White paper: Monitoring the evolution of coastal zones under various forcing factors using space-based observing systems

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White Paper on

"Monitoring the evolution of coastal zones under various forcing factors using space-based observing systems"

This paper is an outcome of the International Space Science Institute (ISSI) Forum on "Monitoring the evolution of coastal zones under various forcing factors using space-based observing systems" (http://www.issibern.ch/forum/costzoneevo/) held at *ISSI, Bern, Switzerland on 11-12 October 2016 (convened by J. Benveniste, A. Cazenave, N. Champollion, G. Le Cozannet and P. Woodworth)*

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Part I. General context & scientific questions

I.1. Introduction

At present, about 10% of the global population live in the world's coastal zones. In many regions, populations are exposed to a variety of natural hazards (e.g., extreme weather such as damaging cyclones and their associated storm surges), as well as to the effects of global climate change (e.g., sea level rise), and to the impacts of human activities (e.g., urbanisation). In low lying coastal areas, these several factors may combine to increase significantly the risks to coastal dwellers. For example, climate-related sea level rise increases the risk of flooding and coastal erosion during extreme events, and can also cause salt water intrusion into rivers and coastal aquifers on which people depend. Land subsidence, caused by ground-water extraction in coastal megacities, is another source of risk as it amplifies the negative impacts of climate-related sea level rise. Because of strong anthropogenic pressures, coastal zones are already suffering ecological and biological stresses, for example poor water quality, pollution, destruction of marine ecosystems, etc. Shoreline change and coastal flooding are critical concerns for many coasts worldwide and they are expected to be strongly aggravated by sea-level rise.

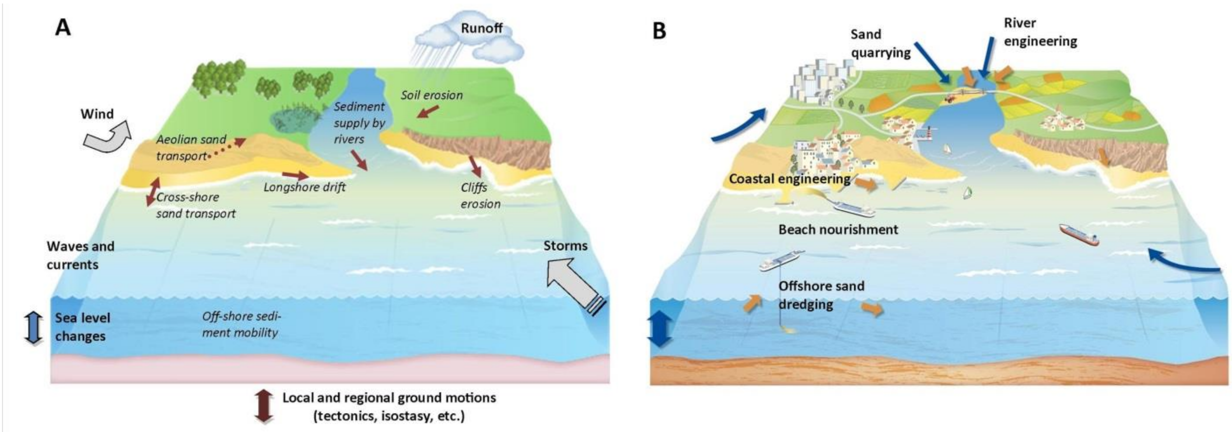

Figure 1: Natural and anthropogenic processes affecting shoreline changes (source: Cazenave and Le Cozannet, 2014).

It has been reported that 70% of the world's sandy beaches are eroding (Bird et al., 1985). Although this number must be considered with caution, because in many regions real observational data are lacking, this raises the question of understanding the underlying causes. Is the reported large-scale erosion due to natural processes only? Is it a consequence of present-day sea level rise? What are the impacts of human activities at the coast? Are all factors playing a role? In what proportion, depending on the region? To gain information about the evolution of the coastal zones during the past few decades, to answer the above questions about the causes of the evolution, and to provide information to decision-makers and coastal zone managers, various types of observations need to be made, with data collected and analysed within an integrated framework.

The response of coastal environments to natural and anthropogenic forcing factors (including climate change) depends on the characteristics of the forcing agents, as well as on the internal properties of the coastal systems. For example, salt marshes and sandy beaches respond differently to the same wave climates: salt marshes are more vulnerable to mean climatic conditions than to extreme events, while unvegetated sandy beaches are generally resilient to mild external agents (such as slow mean sea level rise), but extremely vulnerable to extreme storms due to overwash (Fagherazzi, 2014; Leonardi et al., 2016). The different responses to external agents are reflected in temporal dynamics: salt marsh lateral erosion generally demonstrates a relatively constant variation in time, in spite of exhibiting some spatial and temporal chaotic features, and in spite of the occurrence of extremes (Leonardi and Fagherazzi, 2014, 2015; Leonardi et al., 2016b). This is because these environments are more influenced by average climate conditions. On the other hand, barrier islands, especially when low-lying and poorly-vegetated, undergo rapid landward migration and degradation as a consequence of extreme events, and little changes occur under mild conditions, which results in them exhibiting intermittent temporal variations (Fagherazzi, 2014; Vinent and Moore, 2015).

The main motivation for this Forum was to investigate the observational and modelling needs in order to try to respond to the following questions:

- What is the role of climate-related sea level rise in present-day coastal changes?
- What is the role of vertical land motion (i.e., relative sea level) in present-day coastal changes?
- What is the role of small scale processes and extremes on present-day coastal evolution?
- What is the relative importance of the different roles of natural variability, climate change and human activities in present-day, and possibly future, coastal changes and processes?
- What is the best approach for monitoring coastal erosion/flood dynamics in transitional ecosystems like deltas under threat of sea level rise?

During this 2-day Forum, discussions took place on existing space-based and in situ observations, and their suitability to provide precise and systematic information about coastal zone evolution in response to extreme events (e.g., storm surges arising from tropical and extra-tropical cyclones), natural climate variability, slow processes such as long-term sea level rise, and direct anthropogenic forcing. The Forum mainly focused on physical aspects but biological and ecological issues were also considered. The Forum was divided into two main sessions: one on the forcing factors and associated variables (sea level, winds, waves and currents, river runoff, sediment supply, vertical ground motions, land use change, urbanization,…), including their modification in a changing climate; and one on the induced coastal responses (shoreline morphology, bathymetry, topography, erosion, flooding episodes, salt water intrusion in coastal aquifers, ecosystem degradation, …). Both in situ (e.g., tide gauges, Global Navigation Satellite System (GNSS) stations, field and airborne sensors, Unmanned Aerial Vehicles (UAVs) etc.) and space-based (active microwave/Synthetic Aperture Radar (SAR) systems, altimeters, lidars, visible-, infrared-, multi- and hyper-spectral imagery, including ocean colour imagery etc.) observing systems were discussed. The Forum investigated the capabilities and potential for each observing system to provide information on the forcing parameters and the coastal responses and evolution. It also addressed the issues of data precision, resolution, spatio-temporal coverage and continuity, data gaps, and multi-sensor synergetic use, in order to increase the amount of information and data and overall knowledge of coastal change. Although an inventory of past and future observations, and requirements for research, were the main topics of the Forum, processes and modelling issues were also briefly discussed.

The next 3 sections of Part I deal with the definition of the coastline, extreme sea level and sea level rise. Parts II and III focus on observational and modelling needs and provide recommendations for each topic. Part IV deals with user needs for coastal management. Part V discusses the need for international networks of coastal observatories.

I.2. Definition of the coastline

Defining the shoreline (or coastline) remains an important prerequisite for any coastal evolution studies. The instantaneous shoreline is well defined as the interface between land and water. However, the apparent simplicity of this definition is challenged by the high temporal variability of sea level and morphological changes affecting the land-water interface. Coastal sea level is indeed highly dynamic by nature, due to currents, waves, tides and storms, and its interface with the land is constantly changing because of erosional and accretional processes, or anthropogenic actions (e.g., the use of backfill materials). The elevation differences can be of the order of a few centimetres, or up to metres, depending on the averaging time scale considered. In addition, the different sensors (altimetry, photography, in situ observations etc.) and applications (scientists, engineers and managers) lead to different practical definitions of the shoreline. For example, many scientists will use the permanent vegetation line, or dunes, or the base of cliffs as proxies for decadal shoreline change surveys. Conversely, coastal managers concerned with the potential damage to buildings will consider the top of the cliff, or the avalanche slope of an aeolian dune, as observational priorities. It results in the shoreline having to be defined in an ad-hoc sense, depending on the context of investigation by shoreline indicators. Following the conclusions of the review paper of Boak and Turner (2005), we can summarize the state-of-art of coastline definition like this: "*Different data sources or sensors, and a diverse range of applications, will continue to influence the type of shoreline indicators chosen as well as their method of detection. At the present time, it appears unlikely that a single shoreline indicator feature (or definition) will at some time in the future suit all types of data and applications.*"

I.3. Sea level changes

Sea level is a key indicator of climate change. It integrates changes of several components of the climate system in response to anthropogenic forcing as well as natural forcing factors related to natural sources and internal climate variability. The Earth is currently in a state of thermal imbalance because of anthropogenic greenhouse gas emissions. 93% of this heat excess is accumulated in the ocean, the remaining 7% being used to warm the atmosphere and continents, and melt sea and land ice (von Schuckmann et al., 2016). Global Mean Sea Level (GMSL) rise is a direct consequence of this process. Tide gauge records indicate that the GMSL has been rising since the beginning of the 20^{th} century at a mean rate in the range 1.1-1.9 mm yr^{-1} (e.g., Church et al., 2013, Jevrejeva et al., 2014, Hay et al., 2015, Marcos et al., 2016). Since the early 1990s, sea level variations have been routinely measured by high-precision altimeter satellites. These indicate that global mean sea level is rising at a rate of 3.2 ± 0.4 mm yr^{-1} since 1993, i.e., twice as fast as during the previous decades, suggesting an acceleration of the phenomenon (e.g., Ablain et al., 2016). Satellite altimetry has also allowed mapping of the regional variability in sea level and shown that superimposed on the global mean, large variations have occurred in a number of regions, such as the western tropical Pacific, the northern Atlantic and the Southern Ocean. In these regions, the rate of sea level rise can be up to 3 times larger than the global mean. Whatever the future trajectory of Greenhouse Gas (GHG) emissions, sea level will continue to rise in the future.

