Progress in Oceanography 129 (2014) 19–34

Contents lists available at ScienceDirect

Progress in Oceanography

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

Semidiurnal internal tides in a Patagonian fjord

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ARTICLE INFO

Article history:
Available online 24 March 2014

ABSTRACT

The fjords of central Chilean Patagonia (47°S) receive fresh water from both precipitation and the Baker River. This buoyancy input generates a two layer hydrographic system characterized by strong salinity stratification (~30 g kg^{-1} over a depth range of 7–15 m), which favors baroclinic conditions in the fjord. Hourly current velocity profiles were collected with an acoustic Doppler current profiler (ADCP) moored at a depth of 40 m during March–April 2009, and complemented by 11 CTD profiles and hourly sea level time series. These data allowed the detection of semidiurnal internal tidal waves for the first time in this region. Wavelength and horizontal phase speeds were determined by the dynamical mode 1 for internal waves. Maximum wavelength was 52 km, travelling at a horizontal phase speed of ~1.16 m s^{-1}. Wavelet, spectral and empirical orthogonal function (EOF) analysis techniques applied to the echo anomaly signal and to the baroclinic velocity showed largest semidiurnal amplitudes near the pycnocline. Out of three modes obtained from the EOF analysis, two modes displayed a two- or three-layer flow structure with flow direction reversing at the pycnocline. The semidiurnal internal waves were found as fluctuations near the pycnocline in sporadic packets correlated to high discharge pulses of the Baker River (r^2 = 0.77). Additionally, internal Froude number calculations at the mouth of the Baker River indicated critical flow conditions, which allowed for generation of internal waves at the plume front. These waves are separated from the river plume after internal wave phase speeds surpassed frontal speeds. This suggests that the internal waves were modulated by pulses in high river discharge rather than the interaction of barotropic tide with bathymetry (a sill). An implication of these internal waves would be to increase vertical mixing of nutrients toward the surface, through shear instabilities, which would favor primary production.

1. Introduction

Fjords are mid- to high-latitude estuaries formed by the advance of glaciers through mountainous terrain. They are narrow and deep and may contain one or more submarine sills (Farmer and Freeland, 1983; Inall and Gillibrand, 2010; Stigebrandt, 2012). The main mechanisms for mixing in fjords are thought to be linked to shear instabilities caused by wind stresses and internal waves/tides (Farmer and Freeland, 1983). Inall and Gillibrand (2010) and Stigebrandt (2012) discuss how the barotopic tide supplies energy to internal waves. This energy is in turn lost to an increase in potential energy either through mixing or heat transfer; the latter not being likely because of the large specific heat capacity of water. The energy transfer from internal waves to turbulence and mixing is of particular importance to deep basin waters where wind-driven mixing has little effect. Therefore, the study of internal waves (tides) in fjords is basic and timely (Stigebrandt, 2012; Aguirre et al., 2010; Inall and Gillibrand, 2010; Drujhout and Maas, 2007; Allen and Simpson, 1998; Farmer and Freeland, 1983).

Internal waves are common in fjords because of the barotropic tide interacting with abrupt changes in bottom topography related to the presence of sills, as explained in, for example, Farmer and Freeland (1983) and St. Laurent et al. (2003). However, internal waves can also be generated at tidal frequencies when the barotropic tide interacts with river plumes (Nash and Moum, 2005; Stashchuk and Vlaskenko, 2009).

In central Patagonia (47°S), cold and fresh estuarine water enters the fjord through glacial ice melt from Glacier Steffen and through discharge from the Baker River (Pérez-Santos et al., 2013,2014). The interactions of these freshwater sources with the oceanic water produce haline stratification in the fjord, favoring the development of internal waves. The Baker River transports silt to the fjord, increasing water turbidity and reducing light. Most of

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http://dx.doi.org/10.1016/j.pocean.2014.03.006

the silt is accumulated in the stratified layer, while some escapes to the bottom of the fjord. This accumulation of silt, together with accumulation of plankton and a typically sharp sound signal at the pycnocline, provide an opportunity to describe pycnocline undulations with the echo anomaly of a Doppler profiler (Valle-Levinson et al., 2001). Farmer and Freeland (1983) used a similar technique with echo-sounding in order to identify internal waves in Knight Inlet.

The objective of this study was to describe the presence of internal tides in the Steffen–Baker fjord and identify their triggering mechanism. This objective was addressed with acoustic measurements of current velocity and echo anomaly profiles collected from an acoustic Doppler current profiler (ADCP), and complemented by CTD profiles and sea level data. Observations revealed, for the first time in Patagonian fjords, the presence of semidiurnal internal tides. These findings are fundamental for the study of fjord physics because internal waves are one of the most dominant mechanisms for vertical mixing in these estuarine ecosystems (Monismith, 2010).

