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# High resolution sedimentary record of dinoflagellate cysts reflects decadal variability and 20th century warming in the Santa Barbara Basin

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ABSTRACT

We present a continuous record of dinoflagellate cysts from a core of laminated sediments collected in the Santa Barbara Basin (SBB), off Southern California. The core spans the last ~260 years and is analysed at biennial (two-year) resolution. Variations in dinoflagellate cyst assemblages are compared with 20th century historical changes, and are used to examine changes in primary productivity and species composition, which are bound to the variability in upwelling and sea-surface temperature (SST) in the region.

Cysts produced by heterotrophic dinoflagellates dominate the assemblages. In particular, *Brigantedinium* spp. (on average 64.2% of the assemblages) are commonly associated with high levels of primary productivity, typically observed under active upwelling conditions, when nutrient supply is higher. Other heterotrophic taxa such as cysts of *Protoperidinium americanum*, *Protoperidinium fukuyoi*, *Protoperidinium minutum* and *Archaeperidinium saanichi*, all *Echinidinium* species, *Quinquecuspis concreta* and *Selenopemphix undulata* are more abundant in the early part of the record (~1750s–1870s). These taxa are generally associated with high primary productivity and are observed predominantly during intervals marked by relatively variable conditions of SST, stratification and nutrient loading. The 20th century is marked by an increase in several species of autotrophic affinity, primarily *Lingulodinium machaerophorum* and *Spiniferites ramosus*. In recent surface sediments from the region, these species are more abundant in the Southern California Bight, and they are associated with conditions of relaxed upwelling in the SBB (typically observed during summer and fall), when SST is higher and nutrient supply is moderate. Their increasing concentrations since the early 20th century reflect warmer SST and possibly stronger stratification during the warmest season. Taken together, the changes in cyst assemblages provide further evidence that persistently warmer conditions in the SBB began affecting marine populations by the late 1920s.

Decadal-scale variations in primary productivity are encoded in the heterotrophic dinoflagellate cyst record, with higher (lower) concentrations of heterotrophic taxa occurring during “cool” (“warm”) phases of the Pacific Decadal Oscillation (PDO) index. Wavelet analysis of heterotrophic taxa concentrations suggests a weaker influence of the PDO on biota of the region during the 19th century.



## 1. Introduction

Documenting past climate variability, and the response of organisms to variability, is a key to understanding recent changes observed in oceanic surface conditions and marine pelagic ecosystems. In the California Current System (CCS), instrumental measurements of sea-surface temperature since the early 20th century show large interannual variations associated with the El Niño-Southern Oscillation phenomenon (e.g., Enfield, 1989; McGowan et al., 1998) and decadal-scale fluctuations characterized by the Pacific Decadal Oscillation (Mantua et al., 1997). These fluctuations are superimposed on a warming trend of surface waters over the past several decades that appears to be part of the increase in oceanic heat content (e.g., McGowan et al., 1998; Levitus

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et al., 2001; Field et al., 2006a; Smith et al., 2008). Monitoring of marine populations through the California Cooperative Oceanic Fisheries Investigations program since the 1950s (CalCOFI; www.calcofi.org) reveals a shifting composition in many zooplankton and higher trophic levels, with notable declines in many important species and increases in others (e.g., Roemmich and McGowan, 1995; Veit et al., 1996; Hare and Mantua, 2000; Lavaniegos and Ohman, 2003; McGowan et al., 2003). While the mechanisms underlying such changes in the pelagic ecosystem are still under debate (Hsieh et al., 2005; Overland et al., 2010; McClatchie, 2012), several studies suggest that changes in marine populations in the CCS can be attributed to phytoplankton dynamics that respond to changes in environmental and climatic conditions (e.g., Trenberth and Hurrell, 1994; Mantua et al., 1997; McGowan et al., 1998, 2003; Hendy and Kennett, 1999; Pospelova et al., 2008). In particular, variations in the cyclonic activity of the Aleutian Low pressure system are inferred to affect primary productivity in the CCS by modulating the strength of coastal upwelling, horizontal transport of nutrient-rich waters from the north, as well as through increased stratification due to warming (e.g., McGowan et al., 2003).

The Santa Barbara Basin (SBB) sediments form a continuous, high resolution record of recent climatic fluctuations over most of the Holocene (e.g., Behl and Kennett, 1996; Pospelova et al., 2006; Fisler and Hendy, 2008). Many studies have shown that the SBB laminated sediments are particularly effective in preserving annual climatic signals inferred from proxy evidence (e.g., Emery, 1960; Soutar and Crill, 1977; Field et al., 2006b; Barron et al., 2013).

However, less work has been done with dinoflagellate cysts than many other taxa at interannual timescales, even though dinoflagellates are one of the major groups of marine phytoplankton in terms of diversity and biomass (e.g., Taylor, 1987). While some studies have looked at variations in some cyst species in parts of the 20th century (Mudie et al., 2002; Prauss, 2002), none have compared 20th century variations with prior variations.