I.4. Coastal sea level changes

What counts at the coast, in terms of impacts on the shoreline, is the total relative sea level, i.e., the sum of: global mean rise; regional variability in sea mean sea level; short-spatial and temporal scale ocean processes (e.g., waves, coastal currents); together with local vertical land motions (Stammer et al., 2013).

As discussed by Cipollini et al. (2016a), we still do not know if coastal sea level is rising at the same rate as open ocean sea level. However, recent progress in coastal altimetry obtained during the last decade by different groups, in reprocessing radar waveforms and developing improved corrections for atmospheric effects, as well as innovations in altimetry techniques (e.g., Ka–band altimetry as for the SARAL/AltiKa mission or altimetry in SAR mode as for the CryoSat mission), have enabled the development of new coastal altimetry data sets (see section II.1) of high value to estimate sea level changes in coastal areas and compare with (regional) open ocean changes. Sea level variations in the coastal zone result from a combination of different processes that act at different spatial and temporal scales. It will be important to evaluate the relative importance of each of these processes causing coastal sea level variability at different time-scales. Contributions from the climate related sea-level, vertical land motions, dynamical atmospheric forcing-induced sea level (surges), wave-induced run-up and set-up, and ocean tides need to be estimated from different observational datasets (see sections II.2, II.3, II.4 and III.2). As these processes impact the coast differently, evaluating their relative importance is essential for assessment of the local coastline vulnerability.

Mean Sea Level (MSL) is simply the average of sea level fluctuations over many timescales, each of which will be shorter than the period that the MSL value is calculated over (usually a year). Therefore, while annual MSL (which can be considered as average water depth) might change, there can be different changes over time within the many individual higher-frequency processes that ultimately contribute to the mean. For example, tidal propagation speeds are approximately $\sqrt{(gh)}$, and so tidal patterns might be expected to change as MSL rises; storm surge gradients are proportional to wind stress/water depth so one might expect smaller amplitude surges in deeper water (for a given wind stress forcing); seiches (a much neglected topic with sea level science, sometimes with damaging currents) depend on $1/\sqrt{(h)}$ and so will change character as depth changes; waves can be expected to break closer in-shore and cause more erosion as water depth increases (Wong et al., 2014). There are models that can be used to investigate many of these processes. For example, varieties of the Bruun Rule attempt to explain the equilibrium response of beach profile to a change in MSL itself (Bruun 1962); changes in tidal patterns can be modelled considering changes in bathymetry (e.g., Pickering et al., 2012). However, it is clear that there is much more to understanding the links between sea level and coastal evolution than monitoring changes in global and regional MSL.

I.5. Extreme sea levels

Extreme sea level levels result from the complex interplay of a spectrum of oceanic, atmospheric, and terrestrial processes. They generally occur due to a combination of high astronomical tide, large storm surge and high Mean Sea Level (MSL). However, as shown by Merrifield et al. (2013), the importance of each of these factors can vary around the world.

As regards timescales, the combination of both astronomical tidal and surge components defines the overall variation of extreme sea levels within a year. Extreme levels due to astronomical tide have both perigean and nodal and components, which occur on timescales of approximately 4.5 and 18.6 years in semi-diurnal and diurnal tide areas respectively (e.g. Haigh, 2011). Those due to storm surge at mid and high latitudes will almost all occur during winter months: the middle of the winter season in northern Europe, late winter or beginning of spring on the western European coasts, and from October to January on northeast American coasts (Menéndez and Woodworth, 2010). A seasonal dependence can also occur due to the 'baseline' of MSL, on which any surge-related components will take place, being higher at certain times of the year (Wahl et al., 2014). At inter-annual to decadal timescale, numerous publications show strong influence El Niño-Southern Oscillation (ENSO) and North Atlantic Oscillation (NAO) on extreme sea levels. There are also higher frequency oscillations (of the order of a few minutes) that result from fast, abrupt changes in the atmospheric conditions combined with an amplified topographic response (i.e. seiches or meteo-tsunamis).

As regards spatial scales, there is great deal of evidence that changes in extreme sea levels depend at least to some extent on changes in MSL. Therefore, to the extent that MSL changes tend to be coherent over large areas, then changes in extremes can also be expected to be coherent. For example, Menéndez and Woodworth (2010) demonstrated the spatial influence on sea level extremes of ENSO in the Pacific and NAO and AO in northern Europe, similar to that which occurs between MSL and climate indices. A number of individual studies of changes in extremes and their association with changes in MSL are reviewed in Woodworth et al. (2011) and Intergovernmental Panel of Climate Change (IPCC 2012, see references therein).

However, it is clear that changes in extremes will depend on processes other than MSL, such as changes in the frequency and magnitude of storm surges. Tropical and extra-tropical storms have different generation mechanisms and differ in their size and intensity. As a consequence, the storm surges caused by tropical cyclones are different in character to those produced by higher-latitude storms. Tropical storm surges tend to be of smaller spatial scale (~500 km rather than ~1000 km), and have a shorter duration (hours to days rather than several days), but are much larger in amplitude (sometimes 5-10 m rather than typically 2-3 m, von Storch and Woth, 2008) and require a special modelling approach (Haigh, 2014).

Marcos et al. (2015) studied the decadal to multidecadal variations in sea level extremes unrelated to MSL changes revealing, firstly, that the intensity and the frequency of occurrence of extreme sea levels unrelated to MSL vary coherently on decadal scales in most of the sites examined (63 out of 77) and, second, extreme sea level changes are regionally consistent, thus pointing toward a common large-scale climate forcing linkage.

Nevertheless, it is clear that sometimes sea level extremes can vary considerably spatially. North Sea storms provide many examples, with high surges in one location (such as the German Bight) while other locations a short distance away (such as the United Kingdom coasts) are relatively unaffected. In these situations, the dynamics of the surge mechanism are complicated. For example, the Argentine shelf also provides an example of coastal dynamics leading to a significant positive surge generated at a point on the coast only a short distance from another area experiencing a significant negative surge (Pousa et al., 2012).

As regards seiches or meteo-tsunamis, while the atmospheric forcing may have spatial scales of 10-100 km, their incidence is generally limited to particular locations. The mechanism involves long ocean waves generated in the deep ocean by an atmospheric disturbance (e.g. atmospheric gravity waves, fronts, squalls) which are further amplified at their arrival at the coast (Monserrat et al., 2006). Depending on the particular topo-bathymetric characteristics, the amplification occurs at only given sites.

As regards tide gauge records and data bases of surge events, it has to be recognized that the largest extremes that lead to the most catastrophic flooding, and which are of most practical interest, might not always be represented adequately in the data sets. This reservation applies particularly for surges caused by tropical storms. These events are, by definition, rare ones, and when they do happen the highest sea level may not occur exactly at the gauge, rather than at some distance along the coast. Therefore, these large events may not be sampled at all even in a record of many decades. In addition, some gauge technologies may not allow anomalously high sea levels to be recorded (e.g. if sea level were to exceed the height of a stilling well), and during the most energetic storms a gauge may be destroyed and so the extreme may not be recorded.

I.6. Future sea level rise and extremes

Some of the most challenging questions in climate and sea level research are:

1. How will the probability distribution of extreme sea levels in future be different from that of the 20th century, due to a warmer climate?
2. What are the links between global warming/natural variability and the increase of extreme sea levels?
3. Are there any changes in relationship between the trends in extremes and trends in mean sea levels in warming climate?

Warming could lead to a much increased incidence of coastal hazards such as flooding, which are major concerns for society (Hallegatte et al., 2013; Hinkel et al., 2014). The latest IPCC report (AR5) noted that a 0.5 m rise in mean sea level will result in a dramatic increase in the frequency of high water extremes, by an order of magnitude, or more in some regions (Church et al., 2013). In addition to sea level rise and its role in the changes in extreme sea levels (Menéndez and Woodworth, 2010), there is an evidence that hurricane activity in the North Atlantic are sensitive to global temperature changes, with a doubling frequency of "Katrina magnitude" events over the 20th century due to global warming. Projections show up to a sevenfold increase in the frequency of "Katrina magnitude" storm surges for a 1°C global temperature rise (Grinsted et al., 2013) with trends in mean sea levels removed. There is open question about how the behaviour of mid-latitude and tropical storms will change in warming climate, as these drive extreme sea level events by means of storm surges and wave overtopping (Seneviratne et al., 2012). The Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) emphasized that changes in the regional extreme sea levels are poorly understood and highlighted their further study as a future priority (Seneviratne et al., 2012).

