682	-124.93	PNW	Marine sediment
Kirby et al 2007	Kirby et al 2007	33.37	-117.22	SW	Lake sediment
Kirby et al 2010	Kirby et al 2010	33.37	-117.22	SW	Lake sediment
Kirby et al 2012	Kirby et al 2012	34.253472	-116.920249	SW	Lake sediment
Kirby et al 2014	Kirby et al 2014	34.77	-120.1162	SW	Lake sediment
Kirby et al 2015	Kirby et al 2015	33.37	-117.22	SW	Lake sediment
Kirby et al 2019	Kirby et al 2019	33.6733	-117.3542	SW	Lake sediment
	Kirby et al 2019	33.6734	-117.3641	SW	Lake sediment
Konrad and Clarke, 1998	Konrad and Clarke 1998	37.970176	-119.318354	SW	Lake sediment
	Konrad and Clarke 1998	37.140252	-118.629612	SW	Lake sediment
Lightfoot and Cuthrell 2015	Lightfoot and Cuthrell 2015	37.16305	-122.338183	SW	archeological
Lindstrom, 1990	Lindstrom 1990	38.942579	-120.053067	SW	Tree stump
Long and Whitlock 1998	Long and Whitlock 1998	44.167778	-123.582222	PNW	Lake sediment
Lyle et al., 2012	Lyle et al., 2012	review paper			
Macdonald and Case 2005	Macdonald and Case 2005	34.066667	-116.483333	SW	Tree ring
MacDonald et al., 2016	MacDonald et al 2016	38.3395	-119.4984	SW	Lake sediment

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Malamud-Roam et al 2006	Malamud-Roam et al 2006	37.997233	-122.453821	SW	Marine sediment
Marchitto et al 2010	Marchitto et al., 2010	25.2	-112.7	SW	Marine sediment
Marcott et al., 2013	Marcott et al., 2013	review paper			
Marlon et al., 2006	Marlon et al. 2006	48.168	-114.368	PNW	Lake sediment
	Marlon et al. 2006	44.288	-110.178	PNW	Lake sediment
	Marlon et al. 2006	44.928	-110.358	PNW	Lake sediment
	Marlon et al. 2006	44.668	-110.628	PNW	Lake sediment
	Marlon et al. 2006	45.848	-113.448	PNW	Lake sediment
	Marlon et al. 2006	45.898	-114.268	PNW	Lake sediment
	Marlon et al. 2006	46.328	-114.658	PNW	Lake sediment
	Marlon et al. 2006	45.708	-114.998	PNW	Lake sediment
	Marlon et al. 2006	46.088	-123.908	PNW	Lake sediment
Mayewski et al., 2004	Mayewski et al., 2004	review paper			
McGann 2008	McGann 2008	37.6305	-122.3665	SW	Marine sediment
McGann 2011	McGann 2011	37.223333	-123.243333	SW	Marine sediment
McGann 2015	McGann 2015	36.392167	-123.342	SW	Marine sediment
McQuiod and Hobson 2001	McQuiod and Hobson 2001	48.633333	-123.5	PNW	Marine sediment
Mix et al., 1999	Mix et al 1999	42.117	-125.75	PNW	Marine sediment
	Mix et al 1999	41.682	-124.93	PNW	Marine sediment
Moffitt et al., 2014	Moffitt et al., 2014	34.37	-121.13	SW	Marine sediment
Moffitt et al., 2015	Moffitt et al., 2015	34.37	-121.13	SW	Marine sediment
Mohr et al., 2000	Mohr et al., 2000	41.4	-122.583	PNW	Lake sediment
	Mohr et al., 2000	41.333	-122.55	PNW	Lake sediment
Nederbragt and Thurow 2001	Nederbragt and Thurow 2001	48.59065	-123.503333	PNW	Marine sediment
	Nederbragt and Thurow 2001	48.590617	-123.503417	PNW	Marine sediment
Negrini et al., 2006	Negrini et al., 2006	36.004447	-119.785517	SW	Lake sediment
Oster et al., 2017	Oster et al., 2017	37	-122.1833333	SW	Speleothem
Pellatt et al., 2001	Pellatt et al., 2001	48.59065	-123.503333	PNW	Marine sediment
Platzman and Lund 2019	Platzman and Lund 2019	35.3	-120.05	SW	Lake sediment
Rasmussen et al 2006	Rasmussen et al 2006	32.159	-104.523	SW	Speleothem
Reyes and Clague, 2004	Reyes and Clague 2004	50.75	-123.766667	PNW	Moraine

