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Intraseasonal patterns in coastal plankton biomass off central Chile derived from satellite observations and a biochemical model

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ABSTRACT

Subseasonal (5–130 days) environmental variability can strongly affect plankton dynamics, but is often overlooked in marine ecology studies. We documented the main subseasonal patterns of plankton biomass in the coastal upwelling system off central Chile, the southern part of the Humboldt System. Subseasonal variability was extracted from temporal patterns in satellite data of wind stress, sea surface temperature, and chlorophyll from the period 2003–2011, and from a realistically forced eddy-resolving physical-biochemical model from 2003 to 2008. Although most of the wind variability occurs at submonthly frequencies (<30 days), we found that the dominant subseasonal pattern of phytoplankton biomass is within the intraseasonal band (30–90 days). The strongest intraseasonal coupling between wind and plankton is in spring-summer, when increased solar radiation enhances the phytoplankton response to upwelling. Biochemical model outputs show intraseasonal shifts in plankton community structure, mainly associated with the large fluctuations in diatom biomass. Diatom biomass peaks near surface during strong upwelling, whereas small phytoplankton biomass peaks at subsurface depths during relaxation or downwelling periods. Strong intraseasonally forced changes in biomass and species composition could strongly impact trophodynamics connections in the ecosystem, including the recruitment of commercially important fish species such as common sardine and anchovy. The wind-driven variability of chlorophyll concentration was connected to mid- and high-latitude atmospheric anomalies, which resemble disturbances with frequencies similar to the tropical Madden-Julian Oscillation.

1. Introduction

Subseasonal variability, here defined as environmental oscillations within the 5 to 130 day band, strongly impacts ocean physical dynamics in Eastern Boundary Upwelling Systems. Large-scale atmospheric disturbances that impact local winds are known to be a main driver of subseasonal variability. Off Oregon, in the northern California Current System, meridional changes in the position of the atmospheric jet stream drive 20-day wind oscillations that determine the dominant fluctuations in coastal upwelling strength during summer (Bane et al., 2007), whereas oscillations with frequencies similar to the tropical Madden Julian Oscillation (MJO; Madden and Julian, 1972) appear to force the near 45 day variability in sea temperature and sea level off central California (Breaker et al., 2001). Intraseasonal (30–90 day) sea surface temperature (SST) variability in the Benguela System is associated with mid-latitude westward-propagating atmospheric disturbances and the Antarctic Oscillation (Goubanova et al., 2013). In the northern Humboldt System, local wind fluctuations, coastal-trapped waves and Rossby waves, the last two triggered by equatorial Kelvin waves, modulate the intraseasonal SST variability (Hormazabal et al., 2001; Bonhomme et al., 2007; Dewitte et al., 2011; Illig et al., 2014). The impact of coastal-trapped and Rossby waves on the Humboldt System decreases southward (Shaffer et al., 1999; Belmadani et al., 2012), while the local wind forcing becomes more important (Hormazabal et al., 2001). Most of the intraseasonal SST variability at Valparaiso (33°S) is explained by local winds (Hormazabal et al., 2001). A coupling between the spatial pattern of SST and the low-level atmospheric jet off central Chile (i.e. the southern Humboldt System) was found at submonthly (<30 days) and intraseasonal frequencies (Renault et al., 2009). Synoptic variability associated with the atmospheric jet appears to be intraseasonally modulated by MJO disturbances (Rahn, 2012), consistent with previous studies suggesting a link between MJO and coastal upwelling (Hormazabal et al., 2002; Rutllant et al., 2004).

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Although many studies have examined subseasonal physical variability in Eastern Boundary Upwelling Systems, few address the impacts on plankton production. From a theoretical point of view, Botsford et al. (2006) described the impact of subseasonal wind dynamics on plankton production off central California. They found a complicated relation between time-varying upwelling favorable winds and shelf phytoplankton production, as it is dependent on the duration and strength of the upwelling winds, the duration of relaxation (non-upwelling) periods and the shelf width. Bane et al. (2007) linked the north-south changes in the atmospheric jet stream position to subseasonal fluctuations in plankton abundance off Oregon. Recently, Echevin et al. (2014), using a regional ocean model, identified significant intraseasonal variability in plankton production off Peru (north of 14°S), linked to the passage of remotely forced coastal-trapped waves. Less is known about the role of subseasonal dynamics on plankton variability in the southern Humboldt System. Monthly plankton observations from a coastal station off Concepcion (~36.8°S) revealed important intraseasonal changes in the copepod community, linked to upwelling intensity and relaxations (Gonzalez et al., 2015). However, a regional characterization of subseasonal response of phyto- and zooplankton biomass, including description of the dominant spatiotemporal patterns and their connection to large-scale atmospheric features, has not been undertaken off central Chile.

Subseasonal fluctuations in plankton biomass and structure will impact higher trophic levels, such as the early life stages of pelagic fish that rely on plankton production to grow and survive. Fish are especially susceptible to food limitation at the beginning of their exogenous feeding (Cushing, 1990), so subseasonal changes in planktonic prey biomass can impact larval fish early survival and, ultimately, recruitment success. Common sardine (*Strangomera bentinki*) and anchovy (*Engraulis ringens*) are ecologically and commercially important species that live on the shelf, where fluctuations in food may impact their growth and survival. Consequently, it is important to identify locations and periods where the strongest subseasonal fluctuations on plankton biomass occur, and connect those changes to underlying driving factors.