Part II. Observational needs

In this section, we discuss observations needed to address the scientific questions described above and provide recommendations.

II.1. Coastal altimetry data base

The processing requirements of coastal altimetry are complex and require the attention of specialists and integration with local knowledge or ancillary information. The resulting know-how could, in principle, be available to many users, but in practice its full exploitation is still limited. For instance, space agencies' ground segments do not include a coastal processor with a dedicated coastal retracker and a specific set of corrections. Nevertheless, the coastal altimetry community is progressing in producing tailored experimental products dedicated to the monitoring of coastal areas (Cipollini et al., 2009, 2016; Vignudelli et al., 2011; Passaro et al., 2014; Gomez-Enri et al., 2016). Table 1 summarises the characteristics of the experimental products available to the community, and http://www.coastalt.eu/community#datasets provides links to coastal altimeter datasets. Compared to standard altimetry products, they may include higher along track resolution, new/improved retrackers, new/improved corrections, refined pre-processing and/or post-processing. The problem is that they are often limited to specific missions or areas of investigation, or available only for limited time periods. There is a requirement for a “multi-mission along-track coastal Archiving, Validation and Interpretation of Satellite Oceanographic data (AVISO)-like” facility, that presents data to users with an optimised processing standard and in a common format for use in integrated analyses. Validation and quality control of these products in some pilot regions is on-going and results show so far that more and better data near the coasts can be retrieved. The challenge now is to demonstrate how coastal altimetry might contribute to a better understanding of relevant ocean processes in the coastal zone. Closely connected is also the goal of experimenting with new data management methods (e.g., European Space Agency (ESA) Thematic Exploitation/Regional Platforms – TEP/REP) to make coastal altimetry easier to access and exploit.

ID	Produced by	Missions	Product level	Posting rate	Coverage	Download from
AVISO	CLS, CNES CNES	e1,tx,e2, en, j1, j2, c2 (LRM/PRLM), sa	L2, L3, L4 also L4	1 Hz	Global + european regions	AVISO+
CMEMS	CLS CNES	e1,tx,e2, en, j1, j2, c2 (LRM/PRLM), sa	L3 L3 for assim	1 Hz	Global + european regions	marine.copernicus.eu
PISTACH	CLS CNES	j2	L2	20 Hz	Global	AVISO+
PEACHI	CLS CNES	sa	L2	40 Hz	Global	AVISO+
XTRACK	LEGOS-CTOH	tx, j1, j2, gfo, en	L2, L3	1 Hz 20Hz (test)	23 regions	CTOH AVISO+
RADS	EUMETSAT, NOAA, TUDelft	gs, e1, tx, pn, e2, gfo, j1, n1, j2, c2, sa		1 Hz	Global	TUDelft
ALES	NOC	j2, n1 (coming)		20 Hz	Global, <50 km from coast	PODAAC
SARvatore	ESA-ESRIN	c2 (SAR only)		20 Hz	SAR mode regions	ESA GPOD
COP	ESA	c2 (LRM/PLRM)	L2	20 Hz	Global	ESA

Table 1: Available coastal altimetry products (source: Cipollini et al., 2016b).

Recommendation

Develop an easy-to-use data base of multi-mission, homogeneous gridded coastal altimetry products, with as global as possible coverage.

II.2. Coastal waves and winds

The retrieval of waves and winds in the coastal zone is as yet not as mature as sea level measurement. Liu et al. (2012) showed the potential usefulness of the 1-Hz along-track altimetry data in contributing to descriptions of the surface circulation on the West Florida Shelf and the challenges of such applications. Passaro et al. (2015) showed that near coast ALES estimations of Significant Wave Height (SWH) at 18/20-Hz are generally better correlated with buoy data than standard processed products. The sea-state bias used to correct the range measurement is altered near the coast and so far has not been estimated for the coastal zone. The spatial variation of the wave field is highly dependent on the local bathymetry, this may require several different algorithms.

Although no study exists in coastal areas, several studies have highlighted the interest of using altimeter-derived winds over open ocean for climate studies. It should be noted that estimates of waves and winds do not require improved corrections. Further studies are necessary to better understand the high-resolution data at short spatial scales. Young et al. (2011) have shown that altimeter-derived winds indicate a global rise of sea-surface wind field of roughly 3-4 cm/s/yr (from 1991 to 2008) with large regional patterns between 1 cm/s/yr and 11 cm/s/yr. Similar sea-surface wind speed increase have been more recently shown by (Zheng et al., 2016) from Cross-Calibrated, Multi-Platform (CCMP) data, not based on altimetry measurements, but confirming the ability of altimetry measurements to measure the long-term evolution of sea surface winds. Furthermore, Ablain et al. (2012) compared thoroughly the long-term stability of global altimeter wind speed by cross-comparison with models. A very good stability of recent missions (Jason-1, Jason-2, Envisat) has been highlighted. Further studies are necessary to better characterize and understand the long-term evolution and uncertainties of altimeter sea-surface wind in coastal areas. SAR and scatterometry data would also be useful in the interpretation of the results.

Recommendation

Altimetry can provide wave height, wind speed and sea level at same time. A unique profile of these quantities is available from offshore to the coast when a satellite altimeter flies over the area. This profile shows the spatial structure of these important quantities that is not available from pointwise measurement systems. Best use the fine-scale information and its variation at the coast is needed. The high resolution wave field in the coastal strip is also relevant, as it helps development of more realistic wave models that can be used to estimate wave setup.

R&D investigations using archived and coming altimeter data sets (in particular with the new SAR mode) need to be conducted. There are important ocean processes that are specific to the coastal zone, e.g., effect of infra-gravity waves on sea level; poorer quality of winds in-shore, effect of strong currents (e.g. tidal) on waves, etc. There is a need for a multi-sensor approach for wind &waves in the coastal zone using altimetry, SAR and scatterometry in selected regions where ground-truth is available for validation. Observations of wind&waves are important to better understand how waves are transformed from the open ocean to coastal zone.

A dedicated study is required to better understand the variations in the wave field near the coast, including the estimation of coastal sea-state bias. As there is a strong dependence on bathymetry, high-resolution bathymetry is required.

II.3. Tide gauges collocated with GPS

Faced with the difficulty of modelling all the relevant geophysical processes that can cause vertical displacements at tide gauges, both globally and accurately, the alternative approach of measuring using space geodesy techniques has been reiterated within the past decade (e.g., Woodworth, 2006; IOC, 2012; Wöppelmann and Marcos, 2016). What is more, first results at the global scale showed that the Global Positioning System (GPS) can indeed provide useful constraints to estimate trends in regional and global mean sea level change (Wöppelmann et al., 2007). However, the GPS antenna co-location with tide gauges and the lack of available data, among other issues, still prevent scientists from using GPS velocities in studies of global mean sea level change (e.g., Jevrejeva et al., 2014). Presently, less than 14% of the Global Sea Level Observing System (GLOSS, a project from the Intergovernmental Oceanographic Commission of United Nation Educational, Scientific and Cultural Organization - UNESCO), tide gauge stations are directly (on top of the tide gauge) equipped with a permanent GPS station. Interestingly, most so-called "co-located" stations are often serendipitous cases (Wöppelmann and Marcos, 2016); i.e., the GPS antenna appears to be located near (but distant) to a tide gauge by chance. This is because in most cases GPS installations were not foreseen originally to monitor the tide gauge, neither as a primary application nor as supplementary, even later on when its coincident location became obvious. Indeed, only 22% of the GPS stations near to a GLOSS tide gauge gather the basic levelling information for sea level applications (geodetic tie between GPS antenna and tide gauge benchmarks). As a consequence, the latest GLOSS implementation plan calls for an important upgrade of its core network of tide gauges with the installation of continuous GPS stations (IOC, 2012), and that their observations and metadata be provided to its dedicated data assembly centre (Système d'Observation du Niveau des Eaux Littorales - SONEL, http://www.sonel.org) so that the observations and generated products be public and free to anyone in line with the IOC/UNESCO oceanographic data exchange policy. Likely, what the limited number of GPS co-located tide gauges tell us is that the best effort approach of the GLOSS programme has found here one of its main limitations.

Recommendation

Increase the number of Global Navigation Satellite System (GNSS) stations collocated with tide gauges for monitoring vertical land motions.

II.4. Vertical land motion from INSAR, GPS and "coastal altimetry minus tide gauge"

Considering the limited amount of GPS data available at tide gauges, other geodetic methods have been investigated to extend the data set of geodetically monitored tide gauges. One noteworthy idea is to combine satellite radar altimetry and tide gauge data (Cazenave et al., 1999). The accuracy of this method is on average twice as large as GPS i.e., on the order of 0.8 mm yr^{-1} (Wöppelmann and Marcos, 2016). Yet, it provides information on vertical land motion at the very tide gauge locations where GPS data is often missing, and can increase the number of geodetically monitored tide gauges by at least 60%. In addition, the accuracy of this method obviously improves not only as the satellite record length increases, but also when reanalysed satellite altimeter data are produced using homogeneous analysis strategies with improved models and corrections (Ablain et al., 2015), especially in the coastal zone.

