Journal of Coastal Research | 30 | 1 | 210–213 | Coconut Creek, Florida | January 2014

TECHNICAL COMMUNICATIONS

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Sea-Level Trend at the Southernmost Region of South America

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ABSTRACT

Dragani, W.C.; D'Onofrio, E.; Alonso, G.; Fiore, M., and Oreiro, F., 2014. Sea-level trend at the southernmost region of South America. *Journal of Coastal Research,* 30(1), 210–213. Coconut Creek (Florida), ISSN 0749-0208.

Tide gauge data were used to estimate the sea-level trend at the Ushuaia tidal station (54°49′ S, 68°13′ W), located at the southernmost city in the world. The Ushuaia tidal station began working in 1951 but was relocated in 1970 approximately 900 m from its original location. Special care was taken in linking both data series to compose a single and reliable sea-level record gathered from 1952 to 2005. The least-square regression line for annual mean sea level (relative to the benchmark) was fitted, and the computed slope that resulted was not significantly different from zero. A low-pass filter was applied to the annual sea-level data series to smooth the constituents of tide longer than 1 year, which could mislead the trend of the mean sea level. The trend of the best fit line computed from the filtered data was –0.2 mm y^{-1}, which was not significantly different from zero. Taking into account the Peltier glacial isostatic adjustment prediction, a corrected sea-level trend was estimated in +1 mm y^{-1} for the Ushuaia tidal station. The sea-level trend was also estimated by processing the altimetry data series gathered at five satellite track crossings located in the adjacent ocean (analyzed period 1992–2011). Resulting sea-level trends computed from altimetry data presented high spatial variability (from –0.9 to +3.1 mm y^{-1}), which is likely associated with the rather short length of the processed data series. The authors of this technical communication foresee that these results will contribute to our knowledge of sea-level change in the Southern Hemisphere, especially southward of 50°S, where long sea-level data series are considerably scarce.

ADDITIONAL INDEX WORDS: *Global climate change, sea-level trend, tidal gauge data series, altimetry data series, Ushuaia Bay, Argentina.*

INTRODUCTION

Sea-level change is an important consequence of climate change, both for society and for the environment. Numerous studies have focused on the impact of sea-level rise along coasts, where population densities are approximately three times higher than the global average (Small and Nicholls, 2003). In addition, eustatic sea-level rise raises flood levels and hence increases flood risk (Bijlsma *et al.,* 1996; Hoozemans, Marchand, and Pennekamp, 1993; Hoozemans and Hulsbergen, 1995).

Considering the results of several estimates based on the Permanent Service for Mean Sea Level (PSMSL) data set (Woodworth and Player, 2003) and altimetry data for the recent years, the Intergovernmental Panel on Climate Change estimates that the rate of eustatic sea-level increase has been 1.8 ± 0.5 mm y^{-1} for the 1961–2003 period and 1.7 ± 0.5 mm y^{-1} for the 20th century (Bindoff *et al.,* 2007). However, several works that contributed to these results included only a few (or no) tide gauge stations from the Southern Hemisphere (Douglas, 2001; Holgate and Woodworth, 2004; Miller and Douglas, 2004; Peltier, 2001). There are few studies about sea-level rise in the Southern Hemisphere and, particularly, at the SE South America continental shelf (Figure 1). Lanfredi, Pousa, and D'Onofrio (1998) reported a long-term trend in the sea level of +1.6 ± 0.1 mm y^{-1} for Buenos Aires Port (analyzed period 1905–92) and +1.4 ± 0.5 mm y^{-1} for Mar del Plata (1954–92). More recently, D'Onofrio, Fiore, and Pousa (2008) reported a trend of +1.68 ± 0.05 mm y^{-1} for Buenos Aires Port (1905–2003) and Fiore *et al.* (2008) reported +1.53 ± 0.11 mm y^{-1} for Mar del Plata (1953–2006). These values are in agreement with the reported trends given by Bindoff *et al.* (2007). Results presented by Cazenave and Llovel (2010) show a high spatial variability (from –1 to +3 mm y^{-1}) in sea-level trends computed from available altimetry data series at the study region (Figure 1).

However, the altimetry data from TOPEX/Poseidon have allowed the observation of the spatial distribution of sea-level rise and provided evidence of the range of values among different regions. Church *et al.* (2004) combined altimetry data with historical tide gauge data to estimate monthly distributions of large-scale sea-level variability and change over the 1950–2000 period. One of the major sources of error mentioned

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DOI: 10.2112/JCOASTRES-D-12-00091.1 received 14 May 2012; accepted in revision 7 September 2012; corrected proofs received 22 November 2012.

