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Coastal Sea Level and Related Fields from Existing Observing Systems

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Abstract :

We review the status of current sea-level observing systems with a focus on the coastal zone. Tide gauges are the major source of coastal sea-level observations monitoring most of the world coastlines, although with limited extent in Africa and part of South America. The longest tide gauge records, however, are unevenly distributed and mostly concentrated along the European and North American coasts. Tide gauges measure relative sea level but the monitoring of vertical land motion through high-precision GNSS, despite being essential to disentangle land and ocean contributions in tide gauge records, is only available in a limited number of stations. (25% of tide gauges have a GNSS station at less than 10 km.) Other data sources are new in situ observing systems fostered by recent progress in GNSS data processing (e.g., GPS reflectometry, GNSS-towed platforms) and coastal altimetry currently measuring sea level as close as 5 km from the coastline. Understanding observed coastal sea level also requires information on various contributing processes, and we provide an overview of some other relevant observing systems, including those on (offshore and coastal) wind waves and water density and mass changes.

Keywords : Sea-level observations, Tide gauges, Coastal altimetry, GNSS, Wind waves, Ocean bottom pressure, Hydrography

41

42 **1. Introduction**

43 Measurements of sea level at the coast have long been required for several purposes, such as
44 for the definition of a reference level for national height systems (e.g. Woppelmann et al., 2014)
45 or for harbour operations and navigation, besides the scientific motivation to understand the
46 changes in sea level and their forcing mechanisms. Coastal sea-level monitoring is nowadays
47 becoming increasingly important as it is a key component of operational oceanographic
48 services aimed at ensuring harbour operability and safety and at generating accurate hazard
49 forecasting and reliable flood or tsunami warning systems. With sea level rise in response to
50 anthropogenic global warming being one of the major threats to the coastal zones, sea-level
51 observations are also essential to quantify the coastal response to the different forcings and thus
52 to determine the potential impacts of future sea-level rise on coastal populations, ecosystems
53 and assets.

54 Coastal sea level is driven by several physical processes acting at many time scales, from
55 seconds (including the effect of wind-waves) to millennia (for a review of the most relevant
56 processes see Woodworth et al., this issue). Understanding this wide range of variability in sea
57 level, therefore, requires considerable information, not only on the amplitude and frequency of
58 coastal sea-level variations, but also on the characteristics of the individual contributors as well
59 as on their possible interactions. In this sense, coastal sea-level observations can be seen as one
60 component of a multi-platform observing system aimed at accurately monitoring the physical
61 processes taking place in the oceans.

62 Observing systems for coastal sea-level and for the various sea-level contributors are addressed
63 in this paper. Among these contributors, wind-waves play an important role on sea level at the
64 coast (for a full discussion see Dodet et al., this issue), either directly, or indirectly through
65 their influence on the wind stress and storm surge (e.g. Mastenbroek et al. 1993, Pineau-Guillou
66 et al. 2018), and their role on the morphodynamic evolution of the nearshore (Coco et al., 2014;
67 Masselink et al, 2016). Over the ocean shelves and along the coasts, ocean mass variations,
68 reflected in ocean bottom pressure changes, are one of the dominant components of sea-level
69 variability. These barotropic processes can be forced by either local or remote atmospheric
70 pressure and wind variations, including travelling signals over the shelves or from the deep
71 ocean. Unlike over shallow waters, the major contributor to sea-level changes in the open
72 ocean, from seasonal to decadal time scales, is steric (density-driven) sea level (Meysignac et
73 al., 2017). Steric sea level in the deep ocean is also relevant to the coastal zone, as these signals
74 can propagate towards shallow waters through various mechanisms (Calafat et al., 2018;
75 Hughes et al., this issue). Thus, hydrographic measurements are also important for the
76 understanding of coastal sea-level variability. Such data, together with other ancillary
77 observations (e.g. surface meteorology), through direct analysis or ingestion in assimilation
78 systems, can significantly inform our ability to simulate and predict coastal sea level.

79 The aim of this work is to provide an overview of the current sea-level observing systems
80 focusing on the coastal zone, as well as other complementary data sets that provide insight into
81 some of the physical processes that drive sea-level variability. In section 2, we first describe
82 the present status of the global tide gauge network and the data availability. We underscore the
83 need of a continuous monitoring of vertical land motion at tide gauge stations and highlight its
84 relevance for the complementarity between tide gauges, space geodetic techniques and coastal
85 satellite altimetry, forming an integrated coastal sea-level observing system. Other emerging
86 sea-level observing platforms that overcome some of the limitations of tide gauges are also
87 described in section 3. In section 4, we describe the capabilities of wind-waves observing
88 systems, whose effects at the coast are generally not captured by tide gauges. Sections 5 and 6

89 address ocean bottom pressure and hydrographic measurements, as observations needed to
90 understand two major contributors to sea-level variability.

91 **2. Coastal sea-level observations: tide gauges and satellite altimetry**

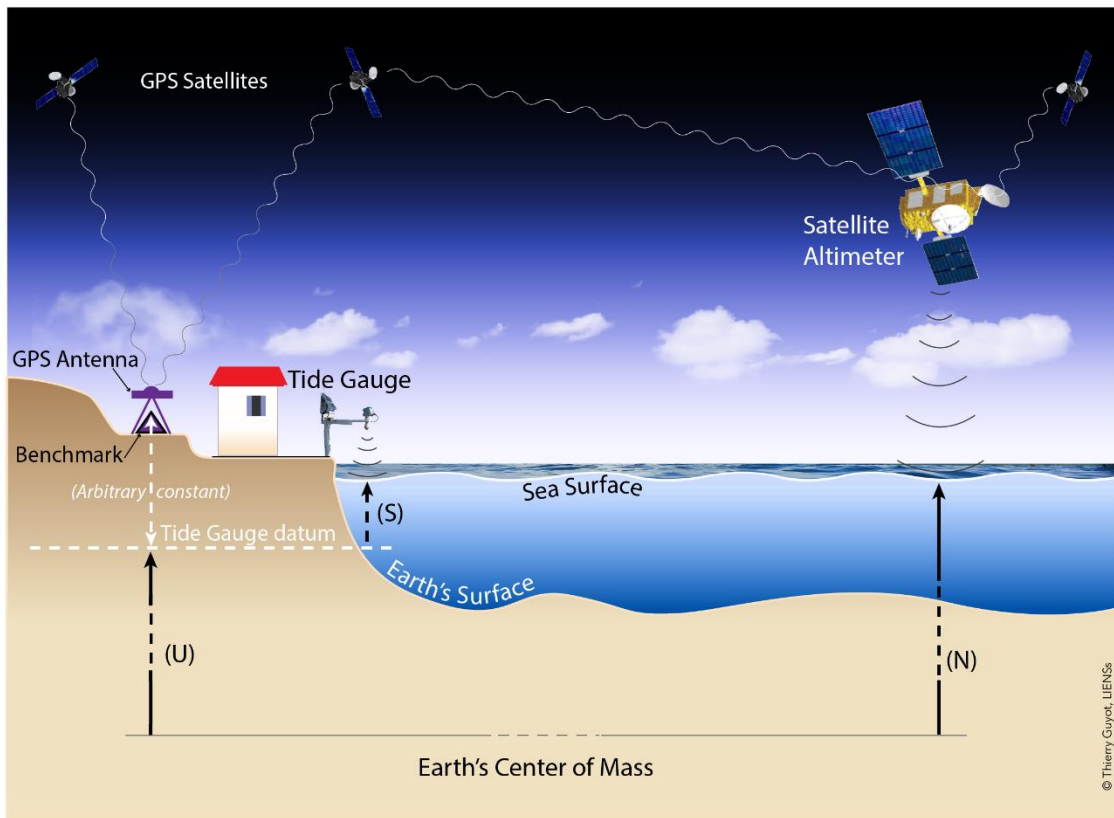
92 Tide gauges are the primary source of coastal sea-level observations, providing point-wise
93 measurements of relative mean sea level and extreme sea levels (Intergovernmental
94 Oceanographic Commission -IOC-, 1985). Initially designed for maritime navigation purposes,
95 some of the oldest tide gauge records date back to the 18th century (e.g. Woodworth and
96 Blackman, 2002; Woppelmann et al., 2006). These earliest sea-level observations were
97 measured with tide poles and registered the time and height of tidal high and low waters (e.g.
98 Woodworth and Blackman, 2002). Since the 19th century, stilling well floating gauges have
99 become the most used technology and still represent the majority of the available records (Pugh
100 and Woodworth, 2014); while originally recording sea-level oscillations in tidal charts, during
101 the 20th century they have been upgraded to provide digital storage and transmission of data.
102 New tidal stations tend to use radar gauges that measure the distance above the sea surface by
103 analysing the time-of-flight of an electromagnetic reflected pulse. This type of gauge is
104 nowadays preferred since it is relatively cheap, easy to install, and able to measure at high
105 frequencies with the required accuracy and long-term stability (Martín Míguez et al., 2008).

