Surveys in Geophysics

Coastal sea level and related fields from existing observing systems

--Manuscript Draft--

Manuscript Number:	GEOP-D-18-00132
Full Title:	Coastal sea level and related fields from existing observing systems
Article Type:	S.I. : ISSI Workshop on Coastal Sea-Level and Ocean Circulation
Keywords:	sea-level observations; tide gauges; coastal altimetry; GNSS; wind-waves; ocean bottom pressure; hydrography
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Coastal sea level and related fields from existing observing systems

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Abstract (max 200 words)

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

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1. Introduction

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

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

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

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

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

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

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

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

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

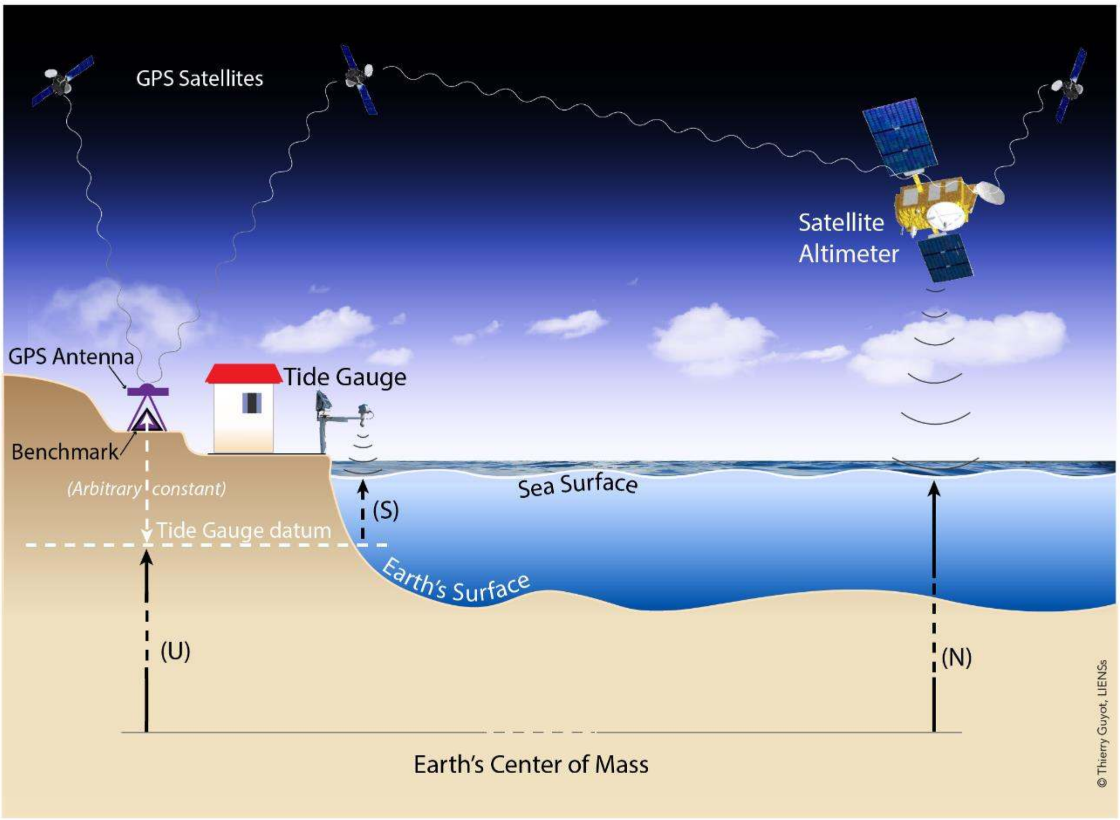

Figure 1. Sketch showing basic observational quantities and techniques associated with sea level measurement discussed in this article

