Continental Shelf Research 167 (2018) 46–54

Contents lists available at ScienceDirect

Continental Shelf Research

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

Observations of semidiurnal internal tides on the Patagonian Shelf

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ARTICLE INFO

Keywords:
Internal waves
Tides
Refraction
Mean current
Patagonian Shelf
The Malvinas Current

ABSTRACT

The Patagonian Shelf in the western South Atlantic is known for strong semidiurnal tides and intense seasonal stratification. Both observations and models reveal substantial cross-isobath tidal energy fluxes at the shelf break between 44 and 41°S. These conditions are potentially favorable for internal wave generation, but global tidal models do not show significant baroclinic energy radiation from this region. A possible explanation for the lack of offshore radiation is explored through analyzing the data from two moorings deployed along the Patagonian shelf break. At both mooring sites, the velocity spectra reveal strong baroclinic oscillations at the semidiurnal frequency with a vertical structure resembling the first mode. Unlike barotropic tides with strong cross-isobath polarization, the baroclinic tidal ellipses are less polarized. Internal tide propagation is delineated by estimating a proxy for the baroclinic energy flux, which is the product of band-passed baroclinic velocity near the bottom and temperature at mid-depth. The proxy vectors show that internal tide propagation is highly sensitive to the strength of the Malvinas Current propagating northward over the continental slope. When the mean current becomes stronger, the proxy vectors turn southward, pointing upstream of the Malvinas Current direction. It is concluded that the presence of an energetic western boundary current reduces the offshore radiation of internal tides, likely due to the wave refraction on the mean current.

1. Introduction

Semidiurnal tidal waves propagating along continental margins are strongly affected by wide continental shelves (e.g., Ke and Yankovsky, 2010; Zhang and Yankovsky, 2016): the across-shelf wave structure no longer resembles an analytical Kelvin wave solution and concentrates over the variable topography, while both the phase speed and group velocity are substantially reduced compared to long gravity waves in the open ocean. Furthermore, these modified Kelvin waves are very sensitive to alongshore changes of continental shelf topography. When shelf width changes in the alongshore direction, the alongshore energy flux on the shelf becomes divergent and results in compensating cross-isobath energy flux farther offshore, over the continental slope. The combination of cross-isobath barotropic velocities at the shelf break and a stratified water column results in the radiation of internal waves (IWs). Under favorable conditions, 15% or more of the incident barotropic tidal energy flux can radiate as IWs (Yankovsky and Zhang, 2017).

One of the regions in the World Ocean which fits this scenario is the Patagonian Shelf (PS) in the southwestern Atlantic Ocean. The Patagonian continental shelf extends from the southeastern tip of South America (55°S) to ∼ 40°S. North of the Malvinas Islands, the shelf width of the PS is more than 500 km, and gradually narrows in the downstream direction to less than 200 km at 38°S. Water depth increases to over 4 km in the open ocean across the 200 km wide continental slope. The Patagonian Shelf is known for energetic semidiurnal tides propagating along the shelf (e.g., Webb, 1973; Kantha et al., 1995; Glorioso and Flather, 1997). Palma's et al. (2004) numerical study found strong M_2 tidal energy flux along and across the northern part of the PS where the shelf narrows, with associated tidal dissipation concentrated in the region. Water stratification in the PS area is characterized by a seasonal thermocline on the mid- and outer shelf (typical bottom depths of 100–200 m), which is significantly weaker during the austral winter (e.g., Martos and Piccolo, 1988; Rivas and Piola, 2002; Bianchi et al., 2009). The shelf is bounded offshore by the Malvinas Current (MC), a western boundary current carrying relatively cold sub-Antarctic water along the western margin of the Argentine Basin (e.g., Piola and Gordon, 1989). The transition between the shelf and the MC water is characterized by moderate cross-shore temperature and salinity gradients (e.g., Saraceno et al., 2004; Romero et al., 2006; Franco et al., 2008). At the shelf break (typical bottom depth of ∼200 m) the stratification is somewhat weaker than observed farther onshore (Romero

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https://doi.org/10.1016/j.csr.2018.08.004
Received 21 December 2017; Received in revised form 23 May 2018; Accepted 9 August 2018
Available online 13 August 2018
0278-4343/

et al., 2006). Nonetheless, temperature and salinity records show the onset of a well-defined pycnocline in early November (Valla and Piola, 2015).

Strong stratification in the warm season and cross-isobath barotropic energy fluxes on the PS provide favorable conditions for internal tide generation. Early theoretical studies of internal tides (e.g., Baines, 1982) considered this region as one of the substantial contributors to global internal tidal energy production. However, due to the lack of observations of internal tides in the region, the barotropic to baroclinic energy conversion was not considered as a major source of barotropic dissipation on the PS. Later studies (e.g. Kantha et al., 1995; Glorioso and Flather, 1997) concluded that most of the tidal energy dissipates through bottom friction. Global internal tide model simulations (e.g. Simmons et al., 2004) found that primary regions of M_2 conversion into baroclinic modes in the South Atlantic Ocean are the Drake Passage and the Scotia Sea, south of the PS, whereas little conversion occurred at the Patagonian Shelf break.

IWs observed by satellite imaging (Jackson, 2007) and global altimetry data (Zhao et al., 2016) suggest that there is baroclinic energy radiation over the Patagonian continental slope. A comparison between observational and model data (Buijsman et al., 2015) shows that the global internal tide model predicts lower tidal dissipation on the PS than the dissipation inferred from the TPXO8-atlas model. A parameterized conversion (Buijsman et al., 2016) can significantly improve the contribution of internal tides to tidal dissipation off the continental slope, but the baroclinic wave drag is not applied on continental shelves due to the shallow water depth; thus the barotropic to baroclinic conversion on the PS remains unresolved.