This study characterizes the main subseasonal patterns in plankton biomass off central Chile. We used satellite observations of SST and chlorophyll to identify the dominant subseasonal patterns in coastal upwelling and phytoplankton biomass, and describe their seasonal and interannual changes during 2003–2011. In addition, we used the output of a coupled physical-biochemical ocean model to describe vertical changes in plankton distribution and composition, associated with subseasonal dynamics. The role of MJO disturbances as a driver of the 30-to-90 day plankton variability is also examined.

2. Data and numerical model

2.1. Satellite products

Daily 1 km chlorophyll and SST data from the period 2003–2011 were obtained from level-2 products of the Moderate Resolution Imaging Spectro-radiometer MODIS-Aqua mission (http://oceancolor.gsfc.nasa.gov). The region off central Chile has a relatively high percentage of MODIS cloudless data (>35%), and the temporal gaps at each grid point are usually shorter than 4 days (Morales et al., 2013). Temporal gaps were filled using the Data Interpolating Empirical Orthogonal Function (DINEOF) method, a robust interpolation procedure that is based on an iterative EOF decomposition and preserves time series variance (Beckers and Rixen, 2003). DINEOF does not require extra input parameters, such as signal/noise ratio, anisotropy or minimal number of decompositions, like other methods do. DINEOF has been successfully used in our study region to examine MODIS SST and surface chlorophyll time series variability (Correa-Ramirez et al., 2012). The interpolation was done using a 31-day window for computational convenience, as well as to increase the statistical independence between estimated data in contiguous days. Daily surface wind data with a 0.25° spatial resolution were obtained from the Cross Calibrated Multi-Platform project (CCMP, L3.0; Atlas et al., 2011; https://podaac.jpl.nasa.gov/Cross-Calibrated_Multi-Platform_OceanSurfaceWindVectorAnalyses). CCMP wind stress was derived from CCMP wind speed using the Large and Pond (1981) bulk formulation.

2.2. Numerical model

The Rutgers version of the Regional Ocean Model System (ROMS) (Song and Haidvogel, 1994; Shchepetkin and McWilliams, 2005) was used to simulate the physical dynamics of the upwelling system during the period 2003–2008. The model domain extends from 30.5° to 43°S, and from the coast to 81°W (Fig. 1), with a mean horizontal resolution of 3 km. The 3 km resolution provides realistic representation of mesoscale dynamics over the relatively narrow shelf off Chile, considering that the baroclinic Rossby radius of deformation varies from 34 km at 32°S to 23 km at 43°S, and that the coastal upwelling jet is about 25 km wide. 40 terrain-following vertical layers are arranged to provide enhanced vertical resolution near the surface. Model bathymetry is from the 1 arc degree resolution Smith and Sandwell (1997) version 12.1 bathymetry.

The biochemical model has 8 components: nitrate (NO_3), ammonium (NH_4), small phytoplankton (PS, flagellates and dinoflagellates), large phytoplankton (PL, diatom), small zooplankton (ZS, microzooplankton), large zooplankton (ZL, mesozooplankton), and slow (DS) and fast sinking detritus (DL). The model is parameterized similarly to the North Pacific Ecosystem Model for Understanding Regional Oceanography (NEMURO, Kishi et al., 2007). The differences from Kishi et al. (2007) are the elimination of the silica cycle, dissolved organic nitrogen (DON), and predatory zooplankton in our model. Although silica may limit diatom growth, the observed nitrate-silica ratio off central Chile is usually close to 1 (Anabalon et al., 2007), so

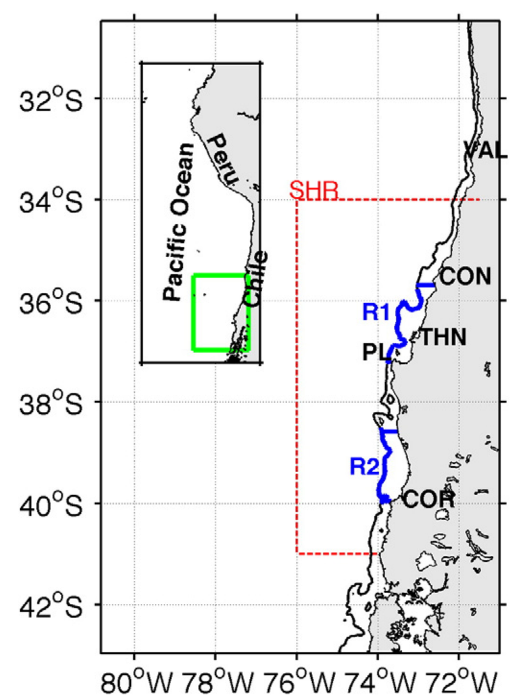

Fig. 1. Full model domain (outermost box). The dashed red lines enclose the southern Humboldt region (SHR) from 34 to 41°S that is examined in the spectral and EOF analysis, and the black contour shows the 200 m isobath. Blue lines depict regions R1 and R2. R1 is used to estimate time series in Fig. 7, and R2 is used to estimate time series in Figs. 7–9. The locations of Valparaiso (VAL), Constitucion (CON), Talcahuano (THN), Point Lavapie (PL), and Corral (COR) are shown. The inset figure shows the Humboldt Current System with the full model domain shown by green lines.