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Modern sea surface productivity and temperature estimations off Chile as detected by coccolith accumulation rates

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ABSTRACT

Recent coccoliths from 74 surface sediment samples recovered from the southeastern Pacific off Chile were examined quantitatively to investigate modern regional gradients of sea surface productivity and temperature. All findings are based on coccolith accumulation rates. Therefore an approach was designed to estimate recent sedimentation rates based on ^{210}Pb and bulk chemistry analyses of the same set of surface samples. Highest total coccolith accumulation rates were found off north-central Chile, where seasonal upwelling takes place. Based on a multiple linear regression between calculated coccolith accumulation rates and World Ocean Atlas derived sea surface temperatures, a calibration model to reconstruct annual average temperatures of the uppermost 75 m of the water column is provided. The model was cross-validated and the SST estimates were compared with SST observed and SST estimates based on diatoms and planktonic foraminifera, showing a good correlation.

1. Introduction

Coccolithophores, one of the main open ocean primary producers, are widely distributed in the sedimentary record as microfossils, which makes them an outstanding biostratigraphical group and gives them potential for paleontological study of ecosystem response to global change. As a basic requisite for their application as paleoceanographic proxies it is necessary to maximize the retrieval of paleoecological information from coccolithophore species, and to enhance the understanding of their ecology as a plankton group. Knowing how the present-day environment influences their spatial and temporal distributions, we could use the fossil record of such organisms to reconstruct the state and variation of past environments (Kucera et al., 2005).

One of the modern ocean's most productive upwelling conditions occurs all along the Chilean margin (Strub et al., 1998; Abrantes et al., 2007). In coastal upwelling domains, the dominant primary producers are diatoms, although coccolithophores are also significant contributors to the total phytoplankton community (e.g., Mitchell-Innes and Winter, 1987; Giraudeau et al., 2000; Boeckel and Baumann, 2004). However, there are very few modern studies on coccolithophore ecology and calibration to climate proxies in the Southeast (SE) Pacific, and most of them are based on plankton samples (e.g., Beaufort et al., 2007, 2008, 2011) or on sediment trap samples (e.g., González et al., 2004; Köbrich, 2008). So far, only a small number of surface sediment studies were performed by Saavedra-Pellitero et al. (i.e., 2010, 2011). In such studies the ecological optima of the most important species of coccolithophores in the Pacific sector was studied in order to produce feasible transfer functions to reconstruct climate changes in the past. In this work the focus was on coccolithophore surface sediment assemblages since they represent the former living communities and with that, the overlying surface water conditions (Andruleit et al., 2004). While relative abundances indicate dominance of a certain ecological habitat, absolute fluxes represent more realistic living conditions in the water column, thus providing a more detailed reconstruction of hydrography (Ravelo et al., 1990). Coccolith accumulation rate (CAR) data could furthermore complement and in some cases improve upon the relative abundance data, whereas also comparing with modern flux estimates derived from sediment trap studies.

The estimation of past environmental parameters using micropaleontological data has became a very useful tool from the development of statistical transfer function techniques (IKM — Imbrie and Kipp Method) in which the authors originally used planktonic foraminifera assemblages (Imbrie and Kipp, 1971; Klovan and Imbrie, 1971). It provides quantitative estimations of hydrographical parameters (e.g., sea surface temperature, SST) preserved in the recent sedimentary record (e.g., CLIMAP, 1976, 1981; Ortiz and Mix, 1997; Pisias et al., 1997; Mix et al., 1999; Kucera et al., 2005; Morey et al., 2005; Abrantes et al., 2007). Different statistical techniques were already applied to coccolith census counts from surface sediments of the North and Equatorial Pacific (Geitzenauer et al., 1977; Roth and Coulbourn, 1982; Roth, 1994), of the North Atlantic (Geitzenauer et al., 1977) as well as of the Benguela upwelling system (Giraudeau and Rogers, 1994). However the different sample coverage and the different taxonomies (of traditional broad