It is possible that global internal tide models do not resolve the generation of internal tides at the PS due to insufficient spatial resolution. Palma et al. (2008) used a baroclinic model with a horizontal resolution of 5 km and 25 levels in the vertical to simulate the circulation responses to tides, shelf break fronts, and wind forcing, but the associated IW dynamics response was not reported. A recent study (Magalhães and da Silva, 2017) addresses IWs in the region, but of non-tidal origin. In their study, IWs are identified in high-resolution satellite images, and are suggested to be due to the resonant generation by the MC encountering topographic irregularities over a continental slope. The northward propagating MC has a strong flow of 0.4–0.7 m/s between 50°S to 43.5°S (Piola et al., 2013; Artana et al., 2016) and is therefore likely to influence the generation of IWs.

This study focuses on the semidiurnal internal tides in the PS region inferred from mooring data collected at the shelf break. The rest of the paper is organized as follows: Section 2 describes the collection and analysis of the data; Section 3 presents the results of data analysis; discussion of the possible influence of the MC on internal tides in the study area along with conclusions are presented in Section 4.

2. Data collection and analysis

Velocity and temperature time series were obtained from two mooring deployments (Valla and Piola, 2015) along the 200-m isobath at the shelf break (Fig. 1). Mooring data were collected from October 16 through December 5, 2005 at site A (43.820°S, 59.673°W), and from September 25, 2006 through March 8, 2007 at site B (40.987°S, 57.003°W). Both moorings measured the current velocity at hourly intervals with acoustic Doppler current profilers (ADCP). The current velocities were estimated from 10 m bins and recorded at 7 depth levels (10, 30, 50, 70, 100, 130, and 160 m), spanning nearly the entire water column. Temperature was recorded at 6 depth levels (1, 10, 30, 50, 75, and 100 m) at site A, whereas only near-surface (1 m) temperature was recorded at site B.

Historical CTD data were used to investigate the vertical density structure in the vicinity of the shelf break near the mooring sites. The data are available at the US NODC World Ocean Database 2013 http://www.nodc.noaa.gov/OC5/WOD/pr_wod.html (Boyer et al., 2013).

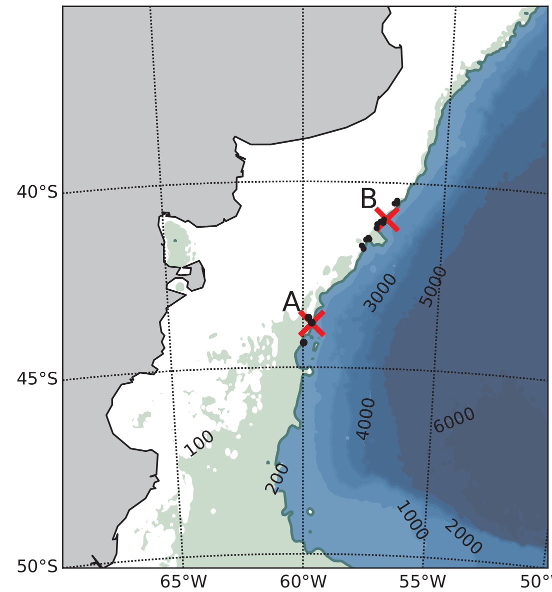

Fig. 1. Map of the study area showing bathymetry (in meters), locations of mooring sites (red crosses), and hydrographic stations (dots). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Hydrographic stations were selected within 100 km from each mooring site and within 11 km inshore from the 200-m isobath (Fig. 1). No data were selected at locations over the continental slope due to strong temperature and salinity gradients associated with the Malvinas Current (e. g., Romero et al., 2006; Piola et al., 2010). Furthermore, CTD profiles were selected for the seasons representing mooring deployments: the austral spring for site A and the austral spring-summer for site B. The selected hydrographic stations are summarized in Table 1 and all density profiles are shown in Fig. 2.

For site A, one of the three available stations was occupied during the actual mooring deployment as a part of the Global Environment Facility (GEF) Patagonia Project (Charo and Piola, 2014). At site B, available stations cluster in two groups, representing early austral spring (September–October) and late summer (February-March) (Fig. 2). Stations from late austral summer are characterized by a seasonal pycnocline within the uppermost 40 m. Profiles of buoyancy frequency N defined as $N^2 = -\frac{g}{\rho_0}\frac{d\rho_0}{dz}$ were estimated for all density profiles. Here, $\rho_0(z)$ is the density, z is the vertical coordinate (positive

Table 1
A summary of the locations and dates of hydrographic stations.

	Latitude	Longitude	Date
Site A			
1	− 43.6638	− 59.7982	9/9/2006
2	− 43.7983	− 59.6722	10/15/2005
3	− 44.338	− 59.974	11/5/1993
Site B			
1	− 41.0833	− 57.1257	2/8/1990
2	− 41.1233	− 57.345	3/23/1989
3	− 40.47	− 56.665	3/9/1994
4	− 41.544	− 57.725	3/10/1994
5	− 40.55	− 56.6667	3/22/1989
6	− 41.7083	− 57.875	3/23/1989
7	− 41.4917	− 57.645	9/5/1989
8	− 41.7932	− 57.8097	9/4/1997
9	− 41.5292	− 57.6095	9/5/1997
10	− 41.2292	− 57.3588	9/5/1997
11	− 41.049	− 57.225	10/10/2005
12	− 40.9883	− 57.1083	10/21/1997
13	− 40.55	− 56.7517	10/21/1997