Continental Shelf Research 73 (2014) 14–30

Contents lists available at ScienceDirect

Continental Shelf Research

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

Research papers

Intraseasonal variability of nearshore productivity in the Northern Humboldt Current System: The role of coastal trapped waves

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ARTICLE INFO

Article history:
Received 16 November 2012
Received in revised form
14 September 2013
Accepted 13 November 2013
Available online 22 November 2013

Keywords:
Coastally trapped waves
Upwelling dynamics
Humboldt system
Intraseasonal variability
Primary productivity

ABSTRACT

The impact of intraseasonal coastal-trapped waves on the nearshore Peru ecosystem is investigated using observations and a regional eddy-resolving physical-ecosystem coupled model. Model results show that intraseasonal variability over the period 2000–2006 represents about one fourth of the total surface chlorophyll variance and one third of the carbon export variance on the Peruvian shelf. Evidence is presented that subsurface nutrient and chlorophyll intraseasonal variability are mainly forced by the coastally trapped waves triggered by intraseasonal equatorial Kelvin waves reaching the South American coast, and propagate poleward along the Peru shore at a speed close to that of high order coastal trapped waves modes. The currents associated with the coastal waves induce an input of nutrients that triggers a subsequent phytoplankton bloom and carbon export. The impact of the local wind-forced intraseasonal variability on the ecosystem is of a similar order of magnitude to that remotely forced in the northern part of the Peru shelf on [50–90] day time scales and dominates over the entire shelf on [20–30] day time scales.

1. Introduction

The Peru upwelling system or Northern Humboldt Current System (hereafter NHCS) holds one of the most productive ecosystems due to its unique dynamics (Bakun and Weeks, 2008). It is sustained by year-long alongshore winds blowing equatorward, which force a coastal upwelling driven by the divergence of Ekman transport. Furthermore, the shoreward decrease of the wind intensity induces a negative wind stress curl which generates a intense Ekman pumping off the central Peru shelf (Halpern, 2002; Albert et al., 2010). These mechanisms induce nearshore upwelling of nutrient-enriched coastal waters, high biological productivity and abundant fisheries (Chavez et al., 2008).

A specific feature of this system in comparison with other Eastern Boundary Upwelling Systems (EBUS) is its relative proximity to the equatorial Pacific ocean which makes it particularly sensitive to oceanic perturbations of equatorial origin. These perturbations are characterized by the eastward propagation of energetic intraseasonal Equatorial Kelvin waves (IEKW) across the tropical ocean, forced by westerly wind bursts in the western Pacific (Kessler and McPhaden, 1995; Cravatte et al., 2003). Upon reaching the coasts of Ecuador and Peru, IEKW generate poleward-propagating coastal trapped waves (hereafter CTW) (Clarke, 1983; Belmadani et al., 2012) which, in turn, may force westward-propagating Rossby waves in frequency-dependent latitude ranges (Clarke and Shi, 1991). Such Rossby waves modulate the width of the nearshore chlorophyll-rich band as the associated currents and eddies transport phytoplankton-rich coastal waters offshore (Bonhomme et al., 2007).

During the course of their poleward propagation, CTW produce vertical displacements of the pycnocline of the order of tens of meters, associated with sea level changes of a few centimeters (Leth and Middleton, 2006; Colas et al., 2008; Belmadani et al., 2012). Associated with these vertical movements, displacements of the nutricline may modulate nutrient input into the euphotic layer and impact the biological productivity of the coastal system. Furthermore, the amplitude of IEKW and hence of CTW is modulated at interannual time scales, as during ENSO events (McPhaden, 1999; Lengaigne et al., 2002). During the onset of strong El Nino events (*e.g.* 1982–1983, 1997–1998), the nearshore nutricline deepens by several tens of meters along the South American coasts as far south as central Chile, leading to tremendous impacts on all trophic levels of the ecosystem (Barber and Chavez, 1983; Carr et al., 2002; Carr, 2003; Ulloa et al., 2001).

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0278-4343/$ - see front matter
http://dx.doi.org/10.1016/j.csr.2013.11.015

Besides the remote forcing of CTW of 60–120 day time periods, intraseasonal wind events may also induce local upwelling and force CTW in the NHCS due to alongshore gradients of wind stress or cape effects (Crépon and Richez, 1982). Such atmospheric events are partly related with meridional displacements of the mid latitude South East Pacific anticyclone (Hormazabal et al., 2002; Dewitte et al., 2011). They result in the intensification of surface winds off north (5°S) and central (15°S) Peru, at time periods near 10–25 days and 35–60 days (Stuart, 1981; Dewitte et al., 2011).

The impact of the remote and locally-forced intraseasonal variability on the nearshore biological productivity of the NHCS has been poorly investigated so far for various reasons. First, it is difficult to evaluate the regional impact of intraseasonal variability from observations. SeaWIFs satellite data long time series are relatively scarce due to the intermittent cloud cover, particularly persistent during austral winter (Chavez, 1995). Second, estimating the impact of CTW on the ecosystem from the few coastal moorings off Peru (Graco et al., 2007) and Chile (Ulloa et al. 2001) is hindered by the intrinsic chaotic variability related with ubiquitous mesoscale eddies and submesoscale filaments of the boundary current system (Penven et al., 2005; Chaigneau et al., 2009). Such dynamical features locally generate vertical displacements of the pycnocline and nutricline, which are intertwined with the CTW-forced movements of larger alongshore scale.