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

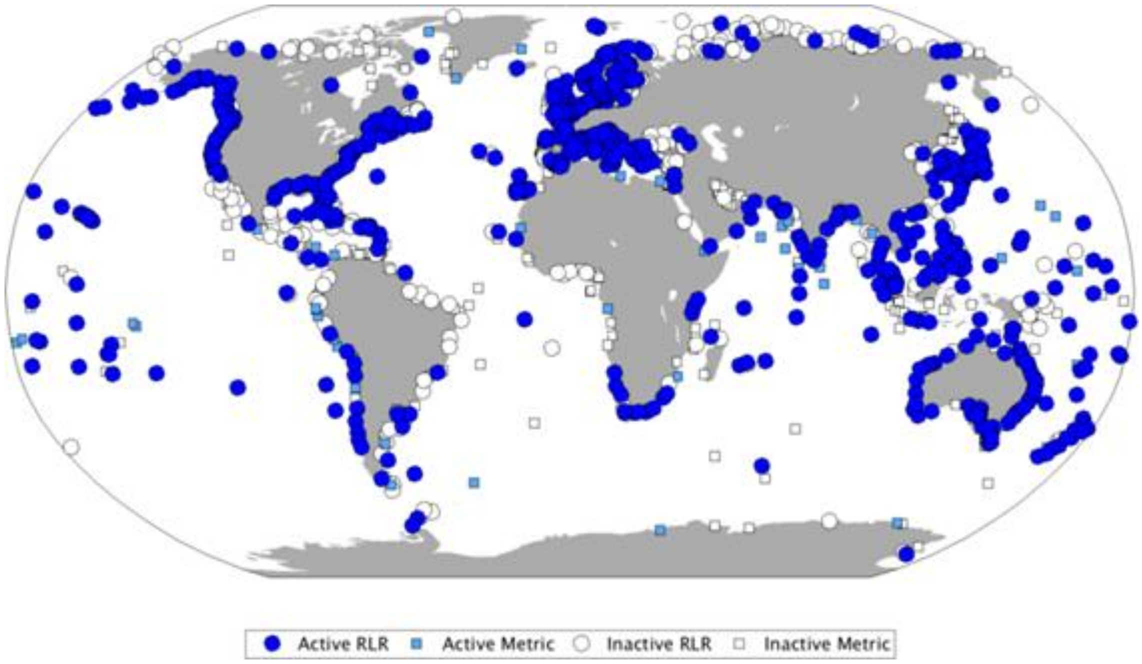

Figure 2. Tide gauge stations in the PSMSL database. Active stations (in blue) are defined as those with data supplied to PSMSL in 2013 or later. Stations with historical levelling information are identified as Revised Local Reference (RLR).

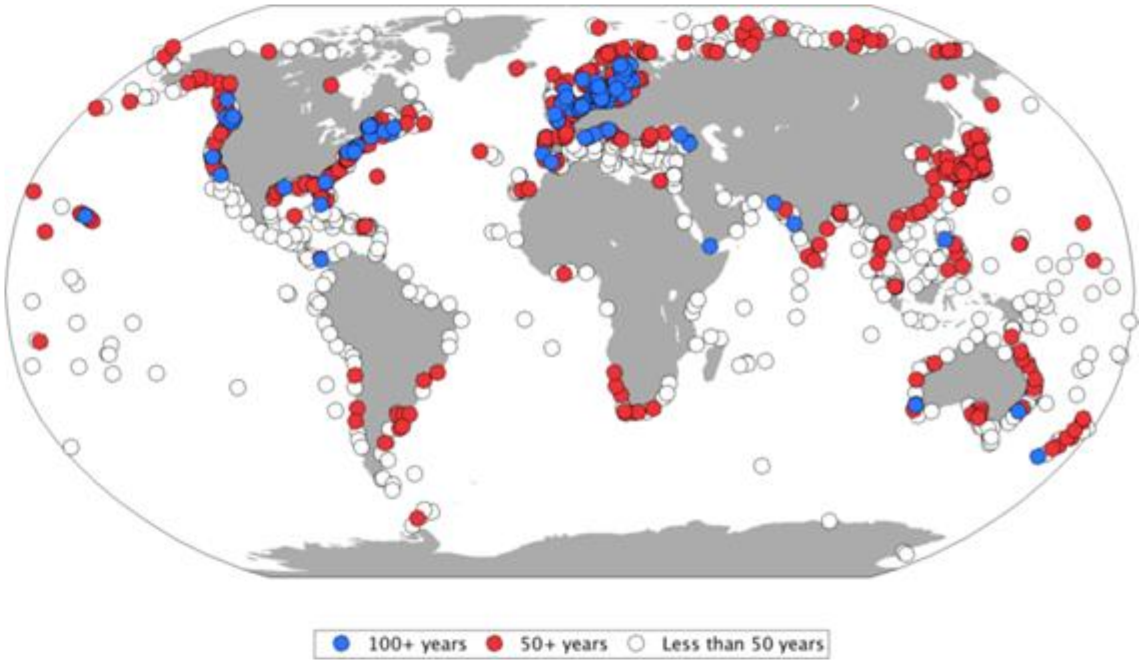

Figure 3: RLR tide gauge records longer than 100 (blue) and 50 (red) years, not accounting for data gaps.

