Challenges in relative sea-level change assessment highlighted through a case study: the central coast of Atlantic Patagonia

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Abstract

There are areas in the world where our understanding of past sea-level changes is less robust than in others. This is partly due to the difficulty past investigators had adopting i) high-resolution elevation measurement techniques (largely available only in the last decade) and ii) standardized methodological approaches to reconstruct past relative sea levels starting from field measurements. The central coast of Atlantic Patagonia (Argentina), preserves a unique succession of coastal landforms, which scientific investigations suggest to have been formed discontinuously since at least marine isotope stage 11 up to the Holocene. Patagonian coastal deposits (in particular raised beach ridges, marine terraces and river mouth terraces) and erosional landforms (slope angles, marine notches) were studied in the past with the aim of reconstructing relative sea-level changes and provide geological evidence to constrain geophysically based models for an area affected by significant vertical displacement due to isostatic adjustment and possibly by tectonic uplift. So far, there is no general agreement about the interpretation of Patagonia landforms and deposits in terms of sea-level index points. This is certainly a gap within a planetary scale overview of sea-level change and represents an obstacle for the construction of a sound model of glacial isostatic adjustment for the area. In this paper we critically analyse previous works on sea-level change along the central coast of Atlantic Patagonia and highlight the major sources of uncertainty, including choices about calculating past relative sea levels from the elevation of indicators and the vertical datum used. We also provide a comparison between different vertical datums (tidal, gravimetric and geodetic) at a real site (Puerto Deseado) where Differential Global Positioning System measurements were performed by our team in 2016, and address the problem from a trans-disciplinary point of view. In order to obtain accurate sea-level change estimates in the area, we suggest the use of a large spectrum of sea-level markers with well-defined indicative meanings and the adoption of specific technical choices capable of minimizing instrumental errors.

Keywords: past relative sea levels, sea-level indicators, vertical datum, Argentina.

1. Introduction

Assessing past relative sea levels (RSLs) is crucial in order to constrain the effects of future sea-level change (Hay et al., 2014; Dutton et al., 2015; DeConto and Pollard, 2016). Indeed predictive models of ice sheets melting dynamics in response to ongoing global warming are tested against past sea levels evidence worldwide, especially for the interglacial periods. The availability of standardised databases is of paramount importance to provide robust quantitative evidence to the community of end users (Düsterhus et al., 2016).

Our knowledge of past relative sea levels is based on estimates obtained from sea-level indicators. These need to be analysed in conjunction with those factors responsible for vertical departures from eustasy, namely Glacial Isostatic Adjustment (GIA) (Tamisiea et al., 2015; Stocchi et al., 2018), tectonics (Simms et al., 2016; Creveling et al., 2015) and dynamic topography (Austermann et al., 2017). Using this approach it is possible to reconstruct eustatic sea-level changes, and hence continental ice volumes, in past climatic stages.

Calculating past relative sea levels from the elevation of sea-level indicators requires adherence to a standardized methodology developed in the past especially in the framework of a number of International Geoscience Programme (IGCP) projects (van de Plassche, 1986; Shennan et al., 2012). This methodology is based on the assessment of the indicative meaning for any sea-level indicator, i.e. for any element (natural or manmade) that was formed (or was built) with a known and well-defined relationship to sea-level, expressed relative to a tidal datum. The indicative meaning represents the description of the sea-level indicator's position and vertical uncertainty relative to sea level, being a function of the indicator's reference water level (RWL) and indicative range (IR). These terms will be defined in section 3.

There are areas in the world where assessing past relative sea levels is particularly important, but proves to be challenging for a combination of different reasons. One of these areas is the central coast of Atlantic Patagonia on the southern end of South America, extending from 44° S to 48° S. This area is particularly relevant because the proxies preserved here may provide sea-level fingerprints that contribute to disentangle the role of Antarctica ice sheet as a source of meltwater during past interglacials (Dutton et al., 2015). Moreover, relative sea levels from this area (in particular those of Rostami et al., 2000) have been extensively employed by GIA modellers to constrain the last interglacial global sea level (Kopp et al., 2009; Stone et al., 2013). Even more importantly, being central Atlantic Patagonia one of the few landmasses of the Southern Hemisphere where a sharp mid-Holocene highstand, due to the isostatic effect known as equatorial syphoning (Milne and Mitrovica, 2002) can be detected, the elevation of palaeo shorelines here preserved has been used to prove the existence of an earth's rotational feedback (e.g. Peltier, 2002; Peltier and Luthcke, 2009), enhancing the effect of equatorial syphoning (Toscano et al., 2011).

75 Nevertheless end-users of central Atlantic Patagonia relative sea level data apparently do not

76 sufficiently consider that, despite the presence of several well-preserved, raised shorelines spanning

77 at least four interglacials (Isla and Bujalesky, 2008), past relative sea-level assessments in this area

78 are often not in agreement with each other (Tab.1; for an updated review see Pedoja et al., 2011,

79 Pappalardo et al., 2015 and Bini et al., 2017a). As a result, only low-resolution GIA models are

80 available (Milne et al., 2005; Milne and Mitrovica, 2008) for this area. Crosschecking of field RSL

81 evidence with model data, though, is necessary to improve sea-level change estimates (Engelhart et

82 al., 2011; Whitehouse et al., 2012; Rovere et al., 2015; Vacchi et al., 2016; Antonioli et al., 2017).

83   The first aim of this work is therefore to revise past approaches in interpretation of

84 indicators along the central coast of Atlantic Patagonia in order to unravel through the reasons why

85 different investigators provided different sea-level estimates for the same highstands. As a result of

86 this review, some fundamental research questions will be addressed:

87   1. Has the standard methodology used to reconstruct past relative sea levels been

88   applied correctly in the papers on central Atlantic Patagonia coast? In case it has not,

89   which are the main issues in previous researchers' work?

90   2. Are there technical issues, apart from the methodological ones, that make obtaining

91   globally comparable past relative sea-level evidence particularly challenging in this

92   remote area? How can they be overcome?