To investigate the impact of CTW on the low trophic levels of the ecosystem, we follow a modeling strategy and make use of previous bio-dynamical model developments focussed on surface chlorophyll variability (Echevin et al., 2008; Albert et al., 2010). Our modeling approach allows us to simulate IEKW, CTW and intraseasonal wind stress events, and investigate their impact on the biogeochemical productivity. Using these tools we characterize the remote and local intraseasonal forcing and the biological response of the upwelling system.

In the next section we describe our modeling methodology, in particular the intraseasonal physical forcing, and the observations which are used to evaluate the model's realism. Then the physical and biogeochemical model components are validated against the available observations. Several diagnostics are proposed to characterize the time scales of the biogeochemical system intraseasonal variability, the alongshore propagating patterns and their vertical structure. The transport mechanisms which drive nutrient input on the shelf during the passage of CTW are also analyzed. Finally, a discussion of the results and limitations of the approach is proposed, and the main conclusions and perspectives of this work are drawn in the closing section.

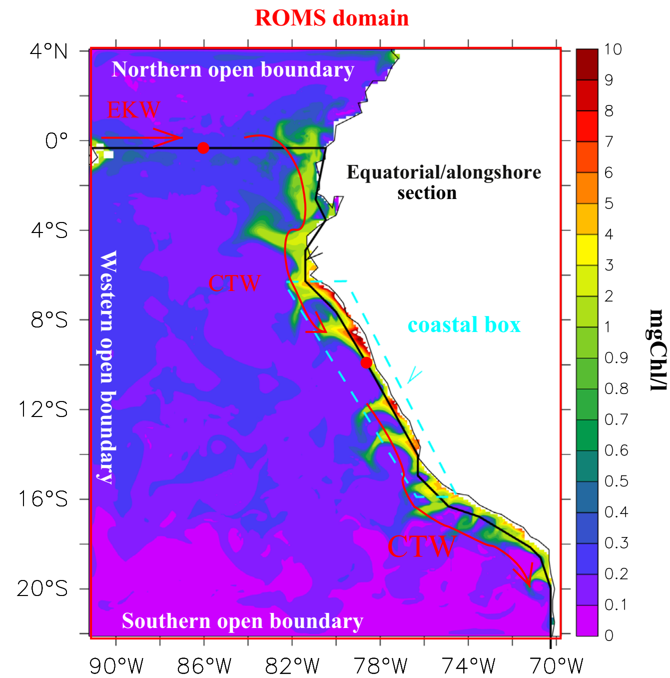

Fig. 1. ROMS model domain with northern, western and southern open boudaries. The black line marks the equatorial section followed by the equatorial Kelvin waves (EKW, red arrow) and the alongshore section followed by the coastal trapped waves (CTW, red arrow). These two sections are used in Fig. 4. The blue dashed line marks a 100-km wide coastal box located on the central Peru shelf. Red circles mark two locations from which sea level is plotted (see Fig. 5). Model surface chlorophyll in January 2000 (in mg Chl l^{-1}) is shown in the background. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2. Material and methods

2.1. Numerical model and configuration

The ROMS-AGRIF (http://roms.mpl.ird.fr/) model is used for ocean dynamics. It solves the primitive equations in an Earth centered rotating environment, based on the Boussinesq approximation and hydrostatic vertical momentum balance. It is discretized in terrain-following vertical coordinates. A third-order, upstream-biased advection scheme allows the generation of steep tracer and velocity gradients. The horizontal grid is isotropic ($\Delta x = \Delta y = 1/9°$, corresponding to ~13 km in the study region) and contains 192 × 240 points that span the region between 4°N and 22°S and from 70°W to 90°W (Fig. 1). The western boundary intersects the Galapagos Islands at 0.6°S. The bottom topography derived from the ETOPO2 database (Smith and Sandwell, 1997) has been smoothed in order to reduce potential error in the horizontal pressure gradient. The model posesses 32 stretched vertical sigma levels to obtain a vertical resolution ranging from 0.3 m to 6.25 m for the surface layer and from 0.3 m to 1086 m for the bottom layer. For more details on the dynamical model parameterizations and configuration, the reader is referred to Shchepetkin and McWilliams (2005) and to a series of paper using the same model configuration (Penven et al., 2005; Montes et al., 2010; Echevin et al., 2011).

The physical model is coupled to the PISCES (Pelagic Interaction Scheme for Carbon and Ecosystem Studies) biogeochemical model (Aumont and Bopp, 2006), which simulates the marine biological productivity, carbon and main nutrients cycling (nitrate, phosphate, silicate and iron). It includes two size classes for phytoplankton (nanophytoplankton and diatoms), zooplankton (microzooplankton and mesozooplankton) and detritus. Diatoms differ from nanophytoplankton by their need for Si, higher requirements for iron (Sunda and Huntsman, 1997), and higher half-saturation constants because of their larger size. Iron is supplied to the ecosystem by climatological atmospheric dust deposition (Tegen and Fung, 1995) and by time-constant depth-dependent sediment mobilization (Moore et al., 2004). The model structure is identical to that used in the global simulation of Aumont and Bopp (2006) and in previous NHCS regional studies (Echevin et al., 2008; Albert et al., 2010). However, some of the biological parameters used here differ from those used in previous regional and global simulations (see Table 1). Changes in the mean Si/C ratio (−25% with respect to values in Albert et al., 2010) and Si remineralization rate (+60%) substantially improved the fit with silicate cross-shore observations, while an increase in the nearshore source of iron improved the fit with 2000 iron observations of Bruland et al. (2005). We also verified that moderate changes (±10%) in the grazing coefficients did not affect the phytoplankton propagative patterns characterized in Section 3.2.3. Details on the comparison with observations are given in Section 3.2.1.