The uneven spatial and temporal distribution of tide gauge records and, in particular, the scarcity of data during the early 20th century and before, are factors that hinder the quantification and understanding of past regional and global long term mean sea level changes and their driving mechanisms (Dangendorf et al., 2017). Many efforts have therefore been devoted to the discovery, recovery and quality control of historical archived sea-level measurements (Bradshaw et al., 2015; Hogarth, 2014). These so-called exercises of data archaeology have successfully recovered sea-level information at sites as remote as the Kerguelen Islands (Testut et al., 2006) or the Falklands (Woodworth et al., 2010) and as far back in time as the 19th century (Talke et al., 2018; Woppelmann et al., 2014; Marcos et al., 2011). Tide gauge data archaeology has been a useful tool to recover sea-level measurements valuable for climate studies, given the potential to expand the databases during periods and in places where no other observations exist.

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

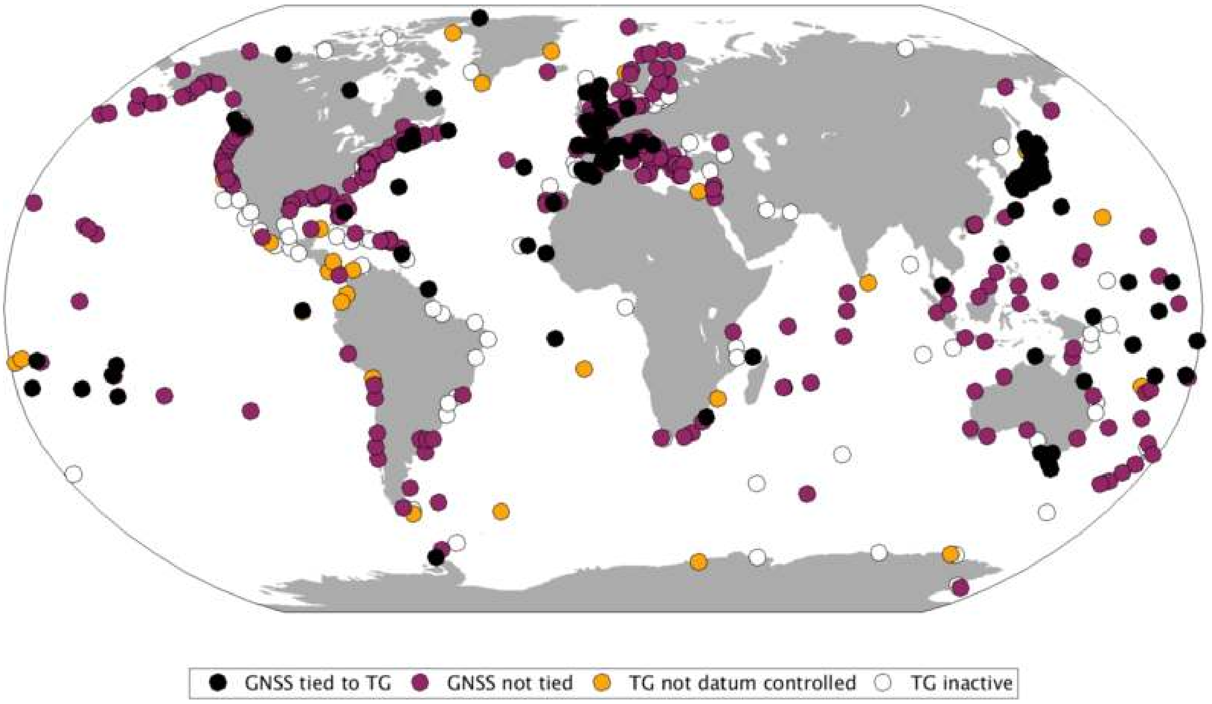

Figure 4. GNSS stations with (coloured) and without (blank) a tide gauge within 10 km, according to PSMSL and SONEL databases [data accessed on 3 September 2018]. Black dots indicate RLR stations where GNSS and tide gauge datum are tied, purple dots indicate otherwise. Orange stations have no information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

