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A Holocene record of ocean productivity and upwelling from the northern California continental slope

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ABSTRACT

The Holocene upwelling history of the northern California continental slope is examined using the high-resolution record of TN062-O550 (40.9°N, 124.6°W, 550 m water depth). This 7-m-long marine sediment core spans the last ~7500 years, and we use it to test the hypothesis that marine productivity in the California Current System (CCS) driven by coastal upwelling has co-varied with Holocene millennial-scale warm intervals. A combination of biogenic sediment concentrations (opal, total organic C, and total N), stable isotopes (organic matter δ^{13}C and bulk sedimentary δ^{15}N), and key microfossil indicators of upwelling were used to test this hypothesis. The record of biogenic accumulation in TN062-O550 shows considerable Holocene variability despite being located within 50 km of the mouth of the Eel River, which is one of the largest sources of terrigenous sediment to the Northeast Pacific Ocean margin. A key time interval beginning at ~2900 calibrated years before present (cal yr BP) indicates the onset of modern upwelling in the CCS, and this period also corresponds to the most intense period of upwelling in the last 7500 years. When these results are placed into a regional CCS context during the Holocene, it was found that the timing of upwelling intensification at TN062-O550 corresponds closely to that seen at nearby ODP Site 1019, as well as in the Santa Barbara Basin of southern California. Other CCS records with less refined age control show similar results, which suggest late Holocene upwelling intensification may be synchronous throughout the CCS. Based on the strong correspondence between the alkenone sea surface temperature record at ODP Site 1019 and the onset of late Holocene upwelling in northern California, we suggest that CCS warming may be conducive to upwelling intensification, though future changes are unclear as the mechanisms forcing SST variability may differ.

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1. Introduction

Wind-driven coastal upwelling is an important feature of most eastern boundary currents that profoundly affects the physical and biological environment in these regions. Many of the world's major fisheries resources rely on upwelling which provides nutrients crucial to maintain high biological productivity (Pauly and Christensen, 1995), making understanding the response of upwelling to future climate change critical. Several recent studies discuss the complexities of predicting the future of these regions under potential climatic scenarios, sometimes with conflicting results. A meta-analysis literature review of modern upwelling changes by Sydeman et al. (2014) reveals a preponderance of studies indicate an intensification of upwelling affecting the California, Benguela, and Humboldt regions for at least the last 60 years. On the other hand, weakening of upwelling conditions is indicated along the Iberian margin, and inconclusive changes are associated with the Canary upwelling system. This contrasts with the results of Wang et al. (2015), who used an ensemble of CMIP5 climate model experiments designed to predict changes in future upwelling as a function of land-sea temperature differences between 1950 CE and 2099. Their results show high likelihoods of

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upwelling intensification occurring in the Canary, Humboldt, and Benguela regions, while the California upwelling system exhibits greater potential variability. A recent paper by Rykaczewski et al. (2015) argues instead that projected poleward migration of the major atmospheric high-pressure cells will be responsible for changes in the major upwelling zones, and that relative to an 1861 CE–1890 base period, upwelling projections for 2071 CE–2100 suggest intensified summer upwelling in the Canary and Humboldt systems, equivocal change in the Benguela region, and a reduction in upwelling for the California system.

Because of these strongly conflicting predictions, independent analyses of the response of past upwelling to changes in climate boundary conditions are needed. Paleoceanographic studies of upwelling under past climatic states, particularly those associated with past warm intervals, can therefore offer insight into these dynamic settings. In this study, we present new geochemical evidence of phytoplankton productivity from marine sediment core TN062-O550 which covers the last ~7500 years. When paired with the microfossil analysis of Barron et al. (this issue), these data will be examined to reconstruct past upwelling along the northern California margin, and to test our hypothesis that Holocene warm intervals were associated with higher upwelling intensity.

1.1. Modern upwelling along the California margin

The California Current System (CCS) is one of the world's most studied upwelling regions, and is considered a high-value resource for many reasons, including (i) surface primary productivity (Hayward and Venrick, 1998); (ii) marine biodiversity (Block et al., 2011); (iii) marine mammal aggregations (e.g., Croll et al., 2005); and (iv) commercial catch value (>$250 million USD in 2013; California Department of Fish and Game (2014)). As summarized by Gangopadhyay et al. (2011) and references therein, the generalized oceanography of the CCS includes the equatorward-flowing California Current which contains a low-salinity core located at ~160 m depth and 500 km offshore, the seasonal surface California Inshore Countercurrent (also called the Davidson Current) that is commonly within 150 km of the coast, and the oxygen-deficient California Undercurrent at ~250 m depth (Lynn and Simpson, 1987). Other distinct features include upwelling in the coastal transition zone (see below), mesoscale eddies, jets, and filaments along frontal structures. Further offshore, anticyclonic wind-stress curl causes Ekman convergence and oceanic upwelling in the eastern portion of the Subtropical North Pacific Gyre (Bakun and Nelson, 1991).

