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Effects of future sea-level rise on tidal processes on the Patagonian Shelf

Stacey J. Carless[a], J.A. Mattias Green[a,*], Holly E. Pelling[a,b], Sophie-Berenice Wilmes[a]

[a]School of Ocean Sciences, Bangor University, Menai Bridge, Anglesey LL59 5AB, UK
[b]National Oceanography Center, Liverpool L3 5DA, UK

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ABSTRACT

The response of tidally driven processes on the Patagonian Shelf to sea-level rise (SLR) is revisited using large but realistic levels of change in a numerical tidal model. The results relate to previous studies through significant differences in the impact, depending on how SLR is implemented. This is true for how the boundary at the coastline is treated, i.e., if we allow for inundation of land or assume flood defences along the coast, but also for how the sea-level change itself is implemented. Simulations with uniform SLR provide a different, and slightly larger, response than do runs where SLR is based on observed trends. In all cases, the effect on the tidal amplitudes is patchy, with alternating increases and decreases in amplitude along the shelf. Furthermore, simulations with a realistic future change in vertical stratification, thus affecting tidal conversion rates, imply that there may be a small but significant decrease in the amplitudes along the coast. Associated processes, e.g., the location of mixing fronts and potential impacts on biogeochemical cycles on the shelf are also discussed.

1. Introduction

Global sea-level rise (SLR) occurred at an average rate of 1.7 mm yr^{-1} during the 20th century, and has since accelerated to 3.2 mm yr^{-1} (Church et al., 2013; Church and White, 2011a, 2006b; Woodworth et al., 2011). The global change in sea-level at the end of the 21st century will therefore most likely be between 0.63–0.98 m (Church et al., 2013). However, due to uncertainties in the contribution of ice melt it is possible that this rate is severely underestimated (Nicholls et al., 2011), and by the year 2500 the SLR signal from Antarctica alone may exceed 5 m under the RCP4.5 scenario, and over 12 m under RCP8.5 (DeConto and Pollard, 2016). Several papers have recently investigated how large levels of future SLR may impact on the tides on the European Shelf (Pelling and Green, 2014b; Pickering et al., 2012; Ward and Pelling, 2012) and in the Gulf of Maine (Pelling and Green, 2013a). Furthermore, Pelling et al. (2013b) showed that anthropogenic land reclamation in the Bohai Sea has led to changes in the tide equivalent to those which could be expected from realistic levels of future SLR, and Clara et al. (2015) investigated the response of the Patagonian Shelf tides to uniform sea-level rise, and find significant changes in tidal dissipation rates and the location of tidal mixing fronts. They also suggest that the M_2 amplitude changes non-uniformly with (uniform) SLR. Here, we revisit the Patagonian Shelf and investigate the sensitivity of the tides and tidally driven processes there to various levels of homogenous and spatially varying SLR.

The Patagonian Shelf (Fig. 1) is a tidally dynamic region (see, e.g., Glorioso and Flather, 1997, Moreira et al., 2011), with a very different geometry to other investigated areas: the Patagonian Shelf is zonally narrow and stretched meridionally. It is also generally quite shallow in the north, with a depth of less than 10 m in Rio de la Plata, whereas the southern part of the domain is deeper. For example, the main portion of Golfo San Matias is deeper than 100 m, with a sill at 60 m, and that Bahia Blanca is mostly shallower than 50 m. This leads to different tidal dynamics compared to the complex topography of the European Shelf (Ward and Pelling, 2012), and the embayment-like Gulf of Maine (Pelling and Green, 2013a) and Bohai Sea (Pelling et al., 2013b). Furthermore, Arbic et al. (2009) and Arbic and Garrett (2009) suggest that the Patagonian Shelf may be near-resonant, which would make it highly sensitive to future SLR (see also Webb, 1976).

As discussed by Clara et al. (2015), changes in the tides on the Patagonian Shelf could impact the local biogeochemistry. The Patagonian Shelf is one of the world's largest sinks of CO_2, with an annual mean air-sea CO_2 flux of -3.7 × 10^{-3} mol m^{-2}day^{-1} (Bianchi et al., 2009b). However, there is a strong spatial variability associated with the locations of tidal mixing fronts. Well mixed coastal waters in Bahia Grande and Golfo San Matias are sources of CO_2 with fluxes to the atmosphere of over 40 mmol day^{-1}, whereas the stratified midshelf is a strong sink with drawdown rates reaching

* Corresponding author.
E-mail address: m.green@bangor.ac.uk (J. Green).