106 Tide gauges measure relative sea level with respect to the land upon which they are grounded
107 (Figure 1). Thus, to ensure continuity of the sea-level record, tide gauge measurements must
108 refer to a properly defined datum, generally a fixed point on land referred to as tide gauge
109 benchmark. Continuity can be achieved by systematically measuring the stability of the tide
110 gauge benchmark through high precision levelling with nearby land points that are, ideally,
111 tied to the corresponding national geodetic network. In addition, neither the height of the
112 benchmarks nor the sea-level are constant but change at different spatial and time scales;
113 therefore, precise estimates of the long-term vertical land motion are necessary in order to
114 disentangle the land and ocean contributions to sea-level change in tide gauge records.

115 Currently, space geodetic techniques provide the most accurate way to measure vertical land
116 motion (VLM) at tide gauge benchmarks. Among the Global Navigation Satellite Systems
117 (GNSS), the most common is the Global Positioning System (GPS), a cost-effective, easy to
118 install and maintain and high performance observing system (Figure 1). Woppelmann et al.
119 (2007) published the first global-scale GPS vertical velocity estimates focused on the impact
120 of VLM at tide gauges a decade ago and, since then, GPS estimates of VLM have been
121 progressively incorporated into sea-level studies (Woppelmann and Marcos, 2016). VLM
122 stems from different sources, either anthropogenic (e.g., ground water extraction) or natural
123 (e.g., Glacial Isostatic Adjustment- GIA) and over multi-decadal to centennial time scales, they
124 may display comparable values to those of the climate-related contributions to sea-level
125 change.

126 Presently, the two biggest limitations of GPS-derived VLM corrections for global mean sea
127 level are the accuracy of the reference frame on which they rely on (Santamaría-Gómez et al.,
128 2017) and the shorter length of the GPS series compared to that of the tide gauges. In those
129 cases where VLM at the tide gauge can be assumed to be constant, GPS VLM corrections reach
130 an accuracy one order of magnitude smaller than sea-level trends from climate processes and
131 therefore allow the reliable estimation of absolute sea level changes wherever both
132 measurements are available (Woppelmann and Marcos, 2016). In contrast, limited knowledge
133 of VLM at a tide gauge site can seriously bias the detection of long-term climate signals and
134 hampers the assessment of climate impacts associated with long-term sea-level rise. The
135 international program Global Sea Level Observing System (GLOSS, www.gloss-sealevel.org),

136 in recognition of this need, recommends the installation of GNSS stations co-located with tide
137 gauges.
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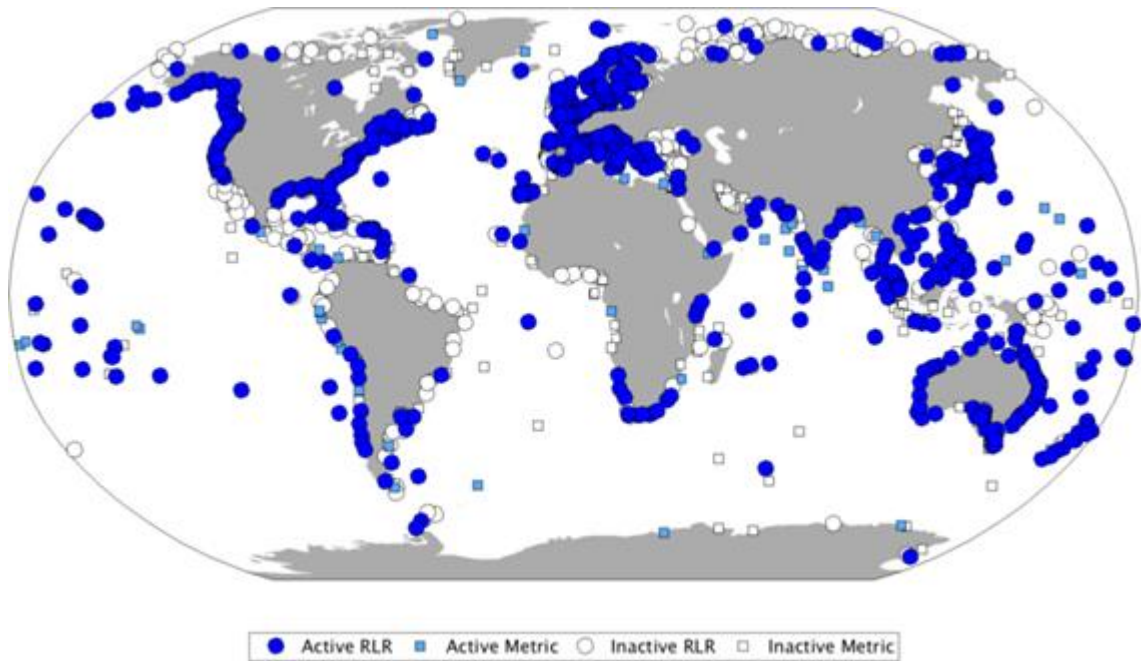


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Figure 1. Sketch showing basic observational quantities and techniques associated with sea level measurement discussed in this article

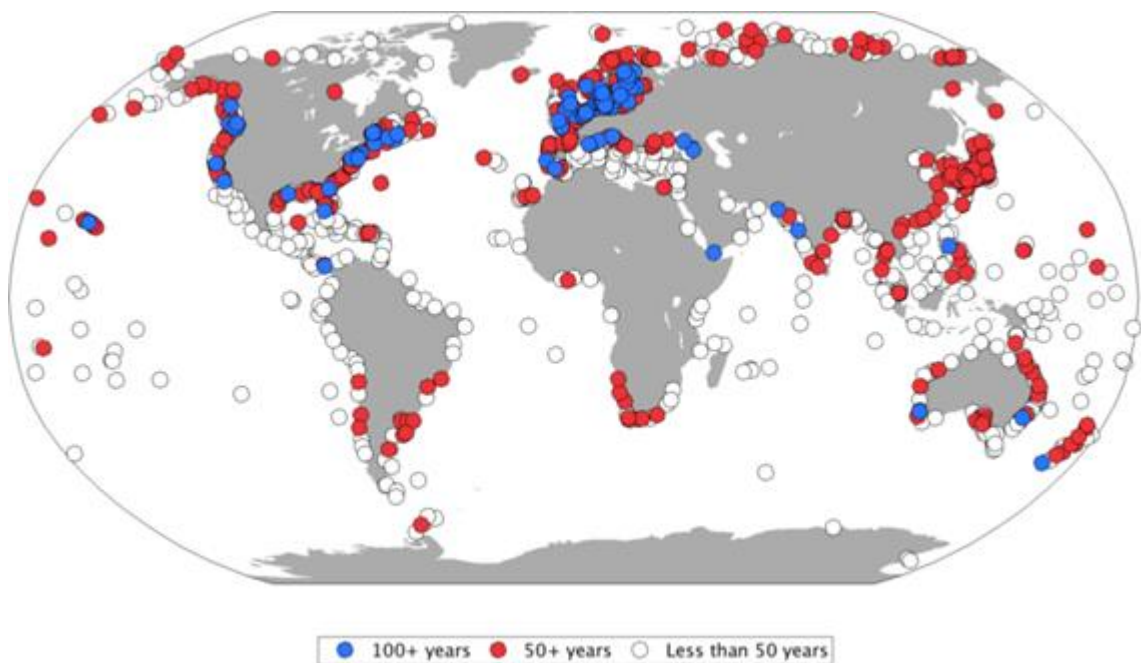
144 Sea-level records from tide gauges are stored in and distributed by international databases. The
145 most extensive data bank of long-term mean sea level changes from tide gauges is the
146 Permanent Service for Mean Sea Level (PSMSL, psmsl.org), hosted by the National
147 Oceanography Centre in Liverpool and founded in 1933. PSMSL distributes monthly mean sea
148 level records compiled from several national and subnational agencies worldwide (Holgate et
149 al., 2013) and currently hosts more than 2000 tide gauge stations, of which 1023 are active
150 (defined as those with data supplied to PSMSL in 2013 or later) (Figure 2). To be useful for
151 climate studies, sea-level records must refer to a consistent datum; these are termed as Revised
152 Local Reference (RLR) in the PSMSL data set and represent 64% of the total number of
153 stations. Despite the present-day global picture mapped in Figure 2 that shows a good spatial
154 tide gauge coverage of the world coastlines, this has not always been the case in the past
155 decades and century. Only a small subset of 89 tide gauge records span more than 100 years
156 (Figure 3), and these stations are mainly concentrated along the historically more developed
157 coastlines, mostly in Europe and North America. The number of tide gauge records increases
158 significantly since the mid-20th century (Holgate et al., 2013), although, again, with most
159 stations being located in the Northern Hemisphere (Figure 3).

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Figure 2. Tide gauge stations in the PSMSL database. Active stations (in blue) are defined as those with data supplied to PSMSL in 2013 or later. Stations with historical levelling information are identified as Revised Local Reference (RLR).



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Figure 3: RLR tide gauge records longer than 100 (blue) and 50 (red) years, not accounting for data gaps.