Rick, 2011	Rick 2011	34.003841	-120.176931	SW	Archeological record
Roark et al 2003	Roark et al 2003	34.2875	-120.036667	SW	Marine sediment
Schimmelmann et al., 2013	Schimmelmann et al., 2013	34.2875	-120.036667	SW	Marine sediment
Shuman et al 2018	Shuman et al 2018	review paper			
Spaulding et al 1991	Spaulding 1990	35.45	-115.1	SW	Terrestrial midden
Steinman et al., 2019	Steinman et al 2019	48.5417	-119.5818	PNW	Lake sediment
	Steinman et al 2019	48.5394	-119.5615	PNW	Lake sediment
Steinman et al., 2016	Steinman et al., 2016	50.82	-116.39	PNW	Lake sediment
Stine 1990	Stine 1990	38.008101	-119.016233	SW	Lake shore
Stine 1994	Stine 1994	37.950538	-119.01395	SW	Tree stump
Taylor et al. 2016	Taylor et al. 2016	40.7	-121.59	PNW	Fire scar
Tomasovych and Kidwell 2017	Tomosovych and Kidwell 2018	33.48	-118.59	SW	Marine sediment
	Tomosovych and Kidwell 2018	32.7555	-117.3617	SW	Marine sediment
Tunnicliffe et al 2001	Tunnicliffe et al 2001	48.59065	-123.503333	PNW	Marine sediment
	Tunnicliffe et al 2001	48.590617	-123.503417	PNW	Marine sediment
van Geen et al 2003	van Geen et al 2003	34.2875	-120.036667	SW	Marine sediment
Viau et al., 2006	Viau et al., 2006	review/modeling paper			
Walsh et al. 2017	Walsh et al. 2017	46.9231	-121.5836	PNW	Lake sediment
	Walsh et al. 2017	46.9198	-121.5886	PNW	Lake sediment
	Walsh et al. 2017	46.9114	-121.6571	PNW	Lake sediment
Whitlock et al 2008	Whitlock et al 2008	41.21	-122.5	PNW	Lake sediment
	Whitlock et al 2008	41.35	-122.56	PNW	Lake sediment
	Whitlock et al 2008	41.4	-122.58	PNW	Lake sediment
	Whitlock et al 2008	42.02	-123.46	PNW	Lake sediment
	Whitlock et al 2008	45.81	-123.57	PNW	Lake sediment
	Whitlock et al 2008	44.16	-123.58	PNW	Lake sediment
	Whitlock et al 2008	46.08	-123.9	PNW	Lake sediment

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Appendix B includes the latitude, longitude, region, and proxy type of all studies used in the coded analysis of previously published records (step 2 of systematic review).

Paper	Latitude	Longitude	Region	Archive	Proxy Type(s)
Addison et al., 2017	40.8656	-124.573	PNW	Marine Sediment	sedimentology, carbon and nitrogen isotopes
Anderson and Byrd 1998	33.291667	-117.34167	SW	Lake Sediment	pollen assemblage
Asmerom et al., 2013	32.163745	-104.51768	SW	Speleothem	sedimentology
Bacon et al 2018	36.542	-117.938	SW	Geomorphology	sedimentology
Bacon et al., 2006	36.441174	-117.97043	SW	Lake Sediment	diatom assemblage, silicoflagellate assemblage
Barron and Anderson 2011	review paper				
Barron and Burky 2007	42.24	-125.89	PNW	Marine Sediment	diatom assemblage, pollen assemblages, alkenones, sedimentology
Barron et al., 2017	40.9	-124.6	PNW	Marine Sediment	diatom assemblage, silicoflagellate assemblage
Barron et al., 2003	42.682	-124.93	PNW	Marine Sediment	diatom assemblage, silicoflagellate assemblage, pollen assemblage
Barron et al., 2010	34.2875	-120.03667	SW	Marine Sediment	
Barron et al., 2019	37.3317	-123.3992	SW	Marine Sediment	
Beatty and Taylor 2009	39.034637	-120.1624	SW	Lake Sediment	charcoal
Beck et al 2018	42.730113	-120.51746	PNW	Lake Sediment	pollen assemblage, oxygen isotopes
Benson et al., 2002	40.073646	-119.5969	PNW	Lake Sediment	sedimentology, pollen assemblages
Bird and Kirby 2006	34.120426	-116.82766	SW	Lake Sediment	sedimentology, ground penetrating radar
Bird et al., 2010	34.121045	-116.82857	SW	Lake Sediment	sedimentology
Braje et al., 2012	34.038578	-120.37907	SW	Archeological record	shell assemblage, plant microfossils, charcoal
Briles et al., 2005	42.025	-123.45833	PNW	Lake Sediment	pollen assemblage, charcoal
Brown and Hebda 2002	48.595278	-124.19733	PNW	Lake Sediment	pollen assemblage, pollen assemblages, carbon isotopes
Byrne et al., 2001	38.098287	-122.02125	SW	Marine Sediment	diatom assemblage
Cannariato and Kennett 1999	34.535	-121.10717	SW	Marine Sediment	foraminiferal assemblage, sedimentology
Cole and Liu 1994	33.956389	-119.97667	SW	Lake Sediment	pollen assemblage, sedimentology, charcoal