93   From the evidence discussed in this paper, suggestions for future work are made,

94 particularly concerning the best strategies of indicators selection and interpretation and practices for

95 obtaining reliable elevation measurements related to a known vertical datum. Our work will help

96 researchers that aim to obtaining new field evidence about past relative sea levels in this area, but

97 also end-users such as shoreline databases compilers and modellers requiring to constrain their

98 work against reliable shorelines elevations.

99

100 **2. Outline of the study area**

101   The coastal fringe of Atlantic Patagonia (Fig. 1) represents the easternmost edge of extra-

102 Andean Patagonia. Geologically it is formed by the south American craton and overlapped by

103 Mesozoic and Tertiary marine/continental volcanic and sedimentary rocks (Rabassa, 2008). They

104 are differentiated as two geological provinces. To the north, the Northern Patagonian Tablelands

105 (Ramos, 1999) include a Jurassic rhyolitic and ignimbritic complex (Complejo Marifil) overlapped

106 by Tertiary formations (Lema et al. 2001) such as the continental Formación Río Chico from the

107 Upper Palaeocene made of mudstones, sandstones and often volcaniclastic conglomerates, and the

108 marine Palaeocene Formación Salamanca. They are mostly shaped in the form of tablelands locally

109 called "mesetas". To the south, the Deseado Massif (Ramos and Ghiglione, 2008) is considered a

110 structural high, formed by a core of Palaeozoic phyllites and schists intruded by granitoids (Leanza,

111 1958), and mostly shaped in volcanic rocks including middle-upper Jurassic rhyolitic pyroclastic

112 density current deposits, and volcanoclastic rocks of the Chon-Aike Formation of Bahía Laura

113 Group (Guido et al., 2004; Sruoga et al., 2004). The early Miocene marine Monte León Formation

114 (Lema et al. 2001) partly overlaps this bedrock. After the Middle Miocene geodynamic changes

115 (Guillaume et al., 2009) limited the extent of penetration of marine transgression, so that Late

116 Miocene and Pliocene marine sediments are underrepresented and poorly known.

117 A temperate arid climate (Coronato et al. 2008) is common to the entire central Patagonia

118 coastal area, with mean annual temperatures ranging from 10° to 15° and rainfall not exceeding 250

119 mm (Roig and Villalba, 2008), well distributed throughout the year. Aridity is bound to the

120 presence of the Andean range that intersects the flow of the Westerly winds creating a sharp west-

121 east rainfall negative gradient. Morphological processes affecting the area are linked to the presence

122 of continuous airflows from the west, shaping deflation landforms, and to a river runoff limited to

123 the infrequent rainstorm events (Blanco Chao et al., 2010). Coastal processes are also widespread,

124 driven by peculiar tide and wave climate. Being a typical passive margin, the coast of Atlantic

125 Patagonia extends towards the east in the form of a continental shelf as wide as 400 km. The

126 Atlantic coast of Patagonia is characterized by a mixed meso-macro-tidal regime with a maximum

127 tidal range of 4–6 m. Exposure to oceanic waves creates a very energetic environment, triggered by

128 cyclonic activity mainly over the south (Coronato et al., 2008).

129 The coastal landforms that dominate the coastal fringe of Atlantic Patagonia are mostly due

130 to its Pleistocene and Holocene evolution that produced both erosional and depositional

131 morphologies, the investigation of which dates back to the mid- 19th century (Darwin, 1846). The

132 first comprehensive investigation of these landforms is due to the Italian geologist Egidio Feruglio

133 (1933, 1950). He subdivided the fringe of coastal marine deposits into 6 morphological units,

134 tentatively assigned, based on elevation and on fossil assemblage content, to different Late

135 Pliocene, Pleistocene and Holocene transgressions. Modern studies account a number of different

136 contributions (for an updated review see Pedoja et al., 2011, Pappalardo et al., 2015 and Bini et al.,

137 2017a). The most recent contributions will be taken into account in the following paragraphs of this

138 work. An amount of work has been carried out also in order to detail the faunal assemblages of such

139 deposits (Aguirre et al., 2006; 2007; 2009; 2011; 2013; Medina et al., 2014). Recent investigations

140 have focussed on sea-level indicators formed since marine isotope stage 11 up to the Holocene,

141 including coastal deposits, in particular raised beach ridges (Schellmann and Radtke 2003; Ribolini

142 et al., 2011; Zanchetta et al., 2012, Isola et al., 2011), marine terraces (Rostami et al., 2000) and

143   river mouth terraces (Schellmann and Radtke 2010), slope angles (Pedoja et al., 2011), marine

144   notches (Zanchetta et al., 2014; Bini et al., 2014; 2017a), but also less common indicators such as

145   bioencrustations (Bini et al., 2017b) and the top of the inter-ridge swale (Pappalardo et al., 2015).

146   Although relative sea-level estimates from different authors mostly disagree (Tab. 1), the commonly

147   recognized evidence is that at least indicators of one MIS 11 and/or MIS9, one MIS 7 (with doubts),

148   only one MIS 5 and one or two Holocene highstands exist.

149

150   **3. Methods**

151   Previous works on sea-level change in central Atlantic Patagonia have been carefully

152   revised, particularly highlighting the methodology adopted in converting observations made in the

153   past into relative sea-level estimates. The standardized approach to reconstructing RSL currently

154   adopted by the sea-level scientific community (Engelhart and Horton, 2012; Shennan et al., 2012;

155   Woodroffe and Barlow, 2015; Shennan, 2015; Düsterhus et al., 2016; Rovere et al., 2016; Stocchi et

156   al., 2018 and references therein) is based on the assessment of the indicative meaning. This is a

157   function of the reference water level and the indicative range, where the reference water level is

158   usually the mid-point where an indicator is found in the modern environment and the indicative

159   range is the range over which it occurs. RSL is calculated subtracting the reference water level from

160   the altitude of the indicative range mid-point or, in case that is null, from the elevation of the

161   sample. Both need to be expressed to the same vertical datum.

162   In the experimental part of this work point elevations were measured in the field using a

163   Trimble R10 DGPS (Differential Global Position System), receiving real-time corrections through

164   OmniSTAR HP facilities, (maximum error in elevation of acquired points was ±10 cm) related to

165   the ITRF2008 datum. The data were acquired in the geographic coordinate system WGS84 and

166   post-processed converting elevations to the current global geoid model EGM2008 (Pavlis et al.,

167   2012) (4 cm planimetric error and 9 cm elevation error) and to the Argentina local geoid Ar 16.