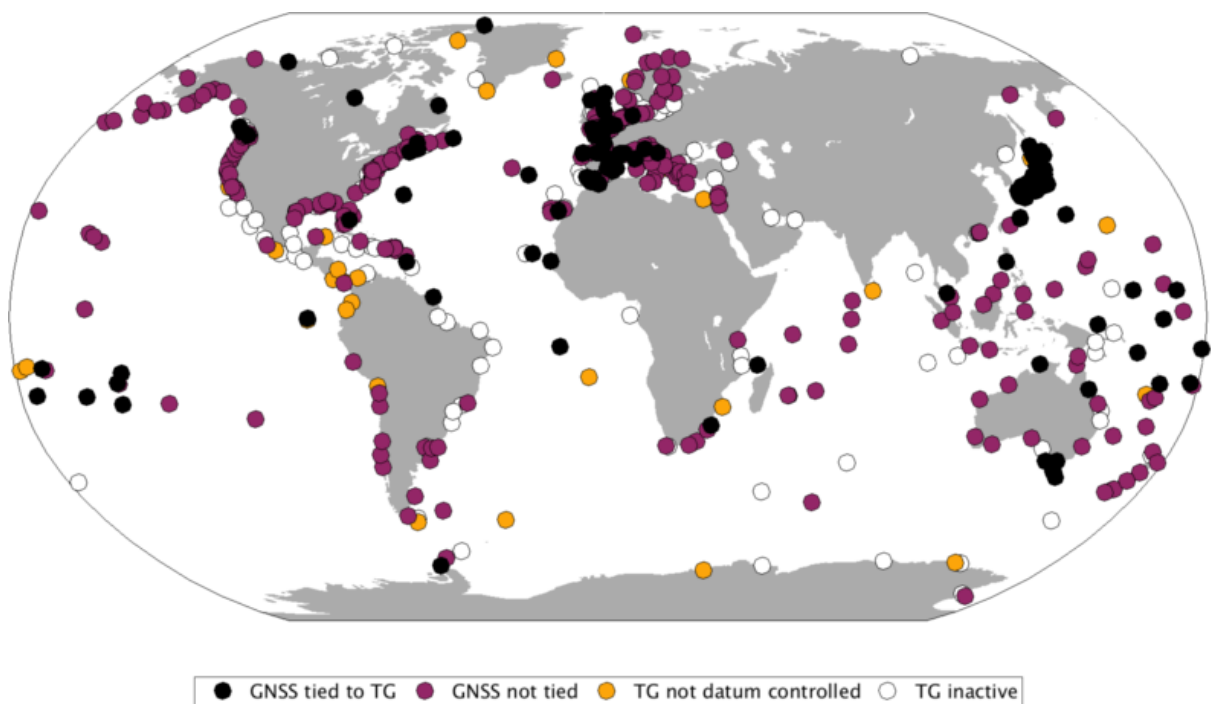
171 The uneven spatial and temporal distribution of tide gauge records and, in particular, the
172 scarcity of data during the early 20th century and before, are factors that hinder the
173 quantification and understanding of past regional and global long term mean sea level changes

174 and their driving mechanisms (Dangendorf et al., 2017). Many efforts have therefore been
175 devoted to the discovery, recovery and quality control of historical archived sea-level
176 measurements (Bradshaw et al., 2015; Hogarth, 2014). These so-called exercises of data
177 archaeology have successfully recovered sea-level information at sites as remote as the
178 Kerguelen Islands (Testut et al., 2006) or the Falklands (Woodworth et al., 2010) and as far
179 back in time as the 19th century (Talke et al., 2018; Woppelmann et al., 2014; Marcos et al.,
180 2011). Tide gauge data archaeology has been a useful tool to recover sea-level measurements
181 valuable for climate studies, given the potential to expand the databases during periods and in
182 places where no other observations exist.

183 Another major factor that hampers the understanding of contemporary sea-level changes is the
184 limited knowledge of VLM at tide gauges during the last century. Before the maturity of the
185 GNSS observations, the only VLM being accounted for in sea level studies was GIA, as it can
186 be modelled with prescribed ice history and solid Earth properties (e.g. mantle viscosity). With
187 the development of high precision GNSS, VLM is nowadays estimated from observations.
188 Global GPS velocity fields are routinely computed and distributed by a number of research
189 institutions (International GNSS Service, Jet Propulsion Laboratory, University of Nevada,
190 University of La Rochelle). Among these, only the French SONEL (Système d'Observations
191 du Niveau des Eaux Littorales) data centre, hosted at the University of La Rochelle, provides
192 GPS observations and velocity estimates focused on the coastal areas and tide gauge stations,
193 thus being closely linked to PSMSL and forming an integrated observing system within the
194 GLOSS program. Unfortunately, and despite the GLOSS recommendations, only a limited
195 number of tide gauges is co-located or tied to a nearby GNSS station (Figure 4). In particular,
196 in the PSMSL database only 394 RLR stations are within a 10km distance from a GNSS station
197 and, among these, only for 102 stations the levelling information between the two datums is
198 available, which is a serious limitation for some applications such as studies on the ocean
199 dynamic topography (Woodworth et al., 2015).

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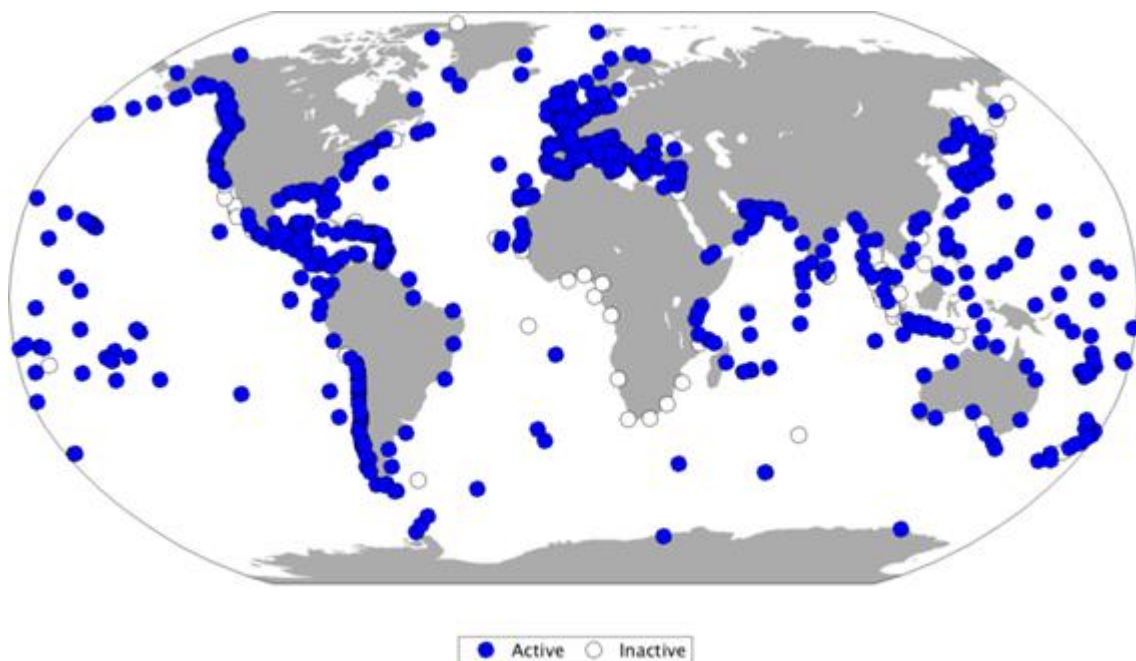
203 Figure 4. GNSS stations with (coloured) and without (blank) a tide gauge within 10 km,
204 according to PSMSL and SONEL databases [data accessed on 3 September 2018]. Black dots
205 indicate RLR stations where GNSS and tide gauge datum are tied, purple dots indicate
206 otherwise. Orange stations have no information about the tide gauge datum continuity (metric
207 stations).

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209 Coastal mean sea level can be also obtained from other data portals. These include the European
210 Copernicus Marine Environment Monitoring Service (CMEMS, <http://marine.copernicus.eu/>),
211 the University of Hawaii Sea Level Center (UHSLC, <https://uhslc.soest.hawaii.edu/>) and
212 numerous national data services. For long-term sea-level studies they provide mostly data that
213 is also available in PSMSL. In addition, some of them distribute high frequency (hourly and
214 higher) sea-level measurements required for the study of tides and extremes and/or real time
215 measurements needed for purposes such as operational oceanographic services or tsunami
216 monitoring and warning systems. The Flanders Marine Institute (VLIZ, www.vliz.be/en) hosts
217 the GLOSS sea level monitoring facility for real time data. Of a total of 993 tide gauge stations
218 currently hosted and distributed by VLIZ (Figure 5), 856 are active (defined here as those
219 stations that have supplied data in 2018). The UHSLC hosts two subsets of high frequency sea
220 level observations: one termed as fast delivery for operational purposes and another one of
221 research quality in which the same data have undergone a quality control process. The Global
222 Extreme Sea Level Analysis initiative (GESLA, www.gesla.org) extends the UHSLC high
223 frequency sea level data set unifying and assembling delayed-mode observations compiled
224 from national and sub-national agencies. The GESLA data set is presently the most complete
225 collection of high-frequency sea level observations, with 1355 tide gauge records (Woodworth
226 et al., 2017).

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230 Figure 5. Tide gauge stations providing real time sea level observations to VLIZ data centre.
231 Active stations are defined as having contributed data in 2018.