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species) as well as the exclusion of species in some of those investigations prevented any transfer function to be properly defined. Consequently, a well established calibration of modern coccolithophore assemblages to surface mixed-layer temperatures has only been previously achieved at a few locations. These were performed at the Benguela and the Peru–Chile upwelling systems (Giraudeau and Rogers, 1994; Saavedra-Pellitero et al., 2010, 2011) and differ from ours by being based on species relative abundances. The main goal of the present study was to investigate whether the modern regional gradients of sea surface productivity and temperature can be detected by studying (a) coccolith accumulation rates and (b) coccolithophore derived temperature estimates.

1.1. Regional setting

The SE Pacific is dominated by the Peru–Chile current system (Strub et al., 1998), one of the most productive eastern boundary systems in the world. Off southern Chile, cool waters from the Antarctic Circumpolar Current reach the continent and split in two branches, the southward-flowing Cape Horn Current and the northward-flowing Peru Current (Fig. 1A). Coastal upwelling, driven by persistent southerly winds along the coast brings cold and nutrient-rich waters to the sea surface along the coast of Chile and Peru towards the equator (Wyrtki, 1981; Bryden and Brady, 1985; Strub et al., 1998). Phytoplankton biomass is high throughout the year in this coastal upwelling system (Rojas de Mendiola, 1981). However, from 15°S to 30°S, minimum chlorophyll seasonality offshore Chile is observed, despite strong seasonality in wind forcing between 20°S and 30°S. South of this area, chlorophyll reaches maxima during austral summer and minima in austral winter, in phase with the seasonal wind forcing (Thomas et al., 2004).

Precipitation patterns in Chile, the most important climate factor driving continental erosion, show one of the most pronounced latitudinal gradients on Earth (Kaiser, 2005; Hebbeln et al., 2007). Rainfall rates rapidly increase from almost zero in the hyper-arid Atacama Desert (north of 27°S) over intermediate precipitation in the semi-arid Mediterranean-type climate of central Chile (from 31°S to 37°S) to year round humid conditions with extraordinary high annual precipitation south of 42°S (Miller, 1976; New et al., 2002). Major atmospheric circulation patterns, specifically the SE Pacific anticyclone in the north and the rain-bearing Southern Westerlies in the south, are responsible for this marked N–S gradient along Chile (Hebbeln et al., 2007, see Fig. 1B). However, expected differences in mass accumulation rates along the Chilean continental margin depend not only on the different hydrological regimes, but also on the topography of margin and on the latitudinal variability of primary productivity and upwelling (Muñoz et al., 2004).

2. Material and methods

For this study we considered 74 out of 106 surface sediment samples located from 22.80°S to 44.28°S and from 70.49°W to 75.86°W offshore Chile. Previous studies (Saavedra-Pellitero et al., 2010, 2011) allowed us to select the best preserved samples and to exclude the samples where coccoliths were poorly preserved. The uppermost centimeter from the undisturbed surface sediment samples (boxcores and multicores) has been used for the analyses reported here. They were retrieved during Genesis III Cruise, RR9702A onboard the American R/V Roger Revelle and during R/V SONNE Cruise SO-156 Valparaiso–Talcahuano (Hebbeln and cruise participants, 2001) onboard the German R/V SONNE.