168   Mareographic data and tidal predictions were obtained through the facilities provided by the

169   Argentinean Servicio de Hidrografia Naval (SHN, http://www.hidro.gov.ar/). Mareographic sensor

170   readings of sea-level elevations were corrected to yield elevations relative to the local vertical tidal

171   datum, i.e. to the adopted zero reference value of the mareograph. The latter was confidently related

172   to local "mean sea level" (*sensu* Pugh., 1996) i.e. to the arithmetic mean of observed hourly sea-

173   level heights. Lanfredi et al. (1998) demonstrated that the difference between the adopted mean sea

174   level (Fig. 2), i.e. the arithmetic mean of hourly heights observed in a determined time span

175   (typically 19 years), and the "calculated" mean sea level, i.e. calculated in the same way but using

176   all the available local mareographic records, is negligible for all the Argentinean mareographic

177 stations considered in their study, and in particular for the Puerto Madryn station, which is the

178 closest to our study area among those in their paper.

179   The position of current "mean sea level" (tidal datum, Pugh et al., 1996) was assessed

180 relative to other vertical datums (gravimetric and geodetic). In order to do this the ellipsoidal

181 elevation of points, measured with DGPS, was corrected to other vertical datums with different

182 approaches:

183 1. Subtracting from the ellipsoidal elevation of the point the ellipsoidal elevation of the vertical

184   tidal datum benchmark of a nearby mareographic station that is a material reference of adopted

185   mean sea level (Fig. 2).

186 2. Cross checking the instantaneous (T) ellipsoidal sea-level elevation measured with the DGPS

187   with its tidal elevation as revealed by the mareographic record, to find the correction to be

188   applied to each inland point measured in a time span sufficiently close to T (e.g. T1). The

189   methodology is commonly adopted in both macro and microtidal areas (Woodroffe et al., 2012;

190   Lo Presti et al., 2014; Woodroffe and Barlow, 2015).

191 3. Cross checking ellipsoidal elevations with geodetic elevations of the Argentinean official

192   reference network. In particular in the village of Puerto Deseado the historical geodetic

193   benchmark for the local mareograph (MOP1906, *Red de Nivelación Argentina*) has a known

194   vertical offset (i.e. 8.5975 m) above mean sea level.

195 4.   Using orthometric elevation as an equivalent of mean sea level. This assumption

196   (https://tidesandcurrents.noaa.gov/datum_options.html) is based on the definition of "geoid" as

197   an equipotential surface of the Earth's gravity field that best approximates mean sea level. In

198   order to investigate how global and local geoids approximate mean sea level in the study site,

199   we devised an experimental approach that will be described in section 4.2.

200

201 **4. Results**

202

203 **4.1 Critical review of previous RSL estimates**

204   In order to investigate if previous RSL estimates in central Atlantic Patagonia are affected

205 by errors or inaccuracies rising from an inappropriate application of the standardized RSL

206 calculation methods, we will examine each of the possible error/inaccuracy sources separately,

207 providing examples from the revised papers.

208

209 **4.1.1 Assessment of indicative meaning**

210   In some study sectors no modern analogue of the indicator feature is present and thus the

211   displacement of the indicator cannot be leveled to it. When this is the case, in most of the revised

212   literature, the indicator was considered to have formed not over an elevation range, but "exactly" at

213   a tidal level. For example, Pedoja et al. (2011) based their assessment of Quaternary relative sea-

214   levels in the study area on the elevation of slope angles, i.e. breaks in slope mostly corresponding to

215   cliff-platform or cliff-terrace junctions. The Authors state that slope angles correspond exactly to

216   "high water mark during ordinary spring tides" (Pedoja et al., 2011, page 124). This assumption is

217   largely discretionary as it is not tested in the field and it does not rely on reference in tested regional

218   indicative ranges (e.g. Vacchi et al., 2018). Rostami et al., (2000) using the elevation of marine

219   terraces to fix index points for Holocene and Pleistocene highstands, assume that these features

220   form "exactly" at mean sea level, without being able to refer to local modern analogues. More

221   accurate is the estimate of the reference water level made south of the village of Camarones, where

222   preserved bioencrustations associated to a cliff-platform Holocene morphology enabled Bini et al.,

223   2017a to retrieve a reliable index point for the mid Holocene. The ecological features of the

224   different biota forming the bioencrustation enabled the authors to consider them intertidal.

225   When the modern analogue is available, in few cases RSL was correctly calculated as the

226   displacement of the past from the modern feature. Schellmann and Radtke (2003) used the

227   elevation of fluvial terraces at the mouths of ephemeral streams to obtain sea-level index points for

228   the Holocene. They measured their displacement from their modern analogue, i.e. the bottom of the

229   mouth of current ephemeral streams, locally called Cañadones, forming at "highest tide water level"

230   (hTw). Moreover Bini et al., 2014 demonstrated that that in Puerto Deseado modern notches are

231   currently forming due to abrasion at mean high tide level (MHW) within a range of ± 0.30 m. In the

232   same area two orders of raised notches are present. The lower notch occurs in different tracts along

233   the rocky coast within a range of ± 0.20 m (Bini et al., 2014), mostly buried by beach deposits that

234   enabled to date it for correlation to ca. 0.8 cal. ka BP (Zanchetta et al., 2014). The midpoint of this

235   range is located 1.5 m above the modern analogue. The upper notch, indirectly dated to ca. 3.5 cal.

236   ky BP from outcrops in coastal caves has a retreat point 6 m above that of the active notch

237   (Zanchetta et al., 2014). More data on the displacement of Holocene and also on Pleistocene (MIS5)

238   notches in Puerto Deseado (Bini et al., 2017b, Tab. 2) relative to the modern one represent further

239   valuable evidence to infer relative sea levels for that part of the Patagonian coast. Examples of

240   estimate of the reference water level when modern analogues of the indicators occur, are all those

241   case studies where beach ridges crests are considered (e.g. Codignotto et al., 1992; Shellmann and

242   Radtke, 2010; Fucks et al. 2018). More cautiously Zanchetta et al. (2012) referred to the "high tide

243   level (HTw)", roughly corresponding to the highest astronomical tide (HAT), the beach ridge

244   backing swale used as an indicator for Holocene deposits in the area north of Camarones.

