Progress in Oceanography 151 (2017) 38–48

Contents lists available at ScienceDirect

Progress in Oceanography

journal homepage: www.elsevier.com/locate/pocean

Water-column cooling and sea surface salinity increase in the upwelling region off central-south Chile driven by a poleward displacement of the South Pacific High

Wolfgang Schneider [a,b,*], David Donoso [c], José Garcés-Vargas [d], Rubén Escribano [a,b]

[a] Departamento de Oceanografía, Universidad de Concepción, Campus Concepción, Víctor Lamas 1290, Casilla 160-C, código postal: 4070043 Concepción, Chile
[b] Millennium Institute of Oceanography (IMO), University of Concepcion, P.O. Box 1313, Concepcion 3, Chile
[c] Departamento de Geofísica, Universidad de Concepción, Campus Concepción, Víctor Lamas 1290, Casilla 160-C, código postal: 4070043 Concepción, Chile
[d] Instituto de Ciencias Marinas y Limnológicas, Facultad de Ciencias, y Centro FONDAP de Investigación en Dinámica de Ecosistemas Marinos de Altas Latitudes (IDEAL), Universidad Austral de Chile, Avenida Rector Eduardo Morales, Edificio Emilio Pugín, Valdivia, código postal 5090000, Chile

ARTICLE INFO

Article history:
Received 15 February 2016
Received in revised form 19 October 2016
Accepted 16 November 2016
Available online 27 November 2016

Keywords:
Coastal upwelling
South Pacific High
Climate variability
Eastern South Pacific

ABSTRACT

Here we present results of direct observations of seawater temperature and salinity over the continental shelf off central-south Chile that shows an unprecedented cooling of the entire water column and an increase in upper layer salinity during 2002 to 2013. We provide evidence that this phenomenon is related to the intensification but mostly to a recent southward displacement of the South Pacific High over the same period, from 2007 on. This in turn has accelerated alongshore, equatorward, subtropical coastal upwelling favorable winds, particularly during winter, injecting colder water from below into the upper water column. Consequently, the environmental conditions on the shelf off central-south Chile shifted from a warmer (fresher) to a cooler (saltier) phase; water column temperature dropped from 11.7 °C (2003–2006) to 11.3 °C (2007–2012) and upper layer salinity rose by 0.25; water column stratification gradually decreased. The biological impacts of such abrupt cooling are apparently already happening in this coastal ecosystem, as recent evidence shows substantial changes in the plankton community and negative trends in zooplankton biomass over the same period.

1. Introduction

Sea surface temperature (SST) and the temperature of the upper ocean are controlled by the heat flux through the ocean surface, namely insolation, outgoing and incoming infrared radiation, sensible heat flux, latent heat flux and advection, including upwelling (Stewart, 2002). The concentration of greenhouse gases, mainly carbon dioxide, has increased during the last 100 years with accelerating increase during the last 50 years (IPCC, 2007), hereby altering the absorption and emission of infrared radiation of the atmosphere. As a result, global land and ocean surface temperature warmed by 0.85 [0.65–1.06 (lower and upper 95% confidence bounds)] °C over the period 1880–2012 (IPCC, 2014; Trenberth and Fasullo, 2013). These trends in global SST, however, were not uniform throughout the oceans (Fyfe and Gillett, 2014; England et al., 2014; Kosaka and Xie, 2013). SST warming was observed in most of the Atlantic and Indian oceans, and the Western Pacific Ocean, whereas the Central Tropical and the Eastern Pacific Ocean exhibited a cooling trend. The pattern of observed SST trends in the tropical Pacific were reproduced, when forcing a global ocean model with the observed 1992–2011 Pacific wind trend anomalies (England et al., 2014). The cause of the cooling in the subtropical eastern South Pacific Ocean, however, has remained unclear. Subsurface cooling in this region has not yet been shown but was suggested by Falvey and Garreaud (2009).