Another important limitation is that even extensive GPS networks, such as those deployed in Japan, are essentially a collection of point measurements that are sparse compared to the spatial scales of vertical land motion along many coastlines, where information is needed to determine relative sea level change. Brooks et al. (2007) proposed to combine pointwise but accurate geocentric measurements from GPS with spatially-dense but relative (to an arbitrary point on land) measurements from Interferometric Synthetic Aperture Radar (InSAR; e.g. Massonnet and Feigl, 1998). They show that the combined GPS and InSAR products can yield deeper physical understanding and predictive power for beach morphology evolution. Subsequent studies have explored various methods based on InSAR measurements to further assess its applicability in different coastal environments (Raucoules et al., 2013; Wöppelmann et al., 2013; Le Cozannet et al., 2015), confirming its usefulness in sea level studies. Depending on the processing method used (conventional interferometry or advanced techniques such as Persistent Scatterers Interferometry, Ferretti et al. 1999) and data characteristics, the use of SAR interferometry is appropriate for surface deformations ranging from mm/yr to tens of cm yr^{-1}. InSAR, being more reliable on urban (or arid) areas than on vegetated areas, is particularly efficient for measuring surface deformation on coastal megalopolis. In these cases, as pointed out previously there is a particular interest for cities where most tide gauges are located (Holgate et al., 2013). For mapping long-term deformation with a precision consistent with the sea-level rise rate, the performance of the techniques (in addition to site-dependent elements such the surface characteristics and the deformation rate itself) is related to the number images in the archive (e.g. about 50 images on a studied multi-year period for reaching a mm/yr precision). Worthy of note is the fact that using archived data (up to the 1990s using past space-borne SAR missions), SAR interferometry allows to map past surface deformations in areas where no (or incomplete) ground based geodetic networks exist. However, no project exists at the European or global scale, either using the combination of satellite altimetry and tide gauges or combining GPS and InSAR methods.

<u>Recommendation</u>

Develop precise positioning capabilities in coastal areas combining GNSS, InSAR and altimetry minus tide gauge approaches to monitor regional land motions.

II.5. High-frequency tide gauges

Most tide gauges around the world record sea levels as average values (integrations) over periods such as 6, 10 or 15 minutes. This sampling is adequate for most operational applications involving the monitoring of tides, storm surges and mean sea level. However, some sites that integrate over shorter periods, which includes especially those equipped with modern gauges (such as radar instruments), are also capable of monitoring higher-frequency processes such as seiches and tsunamis (IOC, 2016).

GLOSS (see IOC, 2012) suggests nowadays that gauges address such 'multi-hazard' aspects with sites having more than one type of sensor (perhaps radar plus pressure). For example, the primary sensor (radar) would record typically 3-minute average values, or at higher frequency, while a differential pressure transducer (one that measures the difference between water pressure and atmospheric pressure) would record 1-minute values or at higher frequency. The pressure gauge would be the primary tsunami sensor and provide data to fill any short gaps in the radar record.

All data would be transmitted rapidly to warning and data centres. Gauges with these capabilities would be able to satisfy most coastal monitoring requirements.

GLOSS has historically been focused on completing its Core Network of approximately 300 stations around the world. However, it has always encouraged the development of the densified regional networks that are required for detailed coastal applications. Such investments clearly require major attention at the national level.

Recommendation

The international community should take steps to complete the GLOSS Core Network, including the provision of GNSS equipment at each tide gauge station, as required by the GLOSS Implementation Plan (IOC, 2012).

We also highlight the following issues that have links to the need for high-frequency tide gauge data:

1. *An integrated approach is needed for high-frequency data distribution (e.g. satellite altimetry data, tide gauge data, information about individual extreme events, tidal analysis for high-frequency data from tide gauges, information about vertical land movement and displacement).*
2. *An integrated observational data portal could provide valuable information for the modelling community (e.g. tide gauge, satellite altimetry) developing storm surge models/shelf sea models/Earth System Models.*
3. *Available sea level projections with "upper limit" and rates for sea level rise would facilitate research in coastal areas (for example, sediment transport) as well as making a strong case for high-frequency data.*
4. *There is a need for a high-frequency tide gauge network in Asia as well as along the coasts of South America, the Arctic and Africa. The most vulnerable regions (e.g. Bangladesh) are not covered with long-term high-frequency observations.*
5. *There are no high frequency data available from many other countries, even if there are tide gauge networks. That demonstrates a need for strong national and international efforts to make progress in these countries.*

II.6. Comprehensive database for extreme events such as surges and waves

The most valuable sources of information on sea level extreme events are the data banks of tide gauge records, such as those collected for the GLOSS programme by the University of Hawaii Sea Level Center (UHSLC) and the British Oceanographic Data Centre (BODC). The UHSLC concentrates on hourly values of sea level, as its focus is on ocean and climate processes that can be studied adequately with such uniform sampling. BODC aims to archive the original data, at the recorded frequency. Recently, a data set of sea level combined from various governmental services and research sources, including UHSLC and BODC, has been assembled and called GESLA-2 (Global Extreme Sea Level Analysis, Version 2; Woodworth et al., 2016). This is the most complete set of in situ records assembled to date. Global Extreme Sea Level Analysis (GESLA)-2 and its predecessor GESLA-1 have been used in a number of studies to do with sea level extremes (e.g. Menéndez and Woodworth, 2010); a list of publications using these data sets may be found in www.gesla.org. A priority for the community is to ensure that this activity is maintained and extended in the future.

The databases that provide information about extreme sea surface waves include observations from three sources: buoy records, satellite altimeter data and visual data for the observing ship system. Global wave reanalysis products have also been used to study extreme wave climate variations since they provide long historical reconstructions over coastal and regional areas not covered by observations. Global information of buoy records can be found from different initiatives, such as the National Data Buoy Center (NDBC) from the National Oceanic and Atmospheric Administration (NOAA), and the European SeaDataNet programme. Voluntary Observing Ship (VOS) wind and wave data are collected from the International Comprehensive Ocean-Atmosphere Data Set (ICOADS) and provide long historical information from 1958. Gulev and Grigorieva (2006) analysed this source of information to study winter wave climate in the North Atlantic and Pacific. Nevertheless, VOS dataset only provide wave information through the main ship navigation tracks and the ships tend to dodge the higher sea storms. In regards to altimeter data on sea state parameters, several products are available from space agencies and related institutions. The AVISO and Physical Oceanography Distributed Actice Archive Center (PODAAC) portals are two examples. However, while there are buoy records and multi-mission altimeter products with more than 20 years that have been used to analyse extreme waves (e.g. Menéndez et al., 2008 and Izaguirre et al., 2011 respectively), extreme wave climate is often studied from global reanalysis (e.g. Caires, Swail and Wang, 2006; Wang et al., 2012; Izaguirre et al., 2013; Chawla et al., 2013).

There are many catalogues of historical storms (e.g. Lamb, 1991). Catalogues of storm surges, derived from a mixture of tide gauge and numerical storm surge model information, are available in several countries, especially the United State of America (USA) and UK. For example, the USA storm surge national database currently containing over 5800 storm surge data points from 42 hurricanes. http://psds.wcu.edu/projects-research/storm-surge/surge-database/; there is the US SURGEDAT database (http://surge.srcc.lsu.edu); the UK Surgewatch project at the University of Southampton, (https://www.surgewatch.org/about/); a database for several regions such as the Bay of Bengal, the North Sea, Adriatic and the North Atlantic focused on the modern era when altimeter data are available, the eSurge project (http://www.storm-surge.info/); storm surge archives from tropical cyclones also exist, e.g. the US Navy Joint Typhoon Warning Center (http://www.usno.navy.mil/JTWC/) with information on the Pacific, Atlantic and Indian Oceans; the Atlantic hurricane database (HURricane DATabase - HURDAT2) with information about tropical cyclone activity 1851-2013 http://www.nhc.noaa.gov/data; a North East and North Central Pacific hurricane database (known as NE/NC Pacific HURDAT2) for the period 1949-2013 (http://www.nhc.noaa.gov/data/). Other databases based on the analysis of historical reports and initially aimed at inventorying tsunami events have incidentally identified historical storms, and may provide complementary information back to the 16th century or earlier (e.g., Lambert and Terrier, 2011; http://tsunami.brgm.fr)'.There has to be concern about the completeness and uniformity of such historical databases.

Recommendation

It is important that the above-mentioned essential data bases be maintained and extended as far as possible.

II.7. High-resolution digital elevation models and bathymetry

High resolution Digital Elevation Models (DEM) and coastal bathymetric data are critical datasets for a number of applications in coastal zones, including: (1) modelling accurately the coastal flooding from tides and storm surges (e.g., Le Roy et al., 2015); (2) evaluating coastal morphological changes due to sedimentary processes or human interventions (e.g., Long et al., 2016); (3) mapping tsunamis and earthquake hazards induced by submarine faults and landslides; (4) delineating the limit between the public and the private spaces; (5) providing maps for navigation (6) identifying submarine archaeological sites.