245   Pappalardo et al (2015) did likewise for Holocene and Pleistocene deposits in the same area. In both

246   papers it is stated, based on observations of the modern analogue, that the backing swale top is

247   currently "about" 1 m below the high tide water level (HAT). Multiple measurements of the

248   actively forming counterpart of this sea-level indicator would have been useful to state more

249   accurately the reference water level.

250   The indicative range has been in most cases overlooked..*Pedoja et al. (2011)* observe that

251   on rocky shores the shore angle exhibits "pluri-metric variations" in elevation implicitly suggesting

252   the indicative range should be wide. The elevations of their shoreline "angles", in fact, are

253   expressed with errors up to ± 5 m. . Bini et al., 2017a stated the elevation range of occurrence of the

254   bioencrustations they used as indicators. The error associated with their sea-level estimate was ±0.1

255   m, i.e. half of the elevation range between two "dated barnacles". This is likely to be an

256   underestimation, whereas the whole band of encrustation would be a more cautious, although wider,

257   error.

258

259   **4.1.2 Selection of vertical datum and measurement of points**

260   The second error source in building a relative sea-level curve for central Atlantic Patagonia

261   relates to the fact that indicative range and reference water level have not always been expressed to

262   the same vertical datum. This is not evident because frequently researchers have not clearly

263   specified the datums they are using. This problem may partly depend, especially when the indicator

264   modern analogue is missing, on technical difficulties in measuring the elevation of an indicator

265   relative to the current position of a tidal level in such a remote, typically macrotidal area.

266   In order to measure confidently the offset between two points (e.g. A and B in Fig. 2) barometric

267   altimeters, that have been used in a number of the revised case studies (Rostami et al., 2000, Pedoja

268   et al., 2011; Schellmann and Radtke, 2010; Zanchetta et al., 2012) are unsatisfactory. In fact a

269   random error deriving from the fluctuations of the atmospheric pressure will affect repeated

270   measures. . Our experience in Patagonia suggests that using a barometric altimeter with a precision

271   of ±1 m, after 8 hours the measured value is likely to lie within an interval of confidence of 6 m

272   around the originally measured value. In order to limit this error it should be necessary to record

273   measurements in a short time interval or to employ geodetic surveying techniques (total station or

274   basic levelling equipment, e.g.). In Patagonia this can be quite problematic, due to poor fieldwork

275   facilities (long distances to walk, poor accessibility, hard environmental conditions, e.g. strong

276   winds). In some cases (Zanchetta et al., 2012; 2014; Pappalardo et al., 2015), two 1 m long

277   graduated staffs with centimeter-precision reading, equipped with spirit bubbles, were used to

278   measure vertical offsets between two points over short distances.Reading of the distances on the

279   vertical staffs' scale were taken every meter of horizontal distance, building topographic profiles for

280   lengths up some hundreds of meters. The elevation uncertainty of these measurements proved to be

281   ± 0.50 m (Zanchetta et al., 2014). More recently a Trimble R10 DGPS (the same equipment used in

282   this work, see section 3 for details), was used as a high precision altimeter (Bini et al., 2017a;b).

283   The vertical offset between two points was calculated as the difference between the measured

284   ellipsoidal elevations, with an error of ± 0.10 m.

285   If the instrumental issue is overcome , though, relating elevation of points to a tidal datum

286   may be still be critical. In order to measure the vertical offset between an indicator and a tide level,

287   it is necessary to use physical evidence of current mean tide level (Point B, Fig. 2) or a benchmark

288   that can confidently be related to it. This is normally achieved using tide gauge records. In central

289   Atlantic Patagonia, though, operating mareographs are hundreds of km apart (Fig. 1). Due to the

290   limited availability of suitable records, it seems likely that previous authors (e.g. Rostami et al.,

291   2000; Schellmann and Radtke, 2003) have referred to predicted continuous astronomical tide levels

292   . These however may be rather different from mareograph records as they neglect unpredictable

293   meteorological and steric components, i.e. the physical effect due to changes in atmospheric

294   pressure and in seawater temperature and salinity (Pugh, 2004).

295   Some authors have expressed reference water level and indicative range to different vertical

296   datums, considering the approximation acceptable. Ribolini et al. (2011) chose the Argentinean

297   national geodetic datum to refer the inner margin of the rocky surface of Holocene marine terraces

298   in Cabo Raso, where a benchmark of the Argentinean Geodetic Network (n°9162 nivelacion

299   general) is present. Adopted mean sea level (tidal) in Puerto Madryn, the closest available tide

300   gauge, ca. 250 km north, is + 0.16 m higher than the geodetic datum (Lanfredi et al., 1998, Fig. 9).

301   If tidal levels in Cabo Raso are consistent with those adopted in Puerto Madryn, the inner margin of

302   the rocky terrace measured by Ribolini et al. (2011) 3 m above the zero reference of the

303   Argentinean geodetic datum would testify a relative sea-level fall since its formation, assumed ca. 6

304   ka BP, of 2.84 m, which is broadly consistent with the estimate of 3 m made by Ribolini et al.

305   (2011). This estimate, though, is affected by an uncertainty that cannot be stated because we do not

306   know how reliable the assumption is that the offset of mean sea level relative to the geodetic datum

307   is the same in Cabo Raso as in Puerto Madryn. The Ar 16 local geoid model shows that the geoid

308   surface is 1 m lower in Cabo Raso than in Puerto Madryn.