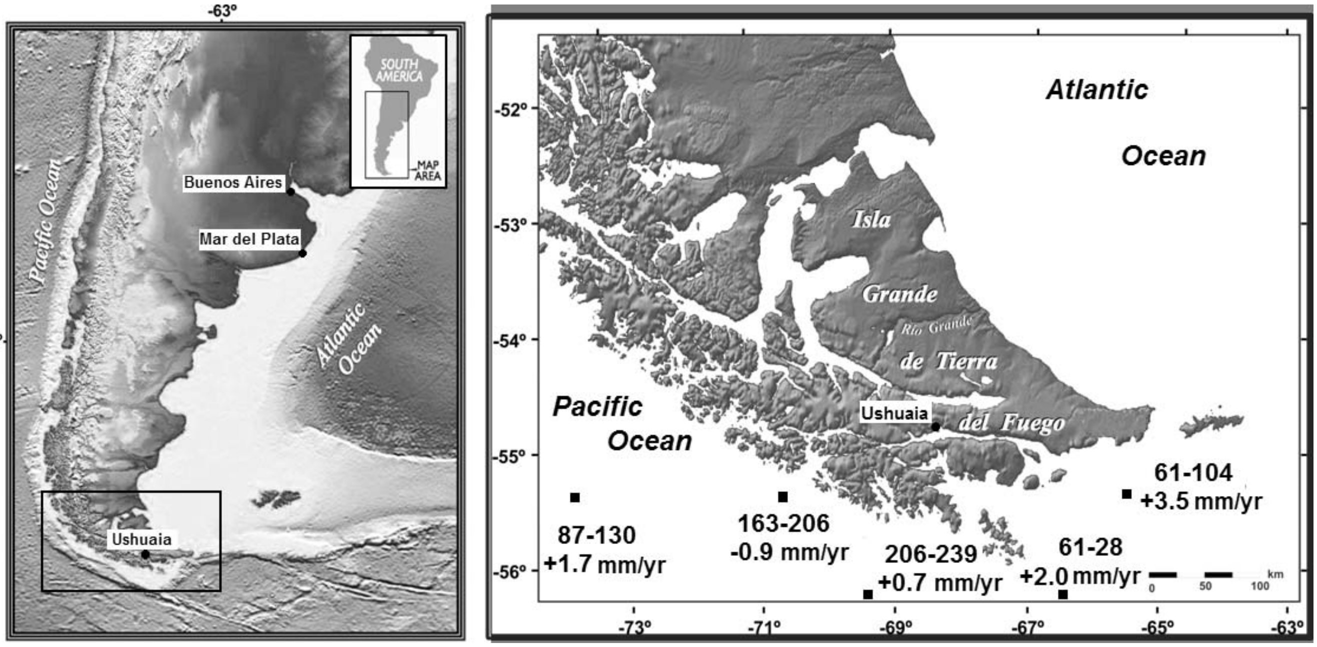

Figure 1. Study area. Sea-level trends (mm y^{-1}) estimated from altimetry data at selected crossing of satellite tracks (black squares). The corresponding pair of satellite track numbers is also given.

by these authors was the inadequate distribution and quality of tide gauges in the Southern Hemisphere.

In the present technical communication, tide gauge data were used to estimate the sea-level trend at the Ushuaia tidal station (54°49′ S, 68°13′ W), located along the coast of the southernmost city in the world (Figure 1) at Ushuaia Bay (Beagle Channel). Beagle Channel occupies a deep (150–200 m) glacial valley, well connected to the Atlantic and Pacific Oceans. The astronomical tide is a mixed mainly semidiurnal type. Tides have mean and spring ranges of 1.18 and 2.28 m, respectively (SHN, 2012). The Beagle Channel is located at the active seismotectonic setting of the Fuegian Andes (Scotia Plate Domain). It is a 5-km-wide tectonic valley that was completely covered by ice during the last glaciation. After this period, glaciofluvial and glaciolacustrine environments developed in the basin. The Beagle valley was rapidly flooded by the sea immediately after the Younger Dryas, 11,000 years BP. Holocene-raised beaches can be recognized in many places along the channel, and their elevations vary considerably, reaching maximum elevations of 10 m above the present counterpart at ages of 6000 years BP. The estimated average tectonic uplift for this period is 1.5 to 2.0 mm y^{-1} (Bujalesky, 2007). The area is characterized by several discontinuous terraces, with elevations varying from about 1.5 to 10 m above sea level. Their possible origin due to tectonic uplifting and resulting from glacioisostatic recovery was discussed by Gordillo *et al*. (1992).