To meet these needs, users ideally require a high-resolution (in time and space) continuous marine-land topography and bathymetry map, with topographic errors reduced to 20cm for coastal flooding applications (see Table 2). However, the applications listed above have different requirements in terms of resolution, accuracy, temporal sampling. For example, seismic-tectonics applications do not require high temporal sampling, nor very shallow waters, with metric to decimetric resolution, whereas navigation requires a high precision mainly in the 15-30m depths ranges, while being in need of information regarding the temporal morphological changes in shallow waters. Coastal flooding is very concerned by shallow waters and temporal changes and requires higher resolution than previous applications (see Table 2). Finally, the required resolution and precision of the bathymetry can depend on the depth itself.

The diversity in these needs raises the following question: should a remote sensing product on coastal topography and bathymetry seek versatility (e.g., multi-applicable product based on the fusion of different Remote Sensing techniques) in order to respond to all potential applications simultaneously? On the other hand, should tailored products be elaborated, so that each application is linked to the most appropriate techniques? In practice, the current developments in coastal DEM and shallow bathymetry have combined the two approach, by providing a generic High Resolution (HR) product based on LiDAR data, which is however difficult to handle and requires post-processing (removing trees and cars from the HR-DEM). In the case of bathymetric mapping, repeated bathymetric surveys with large coverage remain today not fully realistic, due to the limitations in computing capabilities and in each of the techniques, some of them being still in development. As a consequence, most studies currently develop a bathymetric solution for each given problem (depths of interest, turbidity in the area considered, etc.; Su et al. 2008; Capo et al. 2014; Poupardin et al. 2016). In this field, recommendations for future developments can be provided: for example, for applications requiring high temporal resolution, the processing capabilities should allow bathymetry production in short time. A Research and Development activity should be carried out in this perspective.

While the current limitations are real, it must be acknowledged that a great deal of progress has been made in using DEM and bathymetric data based on remote sensing over the last 10 years (see IGOS Coastal Report, 2006). Owing to the increased availability of LiDAR data, numerous coastal flooding studies have been realized (e.g., Le Roy et al., 2015; Bilskie et al., 2014 among many others, including many studies made by coastal consultants and engineering companies). Ultimately, these studies are useful to: (1) prevent or to adapt to coastal flooding, and (2) prepare for potential crisis. In the first case, action from coastal managers focuses on land use planning and vulnerability reduction or adaptation. In the second case, the priority is given to designing alert systems, in support to crisis management. However, the lack of repetitiveness in current LiDAR acquisitions is presently limiting the applications in coastal morphological applications, especially in highly dynamic coastal zones such as beaches, marshes and estuaries. Progress in this field is expected from new techniques such as the use of HR satellite and drones imagery (Table 2).

Earth Observation Product	***Typical requirements for observation data***			***Available techniques and datasets***	***Maturity of the application in coastal zones***
	Resolution in time	***Resolution in space***	***Accuracy (acceptable uncertainties/error bars)***		
Digital elevation model of subtidal zones	*Depending on the hydro sedimentary dynamics: 1 single acquisition to several acquisitions per season*	*1 to 10m depending on the coastal site*	*Less than 20cm (3-sigma uncertainty)*	*LiDAR data*	*Operational*
				Stereo HR imagery	*Development*
				Synthetic Aperture Radar (Tandem)	*Development*
Shallow waters bathymetry (0-5m)	*Depending on applications/site (from 1/season to 1/decade)*	*1 to 10m depending on the coastal site*	*Less than 20cm*	*Multi-spectral imagery*	*Development to operational*
Intermediate depths Coastal bathymetry (up to 50-80m depth)	*Depending on applications/site (from 1/season to 1/decade)*	*1-10m (observation data); 10-100m (final product)*	*few meters*	*Optical imagery: Wave characteristics*	*Development*

Table 2: Typical Earth Observation products needed to meet the coastal risk user requirements for continuous marine-land topography and bathymetry (non-exhaustive list).

Recommendation

Further acquisition of high-resolution topography and near-shore bathymetry data is an observational priority, especially along densely populated coastlines. A second priority is the development of methods to cover the need for repeated acquisitions in highly dynamic areas such as estuaries, sandy inlets and sandy beaches. While this seems technically feasible according to the studies shown in Table 2, further research is needed to meet the user's requirements in terms of resolution, especially in near-shore areas.

II.8. Comprehensive data for surveys of shoreline change

Scientists and coastal managers concerned with shoreline changes can focus on three different types of processes: (1) extreme events such as major storms or cyclones, (2) seasonal to decadal coastline variability (Figure 2), and (3) decadal to multidecadal shoreline changes.

Depending on the process of interest, different types of data and observational strategies are needed. For extreme events, the priority is given to comparing pre- and post-crisis coastal morphologies. In this case, both a background observational mission and a capacity to monitor the coastal sites just after the events are needed. Such capabilities are presently more or less available from both the space and in situ components of coastal observatories (international charter for disaster; post-crisis special missions organized by coastal communities).

Monitoring seasonal to longer term changes requires high resolution observations in space and time. However, the actual specifications depend on the coastal site of interest. For example, multi-decadal surveys in highly dynamic deltas can benefit from medium resolution data (e.g., Landsat data), which can be analysed using a semi-automatic procedure (Shearman et al., 2013). However, most shorelines around the world are currently evolving at rates in the order of +/-1m/year (Bird, 1985). With such settings, obtaining the required accuracy in shoreline position is challenging: currently, most studies use very high resolution optical data of 0.5 to 1m resolution (e.g., from Aerial photographs or satellites such as Pleiades, Quickbird), which are geo-rectified by an operator, who identifies a shoreline proxy visually at each date of interest. With such very high resolution raw datasets, image geo-rectification errors and difficulties in identifying the selected shoreline proxy are the main contributions to the shoreline position errors. Finally, this results in final shoreline position positions with uncertainties typically ranging from 1 to 5m (e.g., Ford, 2013; Yates et al., 2013). Here, the lack of automatic techniques allowing to achieve this level of accuracy explain why there is presently no global database of shoreline changes from satellite remote sensing.

Figure 2: example of impacts of the interannual variability on coastal sediment availability in Montalivet (South-western France): left: situation after the exceptional storm season of 2013/2014; right: situation after the exceptional calm winter of 2014/2015. Exceptionally large differences in intertidal beach levels are obvious when comparing the two photos (source: Aquitaine Coastal Observatory/ONF/ULM Sud-Bassin)

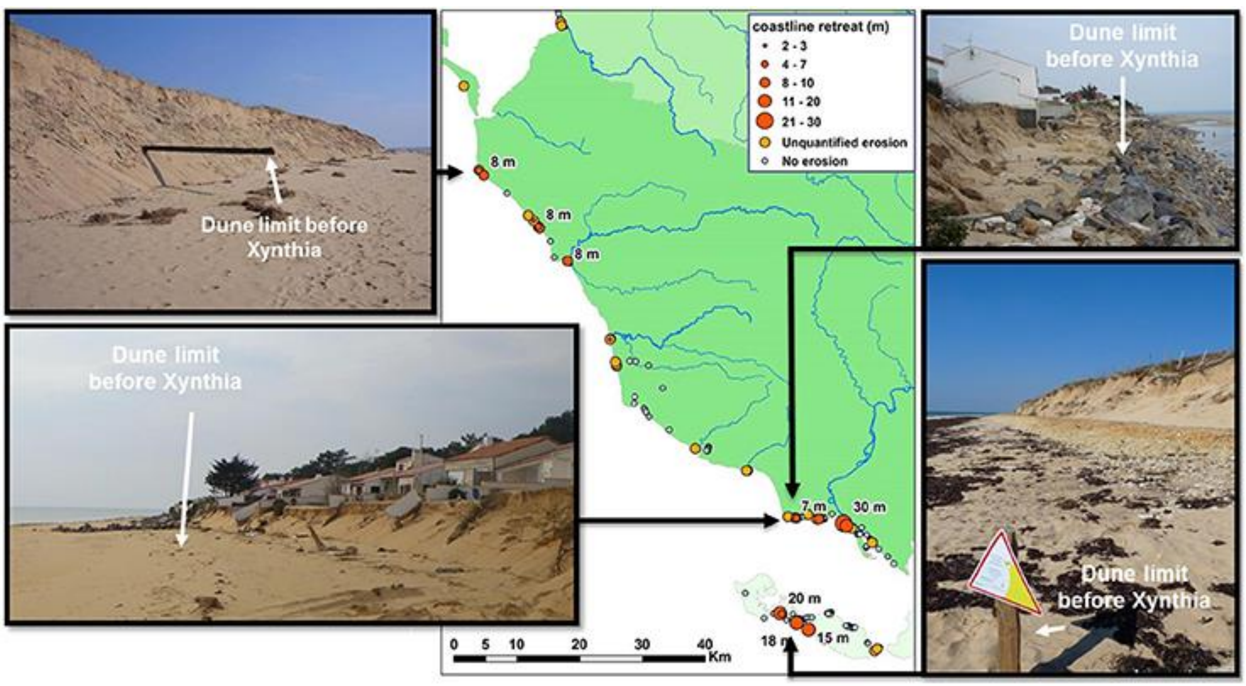

Figure 3: *Examples of impacts induced by a single extreme event along the western French Atlantic coast induced by Xynthia storm in 2010. After this event, beach shorelines have generally retreated by 5 to 20 m depending on the location (source: Le Cozannet et al., 2016).*