2.1. Coccolith counts and estimations of CARs

Coccolith absolute abundance counts were already available from a previous study (Saavedra-Pellitero et al., 2010) although only relative abundances were published in that paper. Slides for coccolith counts were prepared using the standard settling methodology of Flores and Sierro (1997). Coccolith identification was done using a Leica DMRXE and a Nikon Eclipse 80i polarized microscopes at a magnification of ×1000, occasionally ×1250. In order to ensure statistical reliability a minimum of 400 coccoliths per sample were counted. This procedure

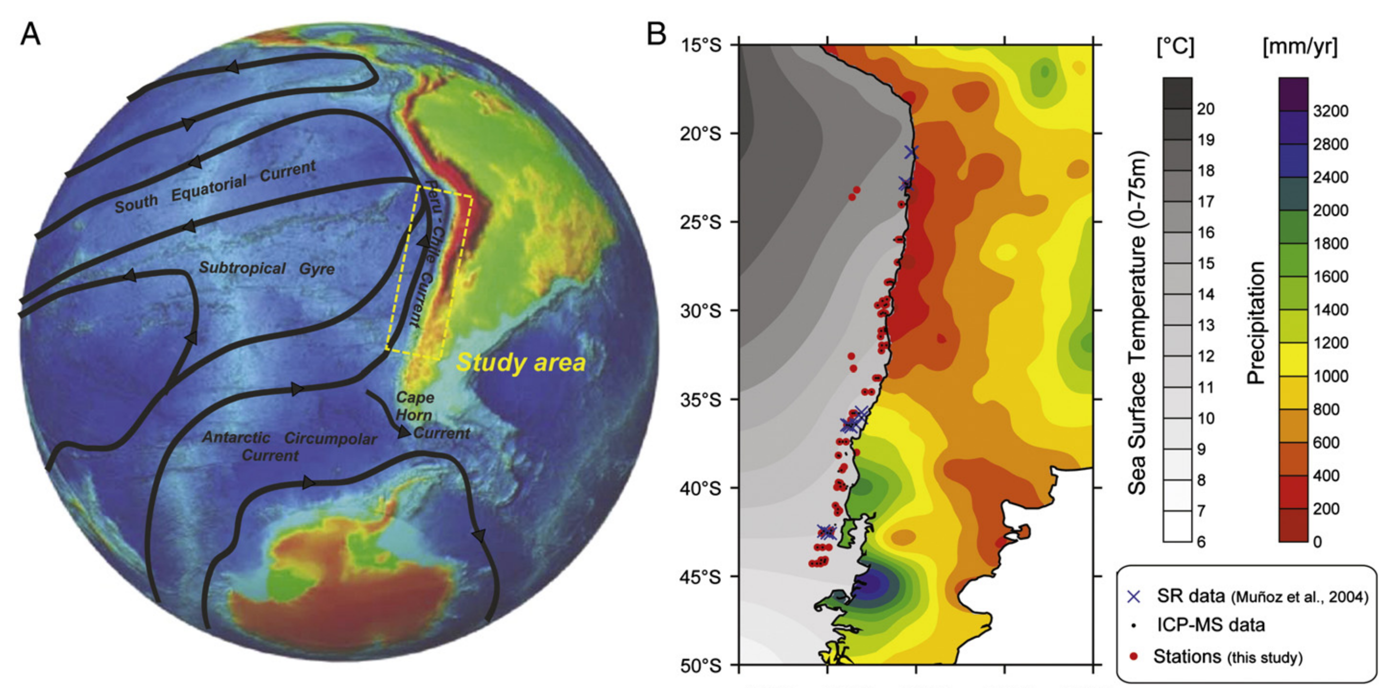

Fig. 1. A. Map of the Pacific and adjacent areas showing major surface currents (after Tomczak and Godfrey, 2003; modified from Lamy and Kaiser, 2009). The study area has been indicated with yellow rectangle. B. Sea surface temperature (SST in °C, Locarnini et al., 2006) expressed as an annual average from 0 m to 75 m water depth and annual mean precipitation (mm/yr) over parts of South America in 2000 (Beck et al., 2005). The location of the sampling stations offshore Chile corresponding to recent sedimentation (SR) data available based on ^{210}Pb (Muñoz et al., 2004) is indicated with blue crosses, the sampling stations corresponding to ICP-MS measurements (Stuut et al., 2007) with black dots, and the 74 sea surface sediment samples used in this study with red dots.