MATERIALS AND METHODS

The Servicio de Hidrografía Naval (Argentina) made measurements with a float-operated tide gauge at the Ushuaia tidal station. It began working in August 1951, but it was relocated approximately 900 m from its original location in 1970. Subsequently, in 1991, this gauge was replaced by a next-generation water level measurement system, which worked until May 2006. The original tidal station was relocated in 1970, with special care taken in linking the levels of both tidal data series. Consequently, both data series gathered at Ushuaia were assembled to compose a single 54-year annual mean sea-level data series (1952–2005), which is used in this work to estimate the sea-level trend in one of the southernmost regions of South America. Data corresponding to 1963, 1975, and 1986–88 were excluded from the analysis because the mentioned periods presented several gaps.

Least-square regression line for annual mean sea level (relative to the benchmark) was fitted (Figure 2), and the computed slope (trend) did not result as significantly different

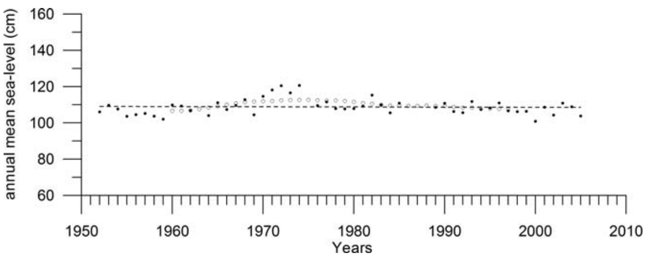

Figure 2. Linear regression (dashed line) calculated from annual mean sea-level data for Ushuaia (black circles) for the 1952–2005 period and filtered mean sea-level data (white circles).

from zero at 95% confidence. The obtained determination coefficient (the correlation coefficient squared) was rather low (<0.1), indicating a relatively high dispersion of the annual mean sea levels that is likely caused by the presence of long-period constituents of tide (longer than 1 y), which could mislead the trend of the mean sea level (Godin, 1972). A low-pass filter was applied to the annual sea-level data series to smooth the aforementioned fluctuations. Least-square regression line was fitted to the filtered annual mean sea-level data series. The obtained determination coefficient was again lower than 0.1. The slope (trend) of the calculated best fit line was equal to –0.2 mm y^{-1}, which is not significantly different from zero (at 95% confidence), similar to the previous result obtained without filtering.

DISCUSSION AND CONCLUSIONS

The interannual and longer variations of sea level can have a significant effect on sea-level trends computed from tide gauge measurements. It is generally accepted (e.g. Douglas, 1997, 2001; Peltier and Tushingham, 1989, 1991) that the determination of a linear trend in sea-level records is more reliable when a long time series of observed annual mean sea level is available (preferably longer than 50 y). In the present work, an assembled 54-year sea-level data series was use to estimate the sea-level trend at Ushuaia Bay, which presented a null trend before and after the filtering. Inspection of Figure 2 indicates that the Ushuaia sea-level data series could also be analyzed by considering two shorter subseries, one consisting of annual mean sea levels corresponding to the 1952–74 period and the other consisting of data corresponding to the 1974–2005 lapse. The first data series presents a significant and positive sea-level trend greater than 3 mm y^{-1} between 1952 and 1974 (23-y period), which is fairly higher than estimates obtained from previous studies (Bindoff *et al.,* 2007). The second data series (32 y long) presents a significant, but negative, trend of –2 mm y^{-1} between 1974 and 2005. For the complete analyzed period, the opposing trends compensate for each other, resulting in a null sea-level trend for the whole lapse (1952–2005). Such a deviation could be an effect of changes produced not only in the ocean but also in the atmosphere, where changes in annual air pressure may modify mean sea level over several years. An example of this was recently provided by Tomasin *et al.* (2011) in southern Europe, with effects on most of the Mediterranean, especially in 2009 and 2010. It is being investigated whether similar effects could have been produced, at a regional scale, around Ushuaia in the late 1960s and early 1970s. This research is the subject of another paper by the authors that is still in progress.