Recommendation

The full potential of remote sensing has not been fully explored yet. For example, preliminary work has analysed the potential of SAR data to monitor shorelines and shoreline changes in tropical *areas, where the use of optical data is frequently hampered by the presence of clouds in images (e.g., Baghdadi et al., 2007). While the resolution of this data set (about 30 m for ASAR on-board Envisat) remains too limited, more recent high-resolution sensors (e.g., Cosmo-Skymed) and improvements in orbital parameters control (e.g. TerraSAR-X) may offer useful alternative. Research to automatize the precise georectification of images (beyond what is classically provided by current workflows) and, ultimately, to retrieve shoreline proxies automatically would be much beneficial to the community.*

II.9. Sediment transports from ocean colour measurements

The monitoring of Suspended Particulate Matter (SPM) in surface coastal waters is essential to understand the evolution of coastal zones (Ouillon et al., 2004; Loisel et al., 2014). Solid water discharge from rivers, terrestrial matter from land washing, and resuspension of bottom sediments occurring in shallow waters under waves and swell action, represent the main sources of suspended particles in coastal waters. Besides mineral particles, SPM also encompasses organic particles from terrestrial origin, or produced locally through the different biogeochemical processes occurring in water (not discussed here). The SPM spatio-temporal variability is directly related to the various physical and geophysical processes responsible to the evolution of these highly dynamics environments. For instance, SPM variability is tightly linked to coastal erosion and accretion processes and then has a direct impact on the coastline evolution. In this context, forecasting SPM dynamics in response to natural or anthropogenic forcing is crucial to better adapt to present and future coastal changes. Such objective can only be achieved by combining modelling and observation efforts.

In this context, ocean colour satellite observations can provide information on the SPM variability of surface waters at relevant spatio-temporal scales. These data, which can be collected over long time period and at relevant spatial resolutions, represent a valuable source of information to better constraint sediment transport models. In addition, combined with physical forcing parameters, such as waves and swell, a better identification of coastal areas affected by erosion and accretion can be achieved (Figure 4). While past ocean colour sensors were able to collect observation at the spatial resolution of 1km x 1km, the new ocean colour sensors generation, such as OLCI on Sentinel-3, allow the water surface to be sampled at a much better spatial resolution (i.e. 300 m x m). Also, high spatial resolution sensors (10 to 60 m x m) such as OLI on Landsat-8 or MSI on Sentinel-2, both originally developed for land observation, have a sufficient radiometric resolution to be used for SPM assessment. The availability of such new sampling platforms paves the way of appropriated researches dedicated to a better understanding of sediment dynamic at relevant spatio-temporal scales. Due to the bio-optical complexity of coastal waters, linked to the tight coupling between physical and biogeochemical processes, permanent land-sea interactions, and the variety of temporal and spatial scales involved, the exploitation of ocean colour satellite data over coastal ocean requires specific algorithmic development (GlobCoast and Coastcolour projects).

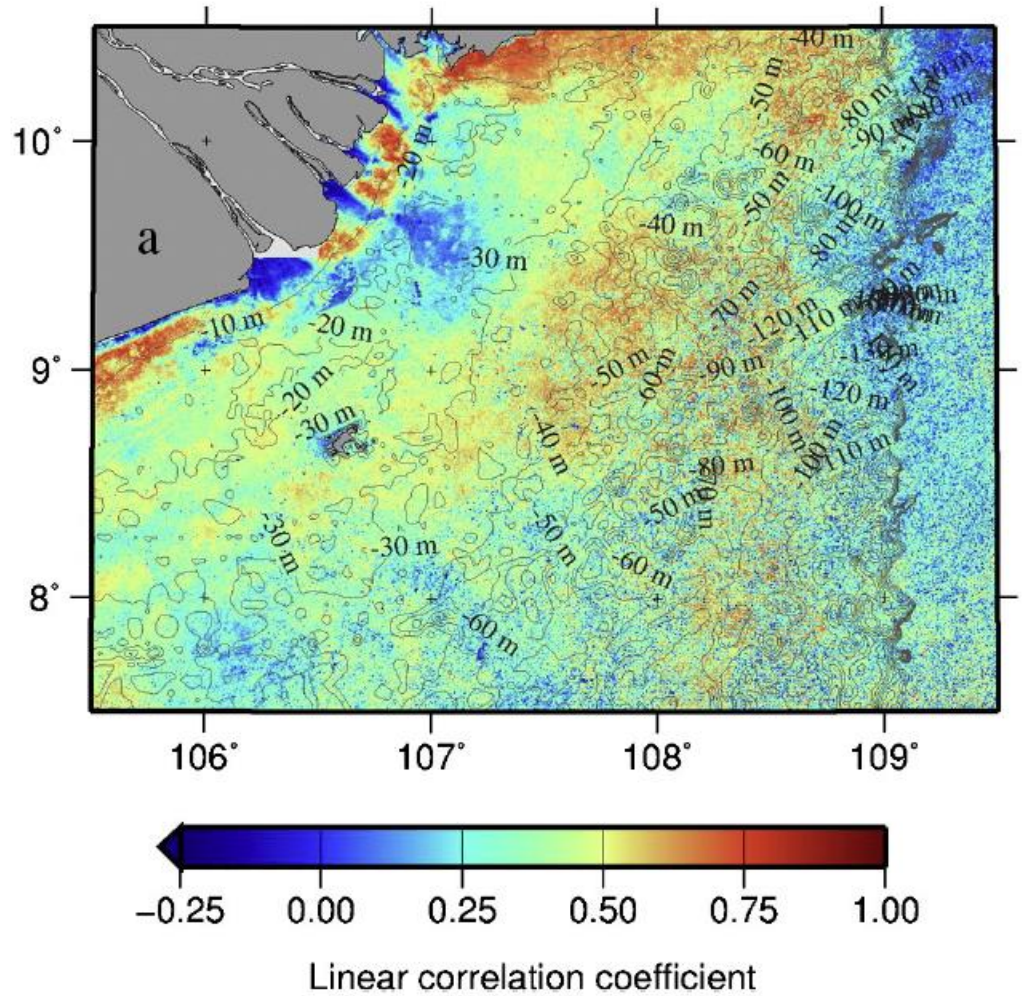

Figure 4: Correlation map between SPM and wave + swell intensity for the Mekong delta area. High positive correlation values show erosion/resuspension areas where waves and swell control the SPM variability (source: Loisel et al., 2014).

Recommendation

Coherent suspended particule matter time series over the global coastal region should be developed from past and present ocean color data. This task requires inter-calibration between the different sensors, as well as the development of common atmospheric and bio-optical algorithms. Uncertainties map should also be provided.
Fusion of high-spatial-low-spectral and medium-spatial-high-spectral resolutions sensors should be undertaken to better sample the coastal environment at the relevant scales

II.10. River discharge (sediments, water flux, etc.) and other parameters from the land

River Water Discharge (RWD) is one of the major processes driving the coastal zone system. It reflects the drainage basin area dynamics and is a function of, among others, parameters such as geology, relief, precipitation, vegetation, climate and human influences. The RWD is of fundamental importance because it provides fresh water, affecting mixing and circulation processes in estuaries; and Suspended Particulate Matter (SPM) in determining the geomorphological and the geochemical properties (Milliman and Farnsworth, 2013). Over the last decades, all these processes have been strongly modified by human activities. Humans are increasing the SPM river transport through soil erosion activities, and decreasing concurrently this flux through their trapping in reservoirs (Syvitski et al., 2005). Another important consequence of RWD control is the high flow amplitudes reduction, which decreases the carrying capacity for SPM, and modifies the seasonal estuarine circulation patterns and salinity distributions. All of those changes can greatly influence coastal erosion, the benthic environments, coral reefs, seagrass communities, and coastal fisheries. Quantifying accurately fluvial delivery to the coastal zone is therefore crucial. Long-term high-resolution RWD and SPM measurements - in both time and space - are needed to assess the impact of global change on coastal zones. However, the SPM concentration, due to its spatial inhomogeneity, is one of the most difficult parameters to obtain from in situ hydrological monitoring network and a decline in the number of river gauges is being seen worldwide, mainly due to economic reasons, social conflicts, or material destruction. Satellite remote sensing of terrestrial surface water provides unique capabilities to obtain a global and consistent measurement network. Radar altimetry offers great perspectives to estimate water level (with 1-2 cm uncertainties), and derive discharge products (once calibrated), for ungauged and poorly gauged hydrological basins, yet largely unexplored by hydrologists, despite the availability of large online datasets.