232

233 In addition to the tide gauge monitoring, sea-level variations are also continuously measured
234 by high-precision satellite altimetry with quasi global coverage since 1992 (Figure 1). The
235 constellation of altimetry missions over the last 25 years will be continued with operational
236 missions in the future (see Vignudelli et al., this issue). Near coastlines, the sea-level data
237 retrieval and interpretation from altimetry measurements become particularly complex.
238 However, in the last decade there have been important advances that have extended the
239 capabilities of satellite altimetry for the observation of coastal sea level: great progress has
240 been made in altimeter instruments (CryoSat-2, AltiKA, Sentinel-3A&B) and also in the
241 processing algorithms and products (see Vignudelli et al., this issue, for more details). Although
242 there is still a gap of information in a coastal band a few kilometres wide, this is continuously
243 reduced thanks to the efforts invested by the altimetry community. Nowadays, sea-level data
244 derived from satellite altimetry are available generally up to 5-10 km from the coastline, much
245 closer than only a few years ago (Biol et al., 2016). Thus, altimetry data is now providing very
246 valuable information for coastal sea level studies (Cipollini et al., 2017) and it is expected that
247 it will become an additional source of long-term sea-level observations, which will be
248 especially relevant in coastal zones where in-situ data are inexistent or scarce.

249 Tide gauges and satellite altimetry have different spatial and temporal sampling. Radar
250 altimeters measure sea level along the satellite ground tracks every 6 km and with a typical
251 distance between the ground-tracks of 50–300 km (depending of the number of satellites in the
252 altimeter constellation). Several projects are currently generating data at a higher rate
253 (corresponding to along-track distances of 175-350 m) with dedicated algorithms. The revisit
254 time of observations is a few days. Although not (yet) available up to the coastline, altimeter
255 data offer a nearly-global regular spatial sampling from the deep ocean to part of continental
256 shelves (sometimes a large part), and thus a regional view of ocean dynamics. In contrast, tide
257 gauges measure sea level every few seconds or minutes but only at a single coastal point, often
258 at relatively sparse locations. The two data sets are therefore complementary and often
259 integrated to maximise the information they provide (Figure 1).

260 One major difference between the two data sets is the geodetic reference frame to which they
261 are related. Tide gauges provide relative sea level while satellite altimetry measures ‘absolute’
262 sea level variations with respect to a reference ellipsoid. Levelling of the tide gauge benchmark
263 by means of geodetic methods is thus necessary if altimetry and tide gauge absolute sea levels
264 are to be compared.

265 As a final remark, it is worth mentioning that relative comparisons between satellite altimeter
266 and tide gauge observations are essential to evaluate the long-term stability of satellite
267 altimetry. They are also systematically used to evaluate and validate new altimeter missions,
268 data processing algorithms and products. In that sense, both types of sea level observations can
269 again be considered as two components of the same global observing system.

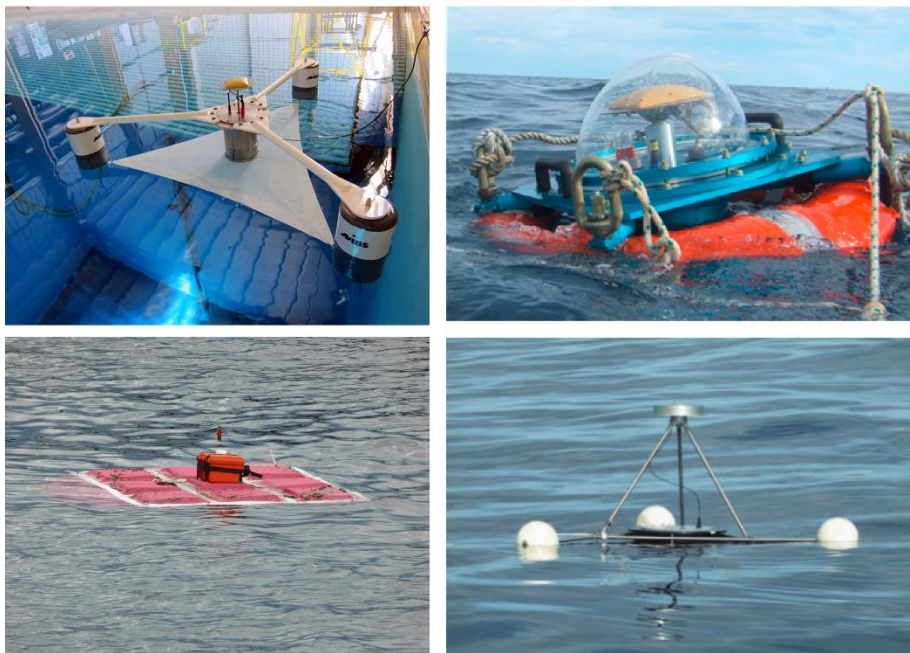
270 **3. Other sea-level monitoring platforms**

271 In addition to extensively used tide gauge and altimetric observations, coastal sea level is also
272 monitored by emerging GNSS-based methods. These observing systems have benefited from
273 progress in GNSS data processing. In particular, the development of GNSS Precise Point
274 Positioning in kinematic mode with integer ambiguity fixing allows for centimetre accuracy
275 (Laurichesse et al., 2009; Fund et al., 2013) without the need of a reference station. Some of
276 these new systems are reviewed here. They provide complementary measurements, often
277 designed for particular purposes and locations.

278 Taking advantage of GNSS co-location with tide gauges, GNSS radio signals reflected from
279 the sea surface have been used recently to estimate coastal mean sea level, with daily mean

280 differences of a few cm with respect to conventional tide gauges (Larson et al., 2013). The
281 GNSS reflectometry technique provides an alternative coastal sea-level observing system with
282 important advantages: coastal mean sea level is measured directly in a geocentric frame
283 consistent with satellite altimetry; it does not require in-situ calibration; the vertical tie between
284 the GNSS antenna and a nearby tide gauge can be done remotely and continuously, i.e., it
285 allows monitoring the stability of the tide gauge zero (Santamaría-Gómez and Watson, 2016).
286 With the new GNSS constellations (e.g. Galileo, Beidou) and the new and more precise signals
287 (e.g. AltBOC, Fantino et al., 2008), this technique will improve precision and sampling rates,
288 maximizing the benefit of co-location with tide gauges.

289 Another example is the use of GNSS, in particular GPS, on floating devices that emerged with
290 the birth of precise satellite altimetry and the subsequent need for in-situ data calibration. These
291 data provided estimates of the absolute bias of the altimetry system, which is critical to monitor
292 its long-term stability and assess sea-level trends. First GNSS buoys were developed for the
293 absolute calibration of TOPEX/Poseidon (Hein et al., 1990; Rocken et al., 1990; Born et al.
294 1994). Since then, many different designs have been proposed to ensure a centimetric sea level
295 height measurement and reduce the impact of the inherent limitation of the system (Figure 6),
296 such as the ease and duration of deployment, the quantification of the height of the GNSS
297 antenna phase centre above the water line and the tilt of the antenna from vertical. The results
298 from an inter-comparison of different GNSS buoy designs carried out at Aix Island (west coast
299 of France) in 2012 showed that these devices are able to measure the absolute sea level height
300 with cm-level accuracy, thus being comparable to the precision of the reference radar tide
301 gauge (André et al., 2013). GNSS buoys are now routinely used in dedicated satellite altimetry
302 calibration sites such as Corsica Island in the Mediterranean Sea (Bonfond et al., 2003a),
303 Bass Strait in southern Australia (Watson et al., 2003) and now the Harvest Platform in the US
304 Pacific coast (Haines et al., 2017). They are also used for tide gauge error characterization and
305 calibration (Watson et al., 2008; Martín Míguez et al. 2012; André et al., 2013) and vertical sea
306 floor height monitoring (Ballu et al., 2010).



307
308 Figure 6. Illustration of four different GNSS buoy designs. Top left and right are respectively
309 buoys designed at DT-INSU and IGP (André et al., 2013). Lower left is a new light buoy
310 design by DT-INSU based on the blanket concept to closely follow the water surface. Lower

311 right buoy is the buoy used at Bass Strait (Australia) for altimetry calibration studies (Watson
312 et al. 2008).