About half of the known dinoflagellate species are autotrophic and contribute directly to primary productivity (Dale, 1996; Jacobson and Anderson, 1996). The other half are heterotrophic and feed mainly on diatoms and smaller flagellates, although some dinoflagellates are mixotrophic (e.g., Jacobson and Anderson, 1996). The life cycle of many dinoflagellates includes a resting cyst stage (e.g., Taylor, 1987). The wall of most dinoflagellate cysts is made of organic polymers highly resistant to physical, chemical and biological degradations (e.g., Versteegh and Blokker, 2004). Even though some species might be affected by aerobic degradation during early diagenesis (e.g., Zonneveld et al., 2007, 2008), the low oxygen content of SBB laminated sediments fosters excellent preservation of dinoflagellate cysts. Globally, the cyst assemblages are influenced primarily by sea-surface conditions such as temperature, salinity, duration of sea-ice cover and productivity (e.g., Dale, 1996; de Vernal et al., 2001; de Vernal and Marret, 2007). In the northeastern (NE) Pacific, primary productivity and sea-surface temperature have been identified as the main factors controlling cyst distribution in surface sediments (e.g., Radi and de Vernal, 2004, 2008; Radi et al., 2007; Pospelova et al., 2008). Furthermore, recent sediment trap studies in the region have revealed the potential of cysts produced by heterotrophic dinoflagellates (particularly from the family Protoperidiniaceae) to reflect variations in primary production in sedimentary records, having a particularly good relationship with diatoms (Pospelova et al., 2010; Price and Pospelova, 2011; Bringué et al., 2013).

This study investigates the response of dinoflagellate cysts and primary productivity to natural variability and warming in the CCS. We reconstruct past variations in the dinoflagellate assemblage in the SBB at biennial resolution over the last ~260 years, which permits for the first time a good comparison of 20th century variations with prior centuries. Dinoflagellate cysts are known to respond to changes in SST and stratification, and reflect primary productivity changes bound to upwelling dynamics. In addition, comparing the response of dinoflagellate cysts and other phytoplankton groups to climatic variations sheds additional light on phytoplankton dynamics in the region.

## 2. Environmental settings

The Santa Barbara Basin is a ~100 km long, 40 km wide and 590 m deep basin located off the coast of Southern California, bound to the south by the Northern Channel Islands (Fig. 1A). The largest river emptying in the basin is the Santa Clara River, whose catchment drains ~4200 km$^2$ (Downs et al., 2013). Deep water circulation is restricted by two sills at ~475 m depth to the west and 230 m the east (Emery, 1960). High sedimentation rates and oxygen depletion below sill depth foster the preservation of laminated sediments in the central part of the basin (e.g., Soutar and Crill, 1977).

Recent Santa Barbara Basin sediment histories and chronologies have been addressed by many studies (Soutar and Crill, 1977; Schimmelmann et al., 1990, 2006; Grimm et al., 1996). Varve thickness is around 2 mm yr$^{-1}$ but can vary by up to 1 mm. Both studies of sediment constituency and cross correlation with local precipitation records over the last century provides clear evidence for an influence of both marine and terrestrial inputs on sedimentation rates, as well as both homogenous and instantaneous deposits (Soutar and Crill, 1977; Schimmelmann et al., 1990, 2006; Grimm et al., 1996). Differences in chronology between investigators are generally 1–2 years in the last 100 years and 3–5 years over the last 200 years. While there is no clear evidence for a change in the sedimentation pattern at 1900, varves are generally better preserved in the 20th century. Thus caution should be used when comparing SBB records with records from different study sites or different chronologies within the SBB. However, studies using the same chronologies based on varve identification provide a highly accurate comparison between records.

The SBB lies within the California Current System (CCS) which includes the California Current, the Davidson Current and the California Undercurrent (Fig. 1B) (e.g., Hickey, 1998). The southward flowing California Current (CC) carries relatively cold, nutrient- and oxygen-rich subarctic waters from Vancouver Island to Baja California (Hickey, 1998). The combination of the geostrophic flow of the CC and upwelling-favourable winds results in a shallow thermocline and high productivity year round. South of Point Conception, a portion of the California Current turns shoreward and then northward to form the Southern California Countercurrent (SCC). The California Undercurrent (CU) transports warmer, saline, phosphate-rich and oxygen-poor water over the continental slope, from the Baja Peninsula to the coast of British Columbia (Hickey, 1998). During fall and winter, the Davidson Current flows northward over the continental shelf and slope from Point Conception to Vancouver Island (Hickey, 1998).

Surface circulation patterns around the SBB are coupled to large-scale processes (influences of the CCS and North Pacific) that enhance the ability of organisms to reflect climate change (e.g., Venrick et al., 2006). Circulation is generally cyclonic but with times of year being more dominated by northerly or southeasterly flow (Harms and Winant, 1998). In spring and summer (and during La Niña years or negative PDO years), upwelling conditions prevail and colder, nutrient-rich water freshly upwelled north of Point Conception enters the basin from the west, often bringing species associated with higher productivity and/or cooler water masses. In winter (or El Niño years or positive PDO years), northerly winds weaken, the poleward flow is enhanced and the SCC and CU bring