The wind regime in the subtropical eastern South Pacific Ocean, including the southeasterly trade winds and the equatorward blowing winds along the Pacific coast of South America as well, is mainly controlled by the South Pacific High (SPH), a high atmospheric pressure system, also referred to as the South Pacific Anticyclone, located in the eastern South Pacific (Montecino et al., 2006), which spins counter-clockwise. Alongshore winds in this geographic region, the eastern boundary current system of the

* Corresponding author at: Departamento de Oceanografía, Universidad de Concepción, Campus Concepción, Víctor Lamas 1290, Casilla 160-C, código postal: 4070043 Concepción, Chile.
E-mail addresses: wschneid@udec.cl (W. Schneider), ddonoso@dgeo.udec.cl (D. Donoso), jgarces@docentes.uach.cl (J. Garcés-Vargas), ruben.escribano@imo-chile.cl (R. Escribano).

http://dx.doi.org/10.1016/j.pocean.2016.11.004
0079-6611/

South Pacific Ocean, undergo a seasonal cycle owing to the annual south-north-south displacement of the SPA (Montecino et al., 2006). The SPH resides at its northern position (26–30°S) during late austral fall and winter when it is also situated at its most coastal location (85–95°W) (Ancapichún and Garcés-Vargas, 2015, based on NCEP/NCAR reanalysis project from 1949 to 2012). The shelf offshore central-south Chile (30–43°S) is least impacted by the SPH during these seasons; thus, alongshore, southerly winds are weakest. Equatorward winds are strongest during austral spring and summer (Montecino et al., 2006) when the SPH has moved southwest, being located between 33–36°S and 100–108°W (Ancapichún and Garcés-Vargas, 2015). This seasonal wind pattern results in favorable conditions for coastal upwelling during austral spring-summer and less favorable conditions are encountered during fall-winter. Coastal winds and upwelling are modulated by the coastline geometry (various capes, e.g. Punta Lavapie, bays and canyons that cut through the continental shelf, e.g. the canyons of the rivers Itata and Bío Bío), the coastal mountain chain, the Andes, sea breeze, low level wind jets, and synoptic cyclonic storms (Strub et al., 2013). The shelf off central-south Chile forms part of one of the major upwelling systems, among the eastern boundary upwelling systems (EBUS) of the world oceans, namely the Humboldt upwelling system; the others are the California, the Benguela and the Iberian/Canary upwelling systems (Sydeman et al., 2014).

Offshore central-south Chile, like in all the other eastern boundary current systems, wind-driven upwelling enriches the sunlit upper water column with nutrients thus stimulating primary and higher level biological productions (Freon et al., 2009). In the Humboldt upwelling system, continuous production of zooplankton occurs year-round but strong seasonal variations in C/N contents were observed, possibly related to shifts in food quality coupled to upwelling variation (Escribano and Schneider, 2007). Among others, a warmer and fresher water column off Talcahuano, Chile (~37°S), was largely dominated by typical small omnivorous and carnivorous copepods in austral winter 2005, conversely, inhabited by larger herbivorous calanoid copepods in winter 2007 when the water column was colder and saltier (Castro et al., 2010).

Coastal upwelling efficiency off central-south Chile is vulnerable to water column stratification introduced by variable buoyancy flux coming from river discharge and precipitation (Sobarzo et al., 2007). In addition, poleward travelling coastal trapped waves might modulate water column stratification (e.g. Strub et al., 2013). Precipitation in central-south Chile occurs mostly during austral winter (JJA) and is associated with extratropical cold fronts that reach this region when the SPH is at its most northern position (Montecinos and Aceituno, 2003). A negative trend in annual rainfall prevailed since the 1950 s in southern central Chile which intensified by the end of the 20th century (Quintana and Aceituno, 2012). The relationship between the meridional position of the SPH and winds off-shore central Chile is illustrated in Fig. 1.

Global and basin-scale climate modes such as global warming, El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) impact on the eastern boundary Humboldt upwelling system: increase of vertical stratification, deepening/shoaling of the mixed layer and the ocean's heat budget (Strub et al., 2013; Wang et al., 2015; García-Reyes et al., 2015).