Throughout much of the CCS, the coastal upwelling cell extends between ~24 and 48°N latitude along a narrow band ~250 km offshore from the coast (Fig. 1). In the northern California area, the upwelling zone has a strong seasonality, with upwelling occurring predominantly between May and August (Fig. 1c) as a direct consequence of the cyclonic wind-stress curl that dominates the nearshore California margin (Bakun and Nelson, 1991). A recent compilation of oceanographic properties related to CCS upwelling shows a demarcation in behavior at ~34°N latitude (Carr and Kearns, 2003). To the north of this latitude, the outer continental shelf is quite narrow (<50 km), spring and summer offshore Ekman transport exceeds the autumn and winter transport by between 100 and 500%, and satellite SeaWiFS estimates of chlorophyll concentrations suggest higher productivity during the spring and summer months. To the south of ~34°N latitude (the California Bight region), the outer shelf commonly exceeds 125 km width, there is little seasonal variability in Ekman transport, and chlorophyll concentrations peak only in the spring.

1.2. Paleoceanographic studies of the California margin

While several previous studies have focused on reconstructing the paleoceanographic history of the California margin, the

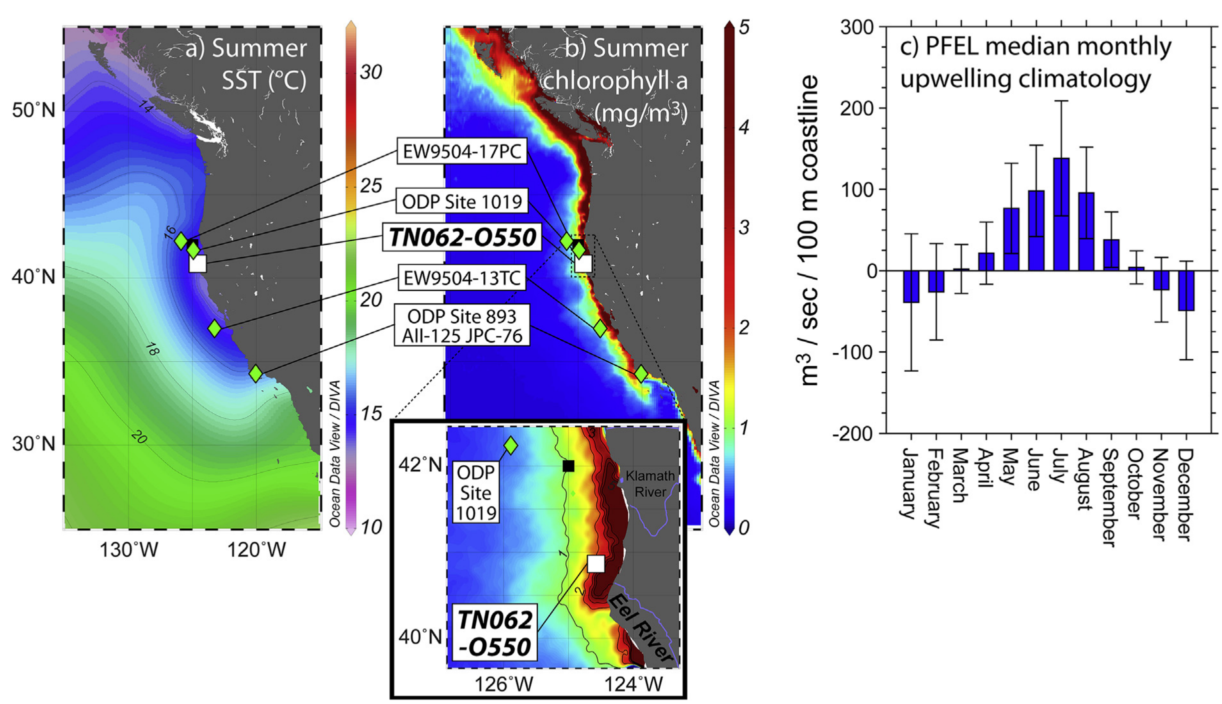

Fig. 1. Location map of TN062-O550 and other sites mentioned in the text plotted on: (a) summer climatological mean SST from the World Ocean Atlas 2009 (Locarnini et al., 2010); and (b) SeaWiFS chlorophyll *a* mean summer (JAS) productivity for the period 1997–2010 (OCI algorithm; Hu et al., 2012). (c) Climatological median monthly NOAA PFEL upwelling index (Schwing et al., 1996) for the period 1946–2016 calculated at 42°N, 125°W (black square on frames a and b). Error bars represent the 1-sigma standard deviation of observations. Negative values indicate downwelling. Frames a and b plotted using Ocean Data View (Schlitzer, 2015). SeaWiFS chlorophyll *a* data extracted using SeaDAS v.7.3.1 (NASA Ocean Biology Group, 2012).