Methodology for this work is discussed in Section 2 with the location of the study site and an overview of data collection in Sections 2.1 and 2.2, respectively. Sections 2.3–2.6 detail data analysis techniques used on data presented in Section 2.2. Results are presented in Section 3, organized as follows: characteristics of the fjord will be discussed in Section 3.1 to determine tidal features such as the location of the pycnocline and internal wave generation. This subsection also details the wavelength, horizontal phase speed and the phase propagation angle of internal waves in this region. Section 3.2 presents analyses on acoustic data including Empirical Orthogonal Functions (EOF), spectral analysis and wavelet techniques. Section 3.3, focuses on the baroclinic velocity with EOF, spectral and wavelet analyses also applied to these data. Section 3.4 presents comparisons of Baker River discharge to the spatial and temporal location of internal waves derived from the echo anomaly as well as from the baroclinic velocity. Discussion and conclusions are presented in Sections 4 and 5, respectively.

2. Methodology

2.1. Study area

Central Patagonia, encompassing approximately 1000 km of the southwest coast of Chile (in a straight line), contains one of the world's most extensive fjordic systems (Pantoja et al., 2011). The study area is located in central Chilean Patagonia (~47°S) and is a region with complex geographic features, e.g. the Martinez Channel, the Steffen fjords, the Baker River mouth and many islands and small channels (Fig. 1a). This extensive area located between the Northern and Southern Ice Field, receives ~3400 $m^3\,s^{-1}$ of fresh water from both precipitation (~2500 $m^3\,s^{-1}$, Dávila et al., 2002) and the Baker River (average flow rate of ~900 $m^3\,s^{-1}$, Cáceres and Gudiño, 2009).

This freshwater input from glacial melt and rivers to the fjords and channels of central Patagonia, as well as sizable pluvial influence, contributes to the formation of a thin surface layer (~5–10 m deep) characterized by low temperatures and salinity (Calvete and Sobarzo, 2011). This buoyant layer can be considered as

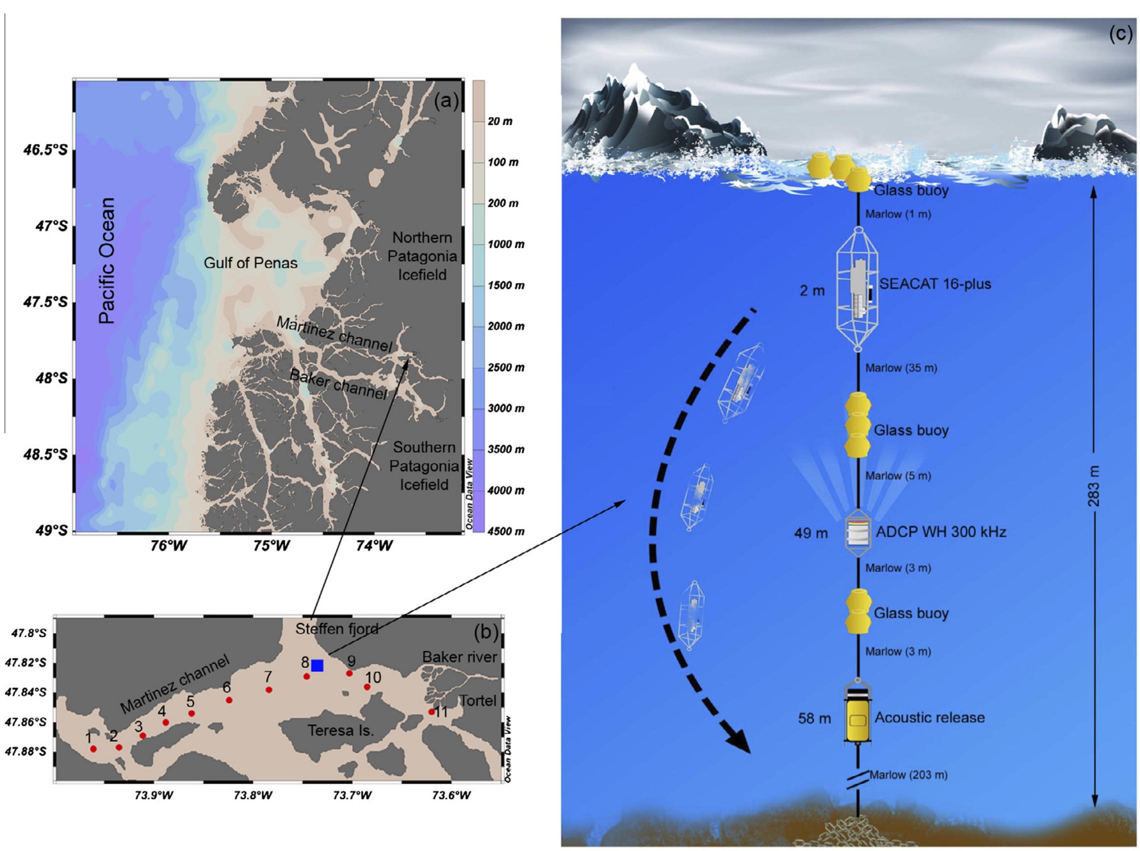

Fig. 1. (a) Overview of study site and nearby Ice fields in relation to the Pacific Ocean. (b) Location of study site in central Chilean Patagonia. The red dots show hydrographic stations and the blue square indicates the ADCP mooring. (c) Mooring scheme with the position of the ADCP and SeaCAT instruments, deployed near the mouth of the Steffen fjord and near the mouth of the Baker River from March 8 to April 30, 2009. The arrow in the figure denotes the path of the SeaCAT CTD once it became dislodged from the mooring after the passage of a storm. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)