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

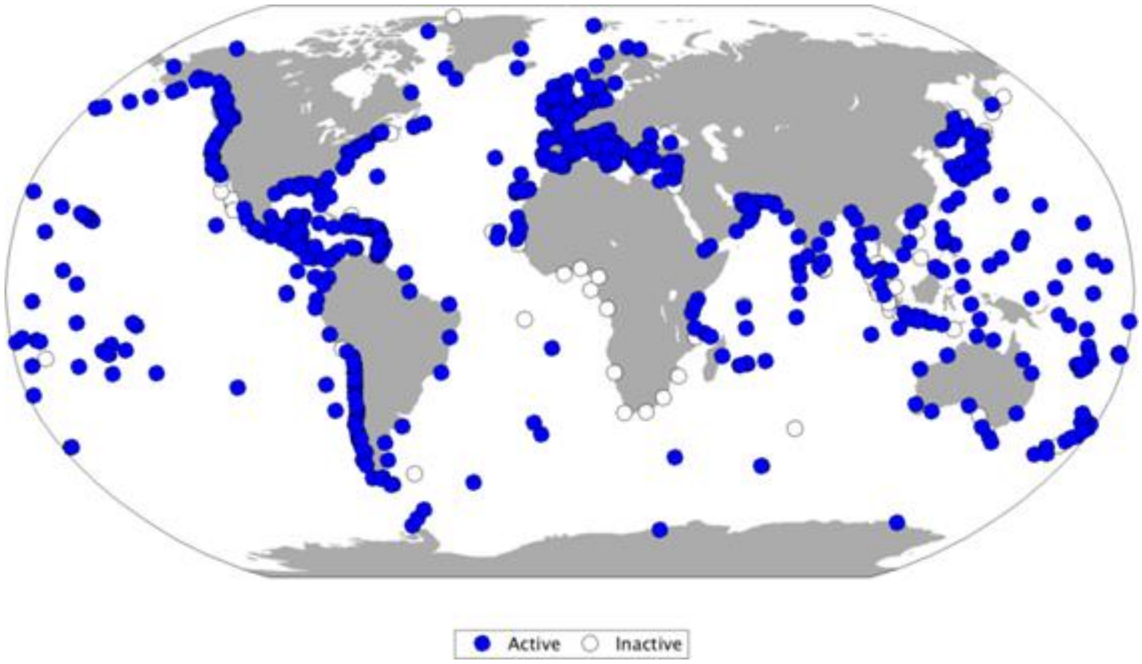

Figure 5. Tide gauge stations providing real time sea level observations to VLIZ data centre. Active stations are defined as having contributed data in 2018.