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Cole and Wahl 2000	32.929595	-117.25673	SW	Lake Sediment	pollen assemblage, charcoal
Du et al 2018	34.281767	-119.96397	SW	Marine Sediment	sedimentology
Fisler and Hendy 2008	34.2875	-120.03667	SW	Marine Sediment	foraminiferal assemblage
Friddell et al 2003	34.271167	-120.07267	SW	Marine Sediment	oxygen isotopes
Hallett and Anderson 2010	37.9085722 2	-119.2864	SW	Lake Sediment	charcoal, pollen assemblages
Hallett et al., 2003	49.36	-121.46667	PNW	Lake Sediment	charcoal
Kennett et al., 2007	34.2875	-120.03667	SW	Marine Sediment	foraminiferal assemblage, radiocarbon, sedimentology
Kirby et al 2007	33.37	-117.22	SW	Lake Sediment	pollen assemblage, sedimentology
Kirby et al 2010	33.37	-117.22	SW	Lake Sediment	sedimentology
Kirby et al 2014	34.77	-120.1162	SW	Lake Sediment	sedimentology, hydrogen isotopes
Kirby et al 2015	33.37	-117.22	SW	Lake Sediment	sedimentology, hydrogen isotopes
Kirby et al 2019	33.6733	-117.3542	SW	Lake Sediment	sedimentology
Konrad and Clarke, 1998	37.970176	-119.31835	SW	Lake Sediment	lichenometry
Lindstrom, 1990	38.942579	-120.05307	SW	Tree stump	tree stumps
Long and Whitlock 1998	44.167778	-123.58222	PNW	Lake Sediment	charcoal, sedimentology
MacDonald et al., 2016	38.3395	-119.4984	SW	Lake Sediment	sedimentology, carbon and nitrogen isotopes, charcoal, pollen analysis
Malamud-Roam et al 2006	37.997233	-122.45382	SW	Marine Sediment	review
Marchitto et al 2010	25.2	-112.7	SW	Marine Sediment	magnesium/calcium foraminifera
Marlon et al., 2006	48.168	-114.368	PNW	Lake Sediment	charcoal
McGann 2011	37.223333	-123.24333	SW	Marine Sediment	foraminiferal assemblage, sedimentology, oxygen and carbon isotopes
McGann 2015	36.392167	-123.342	SW	Marine Sediment	pollen assemblage
Mix et al., 1999	42.117	-125.75	PNW	Marine Sediment	oxygen isotopes, foraminiferal assemblage
Mohr et al., 2000	41.4	-122.583	PNW	Lake Sediment	charcoal, pollen assemblages
Nederbragt and Thurow 2001	48.59065	-123.50333	PNW	Marine Sediment	sedimentology
Pellatt et al., 2001	48.59065	-123.50333	PNW	Marine Sediment	oxygen isotopes, trace elements
Spaulding et al 1991	35.45	-115.1	SW	Terrestrial Midden	oxygen and carbon isotopes, sedimentology
Steinman et al., 2019	48.5417	-119.5818	PNW	Lake Sediment	oxygen isotopes

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Whitlock et al 2008	44.28	-110.17	PNW	Lake Sediment	charcoal

Appendix C

Appendix C shows the results of coded analysis of previously published records (step 2 of systematic review).