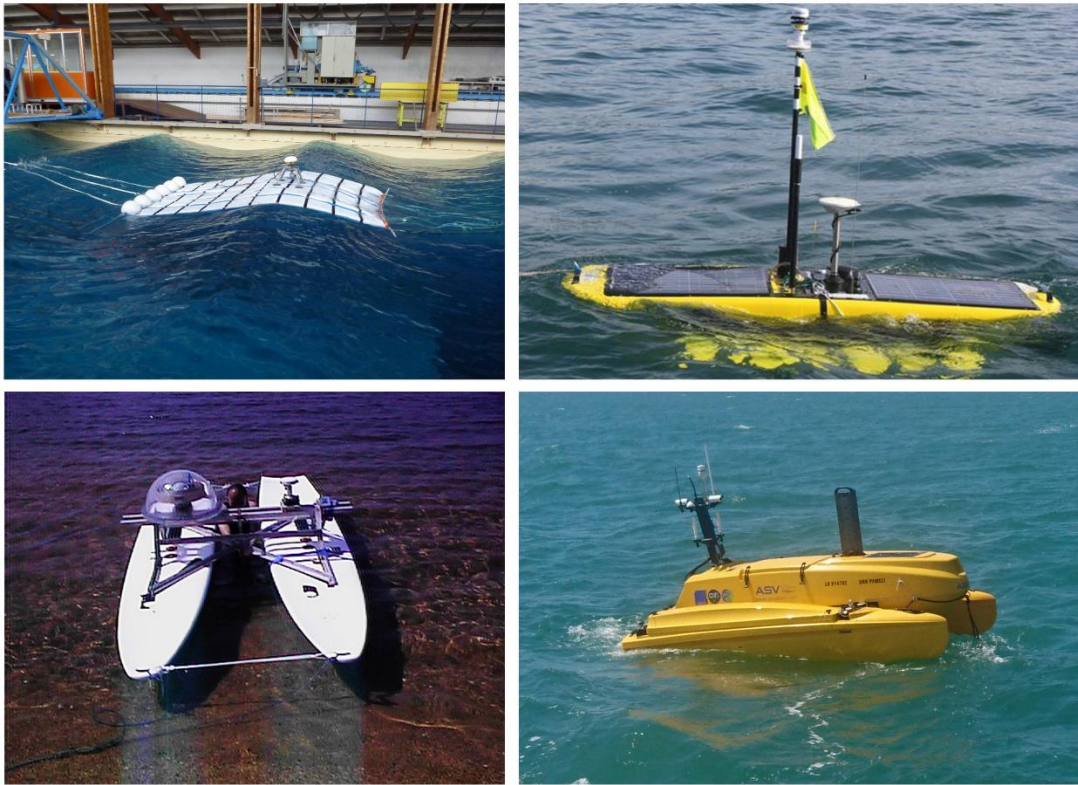
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314 Rather than pointwise measurements, mapping spatial variations of sea surface height in coastal
315 areas brings invaluable information on the local geoid as well as for hydrodynamic processes.
316 These variations cannot be properly apprehended by tide gauges or GNSS buoys, nor by
317 satellite altimetry due to the proximity to land and limited spatial and temporal sampling. Sea
318 surface height mapping has been carried out so far using GNSS equipped boats or towed
319 platforms to retrieve local geoids (Bouin et al., 2009a). Such efforts have been used, for
320 instance, in calibration/validation altimetry studies, both to get the geoid height difference
321 between the reference tide gauge and the nearby satellite track and to increase the quality of
322 the altimetry processing by better accounting for along and across-track gradients (Bonfond
323 et al. 2003b). A major issue for these measurements carried while moving is the monitoring of
324 the GNSS antenna air-draft (elevation difference between the above water GNSS antenna and
325 the water level), which can vary with the load or speed of the measuring platform (Bouin et al.
326 2009b; Foster et al., 2009; Reinking et al., 2012). To overcome this limitation, a new
327 measurement system based on a towed blanket has been proposed, which ensures a perfect
328 coupling between the floating device and the sea surface and therefore, a constant GNSS
329 antenna height above water. The device is a floating blanket made of foam boards assembled
330 with marine fabrics; the GNSS antenna is mounted on the blanket using a tripod, and its
331 verticality while in motion is achieved using a gamble system (see Figure 7). A number of tests
332 of this design have been carried out under various conditions (Bangladesh, Aix Island and
333 Corsica in France, Kerguelen) with successful results (Calzas et al., 2014; Durand et al., 2017).

334

335 Another alternative system to map spatial variations in sea surface height arises with the
336 development of Autonomous Surface Vehicles (ASV). For example, Penna et al. (2018) used
337 a self-propelled Wave Glider (built by Liquid Robotics) equipped with a GNSS recording at
338 5Hz to cover a distance of 600 km in 13 days with centimetric precision. This system proves
339 its efficiency for offshore areas; however, with over 6m of water-draft and a manoeuvrability
340 highly dependent on weather conditions, it is not suitable for shallow coastal waters and areas
341 with heavy maritime traffic. In contrast, the University of La Rochelle and DT_INSU (Division
342 Technique de l'Institut National des Sciences de l'Univers) are currently developing a
343 measurement system, named PAMELi (Plateforme Autonome Multicapteur pour l'Exploration
344 du Littoral, Ballu et al., 2017), integrating a continuous air-draft quantification to be installed
345 on a C-CAT3 built by ASV Global company (<https://www.asvglobal.com/product/c-cat-3>).
346 Unlike the Wave Glider, this system can also measure sea surface heights in shallow waters
347 and should be suitable for zones with significant maritime traffic thanks to its remotely
348 operating capabilities that include real-time camera viewing. The interest of such systems
349 compared to the towed blanket is both its compactness/manoeuvrability and its ability to be
350 used as a multi-sensor platform for an integrated study of the dynamics of coastal waters. For
351 instance, the PAMELi platform will be able to continuously monitor en-route temperature,
352 salinity, turbidity, chlorophyll, bathymetry, atmospheric parameters in addition to mapping sea
353 surface height (Coulombier et al., 2018). Such mobile devices will be key for in-situ calibration
354 of future wide-swath satellite altimeters and validation of coastal hydrodynamical models.
355 Integrated systems will contribute to better monitorization and interpretation of sea surface
356 height variations at short temporal and spatial scales.

357



358

359 Figure 7. Illustration of moving GNSS platform for sea surface height mapping (towed blanket
 360 (Calzas et al., 2014), Wave-glider (Penna et al. 2018), Catamaran (Bonfond et al., 2003b),
 361 and AUV-PAMELi (Coulombier et al., 2018)

362

363 4. Wind-wave observations

364 Direct wave effects on coastal sea level exist at all time scales, from a mean sea level response,
 365 known as wave set-up, to the swash and possible overtopping lasting only a few seconds (Dodet
 366 et al., this issue). Intermediate time scales are dominated by infragravity waves with typical
 367 periods of 30 to 300 s. Due to the range of spatio-temporal scales, the observational
 368 requirements for accurately monitoring these processes are different. Furthermore, all these
 369 effects of waves on the sea level are concentrated in the “surf zone” where the along-shore
 370 variability can be very large as the sea state is strongly influenced by the bathymetry (Munk
 371 and Traylor 1947, Magne et al., 2007), bottom types (e.g. Ardhuin et al., 2002; Lowe et al.,
 372 2007; Monismith et al., 2017) and currents (e.g. Battjes 1982; Ardhuin et al. 2017). As a result,
 373 only specific surf zone locations have been equipped with routine continuous measurements
 374 (including wave height, period and direction), as it is today impossible to monitor the strong
 375 alongshore variability of the wave impacts.

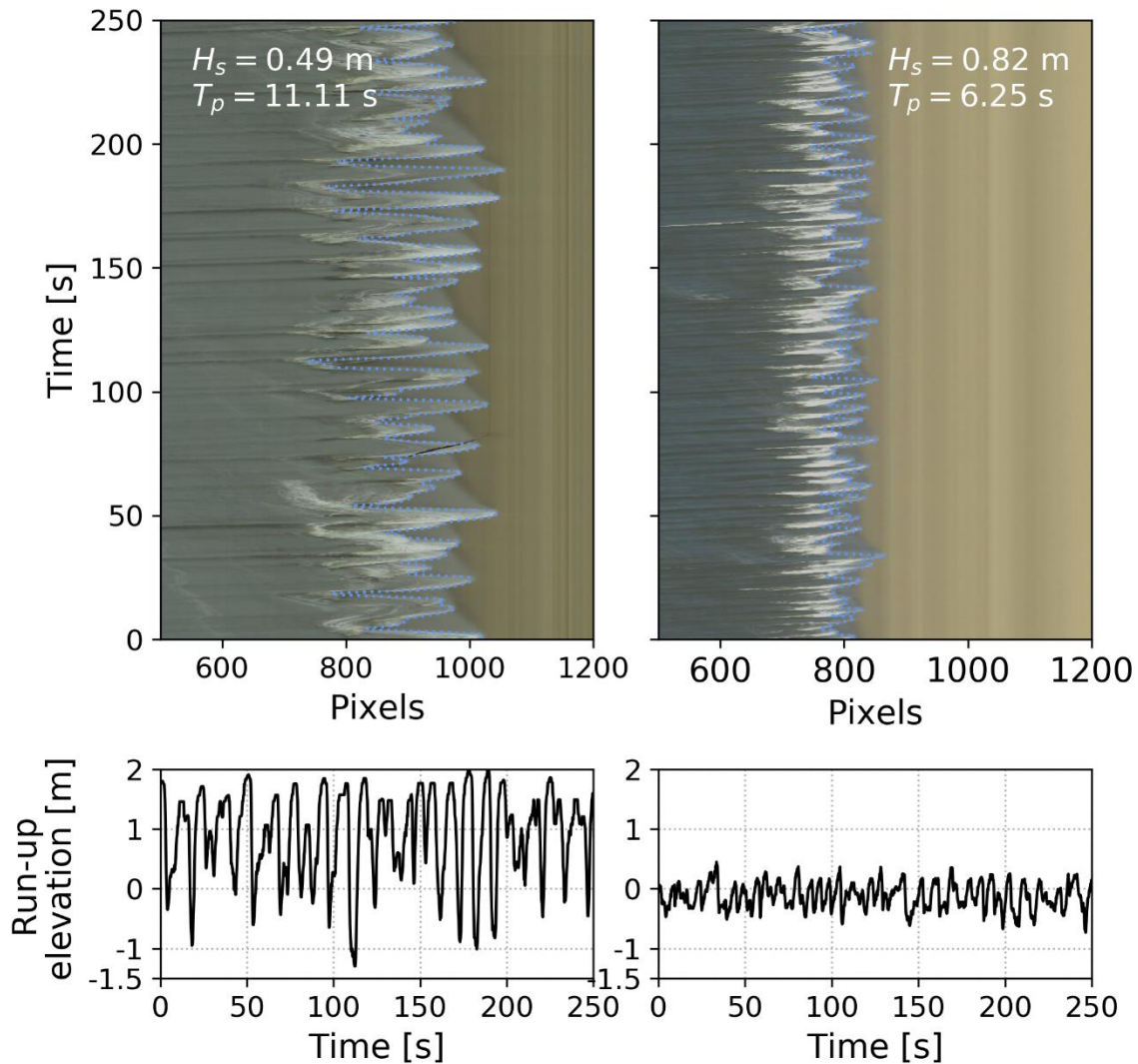
376 Surf zone processes have been the topic of targeted instrument deployments (e.g. Guza and
 377 Thornton 1981; Egar et al., 1997; Senechal et al., 2011a). Such experiments have confirmed
 378 that the wave set-up is caused by the cross-shore convergence of the wave-induced momentum
 379 flux, known as the radiation stress (e.g. Raubenheimer et al., 2001). This balance is also
 380 perturbed by bottom friction in the shallowest regions (Apotsos et al. 2007). Wave set-up, just
 381 like wave transformation in general, is strongly influenced by the nearshore underwater
 382 bathymetry (Stephens et al., 2011), which is problematic to measure directly (e.g., Dugan et
 383 al., 2001) or indirectly (e.g., Holman et al., 2013). Despite their importance, measurements of
 384 underwater bathymetry in the surf zone remain a challenge and at present such data is only