309   Another approach that has been used is considering the morphological marker of high tide

310   sea level along the beach during the austral summer (Schellmann, 1998; Zanchetta et al., 2012;

311   Pappalardo et al., 2015) as a physical benchmark of the highest astronomical tide level (HAT). This

312 can be recognized in a beach cross-profile (Fig. 3) In the austral summer some of the highest yearly

313 tides occur (as shown in Fig. 2 of Bini et al., 2014) in connection with the Summer solstice, and

314 wave action is very limited so that beach morphologies due to tidal energy are preserved. This

315 morphological benchmark of HAT is very useful for practical purposes, as it is a continuous feature

316 visible all along the coast; thus it can be used for altimeter calibration, enabling repeated calibration

317 checks during the day, and provides a reference for topographic profiles performed with graduated

318 staffs.

319   The most recent approach (Bini et al., 2017a,b) is represented by measuring elevations with

320 a Trimble R10 DGPS and converting them to the current global geoid model EGM2008 (Pavlis et

321 al., 2012). For practical purposes the surface of the global geoid was assumed to be equivalent to

322 mean sea level. In the next section this assumption will be discussed cross-checking it with the

323 Puerto Deseado local mareographic height datum.

324

325 **4.2 Measuring the elevation of a point relative to mean sea level in central Atlantic Patagonia**

326   During the 2016 field campaign our team performed elevation measurements with a Trimble

327 R10 DGPS (see section 3 for details) in order to state relative sea level associated with surveyed

328 indicators. Raw data were recorded as ellipsoidal heights, and then converted to orthometric heights

329 both relative to EGM2008 global geoid and to AR 16 local geoid. Based on the methodology

330 outlined in section 3, different approaches were attempted and compared in order to calculate

331 elevations relative to mean sea level.

332   It was impossible to subtract ellipsoidal elevation of measured points from the ellipsoidal

333 elevation of the vertical tidal datum benchmark (section 3, point 1), because the latter, as far as we

334 know, is unavailable (Monica Fiore, SHN, personal communication). Unfortunately, direct

335 measurement of the mareograph tidal benchmark was not possible during our DGPS field survey.

336   Alternatively, since the Puerto Deseado mareograph was active when the DGPS was

337 operated, elevations were corrected using the mareograph measurements of sea level (section 3,

338 point 2) to yield elevations relative to the local vertical tidal datum.

339   In the case study of Puerto Deseado also the methodology described in section 3, point 3

340 might have been possible. There are two points of the old Argentinean geodetic reference network

341 (*Red de Nivelación Argentina,* MOP) available in the village. The first point (MOP1906) represents

342 the historical geodetic benchmark for the Deseado mareograph and is located 8.5975 m above mean

343 sea level (http://www.hidro.gov.ar/). The other point, MOP1904 was measured during the DGPS

344 survey (28 Jan 2016). Unfortunately the geodetic elevation of MOP n°1904 was impossible to know

345 and MOP n°1906 could not be located in the field and measured.

346   Finally, as a working hypothesis we considered the orthometric heights roughly equivalent

347   to mean sea level (section 3, point 4). In order to experimentally investigate how global and local

348   geoids approximate mean sea level in central Atlantic Patagonia on January 27th-29th we carried out

349   a test measuring the ellipsoidal elevations of 4 instantaneous sea-level positions in the area around

350   Puerto Deseado (Fig. 1) within a distance of 10 km from the local mareograph, which was operating

351   during that time, although not continuously. For each point data were post-processed into

352   orthometric elevations subtracting the height of the geoid, obtained using available conversion

353   facilities (see section 3), from ellipsoidal elevations.. For the same points the elevation above

354   adopted mean sea level was inferred from the Puerto Deseado mareographic record (Tab. 2).

355   The misfit (C_g) of both geoids with mean sea level adopted in that tide gauge station is in both

356   cases relevant and similar (Tab. 2; Fig. 2). On average C_g is 3.2±0.3 m if the ellipsoidal height is

357   converted to EGM2008 geoid and 4.0 ±0.4 m if the ellipsoidal height is converted to Ar 16 geoid.

358   C_g can thus be applied as a corrective factor to the orthometric elevation of points (e.g. indicators) ,

359   to obtain an estimate of their elevation above mean sea level (tidal) acceptable in an area

360   sufficiently close to the Puerto Deseado mareograph and accurate enough for sea-level change

361   assessment at geological time scales.

362

363   **5. Discussion**
364

365   The misfit between sea-level estimates from different authors studying the same coasts in

366   central Atlantic Patagonia is due to different and in some cases unsuitable approaches to stating the

367   indicative range and reference water level of indicators, to providing vertical offsets between points

368   with the minimum instrument uncertainty and to measuring the displacement of points relative to a

369   tidal datum.

370

371   **5.1. Inappropriate applications of the standard methodology for RSL assessment**

372   A major error rises from inappropriate or inaccurate reference water level and indicative

373   range (jointly indicative meaning) calculations made by some authors. The indicative range of sea-

374   level indicators should be the first concern when collecting relative sea-level change evidence in

375   central Atlantic Patagonia. This methodology is now standardized for obtaining index points from

376   Holocene sedimentological indicators (Shennan, 1982; Shennan and Horton, 2002; Gehrels and

377   Long, 2007; Engelhart and Horton, 2012; Shennan et al., 2015; Vacchi et al., 2016) and it has since

378   been adapted also for Pleistocene studies on sea-level change (Kopp et al., 2009; Düsterhus et al.,

379   2016; Rovere et al, 2016; Stocchi et al., 2018). This method fixes the problems that occur when

380   researchers assume an indicator has only a constant relationship to a fixed position within the tidal

381 range, and do not state an indicative range, which means the resulting relative sea level has a lower

382 uncertainty but is likely to yield less accurate results. In some of the reviewed papers when the

383 modern analogue of the indicator was not present, RSL was calculated as the elevation of the

384 indicator itself relative to "exactly" a tidal level and not over an elevation range, as stated by the

385 standard methodology. For example the reference water level suggested by Rovere et al. (2016) for

386 marine terraces is from the average storm swash to the breaking depth of significant waves. This

387 issue is particularly relevant for the works by Rostami et al. (2000) and Pedoja et al. (2011). Their

388 estimates of Holocene maximum RSL, using the same indicator (marine terrace/shoreline angle) is

389 respectively 6-7 and 8-10 m. Conversely Ribolini et al (2011) using the inner margin of a Holocene

390 rocky terrace, which is a more precise indicator (Pirazzoli, 2005), provides an estimate of ca. 3 m

391 for the same RSL.