Paper	Latitude	Longitude	Region	Early Fire	Early Temp	Early Hydro	Mid Fire	Mid Temp	Mid Hydro	Late Fire	Late Temp	Late Hydro
Addisson et al 2017	40.8656	-124.573	PNW			dry						
Anderson and Byrd 1998	33.291667	-117.34167	SW			dry			wet			
Asmerom et al 2013	32.163745	-104.51768	SW			dry						
Bacon et al 2018	36.542	-117.938	SW			dry						
Bacon et al., 2006	36.441174	-117.97043	SW			dry						
Barron and Bukry, 2007	42.24	-125.89	PNW		warm	dry		cold				
Barron et al., 2017	40.9	-124.6	PNW			dry		cold			warm	wet
Barron et al., 2003	42.682	-124.93	PNW		warm	dry		cold			warm	wet
Barron et al., 2010	34.2875	-120.03667	SW			dry						
Barron et al., 2019	37.3317	-123.3992	SW		warm	dry		cold			warm	wet
Beatty and Taylor 2009	39.034637	-120.1624	SW	low			high			low	cold	dry
Beck et al 2018	42.730113	-120.51746	PNW			wet						
Benson et al 2002	40.073646	-119.5969	PNW			wet		warm	dry			wet
Bird & Kirby 2006	34.120426	-116.82766	SW			wet						
Bird et al., 2010	34.121045	-116.82857	SW			wet						
Braje et al 2012	34.038578	-120.37907	SW			wet						
Briles et al., 2005	42.025	-123.45833	PNW		warm	wet				high	cold	dry
Brown and Hebda 2002	48.595278	-124.19733	PNW		high	wet	low			low/high	cold	dry

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Paper	Latitude	Longitude	Region	Early Fire	Early Temp	Early Hydro	Mid Fire	Mid Temp	Mid Hydro	Late Fire	Late Temp	Late Hydro
Byrne et al., 2001	38.098287	-122.02125	SW			wet						
Cannariato and Kennett 1999	34.535	-121.10717	SW			wet						
Cole and Liu 1994	33.956389	-119.97667	SW			wet			dry			wet
Cole and Wahl 2000	32.929595	-117.25673	SW			wet						
Du et al., 2018	34.281767	-119.96397	SW						wet			
Fisler and Hendy 2008	34.2875	-120.03667	SW		cold			warm				wet
Friddell et al 2003	34.271167	-120.07267	SW		cold			warm				wet
Hallett and Anderson 2010	37.90857222	-119.2864	SW	low			high	warm	dry	high	cold	dry
Hallett et al., 2003	49.36	-121.46667	PNW	high	warm				wet		cold	dry
Kennett et al., 2007	34.2875	-120.03667	SW					warm	dry			wet
Kirby et al 2007	33.37	-117.22	SW						dry			wet
Kirby et al 2010	33.37	-117.22	SW						dry			wet
Kirby et al 2014	34.77	-120.1162	SW						dry			wet
Kirby et al 2015	33.37	-117.22	SW						dry			
Kirby et al 2019	33.6733	-117.3542	SW						wet			
Konrad and Clarke 1998	37.970176	-119.31835	SW						wet			
Lindstrom 1990	38.942579	-120.05307	SW						dry			

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Paper	Latitude	Longitude	Region	Early Fire	Early Temp	Early Hydro	Mid Fire	Mid Temp	Mid Hydro	Late Fire	Late Temp	Late Hydro
Long and Whitlock 1998	44.167778	-123.58222	PNW	high	warm		low	cold	wet	low	cold	dry
MacDonald et al 2016	38.3395	-119.4984	SW					warm	dry			wet
Malamud-Roam et al 2006	37.997233	-122.45382	SW					cold	wet		cold	
Marchitto et al., 2010	25.2	-112.7	SW		cold			cold				
Marlon et al. 2006	48.168	-114.368	PNW	low	warm		high	cold	wet	high	cold	dry
McGann 2011	37.223333	-123.24333	SW		warm			warm	dry		warm	wet
McGann 2015	36.392167	-123.342	SW		warm				dry			wet
Mix et al 1999	42.117	-125.75	PNW		warm			cold			warm	wet
Mohr et al., 2000	41.4	-122.583	PNW	low	warm		high	cold	wet	high	cold	dry
Nederbragt and Thurow 2001	48.59065	-123.50333	PNW						wet			
Pellatt et al., 2001	48.59065	-123.50333	PNW		warm							
Spaulding 1990	35.45	-115.1	SW						dry			
Steinman et al 2019	48.5417	-119.5818	PNW						wet	high	cold	dry
Whitlock et al 2008	44.28	-110.17	PNW	low				cold	wet	high	cold	dry