Promising results have been obtained using images in the visible and near infrared spectrum with high temporal revisit (MODerate-resolution Imaging Spectroradiometer - MODIS) for estimating discharge for medium size basin (<10,000 km^2). The Surface Water and Ocean Topography (SWOT) satellite mission planned for launch in 2020 will improve the characterization of global runoff processes, especially with a 50 m observability threshold. The suspended sediment monitoring over large spatio-temporal scales have been greatly improved by the combination of RWD data and surface suspended sediment concentrations estimated from standard ocean colour sensors (SeaWiFS, MODIS, MERIS, VIIRS) and from high spatial resolution sensors such as Operational Land Imager (OLI) on LANDSAT-8. Another important parameter is the Submarine Groundwater Discharge (SGD), recognized as an important pathway for material transport to the coastal zone (Burnett et al., 2006). However, SGD is relatively difficult and costly to measure, especially at large-scale. Sawyer et al. (2016) performed a high-resolution continental-scale analysis of SGD, based on a simple water budget analysis and state-of-the-art continental-scale hydrography and climate data sets, along the United States coastline and unveiled hot spots for contaminant discharge to marine waters and saltwater intrusion into coastal aquifers. This kind of work, at large-scale, should be encouraged to better understand and predict vulnerabilities in coastal water quality. Finally, only the use of numerical modelling will allow the integration of the broad range of possible scenarios for change. But, an effort must be brought to integrate linkages between different types of models (hydrodynamic, ecosystemic, water quality, etc.) and strengthened the dialogue between the disciplines, in order to predict the integrative effects of global change in coastal zone. There is also broad agreement in the scientific community that data needs to be more easily accessible, and new strategies must be developed to promote global open access (standardized) data sharing.

Recommendation

Provide long-term high-resolution observations of fluvial delivery (river discharge, ground water discharge, suspended particule matter) to the coastal zones

II.11. Land cover and use

Continent wise, the monitoring of coastal zones and their dynamic processes often involves Land Use and Land Cover maps (LULC), prime information that one can get from any kind of high-resolution (HR) imagery. Historically, descriptions of the soil and its cover by water, vegetation, and man-made features of the land like habitat or agriculture, have mostly been derived from aerial photographs, and since the 1970s from satellite HR imagery (e.g. Landsat TM since the 1970's and Spot HRV since the 1980's). When available, these maps are mainly applied to characterize species covering dunes or intertidal and floodable areas as proxies of the shoreline changes (e.g. Masria et al., 2015; Giri et al., 2008). The regional modelling of coastal processes like erosion or vulnerability can also often consider LULC maps either as objective criteria for the geographic distribution of the models parameters or as multi temporal information to be compared with models results (Gesselbracht et al., 2015).

These studies usually require decimetric resolutions images at different epochs. So far, the technical compromise between the satellites resolution and their revisiting capacity has made difficult the multiannual elaboration of an exhaustive HR Land Cover (LC) mapping that would be necessary to monitor the coastal LC change. *C*apitalizing on the Copernicus land monitoring services, the ongoing CCI Land Cover project (http://www.esa-landcover-cci.org/) has already produced for specific years global maps of LC (GlobCover2005, GLC2000 and GlobCorine2009) and permanent water bodies at the MERIS/Envisat resolution (300m). Although these products present a significant improvement in the field of global LC description, they still do not fulfil the users requirements for the coastal monitoring in term of resolution, time frequency and land cover types. Future CCI LC releases will progress towards higher resolutions (10-20 meters) based for example on the new ESA Sentinel 2 and sentinel 1 satellites. However, by the time such products get ready and relevant, platforms that distribute HR imagery (e.g. https://www.theia-land.fr) appear as efficient sources of HR satellites time series in order to handle the monitoring and the modelling of coastal zones at relevant resolutions and time frequency.

Recommendation

(1) Provide long-term, HR maps of Land Use and Land Cover at the land-sea interface.
(2) Based on new HR missions (e.g., ESA Sentinel 1 and Sentinel 2), pursue ongoing efforts with existing services to produce annual and seasonal HR Land Cover maps, paying specific attention to littoral areas.
(3) By the time such annual and seasonal HR LULC maps become available, use existing methodologies and HR time series in vulnerable coastal regions.

Part III. Modelling needs

In part III, we briefly address a number of modelling needs.

III.1. Improve coastal sea level projections as well as mean sea level projections

As discussed in section 1.5, sea level changes at the coast result from a variety of phenomena. Sea level rise relative to the coast (the quantity of interest for coastal populations and coastal managers) is the sum of the global mean rise, plus the regional variability (due to non-uniform steric effects and gravitational changes caused by GIA and on-going land ice melt), plus small scale coastal sea level variability (due to changes in wave climate at the coast, changes in coastal circulation, interactions of the circulation with tides etc…) plus vertical land motions. For several years, a number of groups worldwide have provided first attempts to simulate future sea level change at regional scales under different future warming scenarios, accounting for the non-uniform steric and land ice loss effects using process-based climate models (Slangen et al., 2014; Church et al., 2013; Carson et al. 2016). Recently, other studies have also provided sea level projections based on probabilistic approaches either at tide gauge sites or at a few coastal megacities (Kopp et al., 2014; Jevrejeva et al., 2016). All these studies represent significant improvements compared to sea level projections available a decade ago which provided only global mean sea level projections. However, efforts are still needed to develop sea level projections at the coast, accounting in particular for changes in wave climate, changes in coastal circulation, and changes in the interaction between the deep ocean, shelf seas and coastal areas (including changes in the penetration of open ocean thermal expansion to the coast). Most of the processes responsible for the coastal changes are small-scale processes. Their projections require high-resolution simulations of the ocean and the atmosphere circulation that are difficult to realise at global scale because they are computationally expensive. Several initiatives based on the downscaling of presently available climate model simulations (ex: COWCLIP initiative for wave climate changes projections based on CMIP5 climate model simulations) or on the development of new high resolution climate model simulations (ex: the highresmip experiment of the CMIP6 exercise) are currently under progress and should lead to significant advances in this field in the coming years. In parallel, there is still a strong need to improve sea level projections at global and regional scales. At these large scales, realistic contributions due to ice sheet dynamics, which is the most uncertain component to future sea level changes, are absolutely necessary to improve the reliability of projections. A better understanding of how heat fluxes will penetrate the ocean and diffuse vertically in response to increased GHG concentrations in the atmosphere are also important as these processes are the main driver of the regional variability of future sea level change. The ISMIP and FAFMIP experiments of the CMIP6 exercises are designed to answer part of these questions and should bring important first insights on these issues in the coming years.

Recommendation

Develop coastal sea level projections accounting for all processes acting in coastal zones.

III.2. Coastal tide model limitations

The main constituents of the deep ocean tides are now known at the centimetre level (Stammer et al., 2014) but much remains to be learned about regional coastal tides. A recent review of the limitations of coastal tide modelling has been provided by Ray et al. (2011).

Ocean tide models are usually formulated as a combination of harmonic components (e.g. Pugh and Woodworth, 2014). However, all models, especially regional coastal models, will be inevitably incomplete and imperfect in their formulation for two sets of reasons which we term 'commission' and 'omission' errors.

Commission errors result from the fact that the tidal harmonic 'constants' (amplitude and phase) at each model grid point will have an associated error. These errors follow from the imperfect representation by the model of the real ocean tide, due to inadequate knowledge of bathymetry, inaccurate lateral boundary information (for regional models) and imprecise parameterisation (e.g. friction). The role of bathymetric errors can be readily visualised, given that the tide propagates at roughly $\sqrt{(gh)}$, and so large gradients in bathymetry near the coast (and errors) will result in large gradients in tidal propagation (and errors), and one might easily have say a 1 m error in a 10 m depth in coastal areas. Moreover, coastal evolution could mean that bathymetric information is not only imprecise but time-dependent. Another commission error will arise from the finite spatial resolution of a model, with imprecise interpolation of tidal information between grid points resulting in an error in total elevation.

Commission errors can be estimated at a limited number of positions by comparison to constants determined from tide gauge data, although the latter will have their own uncertainties. Even if a tidal model is successful in predicting accurately the tidal signal near the coast, as verified by comparison to tide gauge data, its usefulness off-shore will be difficult to assess until copious, accurate coastal altimetry data sets become available.

As regards omission errors, numerical models rarely derive more than a dozen constituents and often omit sizeable semi-diurnal and diurnal components as well as smaller shallow water and long period terms. This contrasts with analysis of tide gauge data in which typically 60 or more constituents are calculable given a one-year time series. Consequently, errors are bound to occur in the use of models to compute total water elevation from the omission of such additional terms. For example, representing the tides in the English Channel by only the eight major semi-diurnal and diurnal components will leave residual tidal signals of several decimetres.

The many shallow water constituents in shelf areas such as the North Sea or German Bight can represent a particularly important challenge for tide modelling. The larger terms tend to be stable from year to year, and so can be reliably estimated from one year of tide gauge data, if not modelled and perfectly understood. However, it is more difficult to verify the individual accuracies of the many smaller terms. In practice, the larger shallow-water terms (e.g. M4) are sometimes included in numerical models but are often poorly determined and inconsistent with tide gauge data due to imprecise parameterisation of friction and inaccurate bathymetry in the models. There are no regional models which could claim to account for shallow water constituents adequately.