392 In those cases when the modern analogue is available, some very good estimates were

393 obtained in the area around Puerto Deseado (Zanchetta et al., 2014; Bini et al., 2017b) using notches

394 (Trenhaile, 2015). This area, though, cannot be considered representative of central Atlantic

395 Patagonia shoreline, in that it is affected by tectonic uplift (Ramos and Ghiglione, 2008).

396 The most evident cases of inappropriate usage of the reference water level concept in

397 presence of the modern analogue of the indicator, are those not uncommon cases in which a

398 mollusk shell from a raised beach ridge was dated and the RSL since its living time was estimated

399 as its elevation relative to "mean sea level" (e.g. Codignotto et al., 1992; Shellmann and Radtke,

400 2010; Fucks et al., 2018). In this case the reference water level should be considered the midpoint of

401 the elevation range at which the modern beach ridge occurs (Rovere et al., 2016). This is a severe

402 limitation in the possibility to exploit beach ridges (Taylor and Stone, 1996), that are the most

403 widespread sea-level indicators occurring in the study area.

404 The reviewed studies, even those that assign the equivalent of a reference water level, very

405 seldom estimate the indicative range. In most cases the reference water level is not subtracted to the

406 indicative range but merely to the elevation of the dated sample. The latter should have been

407 obtained, instead, as the midpoint of the elevation range over which the indicator occurs (Rovere et

408 al., 2016).

409

410 **5.2. Technical issues in points levelling and referencing to a vertical datum**

411 In this area technical issues, in addition to theoretical ones, make sea-level change

412 assessment particularly challenging. The reviewed literature shows that some of them, e.g. the

413 measurement of vertical offsets, can now be overcome thanks to technology made available to end-

414 users in recent years. Some other ones, e.g. the unavailability of mareographic stations, are still

difficult to address. In order to provide vertical offsets between points in the study area with the
minimum instrumental uncertainty, the best system is DGPS receiving real-time correction to
constrain the error within 0.2 m. This is now possible in Patagonia and most of the world thanks to
the Omnistar HP facilities. Displacement between two points can be obtained by subtracting their
ellipsoidal elevations, simply and quickly even if the two points are distant and not in sight from
one another.

Levelling the indicative range to a tidal datum, instead, can be quite difficult in the study
area. In this work we demonstrate that not all the virtually possible approaches are adoptable or
acceptable in the study area.

If the modern analogue of an indicator is present, relative sea-level is the offset between the
midpoint of the indicator's band of occurrence and that of the modern analogue (Düsterhus et al.,
2016). This offset can be measured directly. The palaeo sea-level change estimate performed by
Bini et al. (2014, 2017b) is a good example of this approach in central Atlantic Patagonia.
Unfortunately this is seldom the case in the study area.

In the absence of a modern analogue, with a DGPS it is possible to obtain reliable
assessments of point elevations relative to local mean sea level provided a mareographic station is
available nearby (Shennan et al., 2012). Provided the ellipsoidal elevation of the vertical tidal datum
benchmark (physical reference of the zero level of the mareograph) is known, the best option is
subtracting it from the measured ellipsoidal elevation of the point. If there is a mareograph without
a known ellipsoidal elevation of the vertical datum benchmark but the mareograph's record is
continuous, the simplest way to proceed is to measure by DGPS the displacement between one
point and the instantaneous sea level and correct it to mean sea level, or another tidal level
(Woodroffe and Barlow, 2015). In case the mareograph is not recording during the survey, it is still
possible to level points to intermediate benchmarks (Foster, 2015) the tidal elevation of which is
known, or can be inferred. Some past literature on central Atlantic Patagonia (e.g. Ribolini et al.,
2011) adopted this method. Unfortunately in this area, though, geodetic benchmarks are difficult to
locate and only elevations of those reported on the official national topographic maps are easily
accessible. Further inaccuracy may derive from paramount distance between benchmarks and the
closest mareographer. The solution adopted by Schellmann (1998) who used the morphological
benchmark of the highest astronomical tide level (HAT) yields moderate accurate results especially
if the indicative range can be referred to HAT. Maximum systematic error by using this marker as
benchmark can be estimated as the difference in elevation between minimum and maximum high
tide recorded in the Summer (that e.g. in Puerto Deseado is 2 m, according to Bini et al. (2014).

448 Finally, adopting tidal predictions as a substitute of the measured mareographic record (Stocchi et
449 al., 2018) is, in our opinion, unsuitable in this area.

450   In the experimental part of this work we found out that both global and local geoid surfaces
451 display a considerable offset from adopted mean sea level based on the Puerto Deseado
452 mareograph. This probably depends on the huge distance between Puerto Deseado and Mar del
453 Plata (Lat: 38°02'08" S), where the origin point of the geodetic datum was set. The calculated
454 correction factor (Cg) permits to convert the EGM2008 or Ar 16 orthometric elevation to tidal
455 elevations. This approach, though, is applicable only in a restricted area. Assuming that along the
456 coast of central Atlantic Patagonia mean sea-level changes with latitude according to the
457 displacement of the Ar 16 geoid surface, it is possible to extend the corrections from the area of
458 Puerto Deseado north up to 30" of latitude, maintaining an error within ± 0.4 m, which is an
459 acceptable value at least for Pleistocene sea-level change estimates.

460

461   **6. Conclusions**

462   Researchers wishing to make a sea-level database for central Atlantic Patagonia applying
463 standard RSL methodology have to face relevant limitations in the interpretation of past estimates
464 of RSL due to issues in many of the studies available for this area. These are partly problematic due
465 to inappropriate application of the indicative meaning concepts and omission to assign a reference
466 water level. Moreover practical issues are particularly challenging in this area due to the poor
467 availability of mareographic stations and facilities for geological fieldwork activities that result in
468 difficulties in leveling the reference water level and the indicative range to the same vertical datum.