In this study, sea-level measurements, and therefore trends, were referred to the benchmark of the tidal station, which is located on a pier on piles driven into the bedrock. The benchmark of the tidal station is referred to the provincial leveling network. Consequently, sea-level measurements contain the signal of the vertical movement of the crust. To take into account the eustatic sea-level change, tide gauge records must be corrected for ongoing glacial isostatic adjustment (GIA) and tectonic motions. On a global basis, GIA is one of the most modeled geophysical signals present in tide gauge data. The tectonic uplift related to GIA can be simulated in global geodynamic models using corrections from the ICE-5G model (Peltier, 2004). A number of features of GIA predictions for relative sea-level rates are plotted in a map (PSMSL, 2012). It can be seen that at Ushuaia, the relative sea level is falling due to the continued uplift of the crust. The Peltier GIA prediction at Ushuaia is estimated in –1 mm y^{-1} (predicted difference in relative sea level for the last 100 y; PSMSL, 2012). However, the relative sea level is also affected by changes produced in the ocean. Considering the null sea-level trend obtained in the present work and taking into account the Peltier GIA prediction (–1 mm y^{-1}), a corrected sea-level trend could be estimated in +1 mm y^{-1} for Ushuaia Bay. This corrected sea-level trend is in reasonable agreement with the estimation of global mean sea-level rise from a reconstructed sea-level field using tide gauge data, which is around +1.5 mm y^{-1} for the 1950–2000 period (see Fig. 15 in Church *et al.,* 2004). This correction could be appropriate only for formerly glaciated high-latitude (FGHL) areas, where vertical land motion due to GIA is large compared with motion produced by other phenomena. Houston and Dean (2012) compared global positioning system (GPS) gauge measurements with the vertical land-motion component of GIA predictions at 147 worldwide locations that were near tide gauges outside FGHL areas and found remarkably little correlation. They also found that the average vertical motion for the 147 locations measured by GPS was subsidence, whereas the average GIA prediction is zero. Finally, GIA prediction is necessarily gradual, because it is predicted over a long period. It is known that the area of Ushuaia has been uplifted, because the town has been built over different marine terraces. However, this does not mean that uplift has been always gradual. For example, at Playa Larga, a few kilometers east of Ushuaia, at least five marine terraces have been uplifted during the Holocene (Gordillo *et al.,* 1992), suggesting that part of the uplift may have occurred by jolts. Consequently, GIA predictions are only a rough estimation, and its application to the sea-level trend should be carefully interpreted.

Measurements from the TOPEX/Poseidon, Jason 1, and Jason 2 series of satellite radar altimeters, which are continuously calibrated against a network of tide gauges (University Colorado Sea Level Research Group, 2012), are used to estimate the global mean sea-level trend. In this work, sea-level trend was also estimated (by means of a linear least-squares fit) by processing altimetry data gathered in a circular area (radius = 2.5 km) centered at the crossings of the satellite tracks indicated in Table 1 (analyzed period from September 27, 1992, to December 27, 2011). These data series consist of approximately 1200 corrected sea surface heights and were downloaded from Archiving, Validation and Interpretation of Satellite Oceanographic Data (AVISO, 2012). The resulting sea-level trend (Figure 1) shows high spatial variability in this region (from –0.9 to +3.1 mm y^{-1}), but the available altimetry data series are rather short. In general, results presented in Table 1 are in good agreement with results presented by Cazenave and Llovel (2010), which also show a high spatial variability in this region.

The authors of this technical communication envisage that the sea-level trend estimated at Ushuaia Bay (+1 mm y^{-1})—computed from an observed 54-year-long data series (1952–

Table 1. *Sea-level trends (mm* y^{-1}*) estimated from altimetry data (analyzed period: 1992–2011) at selected crossing of satellite tracks. Satellite track numbers, and latitude and longitude of each selected crossing, are also presented.*

Satellite Tracks (Crossing)	Latitude (°)	Longitude (°)	Data	Mean Sea Level Trend (mm y^{-1})
163–206	−55.341	−70.865	1197	−0.9
206–239	−56.164	−69.448	1177	+0.7
61–28	−56.166	−66.614	1185	+2.0
87–130	−55.343	−73.699	1201	+1.7
61–104	−55.344	−65.191	1216	+3.5

2005) and corrected by GIA—can be seen as a contribution to our knowledge of sea-level change in the Southern Hemisphere, especially southward of 50°S, where long sea-level data series are considerably scarce.

ACKNOWLEDGMENTS

This paper is a contribution to the Consejo Nacional de Investigaciones Científicas y Técnicas Proyectos de Investigación Plurianual 112-200801-02599, UBACyT 2011–14 GC 20020100100840, and Programa de Investigación y Desarrollo para la Defensa 42/10 projects.

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