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

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

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

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

3. Other sea-level monitoring platforms

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

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

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

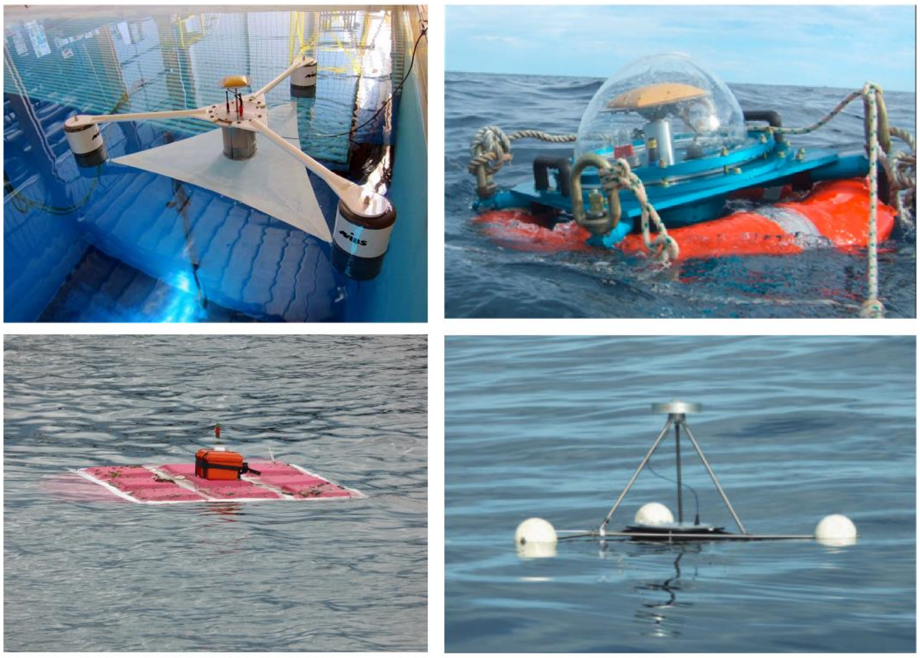

Figure 6. Illustration of four different GNSS buoy designs. Top left and right are respectively buoys designed at DT-INSU and IPGP (André et al., 2013). Lower left is a new light buoy design by DT-INSU based on the blanket concept to closely follow the water surface. Lower

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

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

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

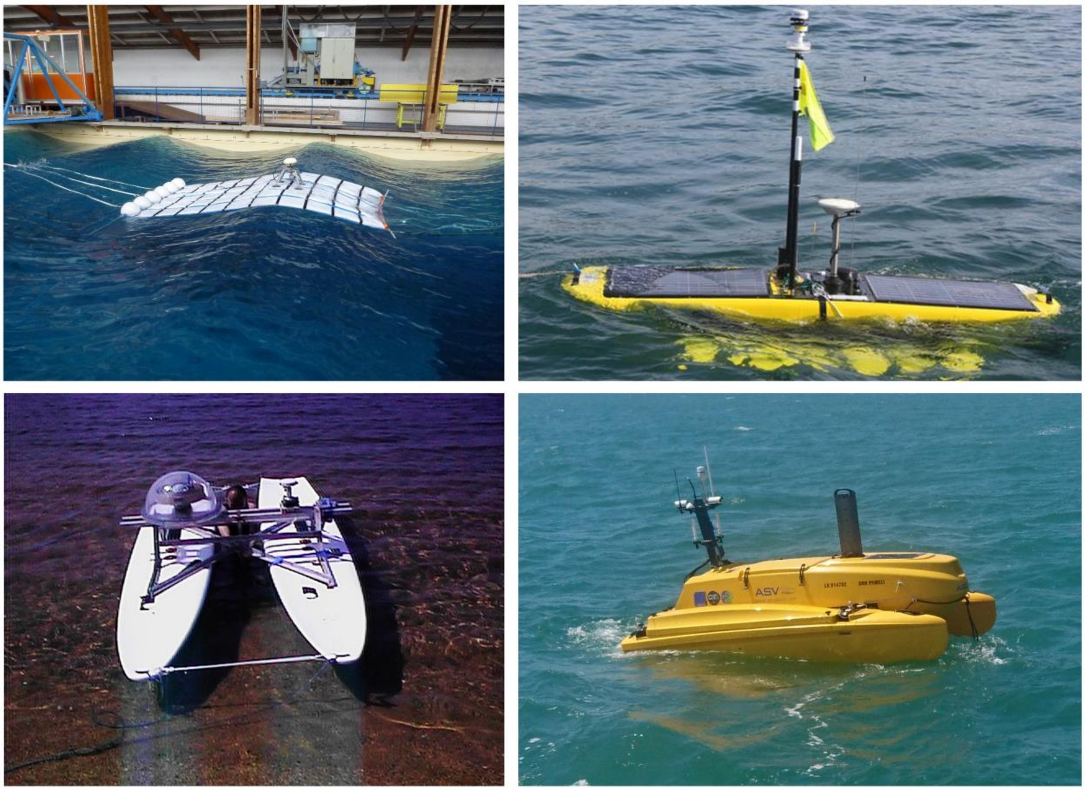

Figure 7. Illustration of moving GNSS platform for sea surface height mapping (towed blanket (Calzas et al., 2014), Wave-glider (Penna et al. 2018), Catamaran (Bonnefond et al., 2003b), and AUV-PAMELi (Coulombier et al., 2018)