385 available at few sites and for short temporal intervals obtained through in-situ surveys. The
386 development of remote sensing techniques from high resolution radar or optical satellite
387 imagery (e.g. Pleskachevsky et al. 2011) now benefits from faster revisits using Landsat 8 and
388 Sentinels 1 & 2 (Hedley et al. 2012) but bathymetric changes during storms, which are larger
389 and most relevant, are still inaccessible.

390 The “infragravity” oscillations of the sea level at the scale of a few minutes are associated to a
391 more complex balance with a transfer of energy from the wind-waves that is influenced by the
392 varying water depth (see Bertin et al., 2018 for a review). Infragravity (IG) wave heights are
393 generally proportional to the wind-wave height but that proportionality factor varies
394 considerably with the depth profile, with larger proportionality factors on steep slopes
395 (Sheremet et al., 2014). Measurements of IG waves have been relatively few so far. Right at
396 the shoreline, the large variation of the cross-shore IG wave height is generally poorly captured
397 by a sparse array of pressure gauges and current meters (e.g., Raubenheimer, 2002). Offshore
398 pressure gauges can provide a region-integrated measurement of IG waves at the coast as they
399 propagate offshore (e.g. Rawat et al., 2014; Neale et al., 2015). The other extreme is given by
400 high frequency tide gauge data, usually from harbours. These are purely local measurements
401 in which the IG frequency band can be strongly amplified into seiches by harbour resonances
402 (e.g. Okihiro et al., 1993; Ardhuin et al., 2010). All these measurements only offer a few proxy
403 of the IG amplitudes on the open coast and just at a few selected locations.

404 Other observation systems of wind-waves include, in daylight, routine monitoring techniques
405 based on video imagery that have been perfected over the past 30 years (e.g. Holman and
406 Stanley, 2007). As video instrumentation, data storage and processing time are becoming
407 cheaper, video records are now included in many coastal monitoring programs (e.g.,
408 <http://ci.wrl.unsw.edu.au/> and Figure 8) and used to study wave runup, also during extreme
409 events (Senechal et al., 2011b). Recent experiments with Lidar are an interesting alternative
410 for all-weather surveys of beach transects (Fiedler et al., 2015). Other sparse surveying
411 strategies have also used photography and high-water marks (Cariolet and Suanez, 2013). Such
412 measurements have provided extensive datasets that form the basis of empirical formulas
413 linking, mean, IG and extreme sea levels to “offshore” wave parameters, generally the
414 significant wave height, mean period and beach slope (Stockdon et al., 2006).

415



416

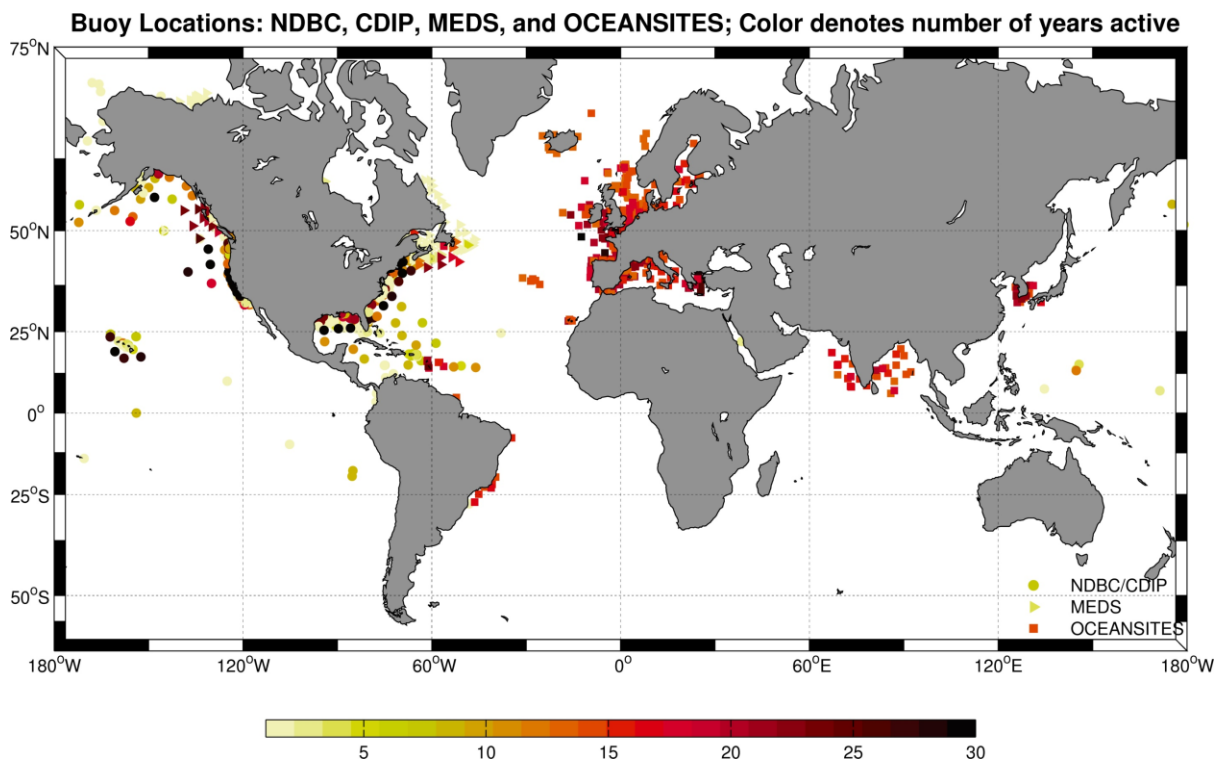
417 Figure 8. Examples of time stacks showing shoreline position over time (top panels) during
 418 (left) high and (right) low tide. The corresponding significant wave height (H_s) and wave peak
 419 period (T_p) are indicated for each case. Bottom panels show the detrended runup elevation time
 420 series. Observations collected at Bunkerhill Beach, Sylt, Germany (courtesy of J. Montano).

421

422 Whatever the wave transformations and impacts along the coast, there is an evident need for
 423 observations on offshore sea state parameters that trigger those effects. The longest time series
 424 are available for wave heights from in-situ measurements using voluntary observing ships
 425 (Gulev et al., 2003) and buoys (Figure 9) and from satellite altimeters (Queffeulou, 2013).
 426 Conversely, the routine measurement of wave periods is limited to the few available buoys or
 427 platforms (Figure 10). To overcome this limitation, proxies for a mean wave period have been
 428 proposed using radar backscatter and wave heights from altimeters (e.g. Gommenginger et al.
 429 2003; Quilfen et al., 2004). It should be still investigated how well these proxies perform for
 430 estimating extreme coastal sea levels. In the near future, it is expected that forthcoming
 431 satellites will bring a direct measurement of the dominant period in most sea state. This is the
 432 case of the SWIM instrument on CFOSAT (Hauser et al., 2017), to be launched in October
 433 2018. The proposed SKIM satellite would go a step further in resolving the dominant waves
 434 even in enclosed seas (Arduin et al., 2018). Still, even with a 300 km wide swath SKIM
 435 would have a revisit time of 4 days at mid-latitudes that is insufficient to resolve the fast time

436 scale of storms. This large revisit time, compared to the typical time scale of 12 hours for storm
 437 duration, makes it impossible, from satellites alone, to derive reliable statistics on extreme
 438 wave parameters and associated impact on sea level.