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Appendix D

Appendix D contains the data accessed for time series plots (Figs. 4, 5).

Paper	Latitude	Longitude	Region	Archive	Figure Number	Accessed From	Link
Addisson et al 2017	40.8656	-124.573	PNW	Marine sediment	4	NOAA Paleoclimate Database	https://www.ncdc.noaa.gov/paleo-search/study/21650
Barron et al 2003	42.682	-124.93	PNW	Marine sediment	4	NOAA Paleoclimate Database	https://www.ncdc.noaa.gov/paleo-search/study/5867
Braje et al 2012	34.038578	-120.37907	SW	Archaeological Record	5	In original paper: Table 1	https://www.sciencedirect.com/science/article/abs/pii/S1040618211005301
Kennett et al., 2007	34.2875	-120.036667	SW	Marine sediment	5	Author webpage	http://php.scripts.psu.edu/dept/liberalarts/sites/kennett/data.php
Kirby et al 2015	33.37	-117.22	SW	Lake sediment	5	NOAA Paleoclimate Database	https://www.ncdc.noaa.gov/paleo-search/study/20106
Long and Whitlock 1998	44.167778	-123.582222	PNW	Lake sediment	4	NOAA Paleoclimate Database	https://www.ncdc.noaa.gov/paleo-search/study/2252
MacDonald et al 2016	38.3395	-119.4984	SW	Lake sediment	5	Harvard Dataverse	https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/P3MCFX
McGann 2015	36.392167	-123.342	SW	Marine sediment	5	In original paper: Table 2	https://www.sciencedirect.com/science/article/pii/S1040618215000610?casa_token=PAo4SBfUSPMAAAAA:g2YzlQACCS_MKrtKGcIN8PbTF0vc44mFxqyNfO_1ojeGltRavFpodrSo1aT7mUaM_KuPUM3aupM
Steinman et al 2016	50.82	-116.39	PNW	Lake sediment	4	NOAA Paleoclimate Database	https://www.ncdc.noaa.gov/paleo-search/study/21250

Data Availability

Data generated for this manuscript is included in the Appendices.

Author Contributions

HMP and TMH conceptualized and designed the project. All authors completed data curation and literature review. HMP conducted data analysis and wrote the manuscript. All authors contributed to editing of the manuscript.

Competing Interests

The authors declare that they have no conflict of interest.

Acknowledgements

We acknowledge National Science Foundation SF support to T. Hill (NSF OCE 1832812), and the UC Davis Dissertation Year Fellowship for support to H. Palmer. We acknowledge all members of the UC Davis Geology Oceans and Climate Change Course (GEL 232) in Spring 2018 for their contributions to initial data gathering and framing of this project. Finally, we acknowledge that this paper includes histories and discussion of Indigenous peoples of Western North America (Turtle Island) who have stewarded the land and sea for millennia. We aim to document the broad histories of interactions between people and environment, but we acknowledge that this record is incomplete due to the erasure of Indigenous histories and oral traditions, genocide of knowledge keepers, and destruction of cultural artifacts. We acknowledge the keepers of intergenerational Indigenous knowledge who maintain stories and data of the human, ecosystem, and climate impacts of settler colonization described here. We do not attempt to name all tribes whose ancestral and present homelands make up this study area, but we acknowledge that the majority of the geographic area covered here represents unceded land of Indigenous tribes and that data used here from previously published studies may have been acquired without consent from Indigenous peoples. We direct readers to the open-source resource: nativelands.ca to identify the homelands of the diverse Indigenous people of this region and encourage readers to use this resource as a starting place to learn about the land and marine stewardship of Indigenous peoples past and present.

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