The tides of many continental shelf areas are dominated by semi-diurnal components, which have a seasonal dependence which is often (or indeed usually) neglected in modelling studies. The source of the seasonal variability is partly astronomical (seasonal sidebands of M2 existing in the tidal potential) and is partly related to tide-surge interaction. The seasonal dependence of M2 (represented by terms MA2 and MB2) and of S2 (represented by R2 and T2) is typically 1% of the corresponding main terms around the UK (Pugh and Woodworth, 2014). However, a large part of this seasonal variation is still poorly understood and is highly irregular from year to year.

Finally regarding omission errors, it has been known for many years that tidal 'constants' vary slightly from year to year, depending upon the amount of non-tidal variability in the area and internal tidal processes, resulting in 'cusps' in the tidal power spectrum. Such variations are also considered to be of the order of 1%, although the percentage could vary considerably between locations. In addition to interannual variability, tidal 'constants' can also contain a secular component (in addition to that due to the secular changes in lunar and solar ephemerides) (e.g. Müller et al., 2011).

Recommendation

Access to high-resolution bathymetry is an essential first requirement for regional tide model development.

III.3. Storm surges

Coastal hydrodynamic tools have made major progresses over the last 15 years (Table 3). Together with the increasing availability of LiDAR data, these developments have enabled us to perform detailed analysis of present-day and future coastal flooding (e.g., Le Roy et al., 2015. Nevertheless, a remaining research challenge consists in developing modelling frameworks that are able to represent how coastal flooding evolves with changing landscapes and bathymetries (e.g., Bilskie et al., 2014).

In this area of storm surge modelling, key observational requirements include high resolution digital elevation models and bathymetry (see Table 3), soil roughness data, sea-level, wind and wave data.

Resources	Available modelling resources	Observation needs
Spectral waves models	SWAN (Booij et al., 1999), WaveWatch3 (Tolman, 2009)	Winds, waves (usually from buoys, but sometimes from Altimetry and SAR)
Tidal and storm surge models	MARS (Lazure and Dumas, 2008), MIKE (Wang et al., 2012)	Sea-level, with resolution in time of less than 15min (see GLOSS, 2012)
Statistical tools for joint probability	Join-Sea (Hawkes et al., 2002)	Sea-level, with resolution in time of less than 15min (see GLOSS, 2012)

analysis of waves and surge		
Phase resolving models for wave overtopping	Swash (Zijlema et al., 2011); SURF-WB (Marche et al., 2007); FUNWAVE-TVD (Shi et al., 2012)	Measurements of water levels (and, ideally, flow velocity) inland during the inundation.
Evaluating risks	Armageddon (Garcin et al., 2008)	Post-event damages

Table 3: examples of available resources useful to model storm surges and their impacts

Recommendation

Hydrodynamic modelling need to be further applied to maximize the ability of current modelling schemes to different types of coastal environments. This implies: (1) further acquiring high resolution bathymetry and topographic data; (2) monitoring sea levels in areas unaffected by wave-setup, and possibly offshore (e.g., at 20m depths). Indeed, in some harbours, tide gauge records include a wave setup component, which is difficult to estimate and makes the practical estimation of extreme water levels difficult.

III.4. Morphological changes

Compared to hydrodynamic modelling, morphodynamic modelling remains far less accurate at the moment. At present, existing tools can be classified in three categories (Table 4):

- detailed coastal morphodynamic tools (also called full process models), which perform well in (1) modelling beach changes during a storm event; (2) modelling overflow impact to a dune system; however, such tools are less efficient in modelling the reconstructions of a system after an event and decadal to multi-decadal changes (e.g., Hanson et al., 2003).
- Simple tools applicable in Geographical Information Systems (GISs), which combine information from different databases to anticipate future changes. A very commonly used approach falling in this category consists in extrapolating past shoreline change to assess the future shoreline position, eventually considering adding an additional contribution of sea-level rise. Other approaches attempt to create semi-quantitative indicators of coastline vulnerability, which also consider how the local coastal geomorphology, wave and storm climate (e.g., Gornitz, 1991; Gutierrez et al., 2011).
- In between, intermediate complexity models attempt to reduce the complexity of full process models while focusing on the most important processes at the spatial and temporal scale of interest (Murray, 2007; French et al., 2016).

As none of these models is presently able to reproduce morphological changes in any given setting and spatial or temporal scale (Hanson et al., 2003), observations are critical to make progress in the modelling of coastal processes.

Resources	Examples of available modelling resources	Observation needs
Detailed coastal morphodynamic tools	Delft3D (Lesser et al., 2004) X-Beach (Roelvink et al., 2009)	Coastal bathymetry, waves, currents, tides, sediments characteristics and location.
Intermediate complexity modelling tools (Murray, 2007; French et al., 2016)	Examples: Coastal Track (Cowell et al., 2003) Estuary Spatial Landscape Evolution Model (Thornhill et al., 2015)	Shoreline coastal morphodynamic changes with resolutions and accuracy varying depending on the application (resolution in space: a few m to a few 10m; resolution in time: pre/post storm settings to a few months
Simple tools applicable in GIS	Extrapolation of past shoreline changes observations Coastal vulnerability index: Gornitz (1991) Bayesian networks (Gutierrez et al., 2011)	Shoreline position, at least 1 acquisition per decade and before/after major storms (need for HR imagery of less than 1m resolution for most coastal settings)

Table 4: Examples of available resources useful for modelling coastal morphodynamics.

<u>Recommendation</u>

Research is needed to improve our understanding of morphological evolutions over decades, in order to support decision making (Ranasinghe, 2016). Special efforts should be dedicated to (1) developing appropriate complexity morphodynamic models, (2) further collecting and analysing data relevant for understanding the coastal morphodynamics processes on decadal to multidecadal timescales. As noted by French et al. (2016), these two complementary efforts are needed to gain confidence in the new generation of morphodynamics models, despite their reduced complexity.

III.5. Vertical land motion due to Glacial Isostatic Adjustment

Glacial Isostatic Adjustment, the solid Earth response to the last deglaciation, has a great impact on the interpretation of sea level data, since it impacts tide gauge-based relative sea level measurements, altimetry-based absolute sea level measurements, Gravimetry Recovery And Climate Experiment (GRACE) data over the oceans, and GRACE-based ocean mass measurements (one of the two components of sea level rise). For each of these variables, the GIA effect is different (see Tamisiea, 2011 Tamisiea and Mitrovica, 2011). It also affects GRACE-based Antarctic ice sheet mass balance (one of the mass components to sea level; the associated GIA signal being about of the same order of magnitude as the climate signal). However, there is still no consensus from GIA modellers on the best estimates of land and ocean changes relevant to the above processes, and important differences between models still exist (a result due to the choice of deglaciation history models and hypotheses on the mantle viscosity, etc.) (Bouin and Wöppelmann, 2010, King et al., 2012, Jeverejeval et al., 2014). New generations of 3-dimensional

GIA models are under development (e.g., by K. Lambeck, Australian National University). These account for lateral variations in mantle viscosity (most importantly mantle viscosity contrasts between ocean and continental domains).

<u>Recommendation</u>

Develop an international comparison between existing GIA models with a focus on the GIA effects on (1) tide gauge-based relative sea level, (2) altimetry-based absolute sea level and (3) GRACE-based ocean mass. Assess any evidence for improvement of GIA models with variable mantle viscosity.

Part IV. Operational services to meet user needs

Part IV briefly addresses the role of operational services to fulfil some user needs.
As mentioned in the introduction, the evolution of coastal zones results from several forcing factors (natural and anthropogenic). Assessing the impacts of present and future coastal evolution requires an understanding of the interactions between biophysical and socioeconomic systems and assets on land, and even in the adjacent sea. Looking to both land and sea, as well as to natural and anthropogenic factors and related consequences, is the only way of pursuing the monitoring of such complex systems under various impacts (not only environmental).
In order to exploit the economic investments in space-based observing systems, the development of operational services based on Earth Observation (EO) data is a key goal. The operational services (downstream services) are based on the integration of multisource information (EO, modelling and in situ) with the institutional/policy, social and economic knowledge.
The sustainability of these operational services can be guaranteed by their usefulness and thus their capacity to fulfil coastal user (intermediate and final) needs (Taramelli et al., 2014, 2015a,b).

Part V. Networks of international coastal observatories

Information on the evolution of coastal zones is currently acquired at local to regional scales by coastal observatories, which act as a means of transferring information between science, operational observations (including space-based), and coastal stakeholders (Suanez et al., 2012). Presently, the existing information at national, multinational and global scales originates from these entities (e.g., Bird, 1985; Eurosion, 2004). However, coastal observatories are far from having the same standards (resource datasets, including from satellite observations, workflows, procedures and objectives), so that the information that currently exists is often extremely heterogeneous. Networks of coastal observatories are being established in different countries to resolve this issue.
Here, we argue that establishing links between global providers of Earth Observation data (such as space agencies), and the emerging networks of coastal observatories, can be beneficial for all parties. In other fields of geosciences, several previous initiatives have efficiently established such links and stimulated the use of satellite-based observations in scientific and operational activities. For example, “supersites” (ESA) or “natural laboratories” (NASA) provide access to all geophysical data for key priority sites affected by earthquakes and volcanic eruptions. To summarize, our vision consists in enabling a meeting between (1) a top-down approach of space

agencies and (2) the bottom-up approach of coastal observatories, in order to stimulate research and innovation in support of coastal zone management.

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