439



440 Figure 9. Location of wave-measuring devices affiliated to the NDBC, CDIP, MEDS or
 441 OCEANSITES networks with the length of records in years indicated by the colours.

442

443 It should be emphasized that all these observations systems have not been designed for the
 444 analysis of wave impacts on sea level trends. Indeed, an increase in significant wave height by
 445 2 cm produces an increase in sea level by 0.5 to 6 cm on typical beaches, depending on
 446 shoreface slope, wave period and bed composition (Stockdon et al., 2006; Poate et al., 2016).
 447 As a result, a reasonable goal for the accuracy of trends on wave height is an accuracy lower
 448 than the mean sea level rise of 3 mm/year. This should apply to the extreme values, be it the
 449 95th percentile or a 10-year maximum wave height, depending on applications. This is more
 450 demanding than the existing requirement of 5 cm per decade that is today the goal listed by
 451 GCOS, but it is also much less than what has been achieved by studies of buoy data for which
 452 the accuracy is of the order of 3 cm/year (Gemrich et al., 2011).

453 **5. Ocean bottom pressure observations**

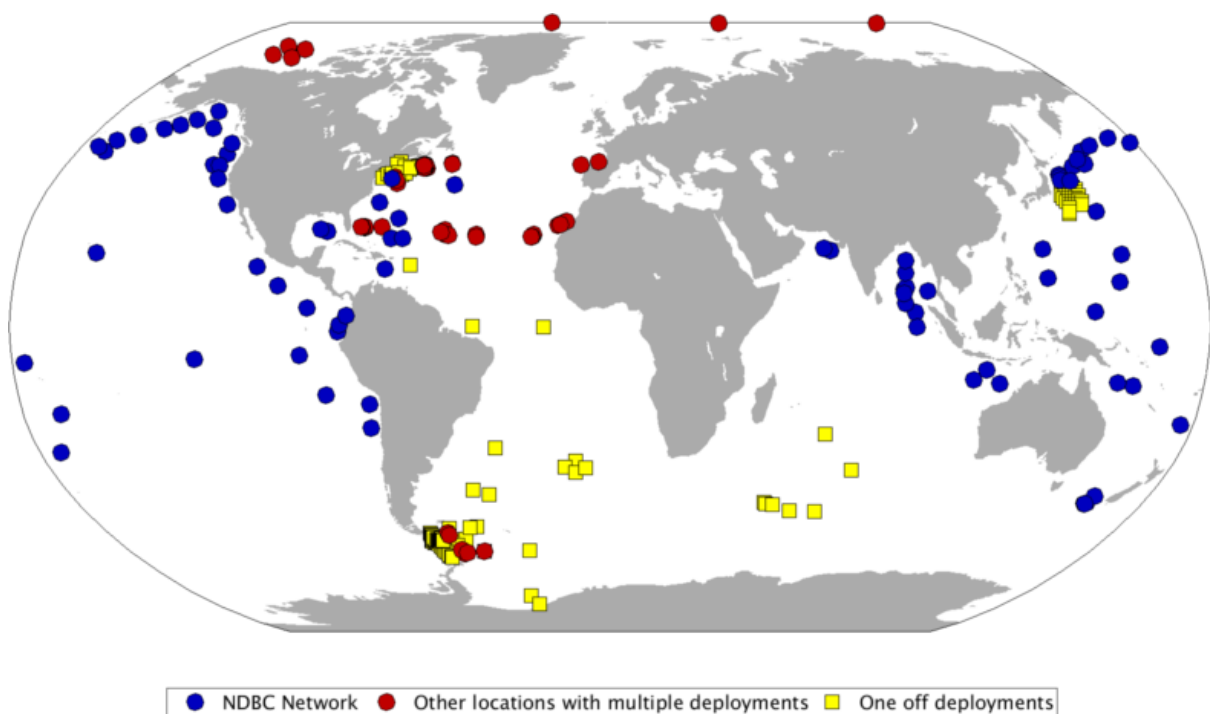
454 The first bottom pressure observations were motivated by the need to understand ocean tides,
 455 which was hampered by the lack of knowledge about tidal cycles in the open oceans, with tide
 456 gauges by definition located at the shore. Attempts began in the 1960s to measure the tides in
 457 the open sea using instruments capable of recording pressure accurately at the seabed
 458 (Cartwright, 1977). As the technology matured, programmes evolved to use a succession of
 459 deployments at a site to provide an ongoing record of sea level variation (Spencer et al., 1993),
 460 with a new sensor deployed to the seabed as the old one was recovered, along with its payload
 461 of data. Unfortunately, pressure sensors are prone to drift over time, best modelled with a
 462 decaying exponential in the short term and a linear drift in the long term (Watts and

463 Kontoyiannis, 1990; Polster et al., 2009). Although there have been some attempts to measure
464 and correct the drift with in-situ calibration systems (e.g. Sasagawa et al., 2016), these are still
465 under development and are not yet able to provide routine corrections.

466 As the drift cannot be distinguished from any long-term secular trends, and the information
467 cannot be connected to a specific datum, records from bottom pressure gauges are presently
468 unsuitable for monitoring long-term changes in sea level. Nevertheless, the records can be used
469 to investigate changes in bottom pressure caused by tides (Ray, 2013), ocean circulation
470 (Spencer et al., 1993), and ocean mass (Hughes et al., 2012). Furthermore, by pairing the sensor
471 with a surface buoy capable of transmitting high frequency real time data, recorders can provide
472 data in real time and thus be used as a vital part of regional tsunami monitoring networks
473 (Meinig et al., 2005).

474 A substantial network of bottom pressure recorders (BPR) is maintained by NOAA, and data
475 can be obtained from the National Data Buoy Center (NDBC) website (www.ndbc.noaa.gov).
476 The PSMSL also distribute some bottom pressure data from various sources, including a subset
477 of the NDBC data, and maintains a list of other available BPR data
478 (www.psmsl.org/data/bottom_pressure). Deployments tend to be clustered in locations where
479 particular phenomena have been studied (such as the Drake Passage), or in tsunami-prone areas
480 (Figure 10), leaving large areas of the ocean unobserved by these in-situ measurements.

481



482

483 Figure 10. Bottom pressure recorder measurements available from the NDBC and PSMSL
484 networks, or other networks linked to by the PSMSL.

485

486 Satellite gravimetry, starting from the launch of the Gravity Recovery and Climate Experiment
487 (GRACE) in March 2002, has demonstrated its usefulness for observing ocean bottom pressure
488 variations in the deep ocean (Bergmann and Dobsław, 2012; Chambers and Bonin, 2012;
489 Johnson and Chambers, 2013; Picuch et al., 2013; Ponte and Picuch, 2014; Makowski et al.,
490 2015), and calculating the mass component of global mean sea level (Chambers et al., 2004;

491 Willis et al., 2008; Leuliette and Miller, 2009; Boening et al., 2012; Church et al., 2013; Fasullo
492 et al., 2013; Johnson and Chambers, 2013; Rietbroek et al., 2016; Chambers et al., 2017). Using
493 the newest release of GRACE data, bottom pressure in the deep, interior ocean averaged over
494 a disk with radius 300 km has a standard error of approximately 1.5 cm of equivalent sea level
495 (Chambers and Bonin, 2012), while the global ocean mass has a standard error of 1.1 mm
496 (Johnson and Chambers, 2013), both at monthly averages.

497 Using GRACE data to accurately measure ocean bottom pressure (and hence, the mass
498 component of sea level) in coastal waters is very difficult and, until recently, has only been
499 attempted in a few regions. This is due to leakage of the much larger mass fluctuations from
500 land hydrology and cryosphere variability into the ocean (Wahr et al., 1998), particularly
501 important at seasonal and longer time scales. Land (and ice sheet) mass variability is often one
502 to two orders of magnitude larger than ocean mass variations, and it is difficult to estimate the
503 leaked signal without knowing the signal that is being leaked. Some studies have attempted to
504 correct for the leakage by iterating with GRACE estimates of land and ice sheet mass changes
505 (Chambers and Bonin, 2012), using an inverse method where land and ocean signals are
506 separated by pre-defined basins (Chen et al., 2013), or, more recently, using a predefined mesh
507 of global mass concentrations, or mascons, to separate ocean and land signals (e.g., Lemoine
508 et al., 2007; Watkins et al., 2015; Save et al., 2016).

509 There have been a few studies where GRACE data in coastal waters have been utilized and
510 shown to explain a large percentage of sea level variance in coastal waters. Landerer et al.
511 (2015) used a GRACE mascon solution to study variability in the Atlantic Meridional
512 Overturning Circulation (AMOC). This required using GRACE-derived ocean bottom pressure
513 along the United States eastern continental shelf, within 300 km of land. Although they could
514 resolve interannual fluctuations in the bottom pressure associated with changes in the AMOC,
515 they found a large, unrealistic trend that they speculated had to be from residual leakage of
516 hydrology signals, even using a mascon solution. GRACE has also shown some level of
517 accuracy in measuring coastal level in two small enclosed gulfs with large sea level variability
518 that is caused by winds at annual periods: the Gulf of Carpentaria in northern Australia
519 (Tregoning et al., 2008) and the Gulf of Thailand (Wouters and Chambers, 2010).