4. Wind-wave observations

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

Surf zone processes have been the topic of targeted instrument deployments (e.g. Guza and Thornton 1981; Egar et al., 1997; Senechal et al., 2011a). Such experiments have confirmed that the wave set-up is caused by the cross-shore convergence of the wave-induced momentum flux, known as the radiation stress (e.g. Raubenheimer et al., 2001). This balance is also perturbed by bottom friction in the shallowest regions (Apotsos et al. 2007). Wave set-up, just like wave transformation in general, is strongly influenced by the nearshore underwater bathymetry (Stephens et al., 2011), which is problematic to measure directly (e.g., Dugan et al., 2001) or indirectly (e.g., Holman et al., 2013). Despite their importance, measurements of underwater bathymetry in the surf zone remain a challenge and at present such data is only available at few sites and for short temporal intervals obtained through in-situ surveys. The development of remote sensing techniques from high resolution radar or optical satellite imagery (e.g. Pleskachevsky et al. 2011) now benefits from faster revisits using Landsat 8 and Sentinels 1 & 2 (Hedley et al. 2012) but bathymetric changes during storms, which are larger and most relevant, are still inaccessible.

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

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

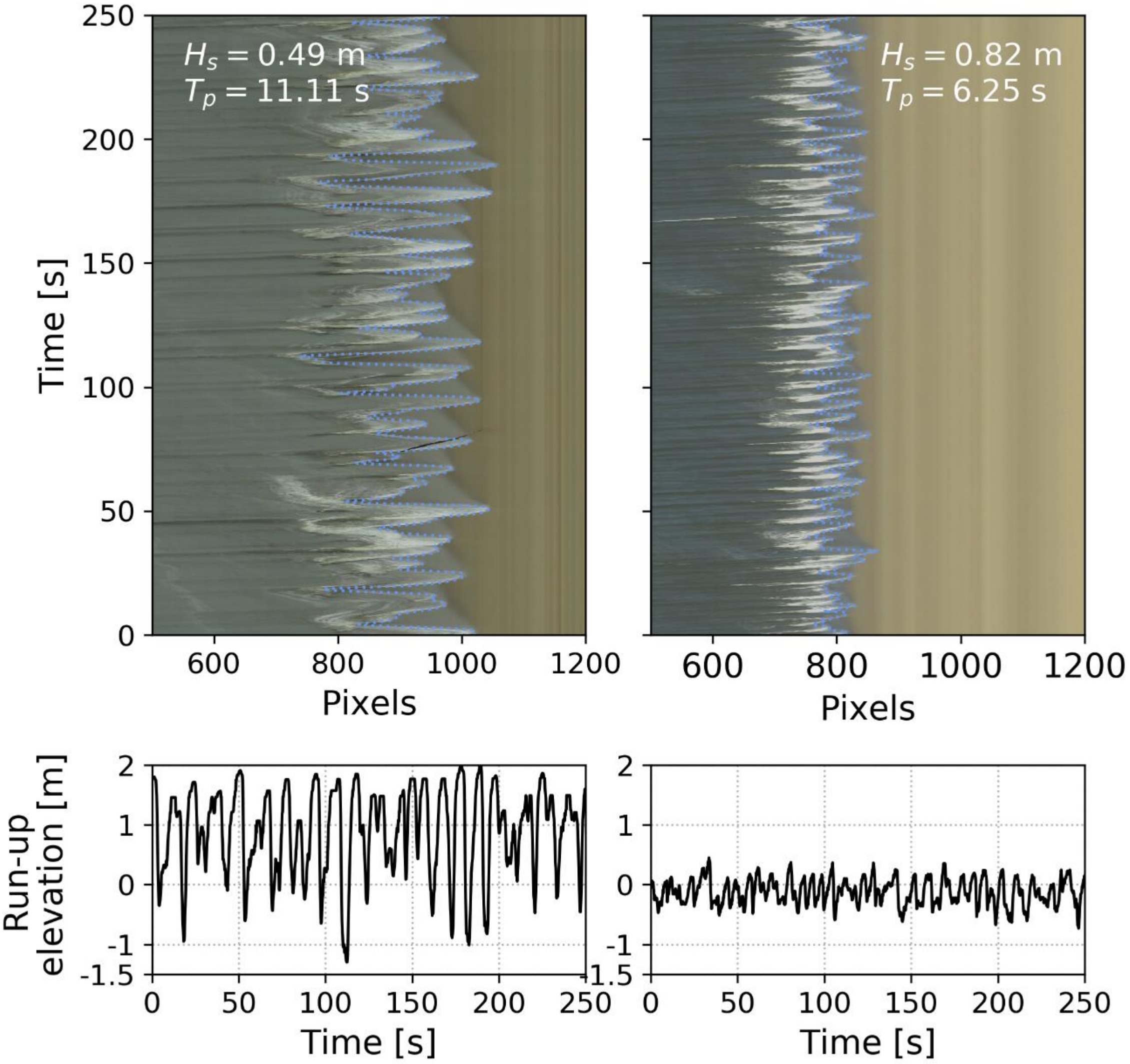

Figure 8. Examples of time stacks showing shoreline position over time (top panels) during (left) high and (right) low tide. The corresponding significant wave height (Hs) and wave peak period (Tp) are indicated for each case. Bottom panels show the detrended runup elevation time series. Observations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