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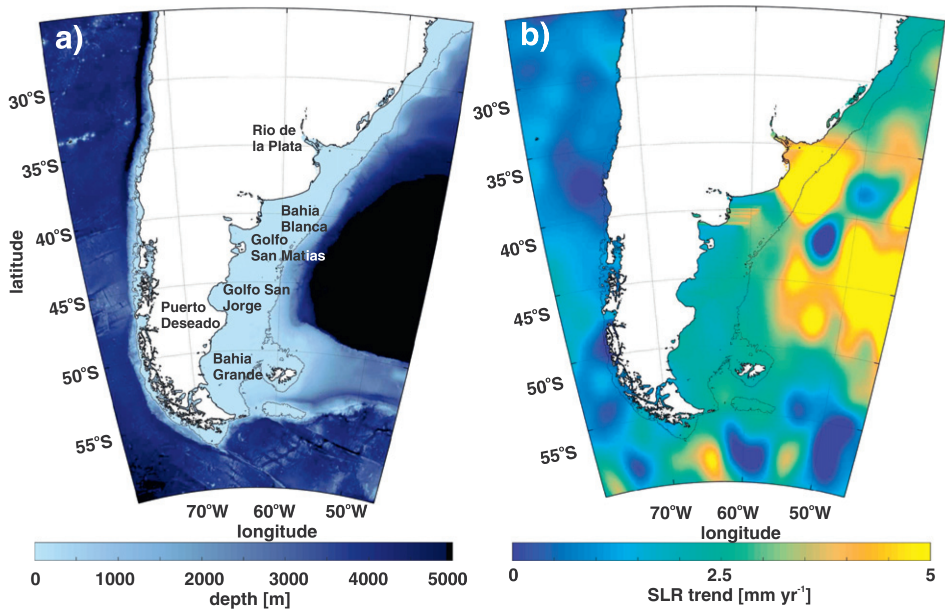

Fig. 1. a) The bathymetry of the domain from the ETOPO database (Amante and Eakins, 2009). Note that for numerical reasons the simulations were made for the domain shown here, but for clarity we are zooming in on the Patagonian Shelf when displaying results. Furthermore, there is no impact of SLR on tides in the Pacific or the northern part of the domain. b) Observed SL trends using satellite altimetry in mm yr^{-1} from Henry et al. (2014).

−55 mmol day^{-1} (Bianchi et al., 2005a). High phytoplankton concentrations are also associated with the frontal system (e.g. Acha et al., 2004), and the fronts have been described as the "axes for the distribution" of the Argentine anchovy (*Engraulis anchoita;*Hansen et al., 2010). They are also spawning sites for a number of other commercial species, e.g., hake and squid (Acha et al., 2004; Alemany et al., 2014), and they influence the concentration of Patagonian scallop (Orensanz et al., 1991). Consequently, any shift in the location of the tidal mixing fronts may have profound biological and ecological impacts.

The location of tidal mixing fronts can be determined by the Simpson–Hunter index, χ (Simpson and Hunter, 1974):

$$\chi = \frac{h}{|u|^3} \tag{1}$$

where h is water depth and $|u|$ the magnitude of the tidal current. In temperate waters a tidal mixing front is typically found on contours of $\log_{10}(\chi) \sim 2.5$ (Simpson and Bowers, 1981; Simpson and Hunter, 1974), and it is evident from Eq. (1) that even a small change in tidal velocity, e.g., due to SLR or future warming, can have a large impact on the location of the fronts. We can therefore expect future SLR to have far-reaching impacts on the Patagonian Shelf, not just on the physical system in the area, but also on local biochemistry and ecology.

Virtually all previous investigations of tides and SLR, both global and regional, have used a uniform SLR over the domain (e.g., Clara et al., 2015, Green, 2010, Pelling and Green, 2013a, Pelling et al., 2013a, Pickering et al., 2012). However, the observed SL trends shown in Fig. 1b indicate that the SL change over the Patagonian Shelf is far from uniform, with an average trend over the domain of +2.7 mm SLR yr^{-1} (see Henry et al., 2014, data available from http://sealevel.colorado.edu/content/map-sea-level-trends). Here, we will therefore reinvestigate how the tides on the Patagonian Shelf may respond to various levels of non-uniform SLR based on the data in Fig. 1b, and compare the results using the trend data to equivalent levels of uniform SLR. Several processes can contribute to variations in local SLR, such as uplift/subsidence land movement, climatic changes in wind patterns and changes in offshore ocean currents like a potential weakening of the Gulf Stream (e.g., Ezer, 2013). In this study, however, focus is not on why SLR is spatially variable, but on how SLR affects (shelf sea) tides. Also, the only actual observation of spatially varying SLR is the trend data in Fig. 1b, we would like to refrain from speculating on causes of the SLR in the present paper. However, because shelf sea tides can be sensitive to changes in tidal conversion around the shelf break we will also investigate how the Patagonian shelf tides may be influenced by some aspects of future warming. We say some aspects, because this is an investigation into potential changes of tidal processes on the Patagonian Shelf. Consequently, we are not discussing large scale ocean circulation or how it may change in the future.

The overarching question here, how the tides on the Patagonian Shelf respond to various levels of (non-uniform) SLR, will be answered using an established numerical tidal model used for similar work in a number of publications (e.g., Green, 2010, Green and Huber, 2013, Pelling and Green, 2013a, Pelling et al., 2013b, Wilmes and Green, 2014). The difference between previous investigations of tides and SLR is 4-fold: we will use a SLR signal based on observed trends, we will investigate changes in the tides due to future warming, we use an unprecedented model resolution of the Patagonian shelf at 1/30° in both latitude and longitude leading to a very high accuracy, and we will put the changes into a dynamical context. The model, simulations, and computations are described in the next section, whereas the results are presented in Section 3. The paper concludes in Section 4 by a discussion, the conclusions, and a future outlook.

2. Modelling tides

2.1. OTIS

The simulations were done using the Oregon State University Tidal Inversion Software (OTIS; see Egbert et al., 2004, Green and Nycander, 2013). The domain is shown in Fig. 1 and runs were done