469   In future work it will be necessary to obtain more evidence of reliable past RSLs throughout
470 the area. Recent papers (e.g. Bini et al., 2017a) demonstrate that new accurate sea-level indicators
471 can be retrieved through detailed field surveys. Reinterpretation of traditionally employed indicators
472 may be possible only if accomplished by new levelling with up-to-date technology and/or survey of
473 modern analogues in order to state their reference water level. Our work highlights that more
474 favorable conditions exist in the southern part of the study area. In Puerto Deseado there is an
475 official mareograph which is operating, although discontinuously, tied to the old geodetic network
476 of Argentina (MOP) through an historical benchmark. Elsewhere technical issues in vertical datum
477 assessment may be overcome by looking for unofficial mareographic records (Woodworth et al.,
478 2010) and/or operating a mareograph or similar device (e.g. water pressure logger) during terrestrial
479 field surveys (Edwards and Horton, 2006; Gehrels and Woodworth, 2013).Using the morphological
480 expression of the highest astronomical tide as a tidal reference may prove an acceptable
481 compromise if very high accuracy is not required. Conversely, using predictive tide tables instead of

mareographic records can lower accuracy in unpredictable ways. Due to the misfit between the gravimetric vertical datum and mean sea level, the error deriving from comparing the global/local geoid surface equivalent to mean sea level in central Atlantic Patagonia should be considered critical in assessing relative sea-level change at geological timescales and its applicability should be tested case by case. In all cases, measuring the ellipsoidal elevation of a point is advisable, as this value can be stored and later converted to a suitable geodetic, geoidic or tidal elevations. It is also advisable to combine the uncertainty due to the indicative meaning with errors from other sources (instrumental errors, errors arising from coordinates conversion etc.) using the root of the sum of the squares of individual error sources.

This paper highlights the difficulty in using available data for a shoreline database compilation in this area. The outlined issues in previous work may impact the data used to constrain and test GIA models, introducing likely errors up to several meters (Tab. 1). New relative sea level evidence for the last four interglacials and the Holocene collected with reliable methodology will improve our knowledge of sea-level change in this part of the world, filling a gap that can help to calibrate high resolution GIA models for the area, constrain the effect of rotational feedback and finally to cast new light on the geodynamic model of southern South America.

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Captions

Table 1 - Relative sea-level estimates for Pleistocene and mid-Holocene highstands recognized by different authors in the central coast of Atlantic Patagonia. In italics are reported the types of indicators employed.

Table 2 – Instantaneous elevations of sea level acquired with DGPS as ellipsoidal heights (WGS84) for specific times of the day during field survey in Puerto Deseado (27-29 January 2016); convertion to orthometric heights (global geoid model EGM2008 and Argentina local geoid Ar 16); simultaneous readings of the "prs " mareographic sensor of the Puerto Deseado mareograph (source: Argentinean Servicio de Hydrographia Naval, http://www.hidro.gov.ar/) were converted to elevations relative to the adopted mean sea level (i.e. zero reference value of the mareograph). The two last columns on the right represent the estimate of the misfit between the tidal and the geoidic vertical datum (i.e. the displacement of orthometric elevation relative to tidal elevation).

Fig. 1 - Sketch map of the study area reporting localities from which predictive tide tables are available and localities from which mareographic records are available (source: Argentinean Servicio de Hydrographia Naval, http://www.hidro.gov.ar/).

Fig. 2 – Schematic cross profile of the coast in Puerto Deseado (not to scale), with indication of the position of sea-level at 10:15 Local time (= UTC-3h) on January 27th, 2016, and its relationship with different vertical datums. For terminology refer to the text and to Tab. 1. In particular: **adopted mean sea-level** is a tidal datum specific to a mareographic station obtained by averaging hourly sea-level in a set time span (typically 19 years), and it can be considered roughly coincident with mean sea level calculated in the same way but using all the available local mareographic