Whatever the wave transformations and impacts along the coast, there is an evident need for observations on offshore sea state parameters that trigger those effects. The longest time series are available for wave heights from in-situ measurements using voluntary observing ships (Gulev et al., 2003) and buoys (Figure 9) and from satellite altimeters (Queffeulou, 2013). Conversely, the routine measurement of wave periods is limited to the few available buoys or platforms (Figure 10). To overcome this limitation, proxies for a mean wave period have been proposed using radar backscatter and wave heights from altimeters (e.g. Gommenginger et al. 2003; Quilfen et al., 2004). It should be still investigated how well these proxies perform for estimating extreme coastal sea levels. In the near future, it is expected that forthcoming satellites will bring a direct measurement of the dominant period in most sea state. This is the case of the SWIM instrument on CFOSAT (Hauser et al., 2017), to be launched in October 2018. The proposed SKIM satellite would go a step further in resolving the dominant waves even in enclosed seas (Ardhuin et al., 2018). Still, even with a 300 km wide swath SKIM would have a revisit time of 4 days at mid-latitudes that is insufficient to resolve the fast time scale of storms. This large revisit time, compared to the typical time scale of 12 hours for storm duration, makes it impossible, from satellites alone, to derive reliable statistics on extreme wave parameters and associated impact on sea level.