520 Newer mascon solutions from GRACE show more promise of being able to recover the ocean
521 mass (barotropic) portion of sea level variability in substantially more coastal waters. Piecuch
522 et al. (2018b) compared ocean bottom pressure from a GRACE mascon solution from the Jet
523 Propulsion Laboratory that incorporated a special filter to optimally separate land and ocean
524 signals (Watkins et al., 2015; Wiese et al., 2016). They found that these new GRACE mascon
525 solutions explained ~30-50% of the sea level variance measured by tide gauges along the
526 Australian shelf, the North Sea around Scandinavia, the eastern coast of the United States and
527 Canada, and around parts of the Chinese coast and Indonesian archipelago. While much of this
528 correspondence is due to the annual signal, Piecuch et al. (2018b) do demonstrate good
529 agreement with interannual and non-seasonal sea level and ocean bottom pressure in many of
530 these same areas. This is expected from theory, since in shallower waters there should be a
531 greater coupling between sea level and ocean bottom pressure as the response will be more
532 barotropic. Thus, although GRACE data have not regularly been used to understand coastal sea
533 level variability, new processing has improved the accuracy sufficiently that the satellite ocean
534 bottom pressure can be useful in understanding coastal sea level variability in shallow waters
535 with a wide shelf.

536 Another area where GRACE has demonstrated usefulness is in measuring a portion of coastal
537 sea level that results from gravitational changes due to land ice melting (e.g., Riva et al., 2010)
538 and fluctuations in land hydrology (e.g., Jensen et al., 2013). Although important for

539 understanding and predicting sea level rise a hundred years from now, these are minor signals
540 in coastal sea level measurements made by tide gauges.

541 **6. Steric sea-level observations**

542 Knowledge about hydrographic changes (from temperature and salinity) is crucial for
543 interpreting sea-level variability and underlying mechanisms, especially in the open ocean, but
544 with impact also along the coastal zones. This section offers a summary of existing observing
545 capabilities of the most relevant variables and discusses improvements on coverage, integration
546 and other issues that could be helpful over the next decade.

547 Knowledge of temperature (T) and salinity (S) distributions can provide information on steric
548 contributions to coastal sea-level variability. As they relate to density, T and S data also carry
549 dynamic information (pressure gradients, velocities). Combined with bottom pressure and
550 other variables, T and S data can be used to elucidate many aspects of sea-level behaviour (e.g.,
551 separating oceanographic and geodetic contributions, discerning causal and forcing
552 mechanisms).

553 With Argo floats not sampling the shallow regions, there are no operational global in-situ
554 observations of coastal T and S, but regional efforts have been implemented over the years
555 using both ship-based and moored platforms (e.g., data collection in many coastal regions set
556 up under the U.S. Integrated Ocean Observing System; <https://ioos.noaa.gov/regions/>) and
557 more recently glider technology (e.g., <https://gliders.ioos.us/>; Pattiaratchi et al. 2017; Rudnick
558 et al. 2017; Heslop et al. 2012). One challenge and perhaps a worthy long-term focus will be
559 to link available T and S data to sea level data at the local level, particularly as coastal observing
560 systems attain operational status.

561 In the case of surface measurements, satellite retrievals provide a useful, global alternative to
562 in-situ platforms, albeit at varying resolutions and with questionable accuracy near the coastal
563 zone, mostly due to the fact most of the in-situ platforms for calibration/validation are offshore
564 (Brewin et al., 2017). For sea surface temperature (SST), a variety of remotely sensed and
565 blended products exist at typical daily sampling, nominal kilometre resolutions, and accuracies
566 of ~0.5K (Donlon et al. 2007, 2009; <https://www.ghrsst.org/>). Although SST has been shown
567 to correlate with sea level over deep water (Meyssignac et al., 2017), the case for the coastal
568 ocean remains to be explored. To the extent that SST can reflect steric sea level, high resolution
569 satellite products could be used to infer potential short scale structures affecting sea level across
570 the coastal zone. Such knowledge can, for example, inform comparisons of tide gauge and
571 altimeter sea level data, which are affected by their different spatial sampling characteristics.

572 Sea surface salinity (SSS) retrievals are much more recent and not as mature nor operational
573 as SST. The Aquarius mission lasted over the period 2011-2015, but the Soil Moisture Ocean
574 Salinity (SMOS) mission continues to be operational since 2009, and data from the Soil
575 Moisture Active Passive (SMAP) mission launched in 2015 has also become available (e.g.,
576 Mecklenburg et al. 2016; Weissman et al. 2017; Köhler et al. 2018; Boutin et al. 2018).
577 Nominal sampling ranges from weekly to monthly at resolutions of ¼ to 1 degree (around 40
578 km for SMAP), and with typical accuracies of ~0.2 psu. Apart from the challenges of relating
579 SSS retrievals to bulk and to subsurface S (e.g., Boutin et al., 2018), the extent to which these
580 quantities are related to coastal sea level has not been explored in any detail. Sea level and SSS
581 are expected to be linked directly through the effects of river runoff (Meade and Emery 1971),
582 but the related SSS signals can be trapped to the coast on scales that are not well resolved with
583 the currently available satellite systems (Durand et al., 2018; Picuch et al., 2018a). Similar
584 issues may also affect the ability to observe possible impacts of ice melt on coastal sea level at
585 high latitudes.

586 **7. Discussion and final remarks**

587 Monitoring networks of in-situ coastal sea level are presently well developed along most of the
588 world coastlines, although with notable exceptions in Africa and part of South America, where
589 the spatial density of instruments is significantly lower than, for example, in Europe.
590 Furthermore, delayed-mode, low-frequency tide gauge data in some parts of the coastlines
591 (including the above-mentioned regions but also others like the Arctic Ocean) are not routinely
592 released to the international databases, limiting the available information in these areas even
593 more. The same geographical bias applies to high-frequency sea-level measurements, as these
594 come from the same tide gauges.

595 The lack of sea level information on poorly sampled regions may be partly overcome with
596 coastal altimetry observations. Despite the longer revisit time of the altimeters, there is a clear
597 complementarity between tide gauges and altimetry that should be exploited in order to
598 improve the current knowledge of sea level variations in coastal regions at low frequencies
599 (monthly and longer periods). In this respect, the information on VLM at the tide gauge is
600 crucial for the consistency between both measurements. This is achieved through GNSS
601 observations and can be further complemented with other geodetic techniques, such as InSAR
602 to extend VLM estimates to larger areas. In the near future, progress in data processing and the
603 continuity of altimetric missions are promising for coastal sea-level studies. This includes the
604 forthcoming SWOT mission (Durand et al., 2010) and the already operational Sentinel
605 missions from the European Space Agency (<https://sentinel.esa.int/web/sentinel/missions>).

606 Overall, an integrated coastal sea-level observing system should:

- 607 1) be able to accurately measure sea-level changes at the coast itself at high frequency
608 rates (hourly or higher, to account for extreme sea levels) and at the nearby coastal
609 region, using in-situ (tide gauges) and satellite altimetry observations, respectively;
- 610 2) use GNSS observations to provide information on VLM in order to separate ocean and
611 land signals in in-situ measurements, especially in the long-term when both components
612 can be of the same order of magnitude;
- 613 3) measure local and regional sea-level contributors, including offshore and coastal wind-
614 waves, water density changes, surface meteorological parameters (atmospheric
615 pressure and winds being among the most important; see Piecuch et al, this issue), and
616 in general any other local process important to identify and understand the coastal
617 dynamics inducing sea-level variations (e.g. river run-off, Durand et al, this issue);
- 618 4) be consolidated on a long-term basis.

619 The scientific and societal benefits of such a system are numerous. Climate studies require
620 long-term, consistent and continuous measurements. In this respect, consolidation of observing
621 systems is crucial to avoid endangering the continuity of the observations and introducing data
622 gaps. Currently, this is ensured for satellite missions (altimetry and gravimetry) but,
623 unfortunately, even in intensively monitored regions, like Europe, national agencies have
624 reported problems with securing funding for maintenance of the current tide gauge networks
625 (Pérez et al, 2017), representing a serious concern especially for the valuable long-term records.
626 An integrated observing system of sea-level and related variables would also provide consistent
627 information to be assimilated into numerical models, including the quantification of data
628 uncertainties that are critical in analyses and model forecasts. It would further contribute to
629 operational oceanographic systems and warning protocols (e.g. flood warnings). Finally, it is
630 also an adequate framework to foster technological development of new emerging monitoring
631 platforms capable of expanding current in-situ observations (e.g. GNSS-towed platforms) and
632 thus contributing to maximise the information provided by in-situ sea-level measurements.

633 Observing sea-level changes at the coast and quantifying its drivers is the first step to
634 understand the complex dynamics of the coastal region, to link the responses of the coastal
635 environment to sea-level changes and to anticipate how projected sea-level variations will
636 impact the coastal areas.

637

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