768 records; **chart datum** is the zero elevation of the depths displayed on nautical charts, corresponding
769 to the lowest astronomical tidal level or other low-tide tidal datum; **SLWGS84** is the ellipsoidal
770 elevation (h) of sea level relative to the WGS84 ellipsoid; **SLgeoid** is the orthometric elevation (H)
771 of sea level relative to geoid global model EGM2008; **N** is known as the "geoid height"; **Cg** is the
772 misfit of EGM2009 geoid relative to adopted mean sea level in Puerto Deseado tide gauge station;
773 **MOP** is a benchmark of the Argentinean Geodetic Network: In particular, MOP1906 is the
774 historical geodetic benchmark for the local mareograph, and has an elevation of 8.5975 m above
775 mean sea level (tidal). **A** = position of an hypothetical sea-level indicator; **B** = benchmark of
776 current mean sea level (tidal datum).
777
778 Fig. 3 The beach cross profile in central Atlantic Patagonia during the peak of the austral Summer
779 (from mid-January to mid-February) displays a morphological step a few cm high representing the
780 innermost penetration of the sea during high tide, which can be seen in this photo at the bottom of
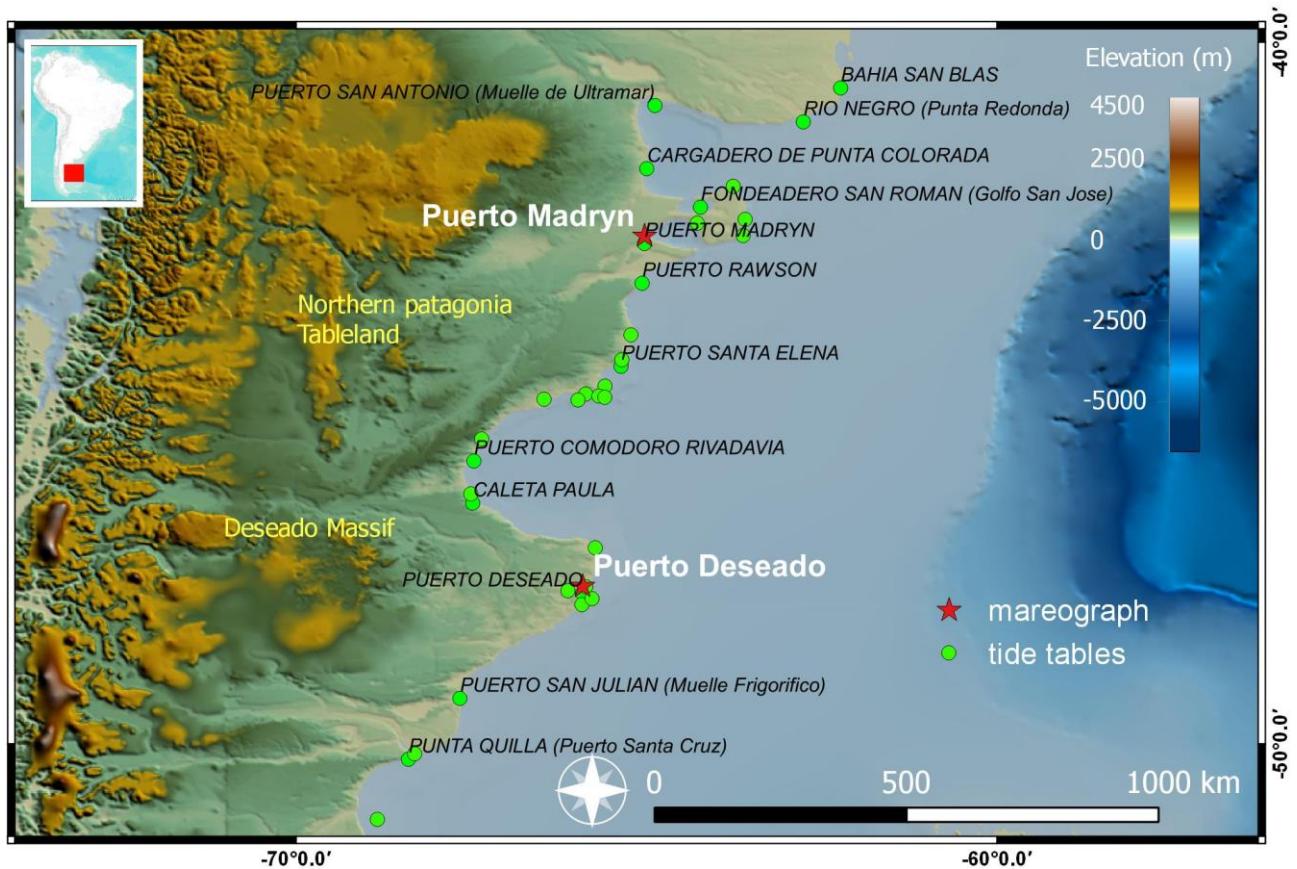781 the seaward slope of the ordinary berm (white line). The photo was taken S of Camarones (Chubut)
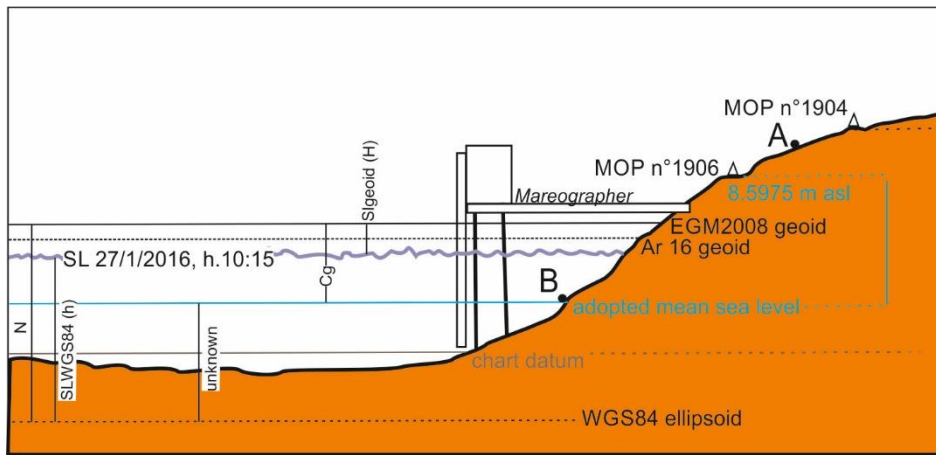782 in 2009.
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786
787 Fig. 1
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791   Fig. 2
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796   Fig. 3
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804 Tab. 1

Marker type MIS	Camarones				Puerto Deseado			
	Beach ridges top	*Marine terraces*	*Slope angles*	*Top of the inter-ridge swales*	*Beach ridges top*	*Marine terraces*	*Slope angles*	*Marine notches*
1	8-10	5.5-6	5.5-6 ± 0.5	2.5 ±1	5-6 **	6	7.5-9.5 ± 1.5	6
5	12-13 16-19 (possibly MIS7)	17	15.5-15 ± 2	7.5 +2/−3.5	18*	16-17	13-18 ± 3	21
7	21-23 (possibly MIS9)	-	24.5-29.5 ± 3	10.5 +2/−3.5	-	-	35 ± 5	-
9	26-29	33-34	41.5 ± 1.5 (uncertain)	22.5 +2/−3.5	-	-	46 ± 5	-
11	33-41 (MIS11 or older)	-	-	32.5	-	-	56 ± 5	-
	Schellmann and Radtke, 2000	Rostami et al., 2000	Pedoja et al., 2011	Pappalardo et al., 2015	* Schellmann, 1998 (Mazarredo) **Schellmann and Radtke, 2010	Rostami et al., 2000 (Mazarredo)	Pedoja et al., 2011	Zanchetta et al., 2014 Bini et al., 2017a

805
806 Tab. 2

Point description	Lat	Lon	Date Time (UTC)	Ellipsoidal (WGS84) elevation (m)	Orthometric (EGM2008) elevation (m)	Orthometric (local geoid AR16) elevation (m)	Sea-level elevation (m) recorded by the Puerto Deseado mareographer
Sea level	-47.751863	-65.863741	27/1/16 13:15	10,5 ± 0.1	-1,1	-1.8	1,8
Sea level	-47.752391	-65.866106	27/1/16 13:30	10,2 ± 0.1	-1,4	-2.1	1,8
Sea level	-47.751103	-65.861418	27/1/16 14:00	10,5 ± 0.1	-1,4	-1.8	1,8
Sea level	-47.749286	-65.940776	29/1/16 17:30	11,5 ± 0.1	0,1	-0.8	3,6

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