Regional Studies in Marine Science 6 (2016) 87–95

Contents lists available at ScienceDirect

Regional Studies in Marine Science

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

An estimation of the effect of a possible wind speed increase on the ocean mixed layer depth at the northern Patagonian continental shelf[☆]

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ARTICLE INFO

Article history:
Received 24 November 2015
Received in revised form
8 March 2016
Accepted 9 March 2016
Available online 14 March 2016

Keywords:
Patagonia
Shelf
Wind
Thermocline

ABSTRACT

A possible deepening of the ocean mixed layer is investigated at two selected points of the Patagonian continental shelf where a significant positive wind speed trend is estimated. Using a 1-dimensional vertical numerical model on a long term simulation (1979–2011) it is found that the mixed layer thickness presents a significant and positive trend of about 10 ± 1.5 cm/yr. The model is forced by atmospheric data from NCEP/NCAR 1 reanalysis and tidal constituents from TPXO 7.2 global model. Several numerical experiments are carried out in order to evaluate the impact of the different atmospheric variables considered in this study (wind components, air temperature, atmospheric pressure, specific humidity and cloud coverage). As a result it is found that a possible increase in the wind speed should be considered as a very significant factor for deepening the ocean mixed layer at the northern Patagonian continental shelf.

1. Introduction

Changes in wind due to global warming may have large geophysical impacts (McInnes et al., 2011). A number of changes in atmospheric processes have been reported at the Southwestern Atlantic Ocean. For instance, Barros et al. (2000) reported that the western border of the South Atlantic High and the atmospheric circulation over Southeastern South America have slowly shifted towards the south during the last decades. Changes in wind speed have a significant impact on storm surge and wind wave climates at the Southeastern South America continental shelf (see, for example, D'Onofrio et al., 2008; Dragani et al., 2010; Codignotto et al., 2012; Dragani et al., 2013). In addition, wind speed changes play a fundamental role in the spatial patterns of sea surface temperature warming, the global hydrological cycle (through evaporation) and in the regional distribution of sea level rise.

From Ekman (1905) to today many advances have been carried out for a better understanding of the dynamic of the mixed layer. Some of the main achievements in this subject were done during the 60 and 70's. For instance, Kraus and Turner (1967) were the first to heed the turbulent kinetic energy budget in a one-dimensional mixed layer model, using the approximately decoupled state of the equations for the thermal and mechanical energies. Later, Geisler and Kraus (1969) as well as Miropol'skiy (1970) and Denman (1973) included the viscous dissipation in the turbulent energy budget. Afterward Niiler (1975) showed that in addition to the equations for thermal (potential) and turbulent (kinetic) energy, an equation for the mean kinetic energy should be properly incorporated since entrainment converts some of the mean flow energy into turbulent energy, over and above the parameterized wind stress production. Important progress has been achieved in the theoretical understanding of the mixed layer during the last decades and, in particular, the development of 3-D ocean–atmosphere coupled model allowed to explore the vertical structure of the ocean in a more integral, complete and comprehensive way.

An increase in the wind speed has an important impact on the mean depth of the mixed layer of the shelf seas (Huang et al., 2006). The vertical structure of the water column is the result of ongoing competition between the buoyancy inputs due to surface heating and freshwater input, on the one hand, and stirring by the tides and wind stress, on the other. Variations in mixed layer depth affect the

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[☆] This article has been assigned the ICAS pre-print number 007/16.

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http://dx.doi.org/10.1016/j.rsma.2016.03.004
2352-4855/

rate of exchange between the atmosphere and deeper ocean, the capacity of the ocean to store heat and carbon and the variability of light and nutrients to support phytoplankton growth. However, the response of the Southern Ocean mixed layer to changes in the atmosphere is not well known (Sallée et al., 2010). On the Patagonian continental shelf the dominant buoyancy is mainly due to the seasonally varying surface heat (Guerrero and Piola, 1997) because the rainfall is very scarce. During the winter months, when heat is lost from the surface, the buoyancy term contributes to stirring by increasing surface density and making all or part of the water column convectively unstable. As a result the shelf waters are vertically well mixed during the winter months. This vertically mixed regime continues until the onset of positive heating at approximately the vernal equinox (September 21st in the southern hemisphere) after which the increasing input of positive buoyancy tends to stabilize the water column. Whether or not the water column stratifies depends on the relative strengths of the surface heating and the stirring due to frictional stresses imposed at the bottom boundary by the tidal flow and at the surface by wind stress. Huang et al. (2006) studied the decade variability of wind-energy input to the world ocean and found that this energy varied greatly on inter-annual to decal time scales. In particular, they showed that it has increased 12% over the past 30 years, and that the inter-annual variability mainly occurs in the latitude bands between 40°S and 60°S.

Direct observations collected over the Patagonian continental shelf waters (Argentina) indicate that during the 90's, winds were 20% stronger than during the 80's and that winds from the northwest direction were more frequent (Gregg and Conkright, 2002). In the region of study in this work (Fig. 1, left panel), a maximum wind speed trend greater than 2.5 cm s^{-1}/yr was estimated from NCEP/NCAR 1 reanalysis (NR1) at the border of the Patagonian continental shelf (at 44°S 60°W, approximately; Fig. 1, right panel).