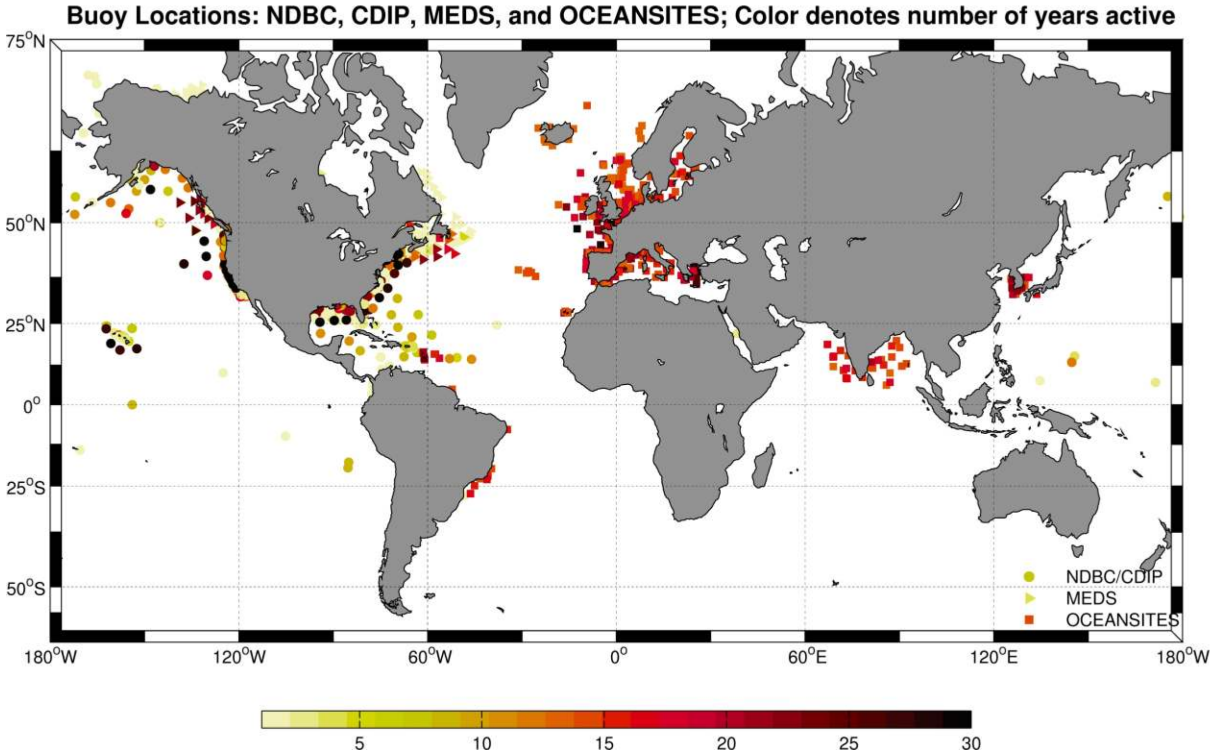

Figure 9. Location of wave-measuring devices affiliated to the NDBC, CDIP, MEDS or OCEANSITES networks with the length of records in years indicated by the colours.

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

5. Ocean bottom pressure observations

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

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

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

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

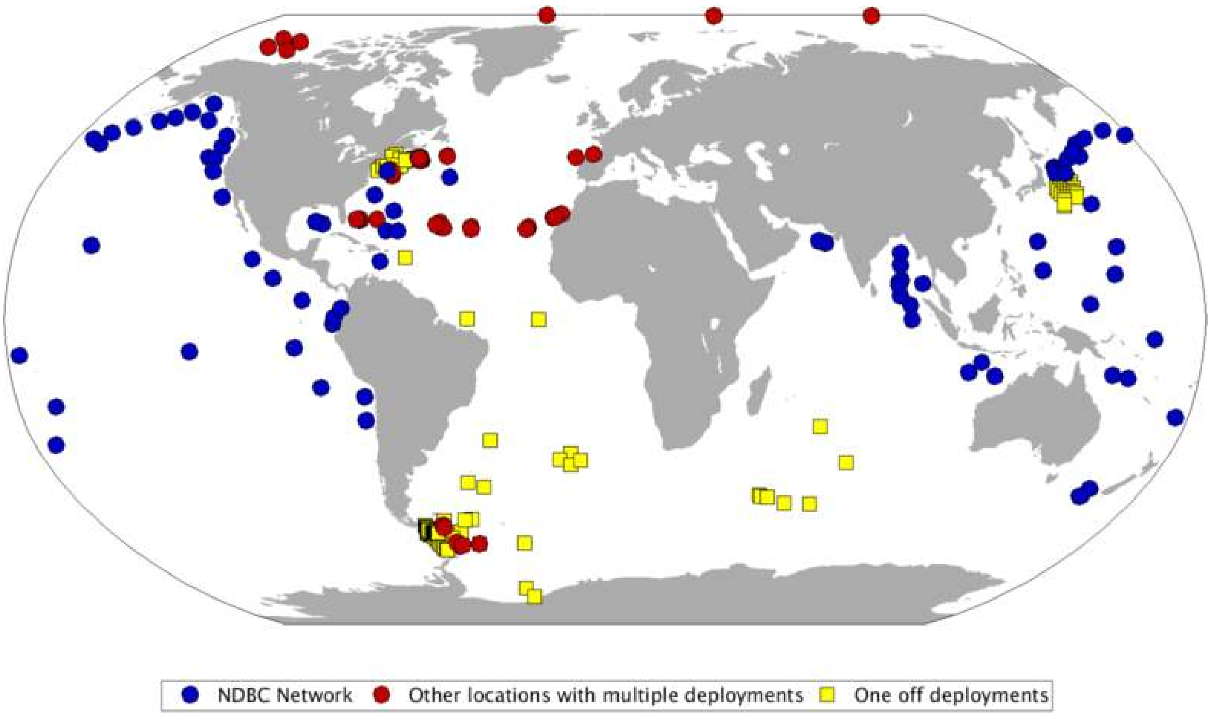

Figure 10. Bottom pressure recorder measurements available from the NDBC and PSMSL networks, or other networks linked to by the PSMSL.

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

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

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

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

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

Another area where GRACE has demonstrated usefulness is in measuring a portion of coastal sea level that results from gravitational changes due to land ice melting (e.g., Riva et al., 2010) and fluctuations in land hydrology (e.g., Jensen et al., 2013). Although important for understanding and predicting sea level rise a hundred years from now, these are minor signals in coastal sea level measurements made by tide gauges.

6. Steric sea-level observations

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

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

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

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

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

7. Discussion and final remarks

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

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

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

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

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

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

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