Bakun (1990) hypothesized that global greenhouse warming could intensify alongshore upwelling favorable wind stress, however, during the upwelling seasons only, by means of increasing

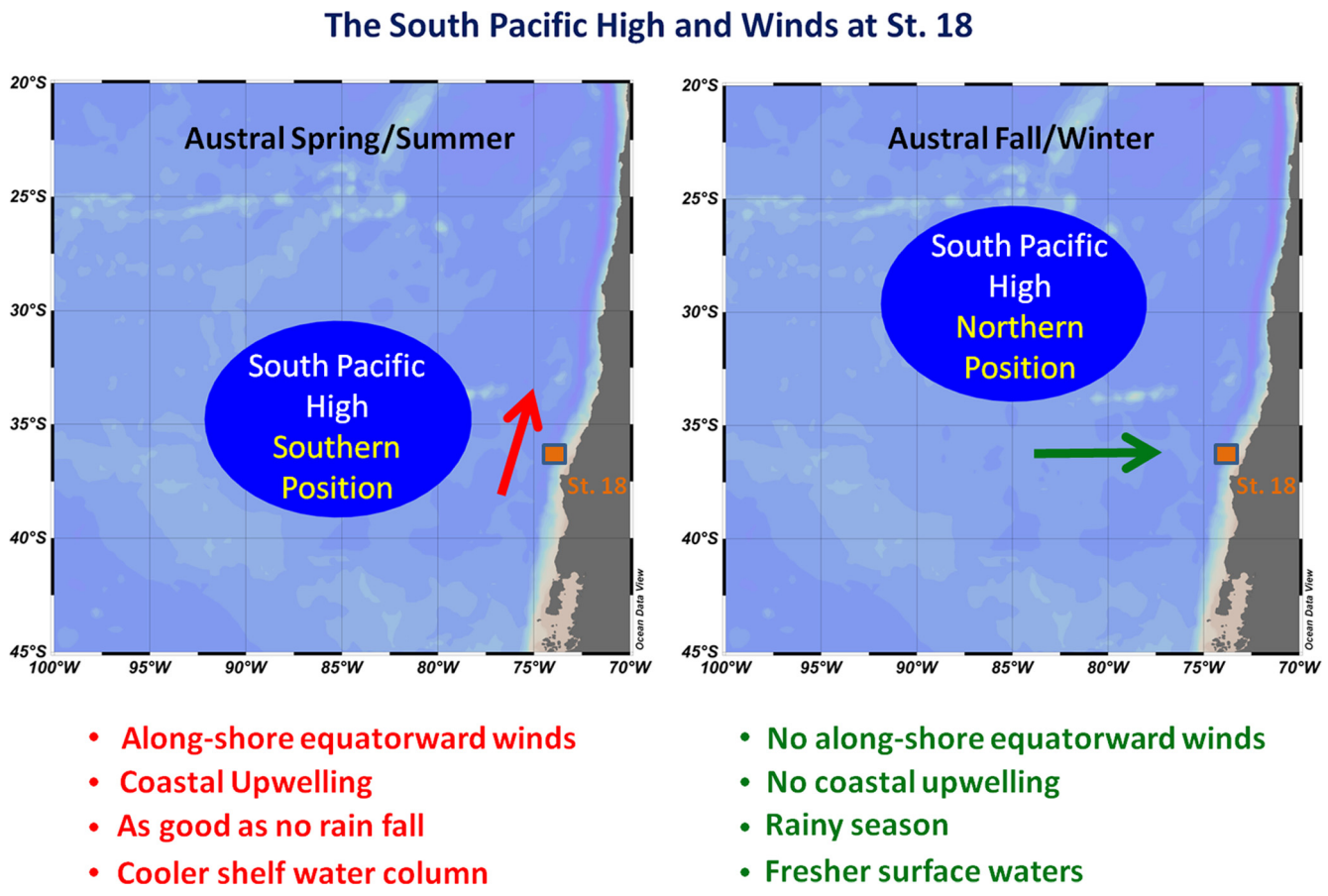

Fig. 1. The South Pacific High. (a) A typical austral summer/spring position of the SPH with alongshore winds off-shore central-south Chile. (b) A typical austral fall/winter position of the SPH with on-shore winds off-shore central-south Chile. The orange square marks the location of Station 18.