The aim of this paper is to investigate and quantify a possible deepening of the mixed layer in a region of the Patagonian shelf where atmospheric and oceanographic data are available (Fig. 1, right panel) approximately at 44°S 61°W. We have studied two reference locations, A and B in Fig. 1, and found similar results for both of them. The study was carried out by means of a 1-dimensional numerical model (Sharples et al., 2006; Sharples, 1999) developed to study the physical structure of the upper layer of the ocean at coastal and shelf seas. This physical model employs a turbulence closure scheme to provide the link between local vertical stability (driven by seasonal solar heating) and the vertical turbulent mixing (driven by tidal currents and surface wind stress). This model was forced using atmospheric data from NR1 reanalysis and tidal constituents from TPXO 7.2 global model (see next section for details). Numerical results were conveniently validated using temperature profiles measured at four locations for three different dates, ranging from 1994 to 2006. The results obtained in this article are valid for the outer Northern Patagonian continental shelf, where the relevant atmospheric and oceanic conditions can be considered quite homogeneous, excluding tidal and shelf break fronts.

This region is ecologically and economically important. One of the most important economic activities in the area is fisheries, while its coastal marine fauna is practically unique in the world. The Patagonian shelf is characterized by a smooth slope and scarce relief features (Parker et al., 1997). The shelf broadens from north to south, ranging from 170 km at 38°S to more than 600 km south of 50°S. The main source of the shelf water masses is the sub-antarctic water flowing from the northern Drake Passage, through the Cape Horn Current (Hart, 1946) between the Atlantic coast and the Malvinas Islands, and the Malvinas Current in the eastern border of the shelf (Bianchi et al., 1982). The freshwater source of the shelf is a small continental discharge. On the other hand, a low salinity water mass gets into the continental shelf through the Magellan Strait, where low salinity is due to high precipitation in the South Pacific, close to the west coast of Tierra del Fuego, and the melting of continental ice (Lusquiños, 1971; Lusquiños and Valdés, 1971; Piola and Rivas, 1997). South of 41°S, the shelf width is close to one quarter of the semi-diurnal tide wavelength, leading to favorable conditions for resonance (Piola and Rivas, 1997). The tidal amplitude in the Patagonian shelf is one of the highest in the world ocean (Kantha et al., 1995), and tidal currents are very energetic (Simionato et al., 2004).

2. Data

Surface (10 m height) zonal and latitudinal wind components, surface (2 m height) air temperature, surface atmospheric pressure, surface (2 m height) specific humidity, and cloud coverage from NR1 (period: 1979–2012) for node A (located at 44.7611°S61.8750°W) and node B (42.8564°S 60°W) were used as atmospheric forcing of the model. The output from NR1 reanalysis is a set of grid data (Global T62 Gaussian grid) with a temporal resolution of 6 h. Data before 1979 were not included in this study due to known deficiencies of the reanalysis prior to satellite era, particularly in data-sparse regions such as the high-latitude Southern Hemisphere (Jones et al., 2009; Bromwich and Fogt, 2004). The main advantages of this reanalysis are its physical consistency and high temporal coverage. Full details of the NR1 project and the data set are given in Kalnay et al. (1996) and discussions on its quality in the Southern Hemisphere can be found in Simmonds and Keay (2000), among others. Since the behavior of nodes A and B are quite similar, in this paper we show the details of the calculations only for node A, whereas the final results are shown for both nodes.

The raw analysis of the NR1 data shows no temporal trend in variables, except in the wind (Pescio et al., 2015) where we find an increment of 1.7 ± 0.9 cm s^{-1}/yr at a 95% confidence level. The analogous result for the B node is 2.2 ± 0.9 cm s^{-1}/yr. In Fig. 2 is plotted the wind speed evolution at grid node A for the studied period of time.

To get a realistic representation of the tidal dynamics, tidal current constituents for five primary harmonic constituents (M2, S2, N2, O1, K1) at the grid node located at 44°S 61°W were obtained from TPXO 7.2 model (http://volkov.oce.orst.edu/tides/global.html). Tide computed from these five selected constituents account for almost all the real tide in the region. For instance, these constituents represent more than 98% of the total tidal energy when 51 harmonic constituents and the available sea level data series measured at Golfo Nuevo (Argentine Patagonia) are used. TPXO 7.2 is a recent version of a global model of ocean tides, which best-fits the Laplace Tidal Equations and along-track averaged data from TOPEX/Poseidon and Jason (on TOPEX/POSEIDON tracks since 2002) obtained with OTIS. The methods used to compute the model are described in detail by Egbert et al. (1994) and further by Egbert and Erofeeva (2002).

We used seven temperature quasi-continuous vertical profiles to validate the numerical simulations. Profiles gathered in 2006 were collected within the framework of the Coastal Contamination, Prevention and Marine Management project, which was part of the scientific agenda of the United Nations Development Program. Cruises were carried out on board the "Oca Balda" and "Puerto Deseado" oceanographic vessels, in March of 1994, 1996 and 2006. In each cruise, hydrographic stations were carried out along cross-shelf sections spanning the shelf from near-shore to the western boundary currents, between 38° and 55°S (Charo and Piola, 2014). For the purposes of this work, it has been used data collected at the following locations and dates (See Fig. 1):